HEAT STRESS-CROP YIELDS INTERACTIONS UNDER SUMMER WARMING TRENDS: INSIGHTS FOR THE SOUTHERN CROPPING LOWLANDS OF ROMANIA

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Key-words: heat stress, crop yield, summer warming, southern cropping regions of Romania.

Abstract. Extreme heat is an emerging threat to the agricultural sector, which severely affected the crop yields in many regions of Romania during the last two decades. Here we investigate a 53-year climatology of daily maximum air temperatures to extract the regional characteristics of summer heat stress in the southern cropping lowlands of Romania (Oltenia and Muntenia regions) and to estimate the yield sensitivity of three major crops (winter wheat, grain maize and sunflower) to the changing heat stress under the ongoing warming. In our approach we aim to test the hypothesis of a cause-effect relationship between seasonal heat stress and the annual crop production at county level (NUTS3), considering the existing adaptation potential through irrigations, especially during the heat stress representative years of 2000, 2007 and 2012. Our results reveal that, in both cropping regions, there is a significant and spatial robust increase in the frequency and duration of heat stress, especially since the mid-1980s, confirming the findings of previous studies on climate variability and climate extremes. The changes in summer heat stress determined different and spatially variable crop yield sensitivities. The main findings of the regression analyses on heat stress-crop yield relationships are: *summer heat stress* allowed explaining 17 to 55% of the annual variability of yields at county level; during the hot and droughty summers of 2000, 2007 and 2012, the detrimental effect of heat stress on crop yields was particularly evident and worsened by the lack of efficient water compensations through irrigations (generally below 5% in Oltenia and 7% in Muntenia); heat stress was found to be an important predictor of crop yield failures, especially for maize crops; for the summer harvesting crops (winter wheat) and good high temperature and drought resistance (sunflower), the detrimental effects of heat stress appear less evident; recurrent heat stress days (HSD, HSDD) and heat stress spells (HSSfr) have had a greater influence on final crops than the persistent individual heat stress spells (HSSdurmax). Both agricultural regions are heat stress sensitive, but the cropping areas which underwent substantial crop production losses due to extreme high temperatures are located in the southernmost floodplain areas (e.g. in the Dolj, Olt, Gorj, Giurgiu, Călăraşi counties), where heat stress is particularly intense and frequent. Rehabilitation of irrigation emerges as an important adaptation measure in agriculture to reduce the current vulnerabilities and future impacts of heat stress on national food security.

1. INTRODUCTION

Climate and agriculture are intrinsically linked and variability in yield, crop biodiversity and water use provides key evidence on the effects of a changing climate. Climate change is impacting the agricultural sector in multiple ways, both directly (e.g. alterations in crop agroecosystems, low productivity levels, changes in the length of the growing season, timing of crop growth stages and harvest dates) and indirectly (e.g. weed competition, expansion of pests and diseases, food-market instability), exacerbating some important challenges faced by this sector (e.g. water scarcity, soil degradation). In the Fifth Assessment of IPCC (AR5, 2014), heat stress is included among crop-focussed threats to global food security.

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The observed effects of recent climate trends and extreme events on agricultural crop production are robust and widespread, with more negative than positive impacts, especially on wheat and maize yields (e.g., Peltonen-Sainio *et al*., 2010; Lobell *et al*., 2011; Olensen *et al*. 2011; Porter *et al*., 2014). Heat waves, drought and excess precipitation were found particularly detrimental to wheat yields (e.g., Zampieri *et al*., 2017; Semenov and Shewry, 2011), while hot weather and severe drought, especially during the sensitive stages of crop development are a significant threat to maize yields in many regions worldwide, including Romania (e.g., Deryng *et al*., 2014; Sandu *et al*., 2010; Croitoru *et al*., 2012). To our knowledge, compared to cereals, only few studies explored the effects of heat stress on sunflower crops (e.g., Harris *et al*., 1978; Rondanini *et al*., 2003, 2006; Moriondo *et al*., 2011; De la Haba *et al*., 2014).

Over the past decades, the frequency and severity of extreme events increased in many regions of Romania (e.g. Croitoru and Piticar, 2012; Vlăduţ and Onţel, 2013; Dumitrescu *et al*., 2015; Busuioc *et al*., 2015; Piticar *et al*., 2017), where farming experienced a wide range of effects: e.g. very low agricultural outputs in the very dry years; important crop losses during flooding; hailstorms-related damages; development of invasive plants; shortening of the vegetation period of certain crops; degradation of the land productive capacity. Currently, agriculture is recognized as one of the most climate-sensitive economic sector. The *National Climate Change Strategy 2013–2020* (2013) highlighted the urgent need for action-oriented measures to support climate change adaptation in this sector, especially in the light of the great economic losses caused by the hot weather episodes and severe droughts of the 2001–2012 period (2000–2003, 2007 and 2012).

The results of prior studies suggest an increased crop sensitivity to various weather and climate-related aspects, especially to drought, heat stress and air freeze (e.g. Fabian and Gomoiu, 1981; Ţerbea *et al*., 1995; Balotă *et al*., 1997; Petcu *et al*., 2001; Prăvălie *et al*., 2017). Increasing temperatures and heat stress were found to play a major limiting role on crop growth and final yields (e.g. Sandu *et al*., 2010; Sandu and Mateescu, 2014; *Cod de bune practici agricole în contextul schimbărilor climatice actuale şi previzibile*, 2014), mainly by being involved in the rate of plant metabolic processes, photosynthesis rates and timing of growth stages. The study of Lazăr and Lazăr (2010) on the effects of temperature increase on winter wheat yields and development in south-eastern Romania showed that an increase in the average daily temperature of 1°C is tolerable for the winter wheat phenology, while a 2°C increase is detrimental and poses a great risk to the stability of high-yield cultivars. Croitoru *et al*. (2012) also evidenced the changes in winter wheat phenology of in the south-eastern region of Romania in response to the long-term seasonal warming: a decreasing length of the anthesis period (up to 3 days/decade) and maturity period (about 1 day/decade), yet not statistically significant. Despite the growing interest in understanding climate change impacts on agriculture, there is still a need for further investigation of the complex and diverse climate-crop interactions, to better cope with the uncertainties related to the occurrence of heat stress under field conditions and the corresponding plant response to stress in changing climatic and socio-economic contexts.

This study investigates the effects of heat stress on the yield anomalies of three major crops in the southern agricultural lowlands of Romania (winter wheat, grain maize and sunflower). The rationale behind our work was to test the hypothesis of a cause-effect relationship between seasonal heat stress and annual production at county level (NUTS3), having in view the regional social and political constraints of the post-communist period, reflected in the poor functioning of the existing irrigation infrastructure.

2. STUDY REGION

The study focuses on the southern agricultural lowlands of Romania, including the territory of the most important and highly productive cropping regions of this country (Oltenia and Muntenia). The study region largely overlaps the Romanian Plain region (Fig. 1).

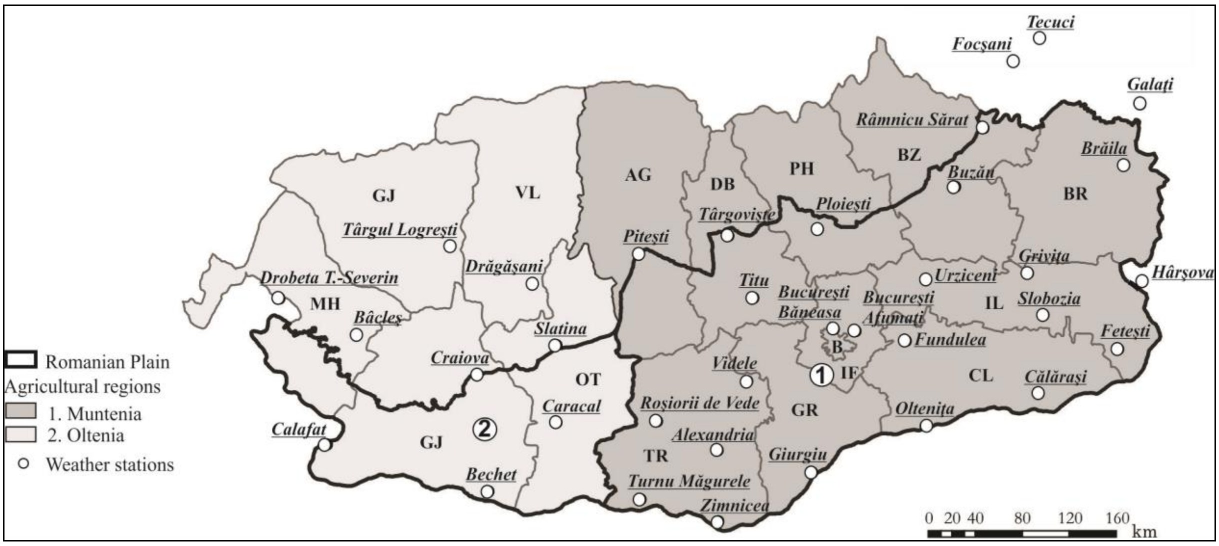


Fig. 1 – Location of the study region

Agricultural land use is prevalent among the main land use types of the region and accounts for 61% in Oltenia and 71% in Muntenia. The agricultural productivity of the two cropping regions is generally high relative to the total national yields: sunflower 40%, winter wheat 37% and maize 17%. At regional scale, winter wheat, maize, sunflower and rapeseed are the dominant crops, representing 79.4% (Muntenia) to 82.2% (Oltenia) of the total cultivated areas. In ”normal” precipitation years, the high soil fertility of arable land and the high technical equipment level of the farms (especially of the large ones), could ensure the conditions for achieving high agricultural yields: e.g., 6,000–10,000 kg/ha for maize; 4,000–6,000 kg /ha for wheat; 2,500 kg /ha for sunflower.

