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Impact of agricultural drought on main crop yields in the Republic of Moldova

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ABSTRACT: Crop loss due to drought is a complex issue, because it changes according to the drought intensity and duration, and the developmental stage of the plants when drought occurs. In order to assess the drought-induced decline in crop harvest, drought variability and the yield sensitivity of winter wheat, maize, sugar beet, and sunflower to drought during their growing seasons is investigated in the Republic of Moldova. This is then used as an example of the response of non-irrigated crops to increasing drought tendency in south-eastern Europe. The quantification of drought was done by using the standardized precipitation evapotranspiration index (SPEI) at 1- to 12-month lags during the period from 1951 to 2012. The relationship between drought at various time scales and the standardized yield residuals series (SYRS) for individual crops over the country and the Balti chernozem steppe of Moldova (represented by Balti experimental site) for the 1962–2012 farming years were investigated. In order to detect the trends and the shifts in the SPEI time series over 62 years, the non-parametric, Mann–Kendall and Pettitt tests were used for each month of the year to cover the main life cycle of the crops. The trend analysis of agricultural drought emphasizes an increasing trend from June to October, and becomes significant in the southern region at the 95% level during July to September. The SPEI highlights the main periods of dry/wet persistence and the regional characteristics of drought which are present in the Southern region, and make this region more prone to severe drought persistence, mostly during the last decade. Drought during the plant reproductive stages may significantly reduce grain yield potential, the relation between the SYRS and the SPEI explaining up to 62% of the low-yield variability.

KEY WORDS agricultural drought; standardized precipitation evapotranspiration index; standardized yield residuals series; crop yield; Mann–Kendall and Pettitt tests; Moldova

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1. Introduction

Food security is one of this century's key global challenges (Lobell and Burke, 2010). The production stage is one of the fundamental parts of food security, and long-term field crop experiments (LTEs) are an essential and unique source of data. LTEs also provide the opportunity to measure the impact of extreme climate events on yield crop formation. Agriculture is one of the most climate-sensitive sector among all the economic sectors. Despite ongoing improvements in technology and crop varieties, weather and climate remain uncontrollable factors affecting the quantity and quality of agricultural production (Lobell and Field, 2007; Lobell *et al.*, 2007; Olesen *et al.*, 2011; Gobin, 2012; Mavromatis, 2012; Rötter *et al.*, 2013; Potopová *et al.*, 2015).

In many countries, such as the Republic of Moldova (RM), the risks of climate change are an immediate and fundamental problem, because the majority of the rural population depends either directly or indirectly on agriculture for their livelihoods (IPCC, 2013; Sutton *et al.*, 2013). Drought is one of the most severe natural hazards, causing environmental constraints that limit plant growth, development, and crop yield with tremendous economic and societal impacts. It is a multi-dimensional stress affecting plants at various levels of their organization. As discussed in Blum (1996), 'the effect of and plant response to drought at the whole plant and crop level is most complex because it reflects the integration of stress effects and responses at all underlying levels of organization over space and time'. A recent study conducted by Trnka *et al.* (2014) demonstrates that an increase in drought frequency may neutralize the expected positive effect of a longer growing season, and may decrease the effects of 'typical drought mitigation strategies'. As noted by Wilhite *et al.* (2014), when precipitation deficiency spans an extended period of time (i.e. meteorological drought), its existence is defined initially in terms of natural characteristics. However, the other common drought types (e.g. agricultural, hydrological, and socio-economic) place greater emphasis on the social aspects of drought and the management of natural resources.

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In Europe, drought impacts both water-stressed areas of Southern Europe, and also countries where water availability has never before been a major concern. The annual economic losses associated with drought are growing, reaching on average 6.2 billion euros per year during recent decades (European Environment Agency, 2010; Vicente-Serrano *et al.*, 2014b; Andreu *et al.*, 2015). Although progress has been made to describe the underlying mechanisms, it remains difficult to adequately characterize, monitor, forecast, and manage drought. This is due to the complexity of droughts, and the nuances of their long-term development and duration, progressive character of impacts, and diffuse spatial limits (Mavromatis, 2007, 2010; Sheffield *et al.*, 2012; Dai, 2013; WMO, 2013; Beguería *et al.*, 2014; Trenberth *et al.*, 2014; Vicente-Serrano *et al.*, 2014a, 2014b, 2014c; Wilhite *et al.*, 2014; Potop *et al.*, 2014). In the RM, the main natural factors that determine high and stable crop yields are timely rainfall and soil fertility. Soil is the main natural resource of the RM. However, the fragmentation of land holdings through land reforms has accelerated the loss of soil organic matter (Boincean *et al.*, 2014). Consequently, changes in soil structure are synchronized with changes in soil moisture.

The main goal of this paper is to study drought variability and to assess the yield sensitivity to drought of winter wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), sugar beet (*Beta vulgaris* L.), and sunflower (*Helianthus annuus* L) during their growing seasons in the RM. The paper is organized as follows: after a short description of the study region in Section 2., Section 3. presents the meteorological and agricultural data and outlines the statistical methods used. Section 4. presents the results which are then discussed in a broader European context in Section 5 Section 6. finally presents the main conclusions of the study.

2. Study region

Though the country of the RM is small (33 846 km^2), three agro-climate regions can be defined from north to south with distinguished drought climatology characteristics. The spatial distribution of the seasonal mean air temperatures and total precipitation across the territory of the RM for the reference period 1961–1990 are presented in Figure 1(a)–(i). The common definition of seasons has been used: winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November). The summer mean air temperature ranges between +18.5 °C (*North agro-climatic region*) and +21.0 °C (*South agro-climatic region*), and the total precipitation between 235 mm in the north and 175 mm in the south, respectively (Figure 1(a)–(i)). The winters are relatively mild and dry, with temperatures ranging from −3.4 °C in the north to −1.4 °C in the south, and the average total precipitation is 104 mm.

Chernozem soils are prevalent in the RM (almost 80%), though in different regions chernozems appear to be pedogenic processes as well as geographic (south–north) sequence (Krupenikov *et al.*, 2011). Two evolutional stems may be distinguished: Calcareous to Common Chernozem with a side branch to Xerophyte – wooded Chernozem in the south, and Typical to Leached Chernozem in more humid areas in the north. The prevailing crops include winter wheat, maize, sunflower, and grapevine in the central and southern agro-climatic regions, and sugar beet and barley in North agro-climatic region.

The Northern agro-climatic region is characterized by optimal moisture conditions for growing cereals, sugar beet, sunflower, tobacco, and fruit trees. It has the shortest frost-free period lasting 178–188 days, and the highest amount of annual precipitation. The annual mean air temperature ranges from 6.3 to 9.7 °C and the mean annual precipitation amount varies from 520 to 680 mm. The accumulated temperature above 10.0 °C is 2750–3100 °C and lasts around 175–182 days. The Central agro-climatic region ensures more accumulated heat ranging between 3000 and 3300 °C with an average annual duration of 182–187 days, which represents optimal agro-climatic conditions for growing cereals, fruit trees, and grapevines. The annual mean temperature ranges from 7.5 °C to 10.0 °C and the average annual precipitation total varies from 520 to 660 mm. The Southern agro-climatic region is characterized by the highest accumulated temperature above 10.0 °C ranging 3200-3400 °C with an average annual duration of 180–190 days. The annual mean air temperature ranges from 8.3 °C to 11.5 °C and the average annual precipitation total varies from 490 to 550 mm. The climatic conditions ensure the longest growing season and the longest frost-free period lasting 181–190 days per year (Constantinov *et al.*, 2002).

The Selectia Research Institute of Field Crops (RIFC) built upon the experience of the Moldavian experimental Plant Breeding Station, where the long-term experimental fields for crop rotations were established in 1962. The average annual precipitation total recorded at the RIFC during the 1962–2012 farming period was 577 mm. Precipitation is not evenly distributed during the year. Summer is the wettest season, with precipitation totals contributing 39% to the annual total. Conversely, winter is the driest season, accounting only for about 17% of the annual precipitation total, followed by fall and spring. The average frost-free period was 165 days per year, and the accumulated temperature above 10 °C was 2700–3000 °C.

3. Data and methods

3.1. Meteorological data and drought identification

The meteorological stations of the three agro-climatic regions are: Briceni, Soroca, Camenca, Falesti, and Ribnita for the North, Cornesti, Chisinau, Bravicea, Baltata, Dubasari, and Tiraspol for the Central region, and Comrat, Leova, and Stefan-Voda for the Southern region, while

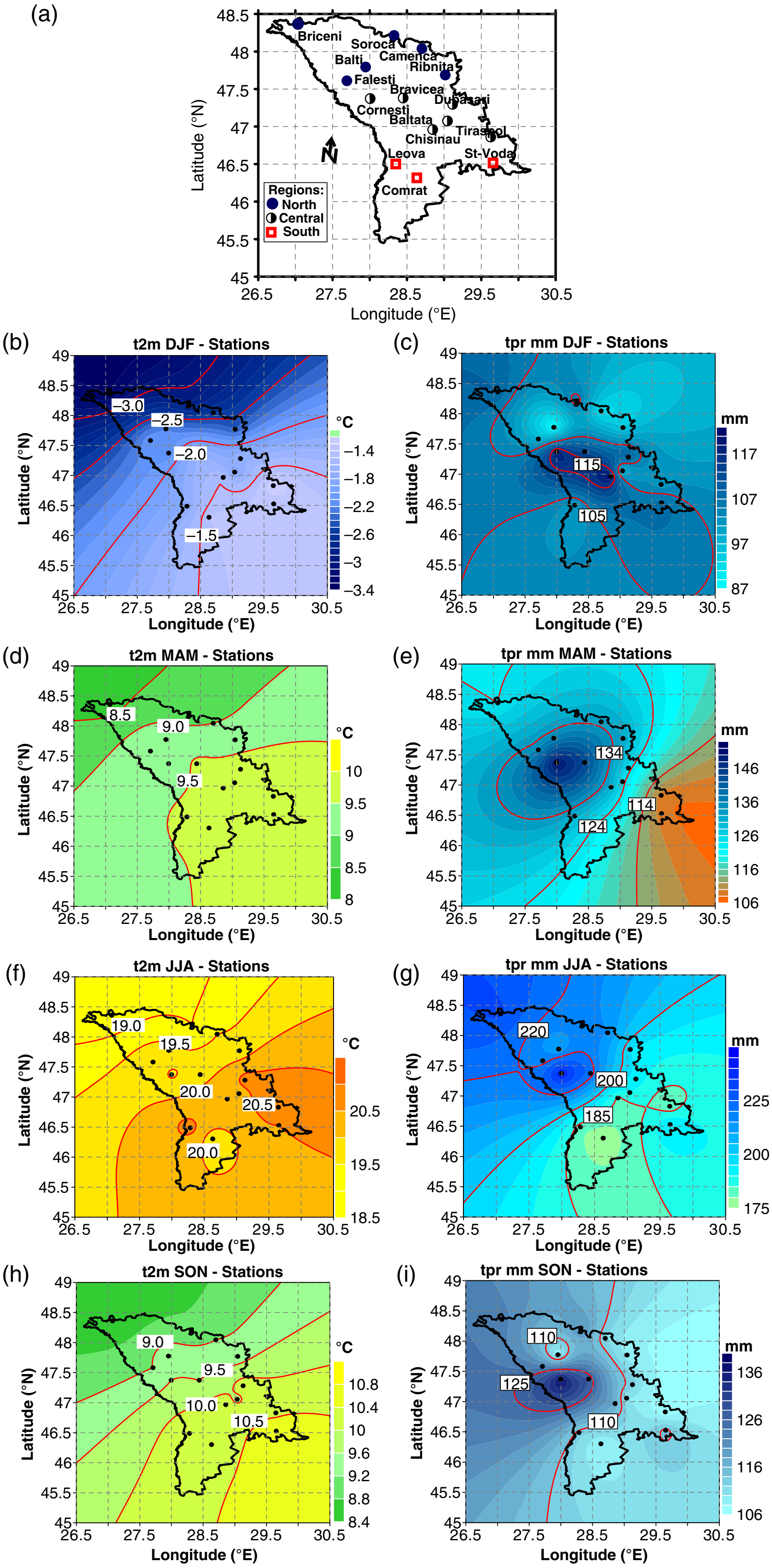


Figure 1. (a) The distribution of meteorological stations by agro-climatic regions (North, Central, and South) in the RM (a); The maps of winter (DFM), spring (MAM), summer (JJA), and autumn (SON) mean air temperatures (t2m, °C) and total precipitation (tpr, mm) for the reference period 1961–1990 at 15 meteorological stations in the RM (b–i). Quantile plot of differences between the empirical cumulative distribution of yield residuals of maize and the cumulative distribution function of the fitted log-logistic distribution (j). Frequency distribution of the SYRS of maize at the country level during the 1962–2012 farming years (k).

