

Evolution of drought severity and its impact on corn in the Republic of Moldova

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Abstract Droughts in Moldova were evaluated using meteorological data since 1955 and a long time series (1891–2009). In addition, yields for corn (*Zea mays* L.), a crop widely grown in Moldova, were used to demonstrate drought impact. The main aim is to propose use of the S_i (S_i -a and S_i -m) drought index while discussing its potential use in studying the evolution of drought severity in Moldova. Also, a new multi-scalar drought index, the standardized precipitation–evapotranspiration index (SPEI), is tested for the first time in identifying drought variability in Moldova while comparing it with the commonly used standardized precipitation index (SPI). S_i -m, SPI, SPEI, and S_i -a indices show an increasing tendency toward more intensive and prolonged severely dry and extremely dry summer months. Drought frequency increased through six decades, which included long dry periods in the 1990s and 2000s. Moreover, the evolution of summer evapotranspiration recorded a positive and significant trend ($+3.3$ mm/year, $R^2=0.46$; $p\leq 0.05$) between 1955 and 2009. A yield model based on the S_i -a agricultural index and historic corn yields explained 43% of observed variability in corn production when drought occurred in May, July, and August. Increasing severity of the 20-year drought during the critical part of the growing season is raising corn yield losses, as net losses have so far exceeded net gains.

1 Introduction

Drought is a very important and complex phenomenon that significantly impacts agriculture in various territories and especially so in Southern and Eastern Europe. The Republic of Moldova is among several eastern European countries affected by extreme drought. Any contribution to understanding and predicting drought conditions will be a step toward minimizing drought impacts. Assessing the effects of extreme droughts on agriculture might help to properly anticipate and adapt farming to maximize agricultural production (e.g., Liu and Kogan 1996; Calderini and Slafer 1998). The recent economic crisis has sent shock waves around the globe, reaching all parts of the economic system, even as the drought situation in many European regions has become more severe (e.g., 2006 in Central Europe, 2007 in Southern and Eastern Europe, and 2010 in Eastern Europe). This underscores just how significant can be the impact on European economies (Potop et al. 2008; Livada and Assimakopoulos 2007; Loukas and Vasiliades 2004; Vicente-Serrano et al. 2007). In Eastern Europe, countries are facing negative climate change impacts, and there are significant vulnerabilities as a result of such extreme weather events as drought, dry winds, frosts, heat waves, as well as due to soil erosion and salinization, shortened growing periods, and the occurrence of new pests and diseases (IPCC 2007). In particular, summer crops are negatively affected by increasing summer drought and heat waves. Drier conditions and increasing temperatures in parts of Eastern Europe may lead to lower yields there and yield variability may increase, especially in the steppe regions. Eastern European agriculture also faces major problems of a socioeconomic nature (EEA 2007). A weak economic condition has negative effects on agricultural production in this region in general (e.g., causing low wages for agricultural labor, low prices for agricultural products, and

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continuing small farm size). An example can be seen in catastrophic effects of a heat wave and drought during summer 2007 on agriculture crops in Moldova. That long period of exceptionally high summer temperatures combined with precipitation deficits created the most extreme drought to occur since 1946 and 1947. Crop failures occurred for cereals in 2007, aggregate yields of winter and summer crops fell by 63%, and the cost of lost production was almost €300 million (FAO/WFP 2007). The 2007 drought was due to an almost continuous persistence of heat waves, such that July and August were the warmest in 120 years (Corobov et al. 2010). In July 2007, the heat was linked to persistent anticyclonic situations favoring the advection of dry air masses. The synoptic at the 500-hPa isobaric area was characterized by a prevalence of tropical continental air from North Africa and a movement of warm air into the inferior troposphere (Bogdan et al. 2008).

Although the recent temporal aspects of drought have been subjects of several papers that include the territory of the Republic of Moldova (see, e.g., Corobov 2002; Mihailescu 2004; Daradur et al. 2007; Potop and Soukup 2009), a number of issues remain to be examined.

The objective of this study is to provide an overview of a methodology for assessing drought in Moldova because drought estimation remains a very serious problem of applied climatology. The main aim is to propose use of the S_i drought index and to discuss its potential for studying the evolution of drought severity in Moldova. To be used for drought characterization, the S_i (S_{i-a} and S_{i-m}) index must meet requirements that it (a) can be calculated using data available from actual data collection systems, (b) has a direct relationship with vulnerable agriculture systems, and (c) can be used for predictions and early monitoring systems. This paper also concentrates on application of the new standardized precipitation–evapotranspiration index (SPEI) and its comparison with the more widely used standardized precipitation index (SPI).

2 Materials and methods

2.1 Data from a network of meteorological stations

Due to the country's small size (33,846 km²), drought severity is examined using data since 1955 from a relatively dense network of meteorological stations. In addition, centennial-scale drought severity is studied using a long-term series of monthly air temperature and precipitation data. The first regular meteorological observations in Moldova began at Chisinau's observatory in 1887. At the end of the nineteenth century, meteorological observations were begun also at four additional stations: Briceni (1887), Soroca (1880), Comrat (1892), and

Tiraspol (1898), but observations from the latter stations have more gaps due to wars (especially for 1917–1920 and 1941–1944). Therefore, the centennial-scale study of drought severity's evolution used only long-term series measurements from the Chisinau station ($\varphi=46^{\circ}58'N$, $\lambda=28^{\circ}51'E$, $h=173$ m a.s.l.). This station is unique in Moldova for having the longest uninterrupted measurement dataset. The meteorological observation network reached its optimal allocation density in the middle of the 1950s. To examine drought variability during the second half of the twentieth century, three agroclimatic regions were delineated. The resulting input dataset (Fig. 1a) consists of four to six stations for each region, with altitudes ranging from 20 to 242 m a.s.l. The agroclimatic regions reflect various physical–geographical conditions (relief, slope, and dissection). Another important feature captured by the regionalization is that the southern part of the Republic of Moldova is usually affected more by drought events than the northern regions. Thus, regional drought patterns in Moldova were evaluated using meteorological data since 1955 and/or a long time series (1891–2009) recorded by the National Fund of Hydrometeorological Data at the State Hydrometeorological Service (SHS). Technical and critical controls of these measurements were made by SHS and the Institute of Geography, Academy of Sciences, Moldova.

The analysis of drought variability in Moldova is based on the following mean monthly series:

1. A time series of monthly temperatures (maximum, minimum, and average in degrees Celsius) was used for calculating evapotranspiration (PET) and drought indices. The processing method is based on the standard normal homogeneity test (SNHT) by Alexandersson (1986).
2. A time series of monthly precipitation was subjected to a process of quality control by SNHT to detect significant inhomogeneities in the average. A series averaged from the measurements of several stations in the vicinity of a given station was used as the reference series (data from the neighboring stations were standardized to the average from the analyzed station in advance).
3. A time series of monthly and/or growing season (April–October) gravimetric observations at 0–100 cm depth of soil moisture under corn (in millimeters) was used for calculating the S_{i-a} agriculture drought index.

In addition to meteorological data, the yields for corn (*Zea mays* L.), a crop widely grown in Moldova, were used to demonstrate drought impact. Agricultural databases containing the yield series for 1951–2008 were available for 35 individual districts as reported by the National Bureau of Statistics of the Republic of Moldova (Fig. 1b).