Muntenia and Oltenia agricultural regions exhibit fairly comparable average agro-climatic conditions, attributed to *Dfa climate type*[1] in the Köppen-Geiger climate classification system. According to the national agro-climatic zonation (Neacşa and Berbecel, 1979), the average climate of the two regions is a warm (10–11°C) and moderately dry one (below 500–550 mm/year), with rich radiative resources (sunshine duration over 2,100–2,200 hours/year). During the warm half of the year (April–October), these regions are highly exposed to hot weather episodes, intense evapotranspiration and persistent water deficit, especially in the western-, southern- and easternmost areas (Păltineanu *et al*., 2007; Sandu *et al*., 2010; Bojariu *et al*., 2015). Over the last two decades, Muntenia and Oltenia experienced considerable impact from various hydro-meteorological extremes, such as severe droughts (2000, 2003, 2007 and 2012), persistent heat waves (e.g. 2007, 2012) and extensive flooding in 2005, which had adverse effects on crop yields (*Cod de bune practici agricole în contextul schimbărilor climatice actuale şi previzibile*, 2014).

Despite the prevailing warm and dry summer climate, the two agricultural regions have a low adaptive capacity through irrigations, due to the small effectively irrigated areas per total area provided with irrigation (Fig. 2). The social and political constraints of the post-communist period are well reflected in the poor functioning of the existing irrigation infrastructure, which is currently unable to fully compensate for the impacts of climate change and associated weather extremes. According to the last updates of the National Institute of Statistics (2013), the total area equipped for irrigations in Muntenia and Oltenia agricultural regions is about 2,109.3 ha, distributed as follows: 71.5% in Muntenia (mainly in Balta Brăilei) and only 28.5% in Oltenia. A substantial decline of the effectively

[1] The *Dfa climate type* is defined as warm (temperate) continental, humid in all seasons with hot summers and cold winter (Kottek *et al*., 2006).

irrigated area has been recorded over the last few decades in both agricultural regions (Fig. 3). Most of this trend is due to the advanced state of the physical degradation of the irrigation infrastructure, through age and low reliability (great energy consumption, great water losses in the system). At county level, the decline is very obvious especially in Oltenia region. Generally, between 2000 and 2013, the largest irrigated areas were in 2007 in the counties of Brăila (29.5% of the total agricultural area managed for irrigation), Călărași (13.3%) and Ialomița (12.6%), where the large farms (over 2,000 ha) are mostly located.

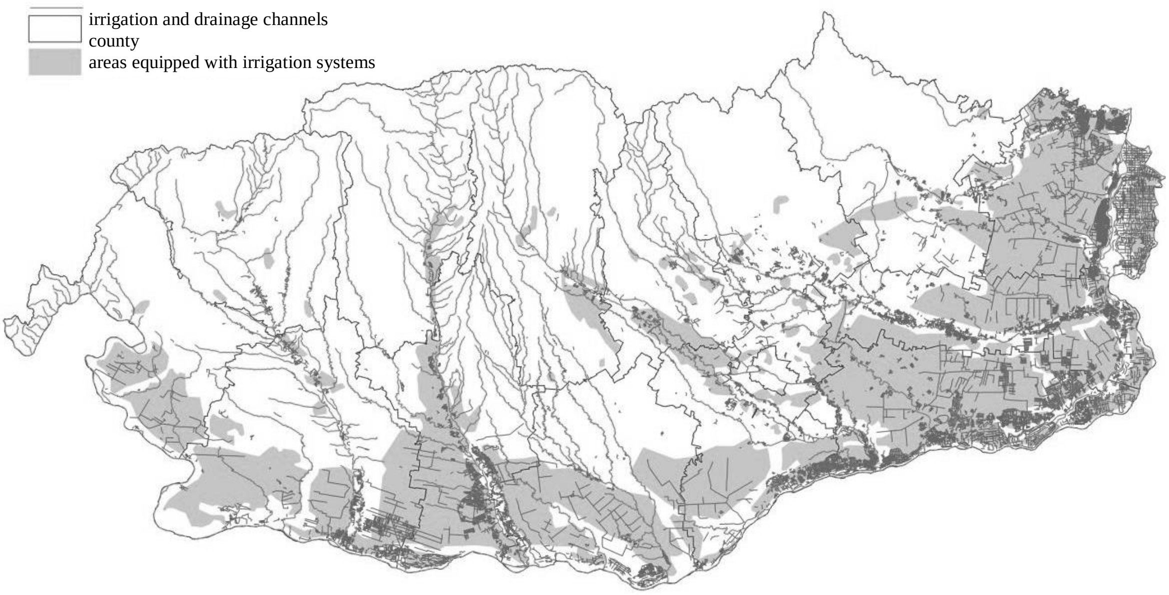


Fig. 2 – Distribution of the agricultural areas equipped for irrigation (1997–2013) in southern Romania.

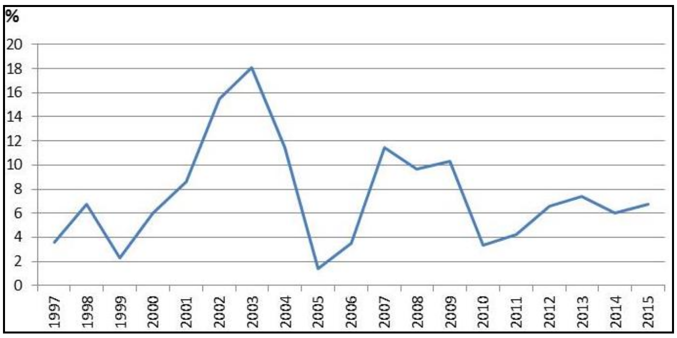


Fig. 3 – Dynamics of the effectively irrigated area in southern Romania between 1997 and 2015.
Values are expressed as % of the total area equipped for irrigation.

3. DATA AND METHODS

3.1. Data

The detection of heat stress is based on the ROCADA dataset (Dumitrescu and Bîrsan, 2015), an observational climatic dataset for Romania, which integrates measurements from all weather stations with full data records and missing data up to 30% in the monitoring network of the National Meteorological

Administration. This dataset is homogenized and gridded using MASHv3.03 (Multiple Analysis of Series for Homogenization) and MISHv1.03 algorithms (Meteorological Interpolation based on the Surface Homogenized Data Basis), both developed by the Hungarian Meteorological Service. In this study we investigate the agro-climatic heat stress using the daily maximum temperature T_{max} on a 0.1°×0.1° longitude-latitude grid between 1961 and 2013. The input meteorological data have been extracted from the corresponding ROCADA grid points for 37 representative weather station locations from the two agricultural regions of southern Romania and their surroundings, which lie in their lowland areas (with elevations below 400–300 m), where selected crops are cultivated. The grid point selection (Figure 1) comprises 21 locations for Muntenia, 9 for Oltenia and, for spatialization reasons, another 5 located close to the study region boundary (Galaţi, Tecuci, Focşani, Hârşova, Drobeta Turnu-Serverin). We present our results for each selected grid point, but also as county or regional averages, based on the grid point selection for the two agricultural regions.

This study uses annual crop yield data (kg/ha/year) for three major crops in Romania: winter wheat (*Triticum aestivum L.*), grain maize (*Zea mays L.*) and sunflower (*Helianthus annuus*). Yield data cover the 1990 to 2013 period and have been obtained at NUTS3 level (county) from the National Institute of Statistics. Irrigation data cover the 1997–2013 period and are available also at NUTS3 level (county).

3.2. Methods

Our investigations focus on the extended summer season (May to September), having in view the following considerations: irrigations are usually applied in this interval of high-water demand crops (e.g. grain maize); grain maize is sensitive to heat stress during its vegetative-reproductive stages (May–September), especially when associated to drought in July–August; winter wheat is highly sensitive to heat stress three months prior to harvesting (May–July, roughly corresponding to the anthesis and grain filling stages); high summer temperature could damage sunflower crops during specific sensitive development stages (e.g. seed filling) and oil quality.

In this study, *hot summers* are evidenced from local average seasonal temperature anomalies exceeding at least two standard deviations.

Agro-climatic heat stress. Crop plant response is variable among species, being dependent on the development stages of the species. There are defined ranges and critical thresholds (“cardinal values”) of maximum daily temperatures which affect negatively crop development and the final yields. Exposure to high maximum temperatures above 30–35°C of wheat (e.g. Balotă *et al*., 1997; Porter and Gawith, 1999; Porter *et al*., 2014), 35–38°C of maize (e.g. Hatfield and Prueger, 2015; Meluţ *et al*., 2014) and above 31°C of sunflower (e.g. Chimenti *et al*., 2001) were reported as unfavourable during the sensitive development stages. In our approach, we considered the daily maximum temperature threshold of 32°C (Tx_{32}), which is a critical biological temperature for crops during the period of maximum water demand according to Sandu *et al*. (2010). Beyond this threshold, heat becomes extreme and adversely impacts the key physiological processes involved in crop growth and development, especially when coinciding with drought episodes.

In this study four metrics (indices) are used to highlight the frequency and duration of the agro-climatic heat stress, namely: i) heat stress days (HSD), defined as days when the critical threshold Tx_{32} is reached or overpassed; ii) heat stress degree-days (HSDD), expressed as degree-days with a daily maximum temperature in excess of the critical threshold Tx_{32}, which are considered a measure of the seasonal extreme heat load; iii) heat stress spells frequency (HSSfr). Herein, a heat stress spell event is defined by considering a minimum sequence of at least three consecutive days when daily Tx is exceeding the critical threshold Tx_{32}; iv) heat stress spell maximum duration (HSSdurmax), which depicts the maximum time-span of an individual heat spell event.

Statistical model fitting. Crop yield sensitivity to extreme heat was investigated using regression and correlation analyses. The associations between seasonal heat stress metrics (as independent variables) and crop yield anomalies (dependent) were tested over the 1990–2013 period for all 15 counties and for each of the three crop types, in relation to the following statistics: Pearson correlation coefficient (*r* – the measure of strength and direction of the correlation between the predictand and predictors), squared correlation coefficient (r^2 – the proportion of variance of the predictand explained by predictors) and p value ($p<0.01$ – as indicator of the significance level so that the null hypothesis to be rejected or accepted against the alternative hypothesis).

Trend analysis. The non-parametric Mann-Kendall test (MK) was used to test the local significance of trends summer temperature and heat stress indices. Slope coefficients were estimated using the Kendall-Theil method (Theil-Slope estimate) and are expressed in corresponding units (°C, days), decennial (decade^{-1}) or relative to the length of the study period (e.g. °C period $^{-1}$). In this study, the significance level was fixed at 5% (two-tailed test).