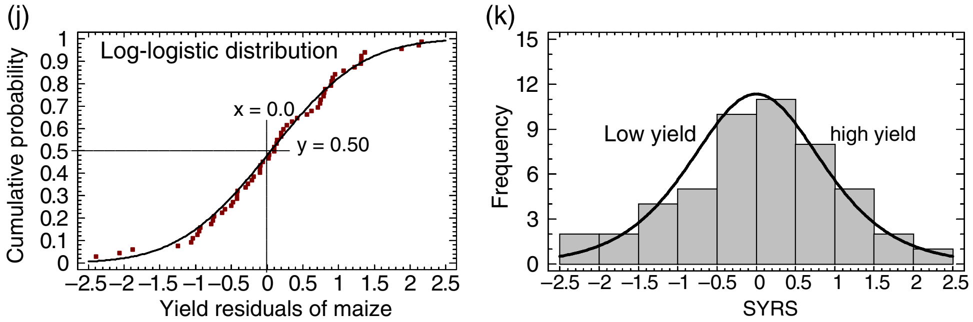


Figure 1. Continued.

Balti is the meteorological station located near the experimental fields of the RIFC (Figure 1(a)–(i)). The network of meteorological observations across the country and the quality control of the datasets were described in detail by Potop (2011). In this study, we updated the time series of monthly precipitation (P), and the minimum ($t_{\min}$) and maximum ($t_{\max}$) air temperatures at 15 meteorological stations for the 1951–2012 period. These data were used to calculate the potential evapotranspiration (PET) with the Hargreaves method (Hargreaves and Allen, 2003), and the standardized precipitation evapotranspiration index (SPEI) based on the method developed by Vicente-Serrano *et al.* (2010). A detailed comparison between the two empirical methods for calculating the PET in the RM, namely the Hargreaves and the Penman–Monteith methods, was described by Potop and Boroneaţ (2014). The results confirm that the Hargreaves method can be used as an acceptable alternative to the Penman–Monteith method to estimate the PET.

The quantification of drought is commonly done by using so-called drought indices, which are proxies based on climatic information, and it is assumed that they adequately quantify the degree of drought intensity. The SPEI is one of the most used indices to quantify drought and/or wet events all over the world (Wang *et al.*, 2014). It is commonly accepted that drought is a multi-scalar phenomenon, and the SPEI quantifies moisture conditions on multiple time scales, taking into account antecedent precipitation and PET at the surface (e.g. the normalized cumulative water deficit over the previous *n* months). This approach is concerned with the time lag that exists between the onset of water shortage and the identification of its consequences on growth (Beguería *et al.*, 2014). This appears as a critical issue in studies focusing on the impacts of drought on agriculture systems, since the response of the different crop types to water shortage varies markedly and with different response times. Moreover, it is difficult to assess the yield sensitivity to drought due to different vulnerabilities of various crop types to drought (Potopová *et al.*, 2015). However, this issue is addressed with the SPEI, as it successfully allows the responses of vegetation productivity and growth to drought time scales to be measured at a global scale (Vicente-Serrano *et al.*, 2014c) through it omits the soil component from the water balance analysis. Chernozem is the prevailing soil in the RM. According to the World Soil Database (FAO *et al.*, 2012b) other soil groups with less percentage in coverage have the same available soil water storage capacity. Therefore, using the SPEI to quantify drought would not introduce uncertainty related to soil conditions. The main limiting factor for soil moisture content is the reduced amount of precipitations in the southern part of Moldova. Thereby, in this study, the SPEI was used to identify the effect of precursor moisture accumulation deficit on crops, including the pre-sowing dryness/wetness conditions. SPEI was used to quantify the moisture conditions for each month of the year for 12 accumulated periods from 1 to 12 months during 1951–2012 at 15 meteorological stations (Figure 1(a)–(i)). The steps used to calculate the SPEI were the following: (1) the parameterization of the PET based on the monthly minimum and maximum air temperature, and extra-terrestrial radiation; (2) monthly water balance (D), calculated as the difference between the monthly P and the PET, and (3) normalization of the climatic water balance into a log-logistic probability distribution to transform the original values to standardized units that are inter-comparable in space and time. Further details of the method used to calculate the SPEI can be found in Vicente-Serrano *et al.* (2010) and Beguería *et al.* (2014).

The performance of the multi-scalar SPEI is used in evaluating the accumulative moisture conditions from the sowing to the harvest period of the crops. For instance, a 3-month lag contains moisture conditions from the current month and the past 2 months. A 6-month lag represents a very good indication of the amount of moisture that has fallen during the current month and the past 5 months, and was used to calculate the SPEI-6 [e.g. for April (March-February-January-December-November)]. The duration of drought was calculated as the number of months from the first month when the SPEI value was lower than −1 to the last month with a negative value before the index turned back to positive. The classes of moisture categories are shown in Table 1(a), and drought severity at various lags was assessed for each month in which the drought indicator was lower than −1.

3.2. Trend analysis – Mann–Kendall and Pettitt tests

In this study, the rank-based non-parametric Mann–Kendall trend test (Mann, 1945; Kendall, 1975), which is recommended by the World Meteorological Organization

Table 1. Classes of moisture categories according to the SPEI (a) and yield categories according to the SYRS (b).

(a)

SPEI	Moisture category	Frequency (%)
≥2.0	Extreme wet	2
1.50–1.99	Severe wet	6
1.49–1.00	Moderate wet	10
0.99 to −0.99	Normal	65
−1.00 to −1.49	Moderate drought	10
−1.50 to −1.99	Severe drought	5
≤−2.00	Extreme drought	2

(b)

SYRS	Yield category	Frequency (%)
≥1.50	High yield increment	2.3
1.00–1.49	Moderate yield increment	4.4
0.51–0.99	Low yield increment	9.2
0.50 to −0.50	Normal	68.2
−0.51 to −0.99	Low yield losses	9.2
−1.00 to −1.49	Moderate yield losses	4.4
≤ −1.50	High yield losses	2.3

(Sneyers, 1990) was used for trend detection of the SPEI and the standardized yield residuals series (SYRS). Its Z-score was used as a trend indicator. Under the null hypothesis of no trend H_0, the Mann–Kendall test statistic (S) is

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(X_j - X_i\right) \qquad (1)$$

$$sgn(\theta) = \begin{cases} +1 \ \ldots \ \theta > 0 \\ 0 \ \ldots \ \theta = 0 \\ -1 \ \ldots \ \theta < 0 \end{cases} \qquad (2)$$

where for independent and randomly distributed random variables, when n ≥ 8, the S statistic is approximately normally distributed, with zero mean and variance:

$$\sigma^2 = \frac{n(n-1)(2n+5)}{18} \qquad (3)$$

As a consequence, the standardized Z statistics follows a normal standardized distribution:

$$Z = \begin{cases} \frac{S-1}{\sigma} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sigma} & if \quad S < 0 \end{cases} \qquad (4)$$

The hypothesis that there is no trend is rejected when the Z value computed by Equation (4) is greater in absolute value than the critical value $Z\alpha$ at a chosen level of significance α.

The Pettitt test (Pettitt, 1979) was used to detect a significant change point in the mean of SPEI time series. The statistic of the test is defined as:

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} Sgn\left(x_i - x_j\right), \ 1 \le t < T, \qquad (5)$$

where similar to the Mann–Kendall test, sgn (θ) has the same significance as in the Equation (2).

The most significant change point is found where the value $|U_{t,T}|$ is maximum: $K_T = max|U_{t,T}|$ and the significance level associated with K_T^+ or K_T^- is determined approximately by

$$p = 2exp\left[\left(-6K_t^2/(T^2 + T^3)\right)\right]$$

Given a certain significance level α, if $p < \alpha$, the null hypothesis is rejected and it can be concluded that x_{t0} is a significant change point at level α.

3.3. Yield data

The annual series of the crop yields of winter wheat, maize, sugar beet, and sunflower at the national level as reported by the National Bureau of Statistics of the RM (NBS, 1962–2012) during the 1962–2012 period were used to assess the crop sensitivity to drought as quantified by the SPEI at 1- to 12-month lags for each month of the growing season. Additionally, the high-quality crop yield experimental data on Typical chernozem soil in the Balti steppe of Moldova, available from the RIFC were compared with the national yield series. The longer duration of the field experiment, the better its scientific and practical value. The RIFC has a half century of field experiments on the Balti steppe in Moldova. The first description of the Typical Chernozem soil of this region was achieved in 1877 by Dokuchaev who also designed a unique system of shelter belts (Dokuchaev, 1952) which is now provisionally listed as the first World Heritage Site for soil (Boincean, 2014).

The crop rotation experimental fields consisted of eight rotations with different proportions of row crops – from 40 up to 70%, including 10–30% sugar beet, 10–20% sunflower, and 20–40% maize. The proportion of winter wheat is 30% in all of the rotations but it is sown after different predecessors: in one field after early harvested predecessors, in the second after silage maize, and in the third after maize for grain. Each plot in the crop rotations is 283 m^2, with three replicates, and in the continuous monocultures 450 m^2 without replicates. The soil of the filed experiments is Typical chernozem heavy clay. Laboratory analysis of the 0–20 cm layer revealed 4.8–5.0% organic matter, pH_{water} 7.3, and pH_{CaCL2} 6.2, and total nitrogen, phosphorus, and potassium contents is 0.20–0.25, 0.09–0.11, and 1.22–1.28%, respectively. Four systems of fertilization are used: unfertilized control, mineral fertilizers, combined manure, and mineral fertilizers and manure. Mineral fertilizers are applied annually for winter wheat, sugar beet, maize, and sunflower before autumn tillage, except for winter wheat where half of the nitrogen is applied in the autumn and the other half in spring. Details on fertilizer regimes and crop management were previously reported by Boincean (2014). No irrigation was used in the experiment.