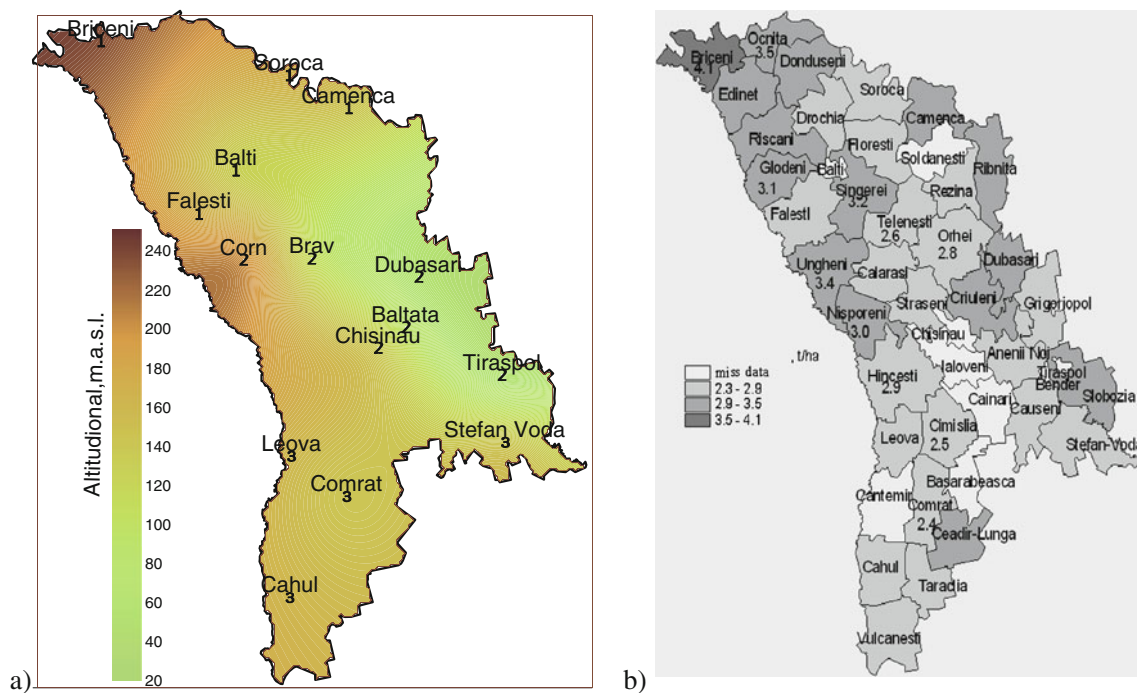


Fig. 1 a Location of the 15 meteorological stations and their classification by agroclimatic regions (1, 2, and 3 refer to North, Central, and South agroclimatic regions). b Long-term corn yields (tons per hectare) in 35 districts (1955–2008) used in this study

2.2 Drought indices used in identifying drought variability

A set of drought indices comprises important tools to detect, monitor, and assess regional and/or local drought events. In this study, time series for S_i (S_i -m and S_i -a), SPI and SPEI drought indices were used. As an illustrative example, Fig. 2 shows the evolution of the S_i -m, SPI and SPEI at 1-month timescales during 1891–2009 from the Chisinau observatory. The proposed set of drought indices can be computed from various sources, including observational and/or theoretical data. These indices were combined for the reason that there is no universal definition of drought, and therefore, it is better not to use a single index to identify drought conditions. More than 80 drought indices were developed by several generations of researchers during the twentieth century to quantify drought. These include the Palmer drought severity index (PDSI; Palmer 1965), rainfall anomaly index (van Rooy 1965), crop moisture index (CMI; Palmer 1968), surface water supply index (Shafer and Dezman 1982), standardized precipitation index (McKee et al. 1993), and standardized precipitation–evapotranspiration index (Vicente-Serrano et al. 2010). The soil moisture drought index (Hollinger et al. 1993) and crop-specific drought index (CSDI; Meyer and Hubbard 1995) appeared after CMI. Furthermore, CSDI is divided into a corn drought index (Meyer and Pulliam 1992) and a soybean drought index (Meyer and Hubbard 1995). Overviews of existing and new drought indices can be found in Heim (2002), Hayes et al. (2007), and Niemeier (2008).

At present, the most advanced drought indices (e.g., the PDSI, SPI, and SPEI) take into account the role of antecedent conditions in quantifying drought severity. Moreover, and given the varied response times of different hydrological, agricultural, and environmental systems to water availability, the timescale chosen for analyzing drought is important, and some of the most advanced indicators may be calculated for different timescales.

Meteorological drought is usually the first step in drought propagation through the entire hydrological cycle and therefore is tremendously important in drought monitoring. In fact, lack of precipitation is usually the predominant factor triggering a drought event. Therefore, it is one reason why the SPI is a widely used meteorological drought index. To date, SPI is also finding more applications in Eastern Europe than other indices due to its limited input data requirements, flexibility, and simplicity of calculations. A major problem of using the PDSI, by contrast, is that its computation is complex and requires substantial meteorological input data. The SPI is an index based on the probability of recording a given amount of precipitation, and the probabilities are standardized so that an index of zero indicates the median precipitation amount. A detailed description on how SPI is computed may be found in Lloyd-Hughes and Saunders (2002), who compute SPI using a Pearson III distribution and L-moment method to obtain distribution parameters as suggested by Vicente-Serrano (2006). In a climatic area with widely

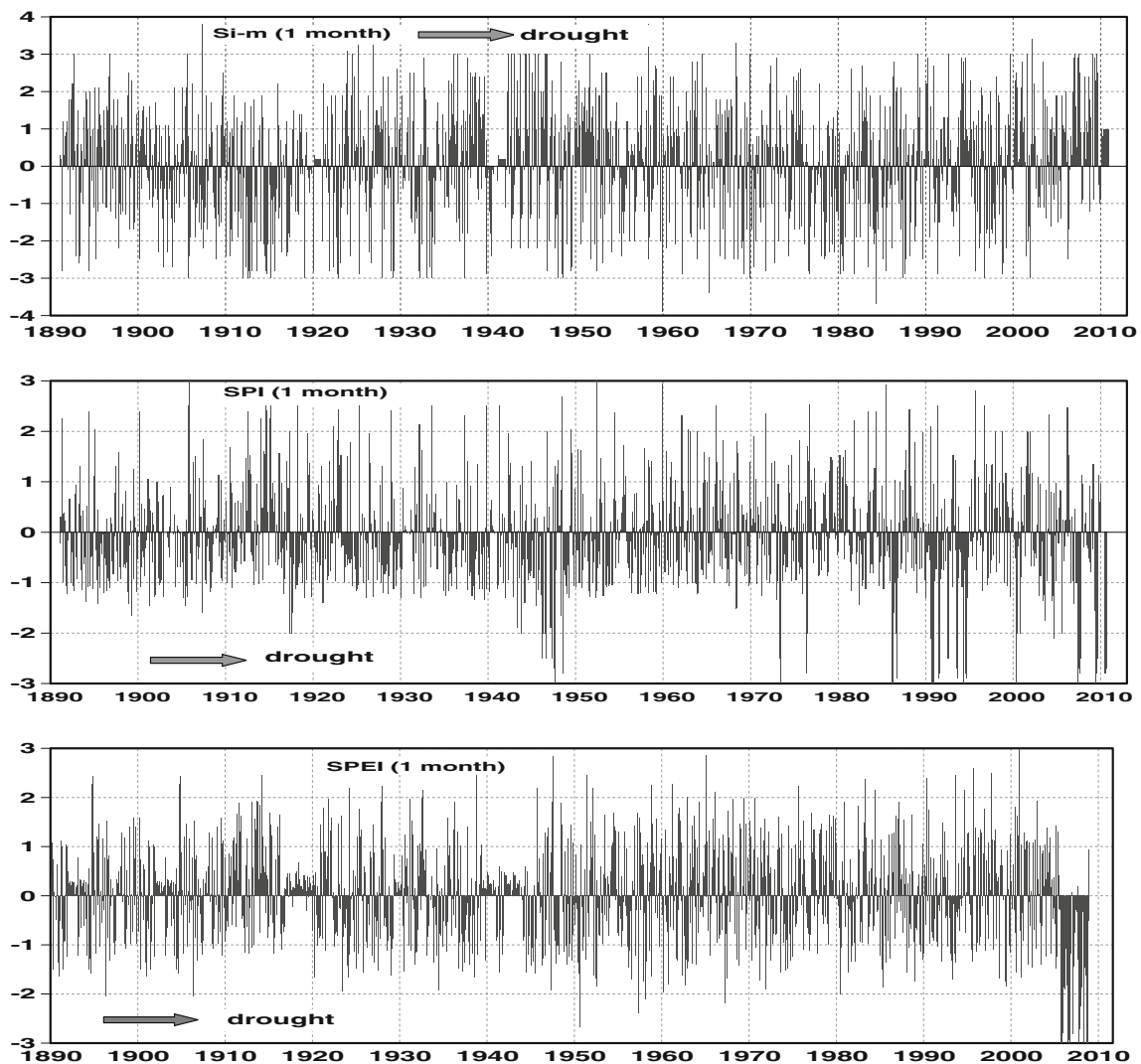


Fig. 2 S_f -m, SPI, and SPEI series calculated on short timescales (1 month) at Chisinau observatory (1891–2009)

ranging precipitation variability, like Moldova, a Pearson III distribution is sufficiently flexible to calculate the drought index on different timescales. In order to assess the evolution of drought conditions in the country, the SPI was calculated to shorter (1 and 3 months) and longer (12 and 24 months) timescales.