4. RESULTS

4.1. Observed temperature change and frequency of hot summers

Southern Romania is experiencing a notable warming, but with non-homogeneous or spatially consistent changes in precipitation regime (e.g., Busuioc *et al*., 2010; Croitoru and Piticar, 2012; Dumitrescu *et al*., 2015).

Over 1961–2013, mean temperatures were steadily increasing since the mid-1980s or the early 1990s. Comparing the local trends, magnitudes throughout the study region, 2001–2013 emerges as a time-interval of intensified regional climate warming. This interval concentrates six of the warmest years of the period throughout both agricultural regions, with annual averages of over 12°C. Relative to the previous decades, this time interval had the greatest upwards (0.11–0.22°C decade^{-1}), especially in contrast to the 1971–80, the coldest decade since 1961. In terms of mean temperatures, regionally-wide, climate warming is observable in most seasons except autumn (the most stable season). In summer, warming is the strongest, with magnitudes of up to 0.43–0.49°C decade^{-1} in Muntenia and 0.37–0.45°C decade^{-1} in Oltenia. By contrast, winter warming is the weakest (below 1.0°C in both regions).

The changes in extreme temperatures are particularly important for farming activities since they do greatly influence the physiological processes responsible for final crop yields. In southern Romania, such changes have been observed both daytime (Tmax) and night-time (Tmin) in all seasons. In summer, temperature increase is generally faster and stronger during the day than at night in both regions. Estimated warming magnitudes of Tmax exceeded 0.47°C decade^{-1} in most areas or even 0.56°C decade^{-1} in some areas of Muntenia (Fig. 4). During the extended summer season (May–September), the corresponding trend slopes of Tmax are commonly below 0.37°C decade^{-1}, reaching 0.43°C decade^{-1} only in the south-easternmost areas of Muntenia (Feteşti and Călăraşi). Regionally, daytime summer warming is stronger in Muntenia, especially in the Danube Floodplain areas (e.g., Zimnicea, Giurgiu, Călăraşi, Feteşti).

July and August, the months of maximum water and radiative demand, have the greatest contribution to the overall seasonal warming, especially in the southernmost agricultural areas, where trend slopes exceed 0.50–0.56°C decade^{-1}.

Smoothed time-series of regionally average air temperature anomalies for the two agricultural regions are illustrated in Figure 5, capturing the ongoing warming process and the effects of the recent extreme warm weather. Since 1986–1987, in both cropping regions, there is a visible concentration of positive anomalies with up to eight consecutive summers in a row over 2006–2013. This time-slice is also recognized as particularly warm at European scale. Luterbacher *et al*. (2016) showed that Europe had experienced a marked summer warming (June–August) of about 1.3°C over the 1986–2015 period. Some recent summers (2003, 2010, 2015) proved unusually warm in most European regions, moreover so in the context of the last two millennia. Analysing the European summer temperatures since Roman times, Luterbacher *et al*. (2016) also provided evidence that there were no 30-year periods in either reconstruction to exceed the mean average European summer temperature of the last three decades (1986–2015 CE). Associated to this, the likelihood of occurrence of warm and hot summers has risen significantly in the first part of the 21^{st} century over large parts of the Continent, some scholars considering such a trend as a response to anthropogenic forcing (e.g., Stott *et al*., 2004; Russo *et al*., 2015; Christidis *et al.*, 2015).

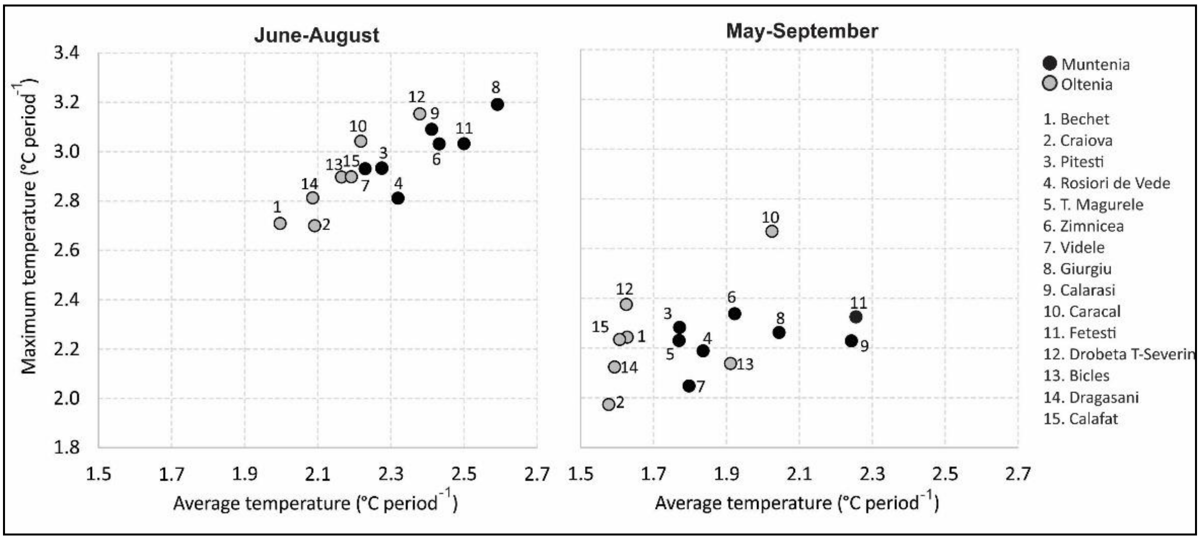


Fig. 4 – Estimated MK slope coefficients (°C/period) of seasonal air temperature trends in Oltenia and Muntenia cropping regions

Despite the clear and significant warming signal over 1961–2013, in southern Romania, the frequency of hot summers (two-to-three standard deviations) is limited to up to 2–4 cases/period (Table 1). It is worthy of note that the summers of 2007 (two standard deviation in all locations) and 2012 (two standard deviation and even three standard deviation in some locations – e.g. Drăgăşani, Craiova, Piteşti, Roşiori de Vede, Giurgiu) were the hottest in both cropping regions, with large positive anomalies relative to the climatological norm of the period, ranging from 2.5 to 2.9°C in 2007 and reaching up to 3.2°C in 2012. The agricultural seasons of 2006–07 and 2011–12 were also the driest in record over the 1961–2013 period, especially in July.

Table 1

Hot and warm summers in the southern agricultural regions of Romania over 1961–2013 and the range of seasonal temperature anomalies

Variables	Hot summers (two-to-three σ)	Warm summers (one σ)
Cases	2012, 2007 (all over the region) 2000, 2003 (in very few locations)	1998–2003, 2008–2010, 2013; 1963, 1988, 1993 (only by Tmax)
Temperature anomalies (Tavg)	2.9–3.2°C	0.9–2.1°C
Temperature anomalies (Tmax)	2.7–4.2°C	0.8–2.2°C

A previous study on changes in summer modes across the Romanian Plain region based on the behaviour of joint temperature-precipitation quantiles (Micu *et al*., 2014), indicated an increasing prevalence of dry-warm summers all over the region, most visible after 1985. Moreover, the frequency and duration of tropical heat-dry spells was found to be on a significant increase, particularly due to the intensification of the daytime tropical heat stress (mostly visible after 1990).