The winter wheat has the longest (October–July) crop life cycle (from sowing to harvest), followed by sugar beet and maize (April–October), and sunflower (April–September). The winter wheat development can be divided into three phases: foundation (from sowing to the start of stem extension, i.e. October–March), construction (from first node to flowering, i.e. April–May), and production (post-flowering to when the grains fill and ripen, i.e. June–July). All study crops recorded an increase in the sown area (NBS, 2012), except for sugar beet. The extent of sugar beet sown area has been reduced from 107 100 ha in 1980 to 31 000 ha in 2012, while the sowing areas for winter wheat has been maintained stable. The slightly increasing areas were registered for maize (up to 100 000 ha) and sunflower (up to 129 000 ha). The largest shares in the total sowing area are wheat (31.1%), maize (28.5%), and sunflower (17.3%).

Yield changes over time depend on several factors besides climate, such as new management practices and technologies, which commonly create a growing trend in the yield. In order to remove the effect of these non-climatic factors, and thus to isolate the variation resulting from climate, the de-trended yield was used (Lobell and Asner, 2003). The fluctuations in crop yields over time were calculated on the following basic components: (1) the average yield change due to management and other non-climatic factors, (2) the second one is based on the agro-meteorological conditions (i.e. dryness/wetness conditions identified by SPEI) during the growing season from one year to the next, (3) the yield response to dryness/wetness conditions, and (4) residual error – the yield fluctuations caused by random factors. Based on the above mentioned components, the yield series were de-trended using a quadratic polynomial trend as the most suitable method according to the minimum mean absolute percentage error. The de-trending of crop yield series was accomplished by extracting a mean dynamical value resulting from fitting a quadratic polynomial trend. This value varies over time depending on technological progress and societal conditions reflected in the series of crop yields. The indicator of agricultural drought risk can be represented (Wu *et al.*, 2004) by the residuals of the de-trended yield $\left(y_i^{(T)}\right)$. The $y_i^{(T)}$ of the crops in the LTEs for the Balti and the average yields for the RM were calculated as follows:

$$y_i^{(T)} = y_i^0 - y_i^{(\tau)} \tag{6}$$

where y_i^0 is the observed crop yield and $y_i^{(\tau)}$ is the value of the de-trended yield in a separate year.

To fit the series of $y_i^{(T)}$ we used the same log-logistic distribution probability function, which showed a very close fit to both series of D and $y_i^{(T)}$ (Potopová *et al.*, 2015). According to the log-logistic distribution, the cumulative distribution function of the $y_i^{(T)}$ series is given by:

$$F(x) = \left(1 + \left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right)^{-1} \tag{7}$$

where α, β, and γ are scale, shape, and origin parameters, respectively.

To compare yield variability among the crops with different means and standard deviations, the series of $y_i^{(T)}$ were standardized for each crop using the Z-score transformation. The SYRS was computed as

$$\mathrm{SYRS} = \frac{y_i^{(T)} - \mu}{\sigma} \tag{8}$$

where $y_i^{(T)}$ is the yield residuals, μ is the mean of the yield residuals, and σ is the standard deviation of yield residuals.

The SYRS is a standardized variable and can therefore be compared with other crops growing in various agricultural technology levels and/or different climatic conditions. The SYRS of 0 indicates a value corresponding to 50% of the cumulative probability of $y_i^{(T)}$ based on the log-logistic distribution (Figure 1(j) and (k)). The SYRS for each crop were used to calculate the terciles corresponding to the above normal, normal, and below normal yields. The thresholds of these terciles were used to identify and select the years in which the yield losses were equal to or below the threshold of the inferior tercile. Classes of yield categories according to the SYRS arising from the normal probability density function are presented in Table 1(b).

The effect of drought on different development periods of crops have been evaluated using the Spearman's rank correlation coefficient. The correlation coefficients between the time series of low-yielding years ($\mathrm{SYRS} \le -0.5$) and drought ($\mathrm{SPEI} \le -1$) for 1- to 12-month lags were calculated. The coefficient of determination (R^2) shows variability in yield losses ($\mathrm{SYRS} \le -0.51$) explained by the $\mathrm{SPEI} \le -1$ (drought). The drought–yield relationship was estimated by a second-order polynomial. This closely represents the nature of the crop–yield water relationship (Ash *et al.*, 1992; Brazdil *et al.*, 2014), as crop yields may be inhibited not only through water stress but also by low global radiation, below-normal temperatures, root anoxia, and higher infestation pressure of fungal diseases, all factors that tend to be associated with unusually wet seasons.

4. Results

4.1. Long-term fluctuation of drought driving factors

The extreme air temperatures ($t_{\min}$ and $t_{\max}$), the PET, and precipitation anomalies are analysed in this section as driving factors for drought during the main growing season (April–October). The long-term anomalies of these climatic elements relative to baseline climate of 1961–1990 at Chisinau station in the Central agro-climatic region are presented as an example in Figure 2. The baseline characteristics of these elements during the growing season for the three agro-climatic regions are summarized in Table 2. The highest temperature and the lower precipitation anomalies (i.e. more than 2.5 °C associated with precipitation anomalies up to 60% below normal) occurred during the 1960, 2000, and 2010s.

The warmest growing seasons associated with unusually low rainfall and the highest air temperature and PET were recorded in 2007 and 2012. In 2007 (2012), the PET was above normal at 123 mm (170 mm) and the precipitation was 60% (39%) below normal; $t_{\max}$ and $t_{\min}$

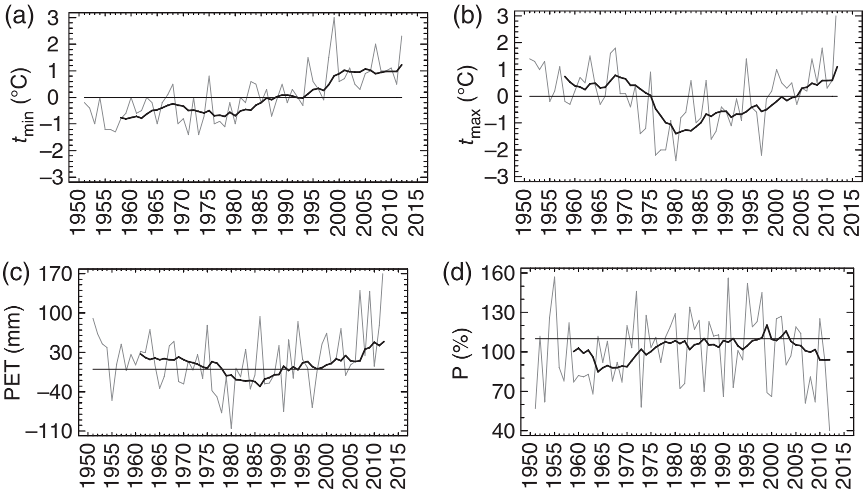


Figure 2. Long-term deviations from the baseline climate 1961–1990 of the maximum and minimum air temperatures (a,b), PET and percentage of precipitation totals (P) during the main growing season (April–October) (c,d) at Chisinau station. The series are smoothed with a 10-year Gaussian filter.

Table 2. Spatially averaged maximum and minimum air temperatures means, precipitation totals and potential evapotranspiration calculated for the main growing season (April–October) per agro-climatic regions for the baseline climate 1961–1990.

Agro-climatic regions	Maximum temperature (°C)	Minimum temperature (°C)	Precipitation totals (mm)	Potential evapotranspiration (mm)
North	21.1	9.9	383.6	680.1
Central	21.9	10.7	380.0	748.0
South	22.0	11.4	342.0	770.2

exceeded the baseline normal by up to 1.4 °C (3.7 °C) and 2.0 °C (2.3 °C), respectively. The year 2012 was the warmest and the driest with record-breaking absolute maximum air temperatures (+42.4 °C), which was 0.9 °C higher than the previous absolute record in 2007 (Bugaeva and Mironova, 2012). The drought of 2012 in the RM was part of a regional phenomenon, which affected large areas of the Black Sea region, the Balkans, and Central Europe (Brazdil *et al.*, 2014; Potopová *et al.*, 2015). Equally, the weather conditions in the Czech Republic from August 2011 to May 2012 produced an extreme drought in the eastern part of the country (Zahradníček *et al.*, 2014).

The driest month of 2012 was June (detected by the SPEI ≤ -1.0 at all stations), followed by August (at 87% of the stations), and July (at 79% of the stations), while moderate drought in April and September was detected at 47% of the stations. The development of extreme drought in 2012 was mainly attributed to (1) unprecedented increased temperature (up to 2.5 °C higher than average) and precipitation deficit (up to 50%) lasting from August to November 2011 and affecting 80% of the country; (2) high positive summer temperature anomalies in 2012 (more than 2.5 °C) associated with below normal rainfall (less than 39% of the normal). The resulting yield losses were attributed to water and temperature stress during: (1) the sowing period of winter crops in 2011, which was delayed by 1.5 months, and even then, only about 77% of the initially anticipated area was planted; (2) the extreme summer dry months of 2012 when winter wheat and maize, the two main rain-fed crops, faced critical phenological growth phases.

4.2. Spatiotemporal variability of drought

In order to assess the drought-induced decline in crop harvest, the analysis of the evolution of drought severity at regional scale was necessary. Hovmoller-type diagrams were generated to provide a visualization of the spatiotemporal evolution of the SPEI calculated for each month of the year at 1- to 12-month lags for the three agro-climatic regions and near the RIFC at Balti (Figure 3). The SPEI evolution over the three regions is alike although, for the southern region, the drought episodes are more frequent and more persistent than for the rest of the country. The main persistent dry periods identified in all regions were 1951–1955, 1990–1994, and 2000–2012, while the prevailing wet persistent periods were during 1968–1974, 1977–1982, 1996–1997, and 2008–2010. The wettest periods in the RM were associated with the coldest decade 1971–1980, which coincided with that reported for Southern and Central Europe, while the driest periods were associated with the warmest decade 2001–2010, which was reported as the warmest at a global scale (WMO, 2013). The spatiotemporal evolution of the SPEI for the three regions (Figure 3) indicates not only the overall moisture characteristics, but also the regional aspects in terms of timing and persistence.