Although precipitation is generally included in drought index calculation, temperatures or evapotranspiration are the most important parameters. Recently, a new drought index, the SPEI, developed by Vicente-Serrano et al. (2010), has been proposed for identifying drought periods. The SPEI is based on a monthly (or weekly) climatic water balance (precipitation [P] minus evapotranspiration [PET]), adjusted using a three-parameter log-logistic distribution to take into account common negative values. The values are accumulated to different timescales, following an approach similar to that of the SPI drought index. The PET is calculated using the method by Thornthwaite (1948). The SPEI combines the

sensitivity of PDSI to changes in evaporation demand (caused by temperature fluctuations and trends) with the simplicity of calculation and multi-temporal nature of the SPI. Among the significant advantages of the SPEI is that it can, like the SPI, be calculated for different timescales to monitor droughts with respect to severity, duration, onset, extent, and end. The SPEI's main advantage over other widely used drought indices lies in its ability to identify the role of PET and temperature variability on drought assessment in the context of global warming. This fact is demonstrated on the basis of metadata from 11 observatories located in different climatic zones in the world (Vicente-Serrano et al. 2010).

Another methodological task addressed in this study is to test for the first time the new SPEI in identifying drought variability in Moldova. For SPEI calculations, the algorithm and software developed by Vicente-Serrano et al. (2010; freely available at <http://digital.csic.es/handle/10261/10002>) were used. In as much as the main step in quantifying the

SPEI is to calculate PET, the main obstacle in its implementation is a lack of meteorological inputs regarding solar radiation, temperature, wind speed, and relative humidity from the majority of weather stations in the country's network. Solar radiation, in fact, is only measured in Moldova at the Chisinau observatory. Detailed analysis of different methods and tools to indirectly estimate PET from various meteorological parameters may be found in Allen et al. (1998), Vicente-Serrano et al. (2007, 2010), and Mavromatis (2007). An approach inspired by Vicente-Serrano et al. (2007) has been taken in calculating PET as a drought identification parameter, and an automatic PET calculator is available on the World Wide Web from the Repository of the Spanish National Research Council. In the present study, PET was calculated following the method of Hargreaves (Hargreaves and Samani 1985) from a database of 15 meteorological stations in Moldova. It has been demonstrated that the Hargreaves method is the best alternative tool for quantifying evapotranspiration in large-scale of studies where data are missing (see, e.g., Jensen et al. 1990; Droogers and Allen 2002). This method calculates PET as a function of minimum and maximum air temperature and extraterrestrial radiation. One of the advantages of SPEI is that, independently of which method is used to calculate PET, the result is identical. Therefore, this study was conducted while calculating PET by Hargreaves' method (Hargreaves and Samani 1985), which uses the following equation:

$$ET_o = 0.0023 \cdot Ra \cdot TD^{0.5} (T_m + 17.8), \tag{1}$$

where ET_o is the daily reference evapotranspiration (monthly average). To obtain the total monthly evapotranspiration, the result must be multiplied by the number of days in the month. TD is the difference between the maximum and minimum temperatures in degrees Celsius (monthly averages). T_m is the average monthly temperature. Ra is the water equivalent of the extraterrestrial radiation in millimeters per day ($1 \text{ MJ/m}^2/\text{day} = 0.408 \text{ mm/day}$) computed according to Allen et al. (1998). Ra is usually calculated theoretically as a function of latitude and month of the year. A number of studies (e.g., Popova et al. 2006; Martinez-Cob and Tejero-Juste 2004) have demonstrated that values of PET obtained by Hargreaves' model are very similar to estimates obtained using the Penman-Monteith method.

Another index that has been employed in Eastern Europe for monitoring agricultural drought is the aridity index (S_i ; Ped 1975). This index has been used for identifying drought's severity, frequency, and time occurrence. It provides a measure of the long-term intensity of drought conditions derived from precipitation and temperature anomalies and their combined effects on soil moisture. A detailed approach

for calculating S_i is shown in Potop et al. 2010. S_i is expressed by the following equation:

$$S_i = \left(\frac{t_\tau - t_n}{\sigma T} \right) - \left(\frac{r_\tau - r_n}{\sigma R} \right) - \left(\frac{e_\tau - e_n}{\sigma E} \right), \tag{2}$$

where $\Delta T = t_\tau - t_n$, $\Delta R = r_\tau - r_n$, and $\Delta E = e_\tau - e_n$,

i and τ	Climatological station and time, respectively
t_τ	Monthly mean air temperatures in τ —a specific year
t_n	Long-term monthly mean air temperatures
r_τ	Monthly precipitation amounts in τ —a specific year
r_n	Long-term monthly precipitation amounts
e_τ	Monthly amount of moisture in a 0–100 cm soil layer in τ —a specific year
e_n	Long-term amount of moisture in a 0–100 cm soil layer
σT , σR , and σE	Root mean square deviation in monthly temperature, precipitation, and soil moisture, respectively.

It should be noted that the soil moisture measurements and calculated values are not always available. Therefore, when calculating the index, it is possible to use the simplified form without soil moisture. In a previous study, we proposed three methods for calculating the S_i index that we characterized as meteorological drought (S_{i-m}), pedological drought (S_{i-p}), and agricultural drought (S_{i-a}). The advantage of the complete S_i index (S_{i-a} , S_{i-p} , and S_{i-m}) is in its capacity to utilize calculations that are based on available data. In addition, the S_{i-m} can accurately predict drought based on temperature and rainfall data alone (Figs. 3 and 4). In case of identifying meteorological drought, only the first and second parameters of the equation need be calculated:

$$S_{i-m}(\tau) = \left(\frac{t_\tau - t_n}{\sigma T} \right) - \left(\frac{r_\tau - r_n}{\sigma R} \right) \tag{3}$$

Because of its ability to detect drought and wet periods and/or distinguish meteorological drought from agricultural drought, S_{i-m} has been used as the indicator for monthly meteorological and/or season drought in the present study (Table 1). In addition, Table 1 displays new drought criteria proposed for the S_{i-m} and S_{i-a} indices.

The indicator of agricultural drought risk may be represented by the residuals of the detrended yield. Detrending yield data is important because historical crop yield data integrate a number of factors in addition to adverse weather, including economic cycles and technological advances. The residual variation reflects the effects of weather on yield, and the residuals amplify the yield departures from normal (Liu

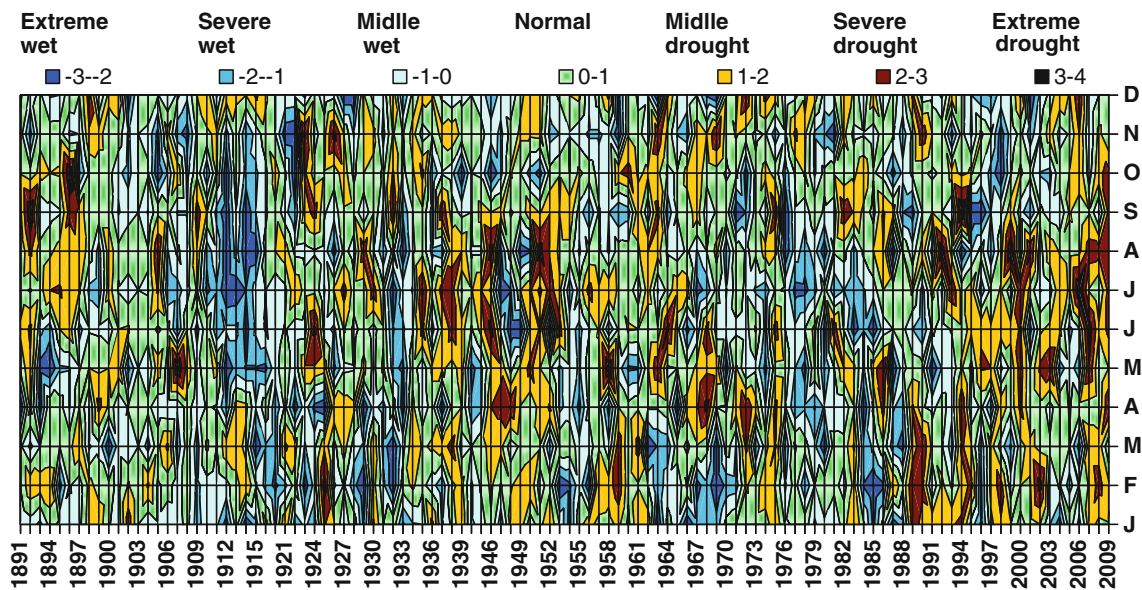


Fig. 3 Secular evolution of the severity of S_i -m values at Chisinau observatory, including assessment of drought episodes (orange), normal episodes (green), and wet episodes (blue)

and Kogan 1996; Mavromatis 2007). The standardized detrended yields were computed using the following:

$$Y = Z/\sigma, \tag{4}$$

where Y =a corn’s yield residual, Z =detrended yield, and σ =standard deviation of the detrended yield.

Positive values of Y denote increases in crop yields due to favorable meteorological conditions, and negative values of Y indicate reductions in yields due to drought conditions.