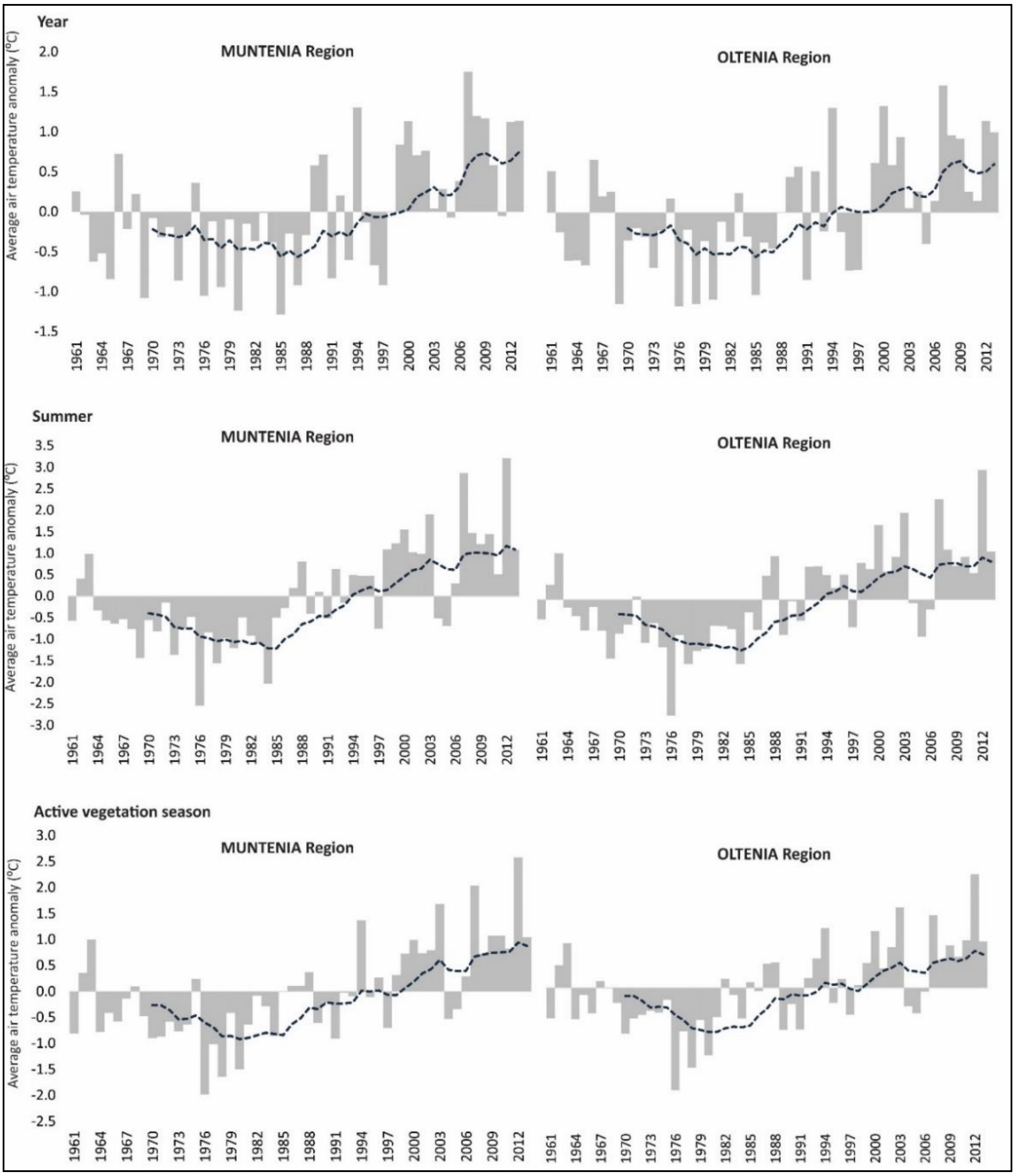


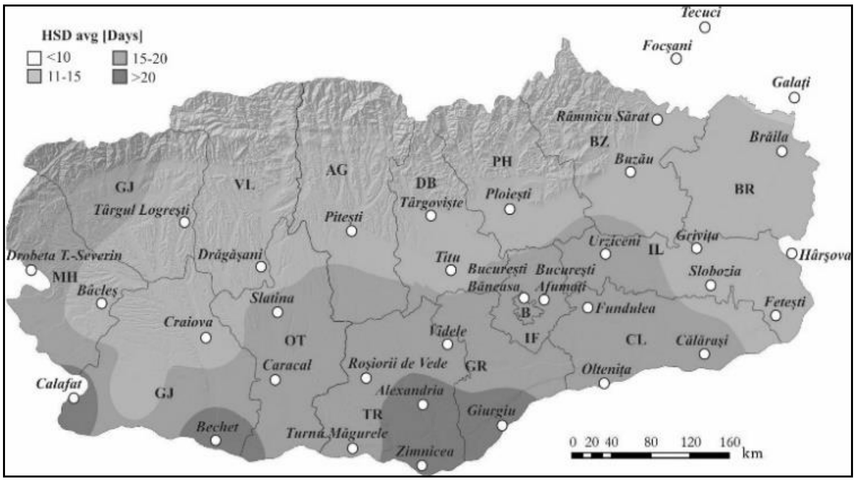
Fig. 5 – Average air temperature anomalies from 1961 to 2013 in the Muntenia and Oltenia cropping regions. Running 10-year regional running averages are shown with the black dashed line

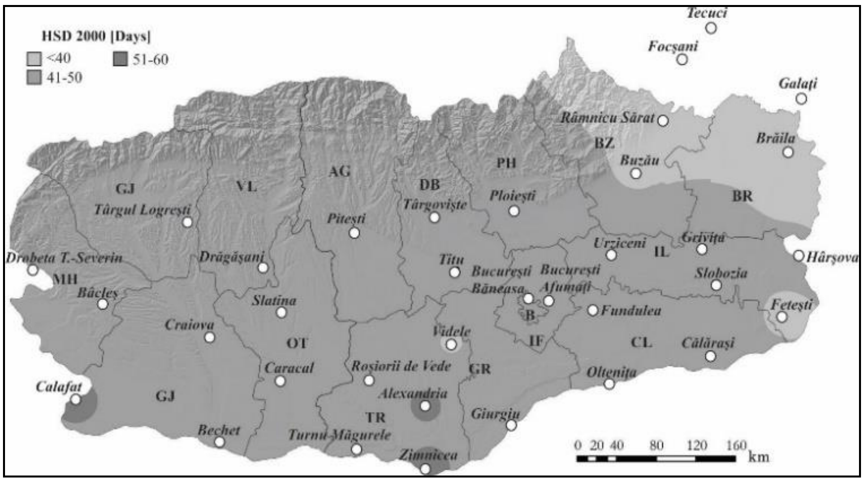
Investigating the mechanisms of controlling hot summer occurrence in Romania, Busuioc *et al*. (2007) showed that the strong summer temperature anomalies in recent years (e.g., 2000, 2003, 2007) were associated to the increased frequency of high-pressure systems at atmospheric heights of 500 hPa. The authors also revealed a good correlation with the positive temperature anomalies at 850 hPa level, especially above the South-East European territory, in terms of both spatial extension and anomalies.

4.2. Agro-climatic heat stress: regional climatology and associated trends over 1961–2013

This section presents an overview on the heat stress characteristics (frequency and duration) and corresponding trends in the cropping Muntenia and Oltenia regions.

Frequency of heat stress days (HSD). The average number of HSD shows a general north-to-south increase across the study region, with a maximum in the central and southernmost floodplain areas (above 21–26 days season^{-1}). These areas emerge as distinct hot-spot areas under the intensified climate warming in the recent decades. By contrast, the northern and northeastern cropping areas are less exposed to heat stress days (below 10–15 days season^{-1}). Regionally, seasonal HSD ranges between 12 days at Fundulea (Muntenia) and 30 days at Calafat (Oltenia). At monthly level, peak HSD frequencies are specific to the July–August interval across both regions with over 7–8 days/month compared to June – the summer month with the lowest load of high-temperature days (3–4 days per month). In terms of intra-seasonal HSD variability, 2000, 2007 and especially, 2012 were the warmest seasons on record across both agricultural regions, with maximum HSD of 50–75 days season^{-1} in Oltenia and over 48–70 days season^{-1} in Muntenia. Figure 6 depicts the spatial distribution patterns of seasonally averaged HSD and maximum HSD in the warmest seasons of the study period across both agricultural regions.





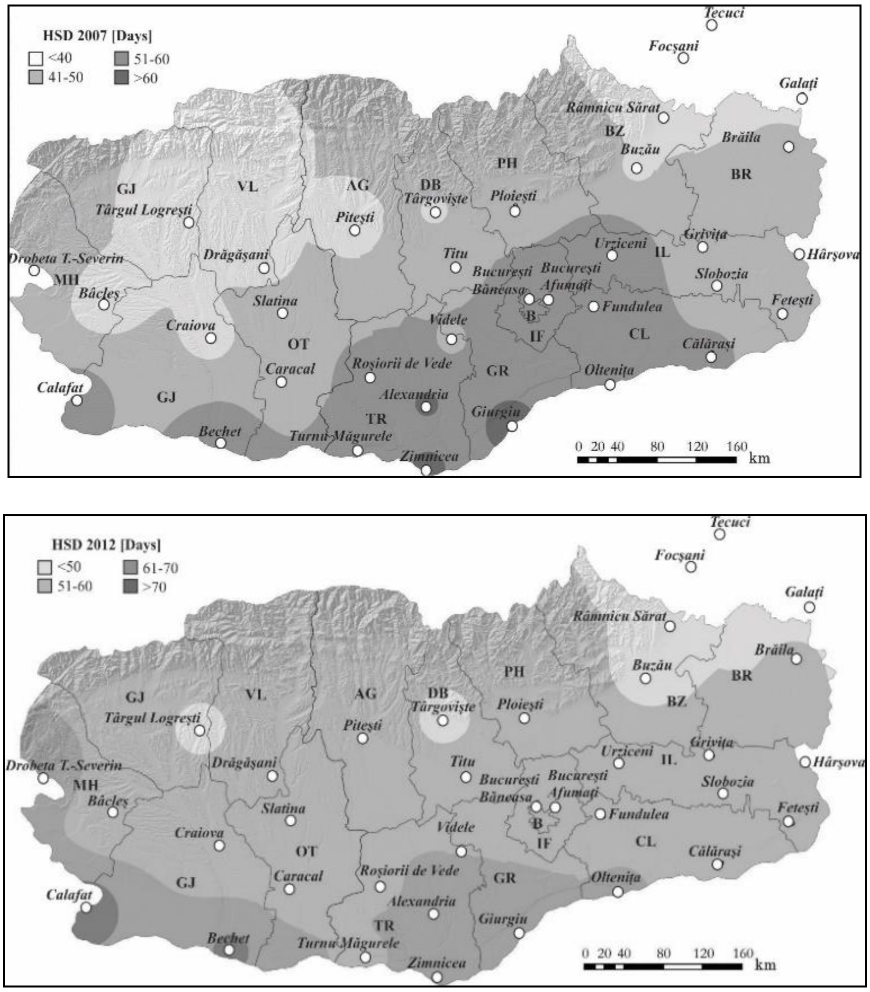


Fig. 6 – Spatial distribution of seasonal HSD in the lowlands of the Muntenia and Oltenia cropping regions: average values (*upper left graph*) and maximum values of 2000, 2007 and 2012 (*the other graphs*)

Trend analysis of seasonal HSD provides clear indication of an increasing heat stress across the two agricultural regions, especially since the mid-1980s ($p<0.05$) (Fig. 7). The change in the seasonal HSD is consistent and highly statistically significant ($p<0.001$) across both regions, with fairly comparable regional magnitudes: +5.1 days decade^{-1} (27 days period^{-1}) in Oltenia and +4.52 days decade^{-1} (24 days period^{-1}) in Muntenia. Regardless the region, the July–August interval shows a great increase in HSD frequency (+9–10 days period^{-1}) relative to the June increase, limited to only 0.75 days decade^{-1} (4 days period^{-1}). In the rest of the months, MK slope coefficients did not reach statistical significant levels.

The seasonal heat stress load through accumulation of temperatures above the critical biological threshold Tx_{32} is well expressed by the *heat stress degree-days* index (HSDD). On average, the seasonal heat stress load is substantial (above 20 degree-days) over most of the Oltenia region, as well as in the central plain and southern floodplain areas of Muntenia (e.g. 29 degree-days at Alexandria, Bechet, Zimnicea) (Fig. 8). The eastern and northern plain areas of Muntenia are less exposed to heat stress accumulation. At monthly level, the July–August interval has the greatest contribution to the overall seasonal heat stress load in both regions (77% in Oltenia and 74% in Muntenia).