Agricultural drought is also related to the timing of the principal crop growth stages. An outlook of the

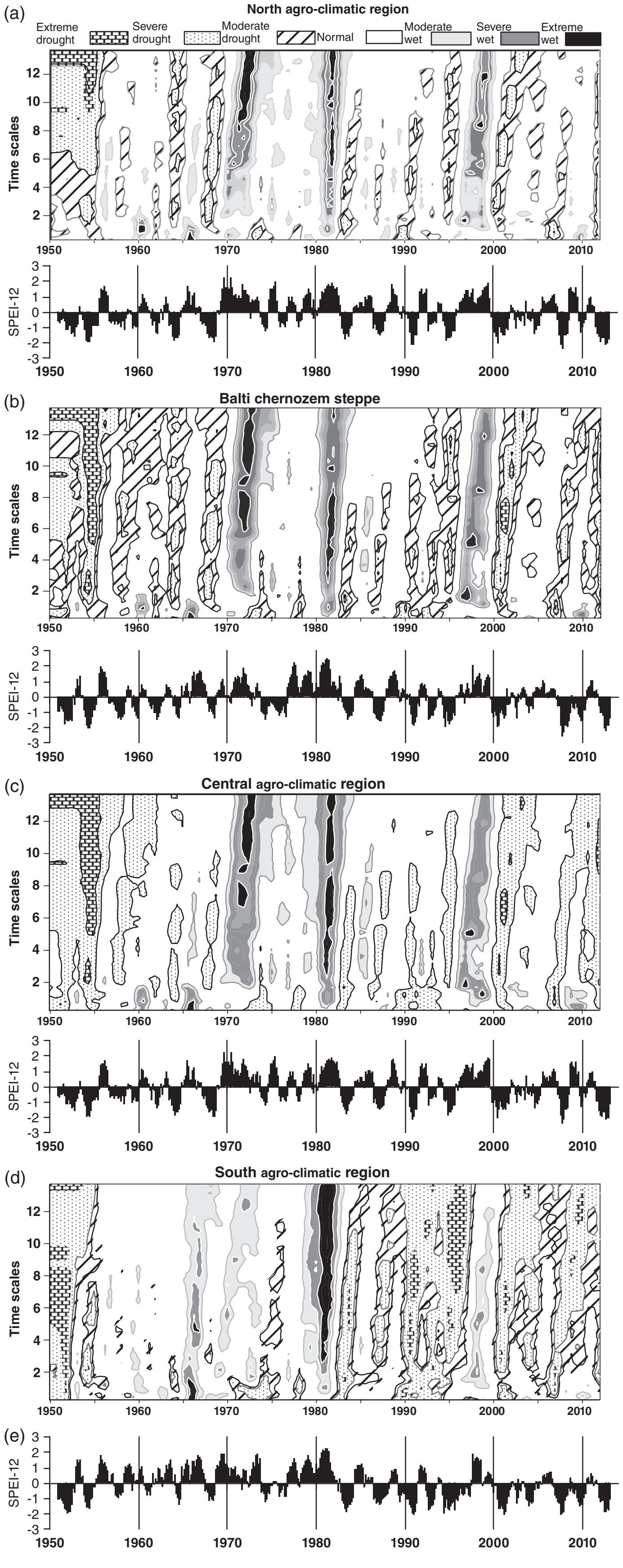


Figure 3. Spatiotemporal evolution of drought (wetness) development from 1- to 12-month lags per region: Northern region (12 months × 12 SPEI time scales × 5 stations) (a); Balti (12 months × 12 SPEI time scales × 1station) (b); Central region (12 months × 12 SPEI time scales × 6 stations) (c), and the Southern region (12 months × 12 SPEI time scales × 3 stations) (d); temporal evolution of the SPEI at 12-month lag (e).

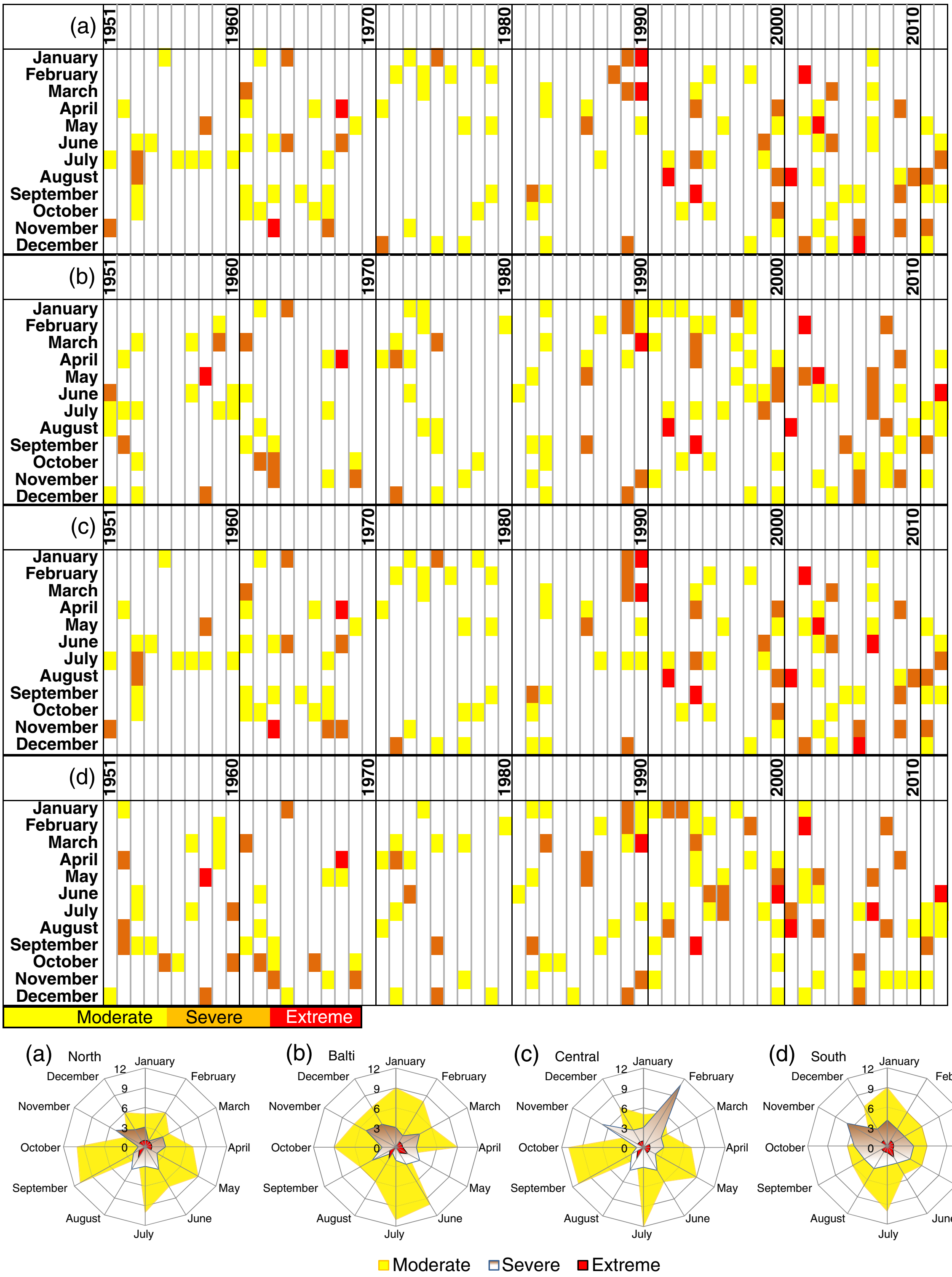


Figure 4. Top panel: Outlook of the regional agricultural drought persistence; Northern agro-climatic region (a), Balti experimental site (b), Central agro-climatic region (c), and Southern agro-climatic region (d). Bottom panel: Multiannual distribution of the moderate, severe, and extreme drought, as quantified by the SPEI at 3-month lag. Both statistics refer to the 1951–2012 period.

agricultural drought persistence and the multiannual distribution of the number of dry months per regions are presented in Figure 4. Large differences in the annual distribution of the dry months per region were observed.

In the North agro-climatic region, the most persistent agricultural drought occurred during the summer–autumn months of 1953 (5 months, which started in June, peaked in July–August, and progressively vanished until October) (top panel, Figure 4(a)). The driest spring–summer agricultural drought occurred in 2003 (3 months, April–June) and 2007 (2 months, May–June), when precipitation was two times lower than the baseline climate. The longest summer droughts were in 1992 (2 months, July–August) and 2012 (2 months, June–July). The highest frequencies of moderate droughts were counted in July, September, October, and May, while the highest frequencies of severe/extreme drought were counted in July–August (bottom panel, Figure 4(a)).

For the Balti chernozem steppe, the longest droughts were recorded during the winter–spring seasons of 1989/1990 (4 months, severe drought in December, followed by moderate drought in January–February and ended with the extreme drought in March), and 1994 (3 months, started in February, peaked in March–April, and ended in April) (bottom panel, Figure 4(b)). The highest number of moderate drought months occurred in June, July, April, and October (bottom panel, Figure 4(b)).

In the Central agro-climatic region, the longest severe drought was recorded during the summer–autumn of 1953 (top panel, Figure 4(c)) similar to the northern region. The longest spring–summer droughts occurred in 2003 (3 months, April–July) and 2007 (2 months, May–June). The long-lasting summer droughts were recorded in 1992 (2 months, July–August) and 2012 (2 months, June–July). The highest number of the months with moderate drought risk was counted for July, September–October, and May (bottom panel, Figure 4(c)). The highest number of extremely drought was counted for August.

In the South agro-climatic region, the most persistent drought was in 1994 (5 months, the first clear drought signal appeared in January, peaked in March, decreased in May, and almost vanished in October) (top panel, Figure 4(d)). The longest summer droughts were recorded in 2012 (3 months, June–August), 1992 (2 months, July–August), and 1953 (2 months, June–July). The highest incidence of moderate, severe, and extreme dry events occurred in May, June, and July, respectively, which actually are the emergence and critical months for maize and sunflower (bottom panel, Figure 4(d)).

4.3. Trend analysis of agricultural drought

The standardized Z statistics of the non-parametric Mann–Kendall test have been calculated for the SPEI series at 6-month accumulated periods (SPEI-6), for each month of the year and, for each of the 15 stations which were considered for this study. In this way, the analysis of the 6-month SPEI series covers the main life cycle of both the overwintering and summer crops. The null hypothesis that there is no trend was rejected when the standardized Z statistic was greater in absolute value than the critical value of Z at 90, 95, 99, and 99.9% confidence levels. Because the SPEI is a multi-scalar drought indicator with values ranging from ≤ -2 (extreme drought) to ≥ 2 (extreme wet) (Table 1(a)), the two-tailed standard normal distribution was considered for the standardized Z statistics of the Mann–Kendall test. The results of the Mann–Kendall trend test at each station are shown in Figure 5.

The spatial distribution patterns of the SPEI-6 trend are very much alike during January, February, and March but no significant trend was detected at any station. However, it is obvious that the stations in the southern part of the country show a decreasing trend, the stations in the centre show both decreasing and increasing trends, while in the northern part of the country, the SPEI-6 series show mostly increasing trends during January and February. During March and April, there is a noticeably increasing number of stations with decreasing trends, though no significant trends are observed at any particular station.

During May and June the SPEI-6 series present decreasing trends at all 15 stations, which indicates a trend towards agricultural drought, but the decreasing trend is only significant at the 90% confidence level at two stations during May. During June, the decreasing trend is significant at the 90% confidence level at three stations from the southern part of the country and, at three other stations the decreasing trend is significant at the 95% confidence level.

During July, a decreasing trend is apparent at most of the stations, but only at the stations from the south and at two stations from the centre is the trend significant at the 90% confidence level. Additionally, increasing but not significant trends are identified at four stations in the northern part of the country during July.

During August, at all 15 stations a decreasing trend is identified, but only at three stations from the south and one from the central part of the country is the trend significant at the 90% level. Most of the stations from the central and southern part of the country present decreasing trends, but only at two stations the trend is significant at the 95% confidence level during September, and at three stations it is significant at the 90% confidence level during October. During the next 2 months, November and December, the decreasing trend mainly prevails at the stations from the south and central part of the country the trend is significant, at the 90% and 95% confidence levels, at only four stations.