The combined data for corn detrended yield and the monthly S_i -a drought index over the corn growing season were analyzed using the following statistical procedures:

1. Multiple linear regressions were estimated for each month during the corn growing season in order to evaluate the contribution of drought to corn detrended yield (Y):

$$Y = a_0 + b_1S_i-a_{April} + b_2S_i-a_{May} + b_3S_i-a_{June} + b_4S_i-a_{July} + b_5S_i-a_{August} + b_6S_i-a_{September} + b_7S_i-a_{October}, \tag{5}$$

where Y =dependent corn yield variability by drought, a_0 =the intercept, b_{1-10} =regression coefficients, and S_i -a=the independent variable expressed by drought index in the given month.

2. A stepwise multiple regression model was used to identify only those drought months having significant impact on corn yield.

3 Results and discussion

3.1 A long-term view of drought severity in the Republic of Moldova

This section discusses the evolution of drought severity in months and/or seasons, defined as winter (DJF), spring (MAM), summer (JJA), and autumn (SON), through a period of 118 years at Chisinau station. Temporal drought

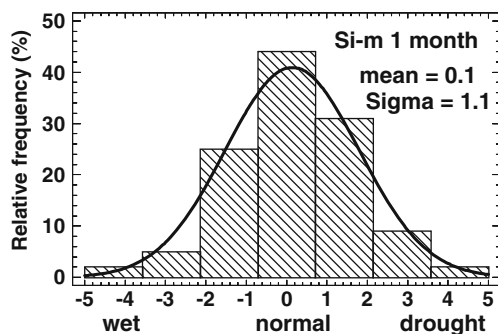


Fig. 4 Normal distribution of S_i -m values at Chisinau observatory (1891–2009)

Table 1 Categories of drought severity according to S_i -m and S_i -a indices

Drought category	S_i -m	S_i -a
Extreme wet	≤ -3.00	≤ -4.00
Severe wet	-2.00 to -2.99	-3.00 to -3.99
Middle wet	-1.00 to -1.99	-2.00 to -2.99
Normal	0.99 to -0.99	1.99 to -1.99
Middle drought	1.99 to 1.00	2.99 to 2.00
Severe drought	2.99 to 2.00	3.99 to 3.00
Extreme drought	≥ 3.00	≥ 4.00

patterns were studied by series using S_i -m, SPI, and SPEI. The analysis of drought severity in the longest available series clearly shows that the recent period of increased drought severity and duration is unprecedented since the beginning of meteorological measurements (1891). In accordance with the S_i -m index, extreme drought years were recorded in the winter season for December of 2006, 1972, 1898, and 1974; January of 1902, 1989, 1936, and 1994; and February of 2002, 1925, 1989, and 1959. It can be noted that the summer drought months of 2007, 2006, and 1999 were ranked highest in severity by the S_i -m drought index. In July 2007, the S_i -m values were equal to or greater than 4.00 (which value indicates disaster drought impact). This made July 2007 the driest July since 1891 at the Chisinau station and the driest on record for all climatological stations since 1955. The most severely dry July on record, occurring in 2006, was also followed by the warmest autumn since recording began in 1891. At the majority of climatological stations, August 1999 was the driest and warmest August ever recorded. In addition, severe heat waves occurred across central and southern Moldova during much of August. These comparisons show that the most extreme droughts in the summer months have occurred in the last decade. This is true also for the winter months, such as December (2006) and February (2002), but January 1989 is ranked as the 2nd most extreme for warmth and drought in that month. The warmest and driest autumn was recorded in 2006. Indeed, the longest enduring drought and the most severe autumn–winter–spring–summer drought started in October 2006 and ended in September 2007. That drought, which prevailed over Moldova and neighboring countries during spring and summer of 2007, was exceptional in regard to both severity and duration. According to one recent study (Bogdan et al. 2008), during the 2007 drought, there developed unusual climatic conditions for the temperate-continental area of Moldova and Romania. For instance, summer temperatures occurred 2 weeks earlier than usual. Moreover, warm spells during the wintertime accentuated the drought event in the later seasons. The summers of 2003, 2006, 2007, and 2009 are evaluated as exceptional droughts for Southeast Europe, and crop production was reduced by more than 20% (FAO/GIEWS 2009). The S_i -m index registered the highest positive values (extreme heat and drought) for July 2007 and August 1999. By contrast, the index's greatest negative value (extreme wet) occurred in September 1996 and August 1994. During these months, there were heavy precipitation events; hence, similar very negative values of S_i -m ≤ -2 were registered for the majority of weather stations. The period from 1890 to 1950 contains a larger number of severe drought months especially in the autumn season. By contrast, the period from 1950 to 2009 clearly shows a large number of extreme drought months in spring

and summer. The change of temperature/precipitation ratio over the year shows that if in Moldova's baseline climate only the end of summer and beginning of autumn were semi-arid, in the future there would likely be significantly longer and deeper dry spells (Corobov and Overcenco 2007).

The long-term variability of S_i -m for summer drought in the period 1891–2009 is illustrated in Fig. 5. The S_i -m shows an increasing trend in the period studied and an increasing tendency toward more intensive and prolonged dry summer months. Koleva and Alexandrov (2008) reached the same conclusion when they examined the evolution of drought by means of S_i -m for drought variability in the Bulgarian low regions during the twentieth century. They designated as severe drought months in Bulgaria for which S_i -m ≥ 2 . As a result, prolonged drought periods in the summer months during the early 1900s, 1930s, 1940s, late 1960s, 1980s to late 1990s, and 2000s were observed. The period 1990–2009 ranks as having drought most frequently in all months. The same patterns were recorded for the SPI and SPEI series, both identifying the most prolonged drought episodes in the decades of the 1940s, 1990s, and 2000s (Fig. 6). The most prolonged droughts starting in autumn and ending in winter were in the following years: 1913/1914, 1948/1949, and 1982/1983. The most prolonged droughts occurring in summer–autumn–winter seasons were 1924/1925, 1945/1946, 1999/2000, and 2006/2007. Extreme winter droughts are often accompanied by warm spells, such as in 1989, 1994, 1998, 2006, and 2007. Detailed results about the chronology of drought severity are discussed in broader climatological and European contexts in, e.g., Potop (2009, 2010) and Potop and Soukup (2010).

3.2 Variability of drought during second half of the twentieth century

In this section, S_i -a, S_i -m, SPEI, and SPI indices are calculated for the whole country from 15 meteorological stations while including data on monthly rainfall, maximum temperature, minimum temperature, mean temperature, and monthly soil moisture under corn (0–100 cm). Numerical values of the drought indices were calculated for each of the 15 weather stations, which then allowed us to evaluate the years according to drought severity (Fig. 7).

The primary cause of drought is a lack of precipitation and in combination with temperature as an intensifying factor that contributes to increasing evaporation rates and soil water deficiency. In spring, the determining factor as to severity of drought in Moldova is lack of moisture in the soil and dry wind (defined by simultaneous occurrence of air temperatures above 25°C, relative humidity under 30%, and wind velocity greater than 5 m/s). Shortage of rainfall is the primary cause of drought's development in autumn. The role of temperature is evident in summer drought

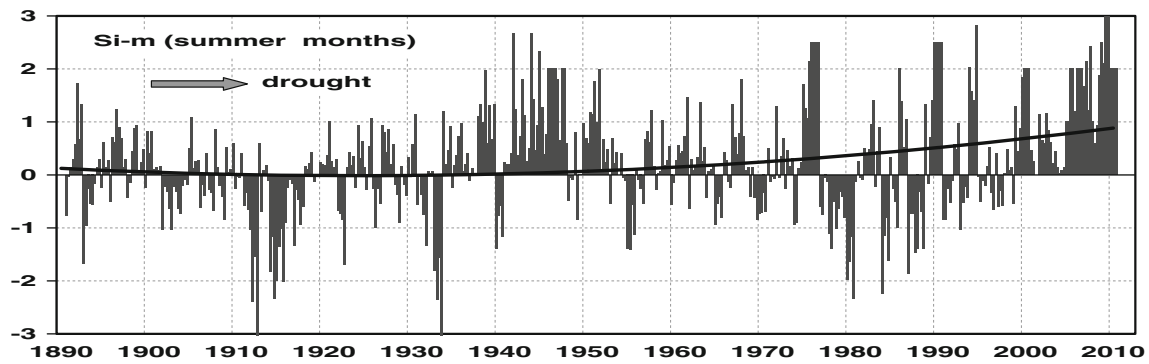


Fig. 5 Fluctuations and exponential trend in summer months of S_i -m index (1891–2009)

episodes, which depend on temperature anomalies (heat waves) that contribute to increasing PET. In Moldova, moreover, the frequency of heat waves has grown fourfold, with both their duration and severity increasing simulta-

neously. An overwhelming percentage (76.2%) of the heat waves in Moldova for the entire period occurred in the last two decades (Overenco and Potop 2010). The summer of 2007 is illustrative. It was extremely hot across southeastern Europe