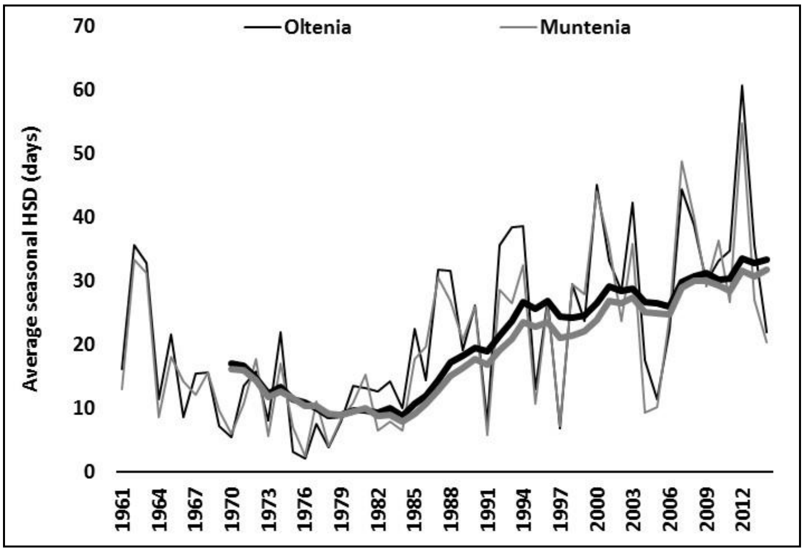
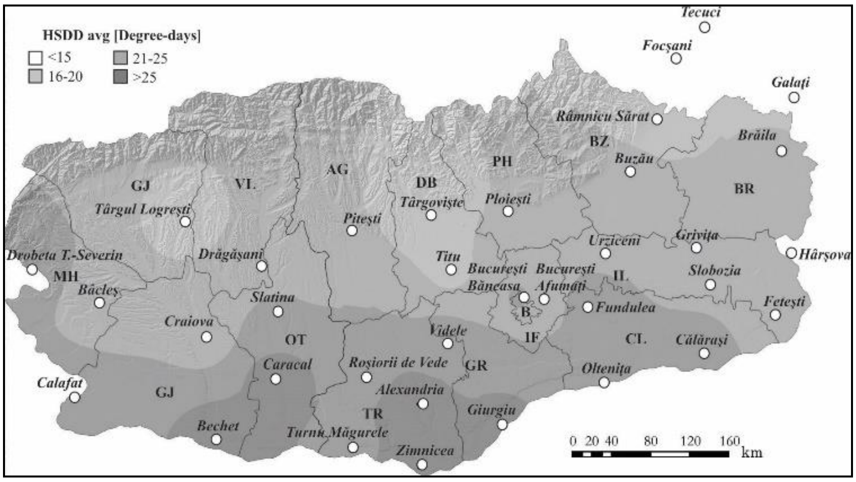
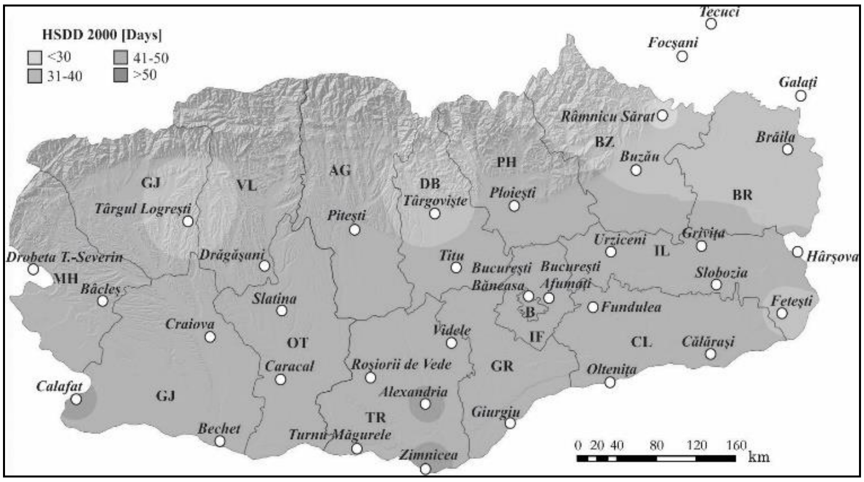


Fig. 7 – Trends in seasonal HSD in the southern agricultural lowlands of Romania: temporal variability with a 10-year low-pass Gaussian filter (solid lines)





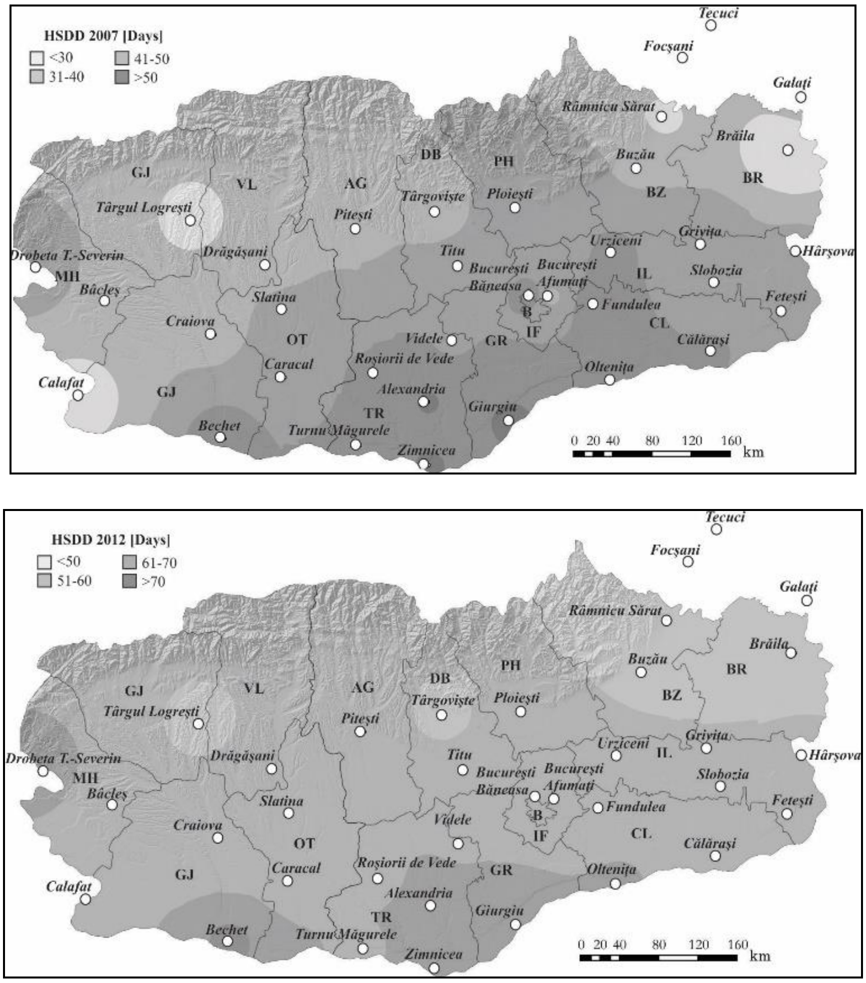


Fig. 8 – Spatial distribution of HSDD in the lowlands of the Muntenia and Oltenia cropping regions: average values (*upper left graph*) and maximum values of 2000, 2007 and 2012 (*the other graphs*)

The number of HSDD increased across both regions, especially after the late 1980s or early 1990s (Fig. 9). This increase is significant ($p<0.05$ to 0.001) at all selected weather stations, with slope coefficients ranging between 3.8 and 5.7 degree-days decade^{-1} (20–30 degree-days period^{-1}) in Oltenia and between 2.5 and 5.8 degree-days decade^{-1} (13–31 degree-days period^{-1}) in Muntenia. Regionally averaged, the change magnitude is slightly higher in Oltenia than in Muntenia (23.2 degree-days period^{-1} and 22.7 degree-days period^{-1}, respectively). Particularly hot seasons, with peak heat stress load, occurred in 2000, but especially in 2007 and 2012, when the HSDD exceeded 50 degree-days over extended areas across the two regions.

Prevailing extreme high temperatures in a row of several days (at least three in this case) were found to be an important impact factor on the quality and quantity of harvests, determining record yield losses and increase production costs in several agricultural regions of Europe, especially in the Central and Southern ones (e.g. UNSDIR, 2003; Ciais *et al*., 2005; Olesen *et al*., 2011). In Romania, the southern plain regions, frequently exposed to persistent hot and dry summer airflows of North-African origins (Barbu *et al*., 2014), are among the most affected by heat spells in summer. The variability of summer maximum temperatures at the weather stations of Oltenia and Muntenia regions shows that the persistent episodes of extreme heat have become a more common feature of the summer climate in the recent years.

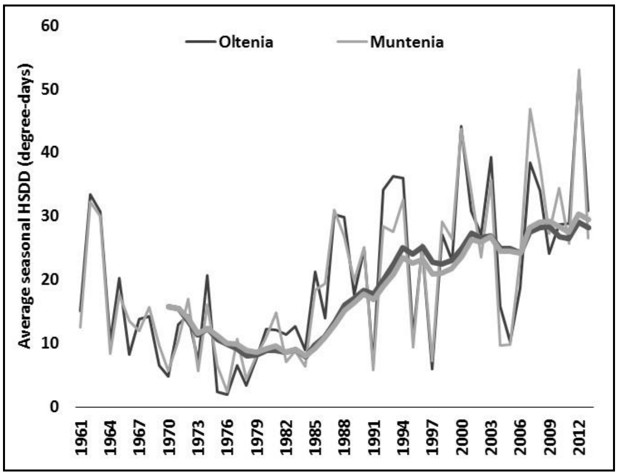


Fig. 9 – Trends in seasonal HSDD in the southern agricultural lowlands of Romania: temporal variability with a 10-year low-pass Gaussian filter (solid lines)

The analysis of heat stress associated to heat spells when the critical biological thermal threshold was systematically reached and/or overpassed at least in three consecutive days shows that the maximum *frequency of heat stress spells* (HSSfr) have a fairly similar value range between the two agricultural regions: 6 cases at Craiova (1990) to 10 cases at Calafat, Caracal and Slatina (2003) in the Oltenia region; 5 cases at Feteşti (1992 and 2000) to 11 cases at Zimnicea (2012). The total HSSfr exceeding 200 cases/period, indicates the emergent "hot-spot areas" across the two agricultural regions, where the agro-climatic heat stress is much recurrent. These areas are located in the Danube floodplain: Bechet (210), Calafat (205), Zimnicea (202). The rest of the areas remain also exposed to heat stress, but the total number of heat stress spell occurrences is limited to less than 150–170 cases/period. In respect to the intra-seasonal variability, there is an evident concentration of high-frequency heat stress spell seasons over the last few decades, especially after 2000 (Fig. 10). Regionally-wide, the warmest seasons in terms of HSSfr were 2000, 2007 and 2012, also known for their prominent soil water deficits and severe droughts.