Since the Mann–Kendall test showed a generally drying tendency, though not always significant, the Pettitt test was further used to detect the change point or transition years in the SPEI-6 series at three representative stations for the northern (Briceni), central (Cornesti), and southern (Comrat) regions of the RM, and at Balti station which was considered as a reference for crop yield experiments. Table 3 presents the results of both Mann–Kendall and Pettitt tests at the representative stations for each month of the main growing season considered between April and October. The results show a drying tendency from April to October, but only for the southern part of the country, the drying trend being significant at the 90% confidence level in June and October, and at the 95% confidence level in July, August, and September according to Mann–Kendall test. The results of Pettitt test also show downward shifts towards drying in the SPEI-6 series, with most of the change point years in the 1980s significant at the 90% confidence level in April, at the 95% confidence level in May, June, and October, and at the 99% confidence level in July, August, and September. During June–July, the shift towards a drying tendency also becomes significant in the central part of the country, including at the reference

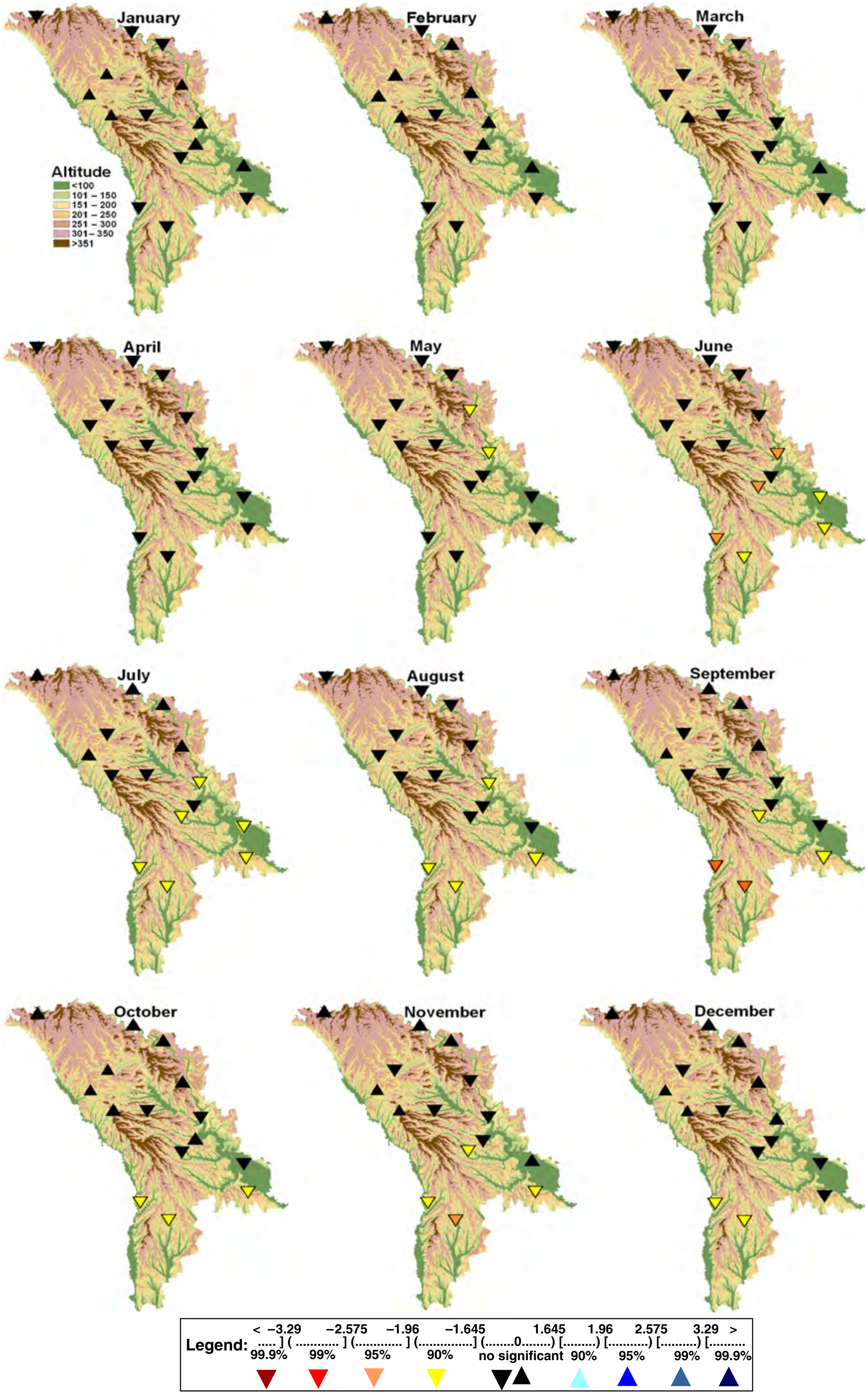


Figure 5. Spatial distribution of 6-month SPEI trend based on Mann–Kendall *Z* statistic at 15 stations in the RM.

Table 3. Results of the Mann–Kendall and Pettit tests for the 6-month SPEI of each month of the main growing season (April–October) during the period 1951–2012.

Stations[a]	Mann–Kendall test		Pettitt test							
	Z	Trend	Change point year	K+	α − max	Shift	Change point year	K−	α − min	Shift
April										
1	−1.25	Decreasing	1982	273	0.158	Downwards	1959	−74	0.873	Upwards
2	−0.80	Decreasing	1985	289	0.126	Downwards	1959	−87	0.829	Upwards
3	−0.99	Decreasing	1985	297	0.112	Downwards	1959	−128	0.666	Upwards
4	−1.45	Decreasing	1982	327	0.071^{*}	Downwards	1952	−100	0.781	Upwards
May										
1	−1.24	Decreasing	1971	228	0.276	Downwards	1952	−62	0.909	Upwards
2	−0.89	Decreasing	1988	263	0.180	Downwards	1959	−129	0.662	Upwards
3	−0.72	Decreasing	1981	272	0.160	Downwards	1959	−174	0.472	Upwards
4	−1.43	Decreasing	1981	352	0.046^{**}	Downwards	2009	−72	0.879	Upwards
June										
1	−0.80	Decreasing	1993	240	0.240	Downwards	1964	−83	0.843	Upwards
2	−1.40	Decreasing	1988	337	0.060^{*}	Downwards	1961	−52	0.935	Upwards
3	−1.49	Decreasing	1993	409	0.016^{**}	Downwards	1960	−126	0.675	Upwards
4	-1.88^{*}	Decreasing	1985	394	0.021^{**}	Downwards	1951	−49	0.942	Upwards
July										
1	0.30	Increasing	1993	140	0.615	Downwards	1968	−246	0.223	Upwards
2	−1.11	Decreasing	1993	337	0.060^{*}	Downwards	1961	−157	0.543	Upwards
3	−0.72	Decreasing	1993	330	0.067^{*}	Downwards	1960	−256	0.197	Upwards
4	-2.25^{**}	Decreasing	1985	466	0.005^{***}	Downwards	1951	−43	0.955	Upwards
August										
1	0.38	Increasing	1991	177	0.460	Downwards	1968	−315	0.086^{*}	Upwards
2	−0.55	Decreasing	1991	297	0.112	Downwards	1961	−172	0.480	Upwards
3	−0.49	Decreasing	1993	302	0.104	Downwards	1968	−264	0.480	Upwards
4	-2.51^{**}	Decreasing	1985	485	0.003^{***}	Downwards	1951	−51	0.178	Upwards
September										
1	0.53	Increasing	1998	190	0.409	Downwards	1968	−355	0.044^{**}	Upwards
2	−0.18	Decreasing	1997	274	0.156	Downwards	1967	−291	0.305	Upwards
3	−0.04	Decreasing	1997	288	0.128	Downwards	1968	−297	0.112	Upwards
4	-2.16^{**}	Decreasing	1985	458	0.006^{***}	Downwards	1954	−100	0.781	Upwards
October										
1	0.78	Increasing	1998	145	0.594	Downwards	1967	−351	0.047^{**}	Upwards
2	0.17	Increasing	1998	232	0.264	Downwards	1967	−253	0.205	Upwards
3	0.22	Increasing	1998	225	0.285	Downwards	1967	−349	0.049^{**}	Upwards
4	-1.68^{*}	Decreasing	1980	348	0.050^{**}	Downwards	1963	−79	0.857	Upwards

Critical values of Z equal to ± 1.645 ($\alpha < 0.1$*), ± 1.96 ($\alpha < 0.05$**), and ± 2.58 ($\alpha < 0.01$***) are associated with 90, 95 and 99% confidence intervals, respectively.

[a] Station 1, Briceni; Station 2, Balti; Station 3, Cornesti; Station 4, Comrat.

station Balti. It is worth noting that the significant shift towards the drying tendency appears in the 1980s during each month of the growing season. Also, for the northern region, the Mann–Kendall test indicated wetting but not a significant tendency during August, September, and October, while the Pettitt test detected a significant upward shift towards wetting with the change point years, 1968 and 1967, respectively.

4.4. The variability of SYRS

Figure 6 shows the temporal evolution and the quadratic trend of yield crops at the national level and at the experimental fields. During the first period of intensive agriculture beginning in 1962–1981, the crop yields increased both at the country level and at the long-term experimental fields (Figure 6). Due to drought intensification, reduced soil fertility, and economical changes, yields levelled off during the period 1985–1991, and recently even decreased. During the period of analysis, the crop yields in the long-term field experiments were significantly above the national averages. Winter wheat yields in the field experiments were higher than the national average by $1.5\,\mathrm{tha}^{-1}$. The yields of sugar beet in the Balti experimental site were systematically above the national average by $17.6\,\mathrm{tha}^{-1}$. Maize (sunflower) under rotation production conditions exceeded the national average by $2.9\,\mathrm{tha}^{-1}$ ($0.9\,\mathrm{tha}^{-1}$). The crop yields are higher in the long-term field experiments relative to farm production conditions because they are grown with full respect to the main technological components (crop rotations, soil tillage, optimal rates of mineral fertilizers, optimal terms of sowing, and weed, pest, and disease control). Worth noting is the large drop in the yields of experimental fields in 2003 which was mostly due to the effect of early spring frosts and large diurnal temperature range. On the other hand, the crop yield series at national level show systematic lower values

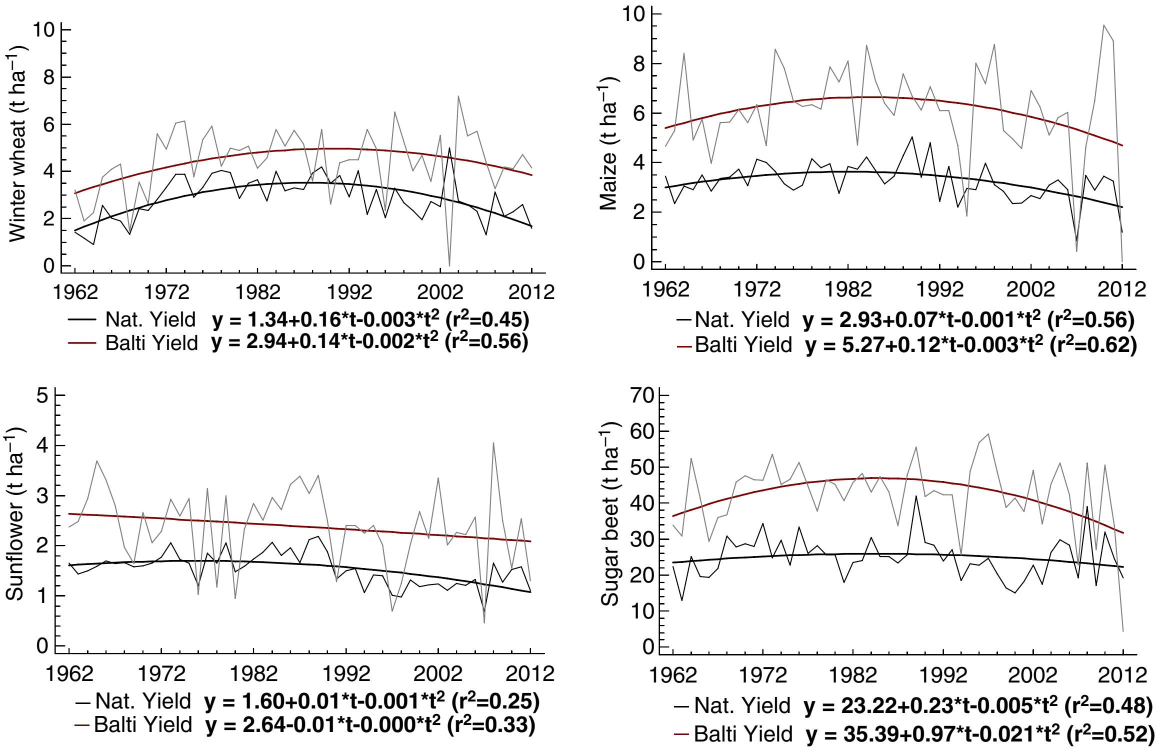


Figure 6. Temporal evolution and quadratic trend of the yield crops series at the country level and Balti experimental site during the 1962–2012 farming years.