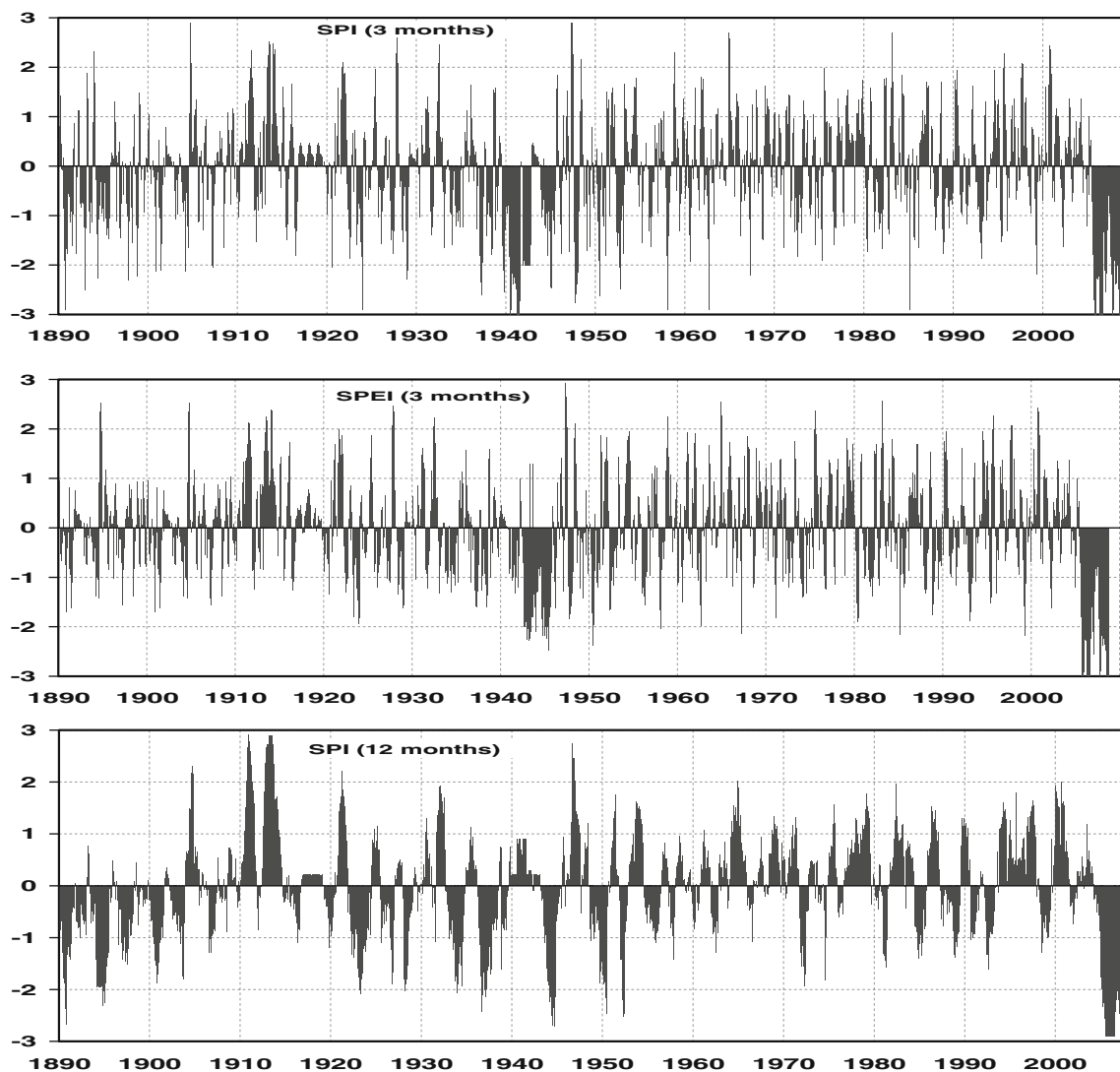


Fig. 6 SPI and SPEI series calculated on timescales of 3, 12, and 24 months at Chisinau observatory (1891–2009)