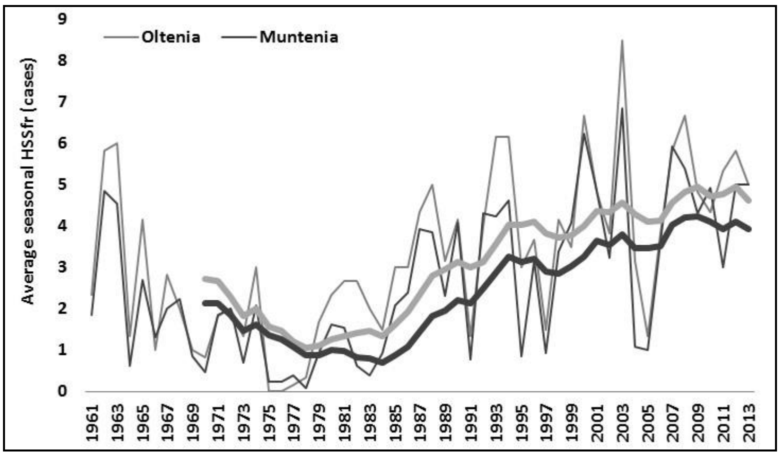


Fig. 10 – The variability of average seasonal frequency of heat stress spells in Oltenia and Muntenia regions. The solid lines depict the observed upwards revealed by a 10-year low-pass Gaussian filter.

The trend analysis of HSSfr has revealed an increasing frequency of heat stress across both regions, slightly more evident in Oltenia (up to 0.75 days decade^{-1} or 4.0 days period^{-1}) than in Muntenia (0.66 days decade^{-1} or 3.5 days period^{-1}) when considering the average regional slopes. At local scale, the MK statistics returned highly significant changes in this heat stress index ($p<0.001…0.05$) in all locations. The areas which experienced large change magnitudes (more than 4.0 days period^{-1}) are Calafat and Zimnicea. Along with other central plain and southern floodplain areas were found highly exposed to large increases in HSSfr (at least 3.5 days period^{-1}): Bechet, Drobeta Turnu-Severin, Caracal, Călăraşi, Giurgiu, Titu and Videle.

The *maximum persistence of each individual heat spell* is a valuable metric of heat stress intensity (*HSSdurmax*). In the study region, the record duration of a heat spell was recorded in the Oltenia region, at Calafat, from July 31 to September 1st, 1992 (33 days), when maximum temperatures ranged between 32.4 and 38.1°C. In Muntenia, the peak HSSdurmax was of 23 days at Giurgiu, during a heat spell which lasted from July 19 to August 10, 2012. In this case, the value range of daily maximum temperatures was more extended (32.0–42.9°C) than in the previous example. Table 2 displays the characteristics of the first five most persistent heat stress spells which affected Oltenia and Muntenia agricultural regions during the extended summer season from 1961 to 2013. All the events were found outstandingly extreme relative to the local and regional climatology of heat spell duration (generally over 20 days, with return periods of over 100–150 years) and daily maximum temperature range during the heat spells (greatly exceeding the critical biological thermal threshold by up to 8–10°C, especially in Muntenia). Throughout the study region, such heat stress events had an occurrence probability below 4% (Fig. 11).

Table 2

Top 5 of the most persistent heat stress spells in the southern agricultural lowlands of Romania (1961–2013)

<table>
<tr><th colspan="4">Oltenia</th><th colspan="4">Muntenia</th></tr>
<tr><th>Location</th><th>HSSdurmax (days)</th><th>Time interval</th><th>Tmax range (°C)</th><th>Location</th><th>HSSdurmax (days)</th><th>Time interval</th><th>Tmax range (°C)</th></tr>
<tr><td>Calafat</td><td>33</td><td>31.07–01.09.1992</td><td>32.4–38.1</td><td>Giurgiu</td><td>23</td><td>19.07–10.08.2012</td><td>32.1–42.9</td></tr>
<tr><td rowspan="3">Bechet</td><td rowspan="3">25</td><td rowspan="3">08.08–01.09.1992</td><td rowspan="3">32.2–37.1</td><td>Bucureşti–Băneasa</td><td>22</td><td>19.07–09.08.2012</td><td>30.0–40.8</td></tr>
<tr><td>Feteşti</td><td>22</td><td>19.07–09.08.2012</td><td>32.2–40.9</td></tr>
<tr><td>Olteniţa</td><td>22</td><td>19.07–09.08.2012</td><td>32.4–42.1</td></tr>
<tr><td rowspan="2">Caracal</td><td rowspan="2">23</td><td rowspan="2">19.07–10.08.2012</td><td rowspan="2">32.0–40.1</td><td>Ploieşti</td><td>21</td><td>20.07–09.08.2012</td><td>32.2–40.2</td></tr>
<tr><td>Titu</td><td>21</td><td>20.07–09.08.2012</td><td>32.0–40.7</td></tr>
<tr><td>Slatina</td><td>22</td><td>19.07–09.08.2012</td><td>32.0–39.7</td><td>Feteşti</td><td>18</td><td>31.07–17.08.2012</td><td>32.3–37.7</td></tr>
<tr><td rowspan="3">Bechet</td><td rowspan="3">19</td><td rowspan="3">13–31.08.2003</td><td rowspan="3">32.3–39.1</td><td>Olteniţa</td><td>17</td><td>31.07–16.08.2010</td><td>32.0–37.7</td></tr>
<tr><td>Giurgiu</td><td>17</td><td>15–31.07.2007</td><td>32.5–42.8</td></tr>
<tr><td>Roşiori de Vede</td><td>17</td><td>15–31.07.2007</td><td>32.0–42.7</td></tr>
</table>

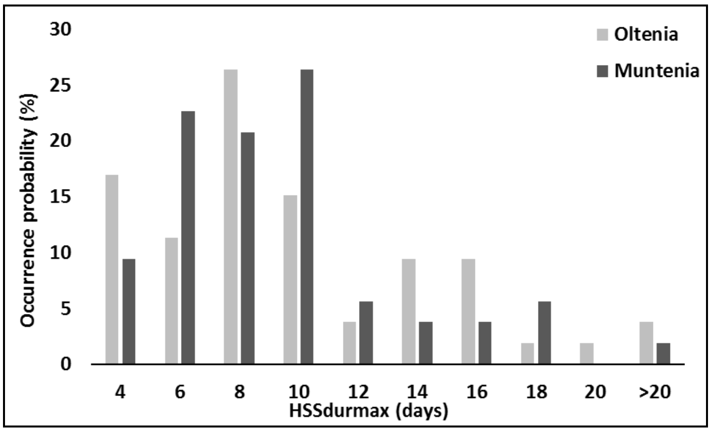


Fig. 11 – Occurrence probability of heat stress spells with different maximum durations in the Oltenia and Muntenia cropping regions.

Complementary to the significant increasing frequency of heat stress spells, southern agricultural lowlands are also under a visible lengthening of the duration of these hot-weather extremes (Fig. 12). This change signal is spatially consistent across the study region and all the trends were found statistically significant (p<0.001…0.05). The maximum length of heat stress spells is on increase by approximately 9 days period^{-1} (1.69 days decade^{-1}) in Oltenia and 8 days period^{-1} (1.51 days decade^{-1}) in Muntenia. At local scale, the largest change magnitudes were estimated for some Danube floodplain areas in Oltenia (over 7 days period^{-1}): Calafat (8.5), Bechet (8.0), Drobeta Turnu-Severin (8.0) and Zimnicea (7.1).

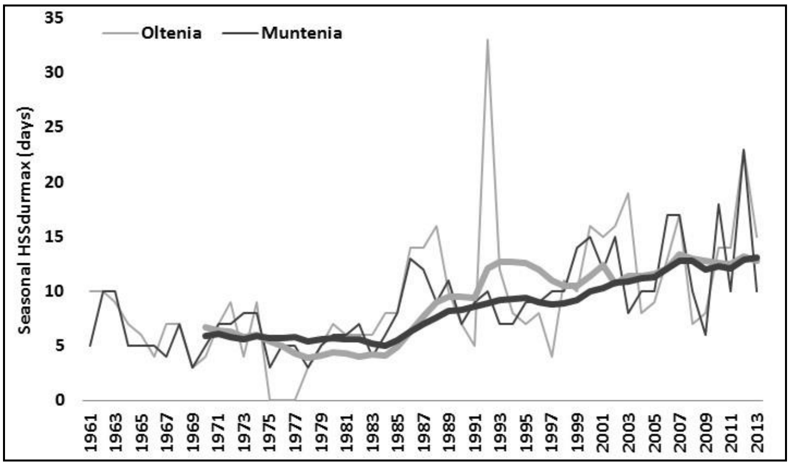


Fig. 12 – Variability of seasonal maximum duration of heat stress spells in Oltenia and Muntenia regions. The solid lines depict the observed upwards revealed by a 10-year low-pass Gaussian filter.

Table 3 summarizes the key findings on the changing of extreme heat conditions at county level, which suggest a gradual intensification of heat stress during the extended summer season in both agricultural regions.