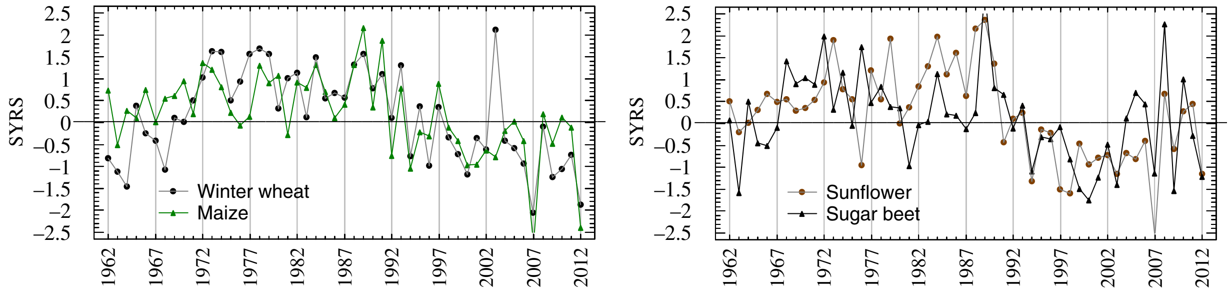


Figure 7. Temporal variability of the SYRS for winter wheat, maize, sunflower, and sugar beet at the country level during the 1962–2012 farming years.

and less fluctuation than in Balti experimental fields which, besides the lack of due technological requirements, could be an averaging effect.

According to the converted yield residuals into standardized values, the number of low-yielding years (SYRS ≤ -0.51) at country level (Balti experimental site) for winter wheat was 16 (12), 12 (8) for maize, 13 (12) for sunflower, and 14 (11) for sugar beet. Figure 7 suggests that the inter-annual variation of SYRS for overwintering and summer crops over the country during 1994–2007 shows strong negative anomalies. The significant decreases of SYRS after 1990s occurred due to the sharp reduction in N-fertilizer consumption (Boincean *et al.*, 2014) in conjunction with intensification of drought. The results of the non-parametric tests show downward shifts (increasing yield losses), significant at 99% confidence level in the SYRS of all crops, with most of the change point years in the 1990s (Table 4).

4.5. Drought impact on main crop yields

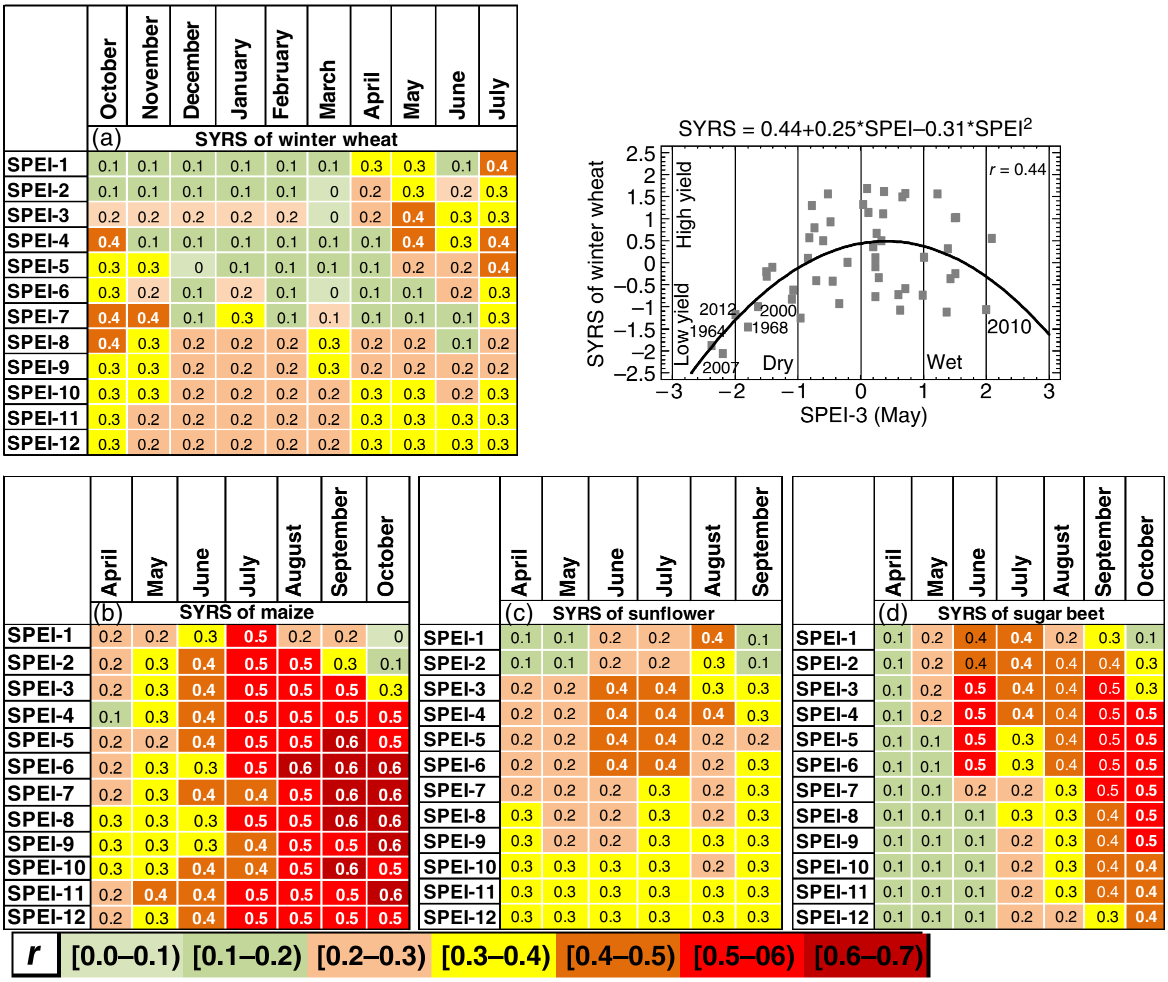
The results of a polynomial regression analysis show large differences in the responses of crops growing under optimal agro-technological experimental conditions (rotations and fertilization) and national yields (series resulting from the average yields at all farms). The correlation coefficients between the SPEI ≤ -1 and the SYRS ≤ -0.51 for the long-term field experiments were significantly smaller than for the national yields (not shown). This result can be explained by the fact that (1) crops of the long-term field experiments exhibited fewer low-yielding years than at the country level and (2) the experimental conditions represent better soil conditions compared to the farming normal of that region.

The correlation coefficients between the time series of SPEI at 1- to 12-month lags for each month of the growing season and the SYRS for each crop at the country level are shown in Figure 8. The correlation coefficient

Table 4. Results of the Mann–Kendall and Pettit tests for the SYRS of overwintering and summer crops at the country level during 1962–2012 farming years.

SYRS	Mann–Kendall test		Pettitt test			
	Z	Trend	Change point year	K+	α − max	Shift
Winter wheat	−2.20	Decreasing	1993	396	0.009	Downwards
Maize	−3.18	Decreasing	1991	499	0.000	Downwards
Sunflower	−2.79	Decreasing	1990	544	0.000	Downwards
Sugar beet	−2.41	Decreasing	1993	334	0.000	Downwards

Critical values of Z equal to ±1.645 ($\alpha < 0.1$), ±1.96 ($\alpha < 0.05$), ±2.58 ($\alpha < 0.01$) and ±3.29($\alpha < 0.001$) are associated with 90, 95, 99, and 99.9% confidence intervals, respectively.



(a) SYRS of winter wheat

	October	November	December	January	February	March	April	May	June	July
SPEI-1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.1	0.4
SPEI-2	0.1	0.1	0.1	0.1	0.1	0	0.2	0.3	0.2	0.3
SPEI-3	0.2	0.2	0.2	0.2	0.2	0	0.2	0.4	0.3	0.3
SPEI-4	0.4	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.3	0.4
SPEI-5	0.3	0.3	0	0.1	0.1	0.1	0.1	0.2	0.2	0.4
SPEI-6	0.3	0.2	0.1	0.2	0.1	0	0.1	0.1	0.2	0.3
SPEI-7	0.4	0.4	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.3
SPEI-8	0.4	0.3	0.2	0.2	0.2	0.3	0.2	0.2	0.1	0.2
SPEI-9	0.3	0.3	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2
SPEI-10	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.3	0.2	0.3
SPEI-11	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
SPEI-12	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3

(b) SYRS of maize

	April	May	June	July	August	September	October
SPEI-1	0.2	0.2	0.3	0.5	0.2	0.2	0
SPEI-2	0.2	0.3	0.4	0.5	0.5	0.3	0.1
SPEI-3	0.2	0.3	0.4	0.5	0.5	0.5	0.3
SPEI-4	0.1	0.3	0.4	0.5	0.5	0.5	0.5
SPEI-5	0.2	0.2	0.4	0.5	0.5	0.6	0.5
SPEI-6	0.2	0.3	0.3	0.5	0.6	0.6	0.6
SPEI-7	0.2	0.3	0.4	0.4	0.5	0.6	0.6
SPEI-8	0.3	0.3	0.3	0.5	0.5	0.6	0.6
SPEI-9	0.3	0.3	0.3	0.4	0.5	0.5	0.6
SPEI-10	0.3	0.3	0.4	0.4	0.5	0.6	0.5
SPEI-11	0.2	0.4	0.4	0.5	0.5	0.5	0.6
SPEI-12	0.2	0.3	0.4	0.5	0.5	0.5	0.5

(c) SYRS of sunflower

	April	May	June	July	August	September
SPEI-1	0.1	0.1	0.2	0.2	0.4	0.1
SPEI-2	0.1	0.1	0.2	0.2	0.3	0.1
SPEI-3	0.2	0.2	0.4	0.4	0.3	0.3
SPEI-4	0.2	0.2	0.4	0.4	0.4	0.3
SPEI-5	0.2	0.2	0.4	0.4	0.2	0.2
SPEI-6	0.2	0.2	0.4	0.4	0.2	0.3
SPEI-7	0.2	0.2	0.2	0.3	0.2	0.3
SPEI-8	0.3	0.2	0.2	0.3	0.2	0.3
SPEI-9	0.3	0.2	0.2	0.3	0.3	0.3
SPEI-10	0.3	0.3	0.3	0.3	0.2	0.3
SPEI-11	0.3	0.3	0.3	0.3	0.3	0.3
SPEI-12	0.3	0.3	0.3	0.3	0.3	0.3