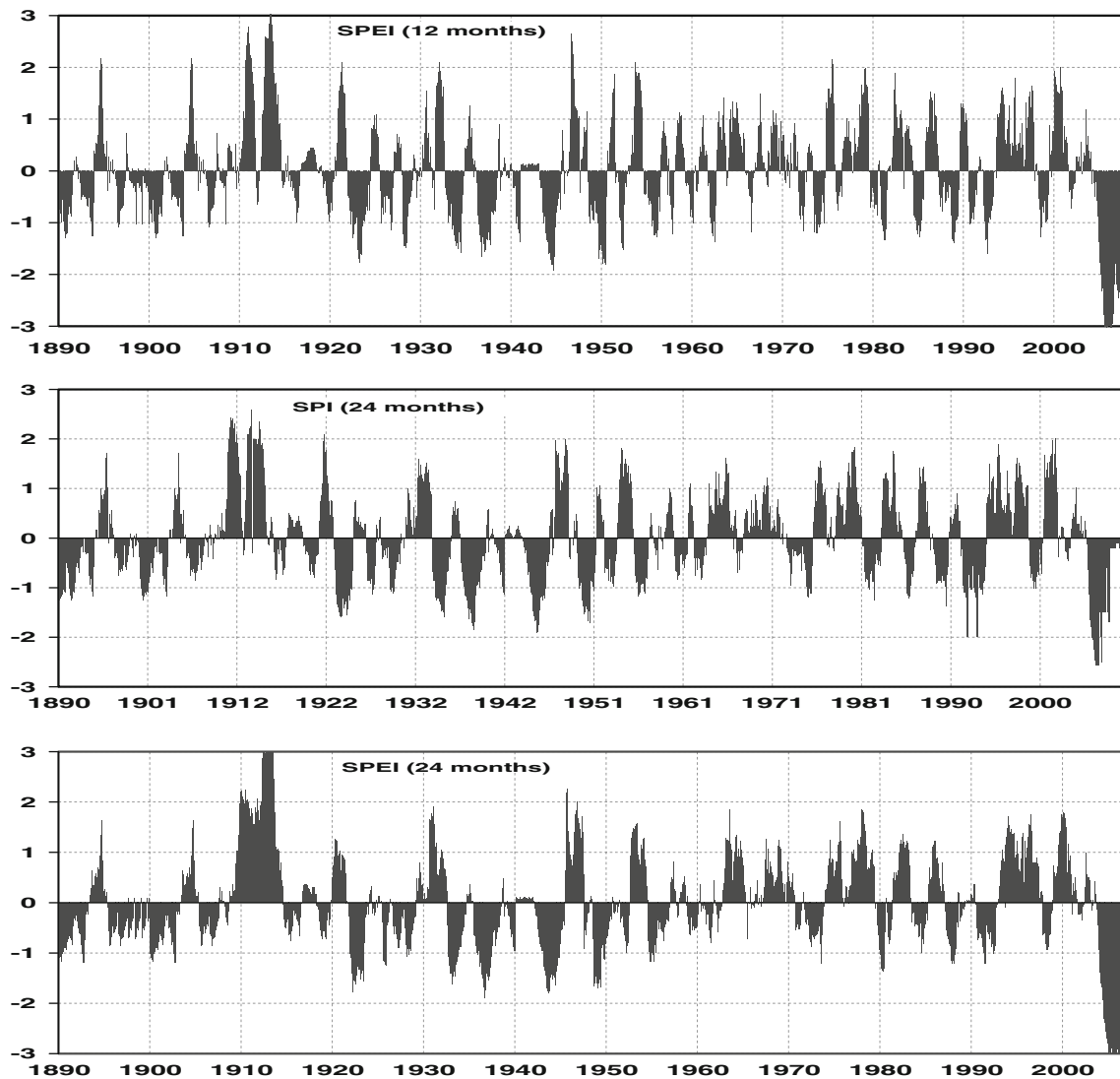


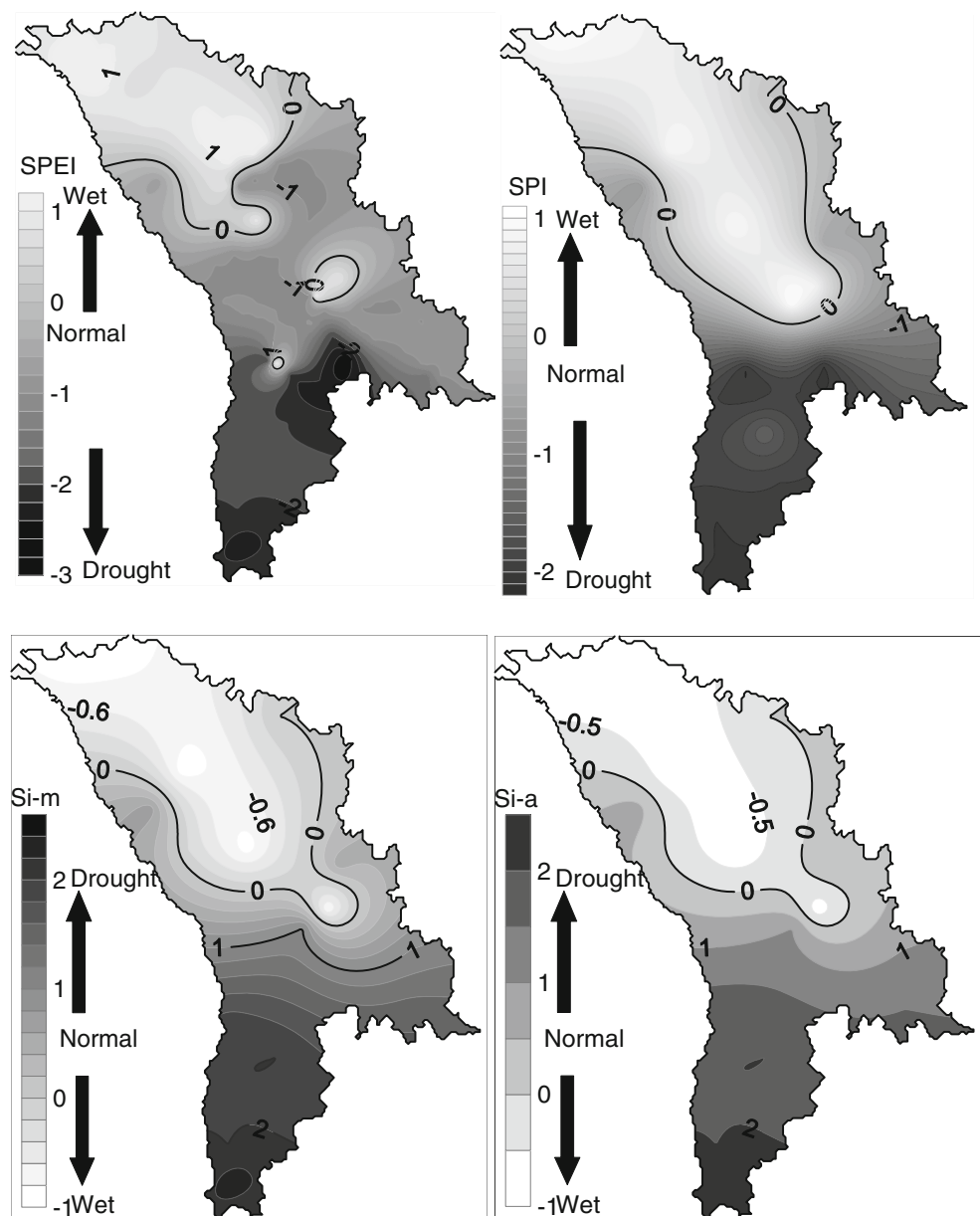
Fig. 6 (continued)

in that year, and it was the warmest and driest in the history of instrumental observations in Moldova. In 2007, all temperature anomalies in Moldova exceeded their baselines in July by 3–4σ and in summer overall by as much as 5σ. Observed 2007 summer temperatures in Moldova were higher not only relative to their mean baseline values but also the values considered as extremes, exceeding the 90th and 95th percentiles (Cazac et al. 2007; Corobov et al. 2010). Figure 8 shows the spatial distribution of PET (millimeters) in July baseline (1961–1990) and driest and warmest July of 2007 calculated by Hargreaves equation in the territory of Moldova. The map for July 2007 provides an excellent demonstration as to the effect of extreme temperatures on PET on the territory of Moldova. The spatiotemporal difference of PET shows that July of 2007 exceeded its baseline by more than 90 mm. Moreover, the evolution of PET during summer recorded a positive and significant trend

(+3.3 mm/year, $R^2=0.46$; $p \leq 0.05$) and explains the increased trend in SPEI and S_i -m for the entire study area between 1955 and 2009. This increased the water demand of agricultural crops, with corn (which is not irrigated in Moldova) being most negatively affected in the semi-arid region. Drought conditions have noticeably increased in the country, with drought duration gaining in persistence during the last 20 years. It is noteworthy, moreover, that since 1980, a high frequency of extreme drought years has been recorded (e.g., 1986, 1989, 1990, 1992, 1994, and 2000).

Table 2 provides a comparison of drought frequency by decades, as measured in percent using S_i -m, S_i -a, SPEI, and SPI. The South agroclimatic region is used as an example in that table. If one compares the frequency of drought years in summer season for the reference period (1961–1990) and the past decade, it is evident that over the past 10 years, the average number of drought years in the summer season has

Fig. 7 Spatial patterns of SPEI, SPI, S_i -m, and S_i -a drought indices (1955–2009) on the territory of Moldova



increased by more than 1.5 times. We can see an increase in the number of summer droughts after 1991 as measured by all indices. The S_i -m and SPI indices show the same excess ratio while SPEI has the highest ratio (1.9 times). Evolution of drought during the six decades shows its increasing frequency, reinforced by long dry periods in the 1990s and 2000s, and an aridity process occurring in the region (in particular, PET losses during summer).

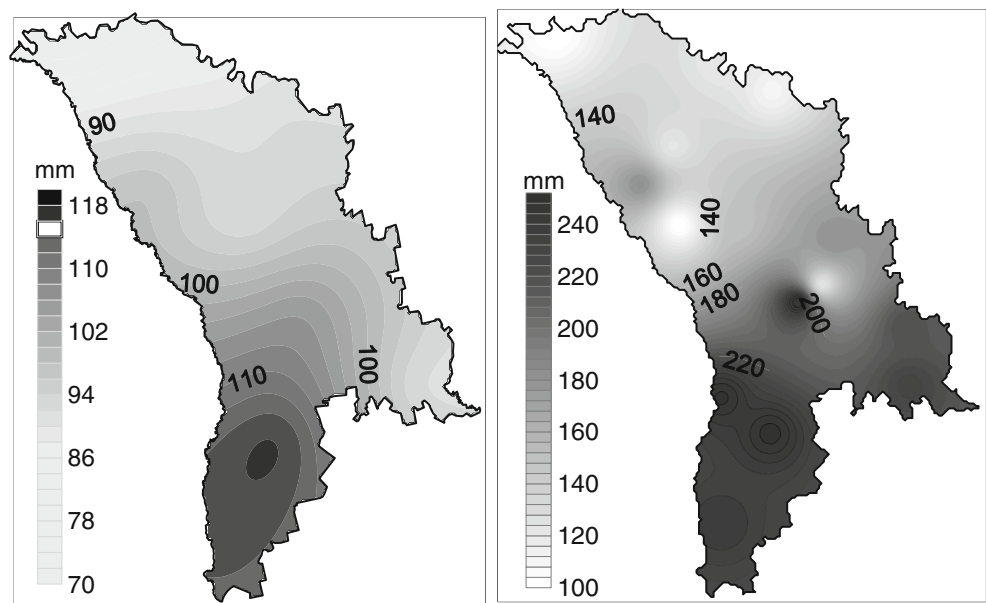
3.3 Evaluating drought indices for assessing effect on corn yield

Some districts in the country suffer from severe droughts approximately once every 2nd year, with serious consequences for the agricultural and food sectors. It is the

purpose of this section to test relationships between the SPEI, SPI, S_i -m, and S_i -a drought indices and variability of corn yield.