Table 3

MK estimates of significant trends in seasonal agro-climatic heat stress at county level over the 1961–2013 period (statistically significant cases are marked in **bold**)

Agricultural regions	**Counties**	**Statistical significance (*p* values) and/slope coefficients (unit/53 years)**			
		HSD	**HSDD**	**HSSfr**	**HSSdurmax**
Oltenia	Mehedinţi	<**0.001**/+26.50	<**0.001**/+25.5	<**0.001**/+8.0	<**0.001**/+7.95
	Dolj	<**0.001**/+29.51	<**0.05**/+21.0	<**0.001**/+7.9	<**0.001**/+8.11
	Gorj	<**0.001**/+21.20	<**0.001**/+17.7	<**0.05**/+2.65	<**0.05**/+4.18
	Olt	<**0.001**/+26.17	<**0.001**/+26.5	<**0.001**/+5.7	<**0.001**/+5.92
	Vâlcea	<**0.001**/+22.84	<**0.001**/+22.7	<**0.001**/+3.45	<**0.05**/+5.30
Muntenia	Argeş	<**0.001**/+21.06	<**0.001**/+21.06	<**0.001**/+2.04	<**0.001**/+3.93
	Dâmboviţa	<**0.001**/+23.96	<**0.001**/+19.14	<**0.001**/+3.31	<**0.001**/+5.30
	Prahova	<**0.001**/+21.20	<**0.001**/+21.20	<**0.001**/+3.53	<**0.001**/+4.61
	Buzău	<**0.001**/+20.66	<**0.001**/+17.67	<**0.001**/+2.80	<**0.05**/+3.92
	Brăila	<**0.05**/+21.20	<**0.01**/+13.79	<**0.001**/+2.76	<**0.001**/+4.92
	Teleorman	<**0.001**/+28.31	<**0.001**/+27.24	<**0.05**/+3.84	<**0.001**/+5.83
	Giurgiu	<**0.001**/+29.44	<**0.001**/+30.01	<**0.05**/+3.79	<**0.05**/+4.82
	Ilfov	<**0.001**/+26.50	<**0.001**/+25.59	<**0.001**/+3.55	<**0.001**/+5.67
	Bucharest	<**0.001**/+25.34	<**0.001**/+25.01	<**0.05**/+2.94	<**0.05**/+4.58
	Călăraşi	<**0.001**/+25.88	<**0.001**/+24.81	<**0.001**/+3.53	<**0.05**/+5.47
	Ialomiţa	<**0.001**/+23.01	<**0.001**/+20.82	<**0.05**/+2.41	<**0.001**/+5.48

4.3. Heat stress-crop yield relationships: interpretation and attribution

Crop production is affected by numerous factors (social, economic, political and climatic), which are complexly interrelated at different spatial and temporal scales (Entwisle and Stern, 2005). In Romania, the cultivated area and the plant production were strongly influenced by the socio-economic and political conditions of the post-communist period. This influence depended on farming practices (the absence of functional irrigation systems, fewer natural and chemical fertilizers, poor mechanization), inadequate farm structure and agricultural policies. Yields vary greatly from one farm to another, depending on their financial resources, as well as on the quantity and the quality of inputs.

Over 1990–2000, the production of wheat, maize and sun flower crops was on a continuous decrease due to the reduction of cultivated surfaces and technological regression. After 2000, as a result of reducing the fragmentation of agricultural land, the implementation of Common Agricultural Policies (CAP) and the presence of subsidies in agriculture, average yields, especially of maize, sunflower, sugar-beet, potatoes and vegetables have improved.

The changes in the present climate and extreme events (e.g. heat waves, drought, floods, hail) are recognized as a major stressor for crop yields and livestock productivity, especially in rainfed systems (e.g. Rojas-Downing *et al.*, 2017; Iizumi and Ramankutty, 2015; Siebert and Ewert, 2014). In southern Romania, the years of 2000 and 2007 emerged as years of failed crop yields for sunflower and maize and 2002–2003 interval for wheat yields (Table 4). The levels of failed crop yields are considered dramatically low relative to the average crop yields over the 1990–2013 period: 60 to 90% for maize, 58 to 98% for wheat and 37 to 83% for sunflower. Reported decreases in agricultural production, especially in the southern and south-eastern lowlands of Romania, were found associated to significant precipitation deficits, persistent atmospheric and pedological drought and extreme heat recorded in some of the driest and hottest years of the examined period (2000, 2007 and 2012) (*Cod de bune practici agricole în contextul schimbărilor climatice actuale şi previzibile*, 2014). In these extreme years, the gross added value from agriculture was generally negative e.g. –18.4 (2000), –15.3 (2007), –21.6 (2012).

Table 4

Failed crop yields of maize, wheat and sunflower crops in the agricultural lowlands of Oltenia and Muntenia cropping regions over the 1990–2013 interval and the corresponding share of effectively irrigated area per total irrigable area

Agricultural regions	**Counties**	**Lowest crops yields (kg/ha/y)/record year**			**Irrigated area during the low crop yield years (% of the total area equipped for irrigation)**
		Grain maize	**Winter wheat**	**Sunflower**	
Oltenia	Mehedinţi	317.9/2007	605.7/2007	181.1/2007	0.0
	Dolj	346.7/1993	261.4/2002	138.2/2002	N/A
	Gorj	1182.0/2000	1012.0/2002	443.0/2000	0.2
	Olt	515.4/2000	832.2/2007	408.4/2007	4.3
	Vâlcea	1243.0/2012	1181.0/2002	333.0/2000	0.0
Muntenia	Argeş	1366.0/2000	1110.0/2003	503.0/2000	2.9
	Dâmboviţa	1033.0/2000	1106.0/1996	395.0/2000	3.7
	Prahova	1327.0/2000	697.0/2002	651.0/2007	3.4
	Buzău	709.0/2007	51.0/2003	511.0/2002	4.8
	Brăila	1203.1/2007	798.2/2003	923.5/2007	29.5
	Teleorman	303.0/1993	718.9/2003	450.3/2000	N/A
	Giurgiu	353.4/2000	1099.0/2003	211.8/2007	4.1
	Ilfov	541.0/2000	707.0/2003	401.0/2007	1.6
	Călăraşi	695.7/2007	403.5/2003	364.3/2007	13.3
	Ialomiţa	426.6/2007	264.5/2003	425.0/2007	12.6

The great yield losses recorded at county level (over 50% of the average production relative to the previous year), were a consequence of the cumulative adverse effects of extreme heat stress, subsequent intense evapotranspiration and limited water compensations though irrigation, most of them non-operational. The total arable area of the Oltenia and Muntenia regions, which was effectively irrigated had a fraction of only 6.1% to 11.1% in the total surface equipped with irrigation systems. During the years of failed crops, the effective irrigated areas accounted for only up to 2.8% in Oltenia and 7.0% in Muntenia in the total irrigable area (Fig. 13). The lack of efficient irrigations was found responsible for up to 57% (2007) of the low record yields of maize (74% in Oltenia and 71% in Muntenia), wheat (53% in Oltenia and 50% in Muntenia) and sunflower (61% in Oltenia and 62% in Muntenia).

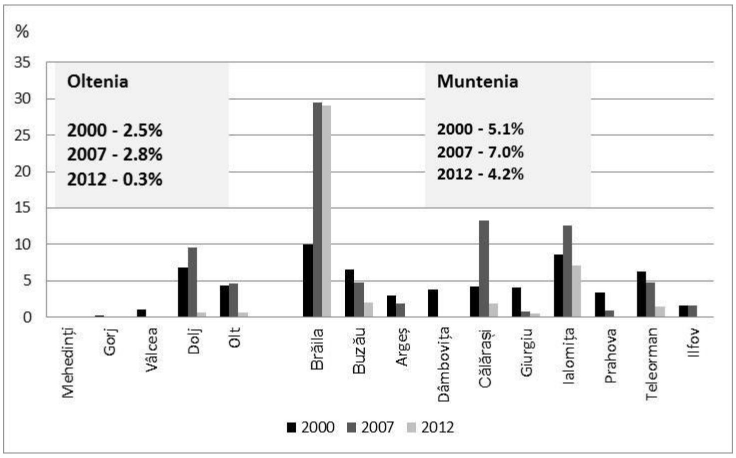


Fig. 13 – Dynamics of effectively irrigated area at county level in the Oltenia and Muntenia cropping regions (% of the total area equipped for irrigation)

In 2000, the most affected crops in the southern agricultural lowlands of Romania were maize and sunflower. Relative to the previous year, maize recorded the most important production losses (over 80%), especially in the counties situated in the western half of the study region: Teleorman 90%, Giurgiu 89%, Olt and Ilfov 87%, Dolj 86%, Mehedinți 82%, Gorj 72%. The losses in sunflower production were also high (over 50–60%), mainly in Olt (66%), Teleorman (61%), Vâlcea (61%), Dolj (60%), Mehedinți (56%), Dâmbovița and Giurgiu counties (53%). Losses in wheat production were lower, of up to 23% only in some counties located in the north-eastern part of the study region (Brăila, Buzău, Ialomița) (Fig. 14).

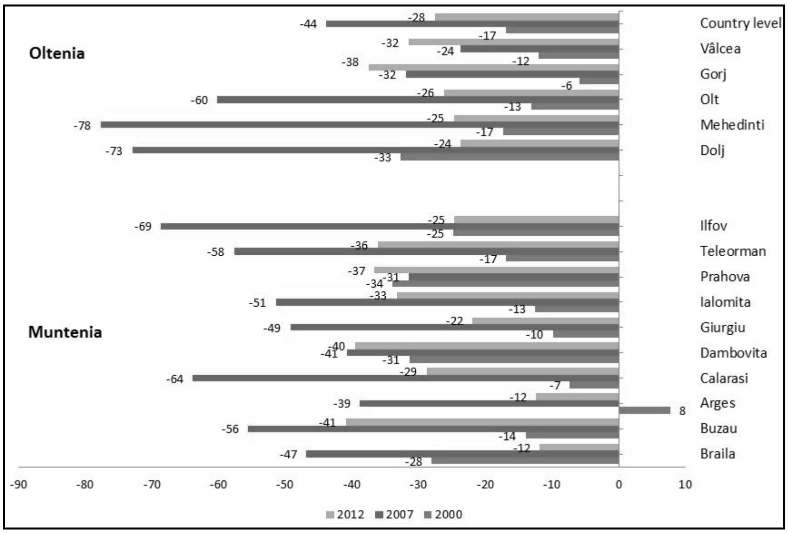


Fig. 14 – Wheat yield losses (% reduction) in the southern agricultural lowlands of Romania, in heat stress representative years: for 2000 versus 1999, 2007 *versus* 2006 and 2012 versus 2011

The heat stress and drought of **2007** had a great impact mainly on sunflower and maize production. Peak losses in maize crop production (up to 90% relative to the previous year) were recorded in Oltenia, with very low yields in Mehedinţi (318 kg/ha), Olt (531 kg/ha) and Dolj counties (549 kg/ha). Muntenia region was also significantly affected, Ialomița (425 kg/ha) and Giurgiu (539 kg/ha) counties facing the most important losses in maize production (80–87% relative to the earlier year). Generally, in that year, the counties lying in the eastern half of the study region registered the steepest declines in the average yields for all the three crops (Fig. 15).