(d) SYRS of sugar beet

	April	May	June	July	August	September	October
SPEI-1	0.1	0.2	0.4	0.4	0.2	0.3	0.1
SPEI-2	0.1	0.2	0.4	0.4	0.4	0.4	0.3
SPEI-3	0.1	0.2	0.5	0.4	0.4	0.5	0.3
SPEI-4	0.1	0.2	0.5	0.4	0.4	0.5	0.5
SPEI-5	0.1	0.1	0.5	0.3	0.4	0.5	0.5
SPEI-6	0.1	0.1	0.5	0.3	0.4	0.5	0.5
SPEI-7	0.1	0.1	0.2	0.2	0.3	0.5	0.5
SPEI-8	0.1	0.1	0.1	0.3	0.3	0.4	0.5
SPEI-9	0.1	0.1	0.1	0.2	0.3	0.4	0.5
SPEI-10	0.1	0.1	0.1	0.2	0.3	0.4	0.4
SPEI-11	0.1	0.1	0.1	0.2	0.3	0.4	0.4
SPEI-12	0.1	0.1	0.1	0.2	0.2	0.3	0.4

r	[0.0–0.1)	[0.1–0.2)	[0.2–0.3)	[0.3–0.4)	[0.4–0.5)	[0.5–06)	[0.6–0.7)

Figure 8. The tables summarize the correlation coefficients (r) of the second-order polynomial regression between the monthly SPEI at 1- to 12-month lags and the SYRS of winter wheat (a), maize (b), sunflower (c), and sugar beet (d) at country level for the period 1962–2012. The graph shows the second-order polynomial regression between the SYRS of winter wheat and the SPEI at a 3-month lag in May (as an example).

from sowing to the start of stem extension of winter wheat ranges from $r = 0.11$ to 0.42 ($p \leq 0.05$; $R^2 = 0.22$), with the maximum correlation occurring during the sowing period and the appearance of the third leaf (October–November) (Figure 8(a)). The relationship between the drought during winter months and low yields is weak, explaining less than 10% of the yield variability. There are many causes of crop diebacks during winter, not all of which are associated with drought and/or lethal temperatures during snow-free days. The correlation coefficient since the first node to flowering (end of April to May) ranges from 0.24 to 0.44 ($p \leq 0.05$; $R^2 = 0.32$) at 1- to 3-month lags. From early to mid-grain filling (June) when young developing grains can be aborted due to lack of assimilate (Turner, 1997), a moderate correlation at the SPEI time lags from 3 to 4 months ($r = 0.34$; $p < 0.04$; $R^2 = 0.28$) was observed. Winter wheat was significantly affected by short- and medium-term drought during wax ripeness (July, $r = 0.35$–0.43; $p < 0.04$; $R^2 = 0.38$).

The correlation coefficients between SYRS of maize yield and SPEI are higher than for winter wheat, meaning that maize yield is more affected by drought (Figure 8(b)).

High temperature stress and low humidity reduces pollen viability and silk receptivity due to desiccation, which results in poor seed set and reduced yield (Craufurd and Oeacock, 1993). The lowest correlation was observed at the beginning of the vegetative stages of maize (from emergence to third leaf; $r = 0.14–0.32$; $p \leq 0.05$; $R^2 = 0.25$), while the highest correlation was observed during the reproductive stages (from silking and milk to physiological maturity; $r = 0.53–0.62$; $p < 0.01$; $R^2 = 0.52$). In all agro-climate regions, the highest drought frequency was observed in July and August, which corresponds with the highest moisture demand for maize. Thereby, for a successful cultivation of maize in the territory of Moldova, irrigation is necessary during these months. Concurrently, during this period (July–August) high temperatures ($t_{\max} \geq 30.0\,°\mathrm{C}$) frequently occurred at country level since 2000. These events could have reduced the pollen viability and thus the number of fertilized kernels.

Sunflower is commonly regarded as a plant that is tolerant to drought and uses water efficiently (Vronschih *et al.*, 2002). Thereby, sunflower does not show a strong correlation between SYRS and SPEI at short time scales during June–July (Figure 8(c)). However, since sunflower is an oil seed crop, it is particularly susceptible to water shortage at flowering (June, $r = 0.40$; $p < 0.03$; $R^2 = 0.42$, SPEI-3 to 6-month lags) and grain fill (July, $r = 0.24–0.43$, $p < 0.03$; $R^2 = 0.42$; SPEI-1 to 6-month lags) stages. At the end of ripening (September), the need for moisture is sharply reduced, and therefore, the rainfall at this stage could adversely affect the crop.

Sugar beet has an effective mechanism for osmotic adjustment, but it is one of the highest water consuming plants ($6000–7000\,\mathrm{m}^3\,\mathrm{ha}^{-1}$) due to its long growing season (160–210 days). A significant correlation was observed between SYRS and SPEI at time scales from 4 to 7 months during September and October ($r = 0.50$; $p < 0.01$; $R^2 = 0.45$) (Figure 8(d)). The dry episodes in September and October (when sugar accumulates in the taproot) lead to decreased root yield but increased sugar content. Nevertheless, drought occurrence at the earliest stage of plant development reduces the leaf area index and over ground biomass more drastically than during other stages of plant development. July–August ($r = 0.41$; $p < 0.02$; $\mathrm{R}^2 = 0.38$) is the period with the highest risk of yield loss, caused by a combination of substantial water demand of sugar beet and the occurrences of severe drought episodes.

4.6. Analysis and attribution of crop yield losses

The effect of drought on agriculture is mainly reflected in the reduction of crop yields. The crop loss due to drought is a complex problem, because it depends on drought intensity and duration, on the plant's developmental stage during which the drought occurs, and on the ability of the genotype to tolerate stress. The annual yield losses were expressed in relative terms (loss in %) for each crop averaged at the country level and the Balti experimental site. The percentage of yield losses was calculated by dividing the annual crop yield by the dynamically mean yield value of the quadratic trend and multiplying the result by 100% (1962–2012). In -Tables 5(a) and (b), the years are ordered by the descending losses. The growth stages (Meier, 2001) in which the severe drought/wet occurred are also shown. In order to make an attribution of crop losses, it is important to calculate the incidence of drought during the crop stages and then to quantify the yield loses owing to these rates. Such a quantification of yield crop losses due to drought impact during the main crop stages is shown in Table 6. The drought frequency was calculated for SPEI-3 ≤ -1.0 and the yield losses were calculated at the country level. For maize the risk period occurs from anthesis-silking to milk, and for winter wheat and sunflower it is during anthesis, when drought and high temperatures, from the onset of anthesis to 10 days after, cause substantial yield losses. For sugar beet, the risk period occurs when the leaves cover from 40 to 90% of the ground and the beginning of the storage root, which corresponds with the highest moisture demands ($40\,\mathrm{m}^3\,\mathrm{ha}^{-1}$ for 24 h).

The results shown in Tables 5(a) and (b) show that the degree of yield losses varies among crops due to drought/wet impact on various crop stages. In this respect, the year 2007 was ranked the highest in terms of crop failures for winter wheat, maize, and sunflower due to drought impact during sowing to harvesting stage. The crop production was reduced by more than 50%, while the cost of the lost production was almost €300 million (FAO/WFP, 2007). As a consequence of drought during 2012, the production of maize and winter wheat at the country level dropped by 46 and 38%, respectively (Table 5(a)). The 2012 drought had the largest impact on maize, and the second most affected crop was winter wheat. The lack of precipitation in the sowing stage of maize, coupled with the extremely high temperatures during the flowering stage led to a drastic decrease in yields. Maize yields dropped by more than 50% in 24 of 34 districts of the country (FAO *et al.*, 2012a), while winter wheat yields dropped by 80 to 86% in the six most affected districts of the country (North and South agro-climatic regions). The drought during the sowing period for winter wheat, which germinated in the autumn of 2011, and the very low temperatures during wheat tillering in the early spring 2012, then the severe drought before the harvest, adversely affected the winter wheat production. The losses for maize and winter wheat have been estimated at around US$78 million (UNDP, 2012).

Out of all farming years considered in this study, the highest crop losses at the country level for winter wheat occurred in 2007 and 1964, while for the Balti experimental site the highest crop losses occurred in 1968 and 1963 (Tables 5(a) and (b)). Our results show that when severe drought episodes occurred during the flowering and post-flowering to late milk stages of winter wheat, the yield fell by at least 36% for the whole territory of Moldova. The highest yield losses (18.8%) were recorded when drought occurred (17.7%) during the crop risk period of winter

Table 5. (a) Percentage of yield crop losses (Y, %) due to severe drought/wet occurrences in the main productive crop stages at the national level. (b) Percentage of yield crop losses (Y, %) due to severe drought/wet occurrences in the main productive crop stages at the Balti experimental site.

Winter wheat			Maize			Sunflower			Sugar beet		
Year	Y (%)	Stages[a]	Year	Y (%)	Stages	Year	Y (%)	Stages	Year	Y (%)	Stages
(a)											
2007	−50	Sowing to harvesting	2007	−67	Sowing to harvesting	2007	−54	Sowing to harvesting	1963	−45	Leaves cover 90% of ground
1964	−44	Sowing to booting	2012	−46	Sowing to anthesis	1998	−35	Leaf development	2000	−39	Sowing to harvesting
1968	−43	Flowering	1994	−35	Sowing to harvesting	1997	−33	Sowing to harvesting	1999	−34	Leaves cover 90% of ground (storage root)
2012	−38	Post-flowering to late milk	1992	−30	Beginning of grain development	1994	−29	Sowing to harvesting	1981	−30	Sowing to harvesting
2000	−36	Post-flowering to late milk	2000	−25	Sowing to fully ripe	2012	−27	Flowering to ripening	2003	−28	Sowing to leaves cover 10% of ground
1994	−36	Stem elongation to flowering	1981	−24	Sowing to harvesting	2003	−26	Stem elongation to inflorescence emergence	1994	−28	Sowing to harvesting
1963	−29	Sowing	1963	−23	Early dough (kernel content soft)	2000	−21	Sowing to flowering	2001	−26	Leaves cover 40% of ground
1999	−25	Ripening	2001	−22	Dough (about 55% dry matter)				2009	−26	Leaves cover 90% of ground (storage root)
(b)											
1968	−66	Flowering to early milk	2007	−93	Sowing to end of flowering	2007	−81	Sowing to flowering	2007	−47	Emergence to storage root enlargement
1963	−57	Sowing to beginning of tillering	1995	−70	Early milk to fully ripe	1997	−71	Flowering to ripening	1994	−40	Leaves cover 60 % of ground
1964	−49	Tillering	1967	−35	Sowing to heading	1980	−60	Sowing to ripening	2009	−37	Leaves cover 40% of ground
1996	−47	Early milk to hard dough	2001	−25	Early milk	1976	−57	Ripening	1966	−32	Sowing to leaves cover 90% of ground (storage root)
1990	−40	Sowing to harvesting	2008	−24	Anthesis	1978	−51	Ripening	1987	−22	Leaves cover 90% of ground (storage root)
1970	−40	Sowing to harvesting	1994	−23	Beginning of tassel emergence	1991	−47	Beginning of ripening	2011	−22	Leaves cover 90% of ground (storage root)
1962	−27	Sowing				2012	−46	Flowering			

Gray cells represent wet episodes and white cells represent drought episodes. [a]Growth stages according to BBCH scale (Meier, 2001).