The effect of agricultural drought on national crop yields was studied using corn as an example. At the same time, second-order polynomials were applied to determine the corn yield variability because they closely approximate the nature of the relationship between crop yield and water use (Mavromatis 2007). The highest corn yield was in the 1960s and 1970s, followed by a stable period, but since the 1990, the harvest has stagnated (which in part reflects effects of economic reform) (Fig. 9a, b). The value of Y was calculated for arable land in 35 districts of Moldova over the period 1951–2008 (Fig. 10). Normalized anomalies of the Y index were averaged over all districts in the three

Fig. 8 Spatial patterns of PET in July (1961–1990) and extremely dry and hot July of 2007 (millimeters) calculated by Hargreaves’ equation on the territory of Moldova



agroclimatic regions (North, Central, and South) and at national mean level. Nonuniform spatial distribution of Y is observed on the territory of Moldova. The spatial distribution of Y suggests that three types of districts can be differentiated, those with stable yield ($Y=0.20$ to 0.25), moderately stable yield ($Y=0.25$ to 0.30), and vulnerable yield ($Y \geq 0.30$). The greatest part of the territory of Moldova can be characterized by stable and moderately stable yield, the exception being in the southern part of the country. In this region, droughts are more frequent than in the other districts. High drought-related variability of the corn yield is characteristic of those districts where the average yield is lower than the average for the country as a whole. For the entire territory of Moldova, the average long-term yield is 2.9 t/ha, but Y is equal 0.23. Regional data for Y in Fig. 10 show that relatively favorable humidity conditions for obtaining high corn yield are in the North ($Y=0.20$) and Central ($Y=0.22$) regions of the country. Districts located in the South agroclimatic region have the highest value of Y (0.30). That region receives less total precipitation and tends to be more vulnerable to drought. This suggests that the more extensive are the drought areas, the greater are the variability and reduction in corn yields. According to the results obtained, low-yielding

years occurred in 13 cases in the North, 16 cases in the Central, and 21 cases in the South regions. A tendency of decreasing productivity in the corn crop has been noted during the last 20 years. This fact is linked with the increasing drought conditions observed for this period, as well as with such other conditions as inappropriate agrotechnical measures and lack of irrigation that contribute to corn crops’ decreasing drought resistance. In agreement with National Human Development Report (2009), small farms in the central hot and semi-humid and the southern hot-arid regions are most vulnerable to the types of extreme climate events expected to become more frequent and severe with climate change. At the same time, economic assessment of climate vulnerability impact on corn in the period 1996–2008 suggests that net losses have so far exceeded net gains.

Response of corn yield to severity of agricultural drought during the growing season was identified by regression analysis. The relationships between corn yields and S_{i-m} , S_{i-a} , SPEI, and SPI drought indices for each region are summarized in Table 3. The coefficient of determination (R^2) indicates to what extent the model as fitted explains how drought indices were able to explain variance in yield departures from normal, whereas the mean absolute error (MAE), root mean square error (RMSE), and

Table 2 Comparison of drought frequency by decades (in percent) as determined using S_{i-m} , S_{i-a} , SPEI, and SPI in South agroclimatic region

Drought indices	1951–1960	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	1961–1990	Excess ratio
S_{i-m}	17.0	4.1	9.0	21.8	25.0	24.0	34.9	1.5
S_{i-a}	14.8	3.5	7.3	19.8	21.4	21.4	30.6	1.4
SPEI	17.2	3.9	9.5	22.0	25.3	19.0	35.4	1.9
SPI	15.6	6.0	8.5	10.7	19.0	17.0	25.2	1.5

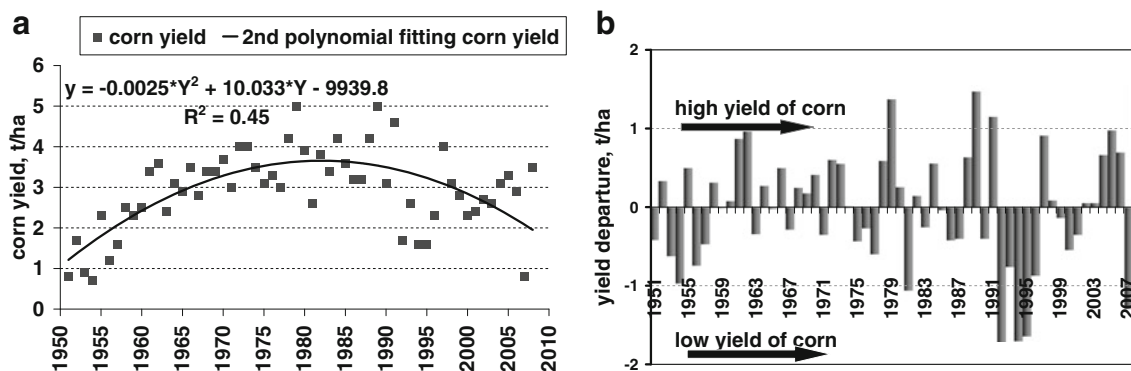


Fig. 9 Yield dynamics of national mean level (a) and annual departures from normal (b) for corn in the Republic of Moldova

index of agreement (*d*) represent additional approaches for statistical comparison of modeling performance for each index. Of the four drought indices, the *S_i-a* ranked best and SPEI ranked second in terms of the summary statistics considered. *S_i-a* correlated best overall with the yield departures from normal (*R*² ranged from 0.240 to 0.430 from north to south). The spatial distribution of *d* values are greater than 0.700 and had the least amount of error (RMSE values from 0.121 to 0.118 t/ha), thus indicating that the *S_i-a* is an effective index for predicting yield departures from normal in Moldova. SPEI explained 19% and 28% of the variance in the measured yield departures in the agroclimatic regions. While the spatial differences of

parameter statistics are less evident for SPEI, *S_i-m* and SPI are weakly related yield departures from normal, which is slightly evident only in the South agroclimatic region (*R*²= 0.160). This fact can be explained by higher precipitation variations during the growing season for corn. Thus, the SPI will tend to perform better in those areas that typically receive less precipitation during the growing season. In the end, then, *S_i-a* was selected for assessing drought effect on yield departures from normal for corn. Figure 11 shows territorial differences of the *S_i-a* series between agroclimatic regions.

In agreement with Eqs. 6 and 7, the impact of agricultural drought (measured by *S_i-a*) on *Y* is estimated

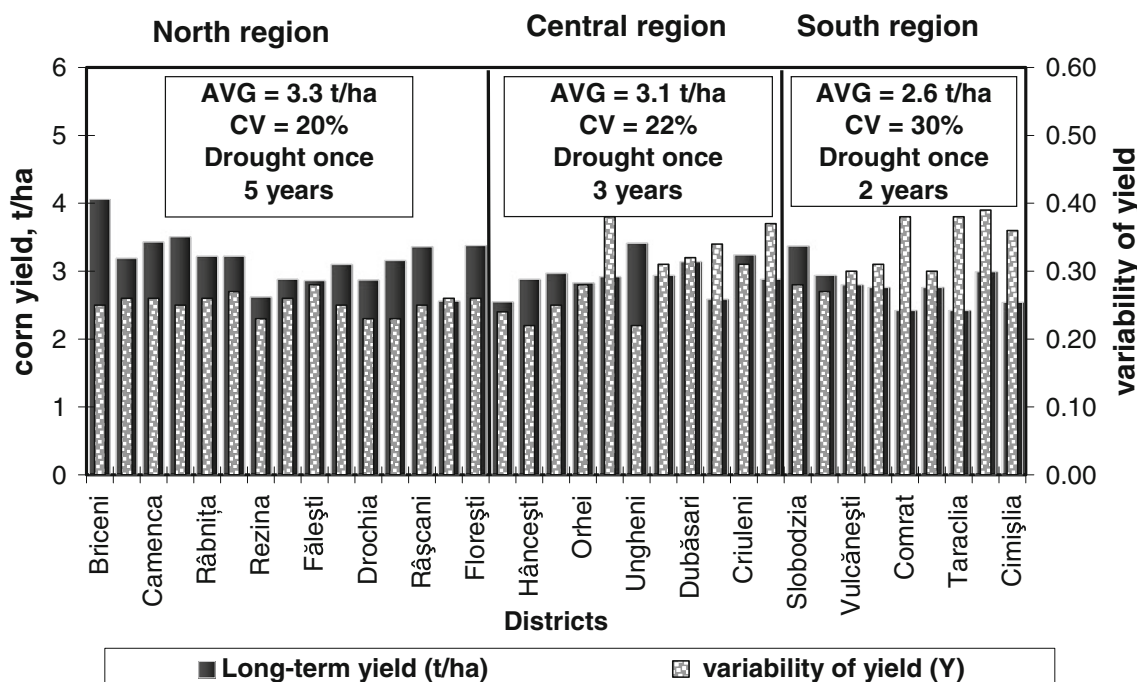


Fig. 10 Long-term corn yield by district (1955–2008) and variability of corn yield in Moldova. *AVG* averaged yield per region, *CV* coefficient of variation as calculated from average and standard deviation of yield

Table 3 Summary of relationships between residuals of corn yields and SPI, SPEI, S_{i-a} , and S_{i-m} drought indices

	SPI	SPEI	S_{i-a}	S_{i-m}
1st agroclimatic region				
R^2	0.072	0.190	0.240	0.101
MAE	0.201	0.125	0.031	0.229
RMSE (t/ha)	0.225	0.214	0.121	0.316
d	0.156	0.686	0.700	0.368
2nd agroclimatic region				
R^2	0.105	0.280	0.310	0.133
MAE	0.239	0.067	0.045	0.250
RMSE (t/ha)	0.363	0.154	0.118	0.363
d	0.314	0.711	0.722	0.390
3rd agroclimatic region				
R^2	0.160	0.280	0.430	0.160
MAE	0.248	0.048	0.036	0.059
RMSE (t/ha)	0.302	0.190	0.111	0.236
d	0.495	0.715	0.762	0.524

by the signs of the regression coefficients. The results of multiple linear regression analysis show that the prediction model for estimating the effect of drought months on corn yield should be formulated as follows:

$$\begin{aligned}
 Y = & 3.69 - 0.74S_{i-aApril} + 0.14S_{i-aMay} \\
 & + 0.14S_{i-aJune} - 0.18S_{i-aJuly} - 0.26S_{i-aAugust} \\
 & + 0.06S_{i-aSeptember} + 0.03S_{i-aOctober}; \\
 R^2 = & 0.73, p = 0.10.
 \end{aligned}
 \tag{6}$$

$$\begin{aligned}
 Y = & 3.0 - 0.15S_{i-aMay} - 0.24S_{i-aJuly} \\
 & - 0.38S_{i-aAugust}; R^2 = 0.43, p = 0.05
 \end{aligned}
 \tag{7}$$

The model indicates that the drought months May, July, and August have contributed significantly to reducing corn yield, while the regression coefficients for other months were not significant. Therefore, they were not included in the analysis due to their low relative contributions. As can be seen from the R^2 , drought conditions have a significant influence on corn yield in Moldova: the cumulative drought contribution during the growing period is more than 70%. The R^2 from Eq. 7 shows that 43% of the lower yield years were recorded for corn when drought occurred during May and July–August. On the other hand, the corn yield is also highly sensitive to the occurrence of a short drought spell occurring in August (e.g. 1994, 1999, 2003, and 2007). Those years with pronounced drought during August indicate large reductions in the harvest, as that month coincides with increased demands for moisture. High temperature stress and low humidity reduce pollen viability and silk receptivity due to desiccation, which results in poor seed set and reduced yield (Craufurd and Oeacock 1993). Finally, the negative regression coefficient indicates that corn is most vulnerable to extreme spring droughts. Spring drought stress is the second major cause after summer drought that reduces grain yield by more than 15%, particularly in southern districts (1946, 1947, and 2000). The highest yield reductions due to extreme and severe drought events occurring in the flowering and grain filling stages on the whole territory of Moldova were in the following years: 1946 (0.6 t/ha of harvest yield), 1953 (1.0 t/ha), 1957 (1.7 t/ha), 1967 (2.8 t/ha), 1983 (3.7 t/ha), 1986 (3.1 t/ha), 1990 (3.4 t/ha), 1992 (2.5 t/ha), 1994 (1.6 t/ha), 2000 (2.1 t/ha), 2003 (2.8 t/ha), and 2007 (0.7 t/ha). According to data of the National Bureau of Statistics documenting corn yield losses, the most significant losses in corn production were in 1946 and 2007. The severity of Moldova’s 2007 drought is comparable only to the worst situation that occurred in 1946, known as the year of the famine, when many people starved to death following the loss of the spring cereal harvest (FAO/GIEWS

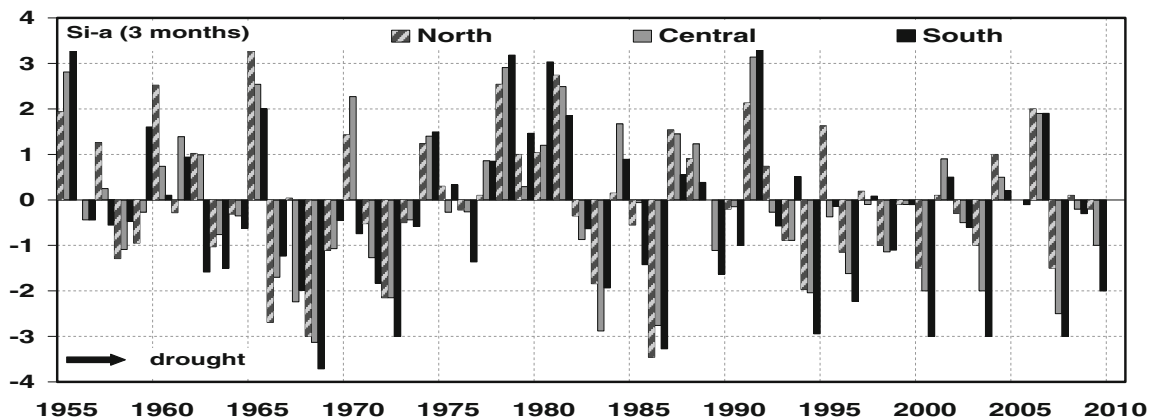


Fig. 11 Territorial differences of S_{i-a} (3 months) series between agroclimatic regions (North, Central, and South) over 1955–2009

2009). As has been shown in various papers (e.g., Corobov 2002; Constantinov and Nedelcov 2007; Koleva and Alexandrov 2008; Mavromatis 2007), the impacts of extreme climate events are very significant for grain production in many Balkan countries, including the Republic of Moldova.

4 Conclusions

The main aim of the present study was to describe a methodology for assessing the evolution of drought severity in different regions of Moldova by means of a set of drought indices while analyzing the relationship between the drought conditions and the departures from normal for corn yield. The frequency of extremely dry months and/or long time series (12 and 24 months) in the past variability of drought was estimated using the S_i -m, S_i -a, SPEI, and SPI indices. Spatial-temporal variability of corn yield was analyzed, and the influence of drought on corn's productivity was studied.

S_i (S_i -m, S_i -a) enables identification of different drought types and impacts. S_i is capable to measure both wetness (S_i -m and S_i -a negative value) and dryness (S_i -m and S_i -a positive value) conditions. The variability of soil moisture directly affects agricultural droughts commonly recorded using short timescale drought indices (S_i -a). S_i -a is the most appropriate index to monitor agricultural drought in Moldova due to the country's well-functioning gravimetric measurement system for collecting soil moisture data under various agricultural crops. It is widely used also in Russia (in cereal-growing regions), Bulgaria, Romania, and Slovenia. S_i -a (based on precipitation, temperature, and soil moisture data) and SPEI (P-PET) detect agricultural drought better than do S_i -m (based on temperature–precipitation data) and SPI (based on precipitation data).

Two multi-scalar indices were used: SPI demonstrated intensification of drought severity due to reduced precipitation in the context of an aridity process, while SPEI has the capacity to identify drought intensification by increasing temperature in relation to general warming in Moldova. Hence, SPEI is a reasonable index for detecting drought conditions, especially in consideration of Moldova's currently warming climate. Including the effect of PET in explaining the intensification of drought conditions is the most important climate parameter in semi-humid and semi-arid agricultural regions. Moreover, the algorithm of SPEI calculations permits use of an alternative empirical equation to compute PET where data are scarce. SPEI and S_i -m have capacity to detect an intensification of drought severity due to increasing temperature conditions in the decades 1990 and 2000. Both indices show an increasing tendency toward more intensive and prolonged severely dry and extremely dry summer months.

It also should be noted that few differences in spatial variability of SPEI, SPI, S_i -m, and S_i -a drought indices were detected when calculated for short timescales. Differences in spatial distribution of SPI in the 3-month time series can be determined by the weight of extreme precipitation events in summer. Therefore, given the spatial differences of drought indices, a set of indices should be used for monitoring drought conditions in Moldova. It is possible to integrate several meteorological parameters into drought monitoring, such as soil moisture measurements under agricultural crops, evapotranspiration, rainfall, and temperatures. From the analysis presented in this paper, it may be concluded that SPEI, SPI, and S_i can be used for drought assessment and monitoring in Moldova.

The relationship between S_i -a and fluctuation in corn yields indicates that drought months May, July, and August have contributed significantly to reduced corn yield. The results suggest that the S_i -a index correlated best with corn yield departures from normal ($R^2=0.43$ at 95% confidence level), and it will be the most appropriate index to use for measuring agricultural drought in Moldova. S_i -a is best suited for predicting yield departures during growing seasons when moisture soil stress is an important yield-limiting factor.

It is important that scientists do everything they can to help diminish the adverse effects of drought, with or without climate change, and Moldova will benefit greatly if methods of analysis are developed to help both in strategic agricultural planning and in seasonal crop forecasting. It is good to know that there exists a substantial archive of both meteorological and crop yield data that can be used for this purpose.

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