Table 6. Quantification of the yield crop losses due to drought impact (SPEI-3 ≤ −1.0) during the main crop stages at the country level for the 1962–2012 farming years.

	Winter wheat		Maize		Sunflower		Sugar beet	
	Frequency of drought, (%)	Yield losses, (%)	Frequency of drought, (%)	Yield losses, (%)	Frequency of drought, (%)	Yield losses, (%)	Frequency of drought, (%)	Yield losses, (%)
Sowing	22.6	9.9	19.4	8.8	17.7	6.1	19.4	7.9
Risk period	17.7	18.8	24.3	30.5	22.6	22.3	24.2	27.2
Harvest	24.2	2.3	17.8	5.8	19.4	1.5	16.1	3.6

wheat (Table 6). During the winter wheat growing season, the reference evapotranspiration (ETo) is higher than the precipitation amount with about 100 mm in the northern and central regions and about 160 mm in the southern region (Piticar *et al.*, 2015).

The highest crop failures in maize yield at the country level occurred in 2007, 2012, and 1994, while for the Balti site these occurred in 2007 and 1995 (Table 5a-b). The maize yield fell on average by 30.5% when the drought occurred during the reproductive stages (Table 6). During the maize growing season, the ETo exceeds the amount of precipitation by 300 mm in the north and more than 400 mm in the south (Piticar *et al.*, 2015). Maize is relatively well adapted to high temperature and also shows good transpiration efficiency because of C_4 characteristic of concentrating CO_2 to bypass the oxygenase activity. However, maize shows large genetic variation in the relative timing of male and female flowering, commonly referred to as the anthesis-silking interval (ASI). Delayed ASI leads to reduced kernel set under drought and a number of other stresses (Edmeades *et al.*, 2000).

The major losses in sunflower yield at the national level occurred in 2007, 1998, 1997, and 1994, while for the Balti site, major yield losses occurred in 2007 and 1997 (Tables 5(a) and (b)). Interestingly, at the Balti experimental site the highest yield reductions for sunflower (from −71 to −47%) were recorded during severe wet growing seasons, specifically during the flowering to ripening stages. The sunflower yields at the national level were reduced on average by 22.3% when they were exposed to drought stress during the flowering and grain fill stages (Table 6).

The highest crop failures of sugar beet yields at the national level occurred in 1963 and 2000, while for the corresponding Balti site yields the highest crop failures occurred in 2007 and 1994 (Tables 5(a) and (b)). The results observed in the experiment fields clearly point out on the fact that the amount of crop yield is most frequently reduced (−40 to −22%) by drought stress in the canopy development and the storage root stages. Since the summer drought can severely limit root yield and quality, as well as the sugar content in sugar beet (Sadeghian and Yavari, 2004), it becomes obvious that the most economical and viable solution for overcoming this problem is the development of cultivars with increased drought and heat tolerance. Estimates of potential sugar beet yield losses in Europe, due to insufficient water resources, vary between 5 and 30% (Pidgeon *et al.*, 2001). According to the study of Choluj *et al.* (2004), water shortage influences both root yield and sugar yield by 16.1–51.6%, depending on the drought timing during the period of plant development. In central Europe, the impact of weather variability on sugar beet yield formation can be up to 37% (Potop and Türkott, 2014). In the RM the effect of drought on yield formation of sugar beet is about 38.7%, of which 27.2% occurs during the risk period (Table 6). Although sugar beet is primarily grown in the districts of the North agro-climatic region, there are many production areas where irrigation is not usually applied and, summer rainfalls are unpredictable and insufficient to fully meet the crop water requirements, which consequently lead to a substantial reduction in the cultivation area in the RM.

5. Discussion

Drought and heat stress often occur simultaneously (e.g. 1994, 2007, and 2012 in the Central and South agro-climatic regions of Moldova), but they can have different effects on various physiological, growth, developmental, and yield forming processes (Craufurd and Oeacock, 1993; Lobell *et al.*, 2005; Lobell, 2007; Lobell *et al.*, 2007; Lobell and Burke, 2010; Gobin, 2012; Mavromatis, 2012, 2015). The effects of drought and heat stress on crop depend on the timing of the event in relation to the crop phenological stage (Wu *et al.*, 2004; Mavromatis, 2007; Li e*t al.*, 2009). Furthermore, in a non-irrigated crop, heat is often exacerbated by drought stress (Edmeades *et al.*, 2000).

The previous experimental results for the Balti site under crop rotation with different systems of fertilization (Boincean *et al.*, 2014) revealed that the yield increase could be attributable to fertilization and yield variation caused by weather variability. The yield fluctuation due to weather variability (e.g. waterlogging, dryness) was greater than the yield increase attributable to fertilization.

The time series of averaged crop yields at the country level and at the experimental fields show systematically higher yields at the experimental fields. Both time series (Figure 6) emphasize an increasing trend from 1962 to 1981 due to intensive agriculture, and a decreasing trend from 1985 to 2012 due to drought (Figures 3–5), heat stress, evapotranspiration intensification, reduced soil fertility, and sharp economic changes. This is in agreement with previous studies (Corobov *et al.*, 2010, Piticar *et al.*, 2015) which concluded that ETo, sunshine duration, and maximum and minimum temperatures increased significantly in recent decades in the RM, whereas relative humidity and precipitation experienced decreasing trends. Stagnating cereal yields in eastern European countries have been attributed to lower yields under higher frequency of droughts, heat stress, and the short duration of the grain-filling period, but changes in management may also have played a role (Lobell and Field, 2007; Olesen *et al.*, 2011). In almost all eastern European countries, crop yields also dropped as a result of sudden decrease of N-fertilization after 1990 due to short-term economic impact.

Although the major part of the RM's territory is agricultural land (73%), and in particular arable land (54%) with fertile chernozem soils, only a small share is irrigated (13% of the arable land). Irrigation is difficult because of inappropriate water quality (due to a high degree of mineralization, i.e. the content of salts is higher than admissible level – $0.7\,\mathrm{g\,l^{-1}}$) and the need for pumping, which makes the irrigation too expensive. As a consequence, the cost of irrigation often exceeds its potential benefits. This makes the agriculture sector highly dependent on natural precipitation, which is expected to increase in variability due to climate change (Potop *et al.*, 2012a, 2012b; Boroneant *et al.*, 2013; Corobov *et al.*, 2013; Dai, 2013; Sutton *et al.*, 2013; Taranu, 2014). Enhancing irrigation due to increased frequency of drought in the South agro-climatic region is not a viable solution to the problem. However, an economically and environmentally desirable solution would be the new varieties of crops with decreased sensitivity to water deficits. In Moldova, the fragmentation of land holdings by land reforms has complicated the use of crop rotation and the implementation of measures to combat erosion. Consequently, soil fertility has been significantly reduced (Krupenikov *et al.*, 2011; Andries *et al.*, 2014), and the effects of drought and yield losses have been amplified. Changes in stock and increases in the annual losses of soil organic matter are more pronounced during the last 25 years (Boincean, 2014).

The results of a recent study on spatial and temporal variability of climate extremes in Romania and the associated large-scale mechanisms (Busuioc *et al.*, 2014) point out the significant increasing trend for temperature extreme indices in all seasons, except autumn, with a more enhanced increasing rate in summer. The large-scale atmospheric circulation was found to be the major drought driver during winter, while thermodynamic factors (such as air temperature and humidity) are the major drivers in summer (Cheval *et al.*, 2014).

The temporal evolution of the SPEI time series highlights not only the general character of drought at the country level with the main periods of dry and wet persistence, but also the regional characteristics of drought which are present in the Southern region of RM, making it more prone to severe drought persistence, mostly during the last decade. The trend analysis of agricultural drought in the RM highlights the increasing trend during April–May, though this is not significant in all regions. From June to October, the trend becomes significant in the southern region at the 90% confidence level, and at the 95% level during September. This area is also affected by the most severe water stress conditions (low precipitation and higher evapotranspiration rates). The significant shift towards drought tendency was detected in 1985 for the southern region during the summer months, while for the central region 1993 was detected as a change point year during June and July. Though an overall trend towards drying conditions was found since the 1980s, a significant upward shift towards wet conditions was detected for the northern region in 1967. These findings are in agreement with the conclusions from the recent study of Piticar *et al.* (2015).

It is evident that severe droughts have occurred and persisted during May–June–July, while moderate droughts occurred during September–October. The statistics based on 62-year records show that July is the month with the highest frequency of drought, while severe drought mostly occurred in August in the northern and central regions, and in June in the southern region. This evidence clearly points out on the demand for developing coping strategies for croppers in Moldova. In previous studies focused on Central Europe, Brazdil *et al.* (2014) and Trnka *et al.* (2014) reported significant trends towards a higher evaporative demand and decreasing precipitation totals between April and June (and, to a certain extent, in August) in the recent decades.

Agricultural production was sharply reduced by extreme drought in 2007 and 2012. In these years, the production of winter wheat dropped by 50 and 38%, of maize by 67 and 46%, of sunflower by 54 and 27%, and of sugar beet by 23 and 23%, respectively. The extreme south-eastern European drought of 2012 had the largest impact on maize and winter wheat, due to the lack of precipitation during the sowing period, coupled with the extremely high temperatures during the reproductive stages which led to drastic decreases in the yields. The RM could serve as a model example of a non-irrigated crop response to the increasing drought tendency in south-eastern Europe.

6. Conclusions

This study presents a detailed analysis of drought-yield relations under optimal agro-technological experimental conditions and agriculture farm production conditions. Detailed agronomic records and field experiments represent a scientific foundation for the development of recommendations for optimizing crop water requirements. During the last 15–20 years droughts increased in intensity and persistence compared to the past in the RM (Potop and Soukup, 2009), mostly due to increased temperatures and decreased precipitation in the region. The results of this study clearly show that drought is one of the limiting factors of crop yields with respect to the climate conditions in Moldova. Drought during the plant reproductive stages may significantly reduce grain yield potential, the relation between the SYRS and the SPEI explaining up to 62% of the low-yield variability. However, other factors which were not considered in this analysis are also important. Short-term heat stress, hailstones, the last spring frost and winter frost, can also influence crop management. In the RM, for instance, hailstorms are often catastrophic; that is, areas with damaged crops reach thousands of hectares with 50–100% damage rates (Potapov *et al.*, 2007).

The risk of overwintering and summer crops being exposed to severe drought during their growing cycle is consequently increasing. Cultivars should be developed to exploit the available moisture in wetter years combined with drought tolerance for years that lack optimum levels of precipitation. Some suggestions for further research and adaptation to climate change policy may arise from this study that are in line with the international literature (Rötter *et al.*, 2013): (1) further consideration should be made for a wider range of agro-climate indicators (especially short-term heat and drought stress, heavy precipitation, and soil water availability) and their shifts across the country for current and future climate, (2) identification of the areas in the RM where crop yield is currently most prone to climate-induced stresses, and (3) combined agro-climatic indicators with crop growth simulation approach.

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