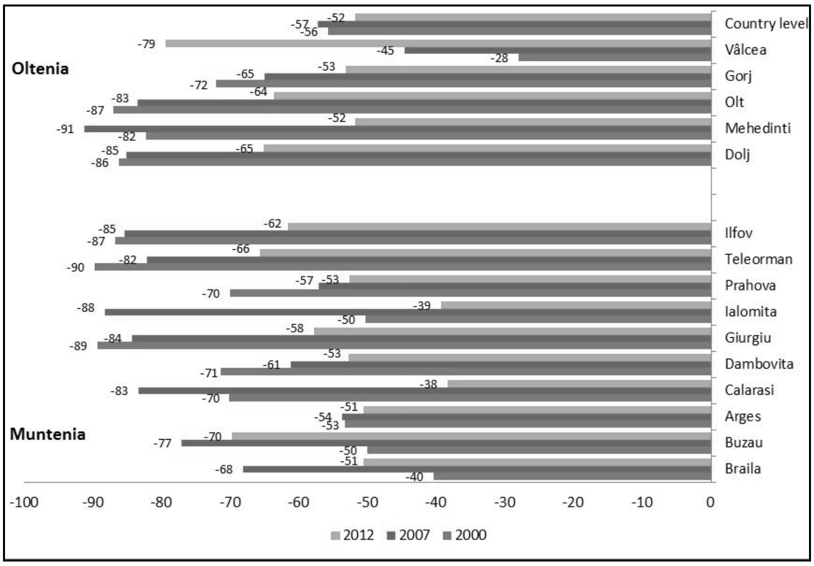


Fig. 15 – Maize yield losses (% reduction) in the southern agricultural lowlands of Romania, in heat stress representative years: for 2000 versus 1999, 2007 *versus* 2006 and 2012 versus 2011

In **2012**, most counties of the Romanian Plain, except for Călăraşi and Ialomița, recorded 50% lower average maize productions compared to 2011 (exceptionally, the decline in Buzău exceeded 70%). For the rest of the crops, yield losses were limited to 12–40% for wheat and sunflower (Fig. 16).

Variations in the annual production of wheat, maize and sun flower crops were investigated in relation to heat stress characteristics during the extended summer season (May–September) over 1990–2013, in order to decompose the detrimental effects of extreme heat alone. Table 5 presents the summarized statistics of the correlation analysis extended to regional averages of the observed crop yields and heat stress condition metrics at county level in the Oltenia and Muntenia cropping regions.

Maize, the crop with the largest yield area across southern Romania, showed the greatest sensitivity to extreme summer heat, with regionally-wide statistically significant and negative relationships. Heat stress days (HSD) and heat stress degree-days (HSDD) were found as best predictors of changes in maize production across both regions, in the range of 36 up to 61% (Table 5). The maximum duration of heat stress spells (HSSdurmax) was found to explain only 24 up to 36% of the decrease in annual maize yield and only sparsely, in Mehedinţi, Dolj, Teleorman and Călăraşi counties.

For the other crops, the correlation coefficients were limited in describing the association between crop production and heat stress indices in most counties and no discernible patterns were found in the behaviour of these variables in a cause-effect relationship. Heat stress is globally considered as one of the most important limiting factors of wheat yields, except for some regions (e.g. China, India) where water stress was found to be a more important predictor (Zampieri *et al*., 2017). In Muntenia and Oltenia, heat stress is not a prominent factor to explain the variability of winter wheat yields. Exceptionally, regression analysis revealed that it is only persistent episodes of heat stress spells (HSSdurmax) that could explain 17% to 24% of crop yield anomalies in a few distinct counties such as: Mehedinţi, Dolj, Teleorman and Călăraşi. The weak predictive role of extreme high temperatures could be generally justified by the early ripening-harvesting stage of this crop, which takes place during the July–August interval when heat in southern Romania is highly recurrent and persistent.

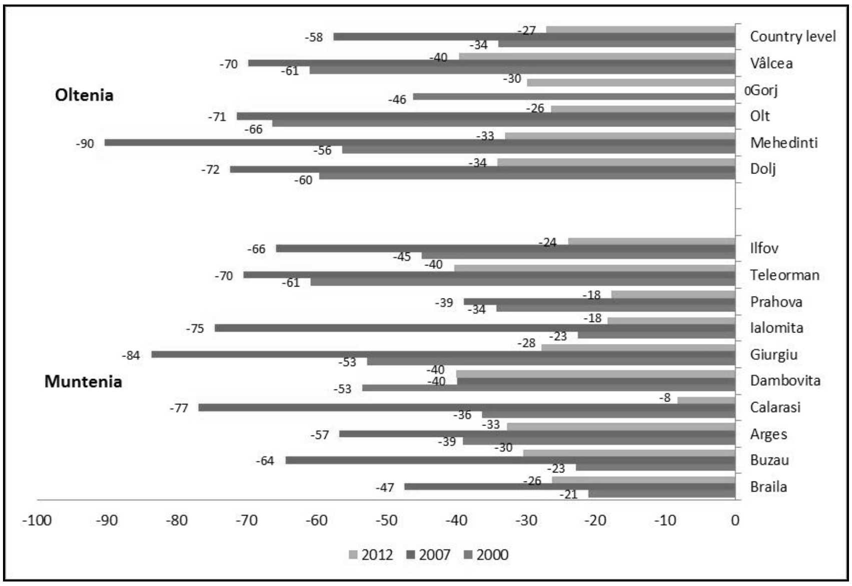


Fig. 16 – Sunflower yield losses (% reduction) in the southern agricultural lowlands of Romania, in heat stress representative years: for 2000 *versus* 1999, 2007 versus 2006 and 2012 versus 2011

In the case of sunflower, the production was found responsive to seasonal heat stress load (HSDD) only in Dolj and Buzău counties (16–18%), as well as to the frequency of heat stress spells, but only in Olt and Dâmboviţa counties (14–22%). Persistent heat stress spells (HSSdurmax), which in southern Romania lasted at least 12 up to 22 consecutive days, were identified as best predictor of sunflower yield variations (13–26%) in five out of the total 15 counties for which the regression analysis was conducted (Mehedinţi, Olt, Dâmboviţa, Buzău and Ilfov).

Table 5 shows that extreme daytime temperatures had a detrimental effect on the final crop yields in most counties of the two agricultural regions. The correlations are mostly negative, indicating a general decrease in crop production in response to the increasing seasonal heat stress, particularly with the contribution of the heat stress representative years (2000, 2007 and 2012), when irrigations were not used at full capacity.

Filtering the data to exclude the effects of potential outliers from the regression analysis (namely, the influence of the very warm and droughty summers of 2000, 2007 and 2012), some relevant changes in the heat stress-crop yield relationship were observed across both regions. The heat stress-maize yield relationship maintained its direction (negative) for all crops and for each county of the two regions, but decreased in strength and significance. These changes were particularly obvious for maize crops:

– The average loss in strength for both regions were 12 to 20%. Greatest decreases were recorded for the HSDD (up to 34–35% in Muntenia – Buzău and Argeş counties; up to 41% in Oltenia – Vâlcea County) and HSD predictors (up to 27–28% in Dâmboviţa, Teleorman and Vâlcea counties). For the other predictors, decreases in strength were limited in general to 20%, with the exception of

Dâmboviţa and Prahova counties for HSSfr (29–32%) and of Vâlcea, Olt, Gorj, Argeş, Dâmboviţa and Călăraşi for HSSdurmax (21–31%). Generally, the greater the decrease in the strength of heat stress-maize yield relationship, the greater the contribution of the heat stress to the crop yield losses during the hot and dry summers of 2000, 2007 and 2012.

Table 5

Regression analysis results on the relationships between annual crop yields and heat stress indices during the extended summer season at NUTS3 level for the Oltenia and Muntenia cropping regions (ns – not significant)

Crop	**Counties**	**HSD (days)**		**HSDD (days)**		**HSSfr (cases)**		**HSSdurmax (days)**	
		R^2	**pvalue**	**R^2**	**pvalue**	**R^2**	**pvalue**	**R^2**	**pvalue**
Wheat	Mehedinţi	.10	ns	.10	ns	.01	ns	**.17**	**<0.05**
	Dolj	.09	ns	.13	ns	.01	ns	**.17**	**<0.05**
	Olt	.10	ns	.10	ns	.11	ns	.07	ns
	Vâlcea	.02	ns	.09	ns	.02	ns	.06	ns
	Gorj	.02	ns	.03	ns	.02	ns	.03	ns
	Argeş	.02	ns	.02	ns	.02	ns	.03	ns
	Dâmboviţa	.04	ns	.09	ns	.03	ns	.06	ns
	Prahova	.02	ns	.07	ns	.02	ns	.02	ns
	Buzău	.02	ns	.01	ns	.01	ns	.03	ns
	Teleorman	.11	ns	.14	ns	.02	ns	**.20**	**<0.05**
	Brăila	.12	ns	**.31**	**<0.001**	**.15**	**<0.05**	.02	ns
	Giurgiu	.02	ns	.03	ns	.05	ns	.02	ns
	Ilfov	.03	ns	.03	ns	.02	ns	.01	ns
	Călăraşi	.13	ns	.13	ns	.04	ns	**.24**	**<0.05**
	Ialomiţa	.09	ns	.07	ns	.02	ns	.02	ns
Maize	Mehedinţi	**.36**	**<0.001**	**.36**	**<0.001**	**.18**	**<0.05**	**.37**	**<0.001**
	Dolj	**.33**	**<0.001**	**.45**	**<0.001**	**.27**	**<0.01**	**.24**	**<0.05**
	Olt	**.41**	**<0.001**	**.46**	**<0.001**	**.32**	**<0.001**	**.28**	**<0.001**
	Vâlcea	**.40**	**<0.001**	**.52**	**<0.001**	**.25**	**<0.05**	**.30**	**<0.01**
	Gorj	**.47**	**<0.001**	**.55**	**<0.001**	**.45**	**<0.001**	**.39**	**<0.001**
	Argeş	**.32**	**<0.001**	**.45**	**<0.001**	**.43**	**<0.001**	**.36**	**<0.001**
	Dâmboviţa	**.39**	**<0.001**	**.39**	**<0.001**	**.42**	**<0.001**	**.25**	**<0.05**
	Prahova	**.54**	**<0.001**	**.40**	**<0.001**	**.44**	**<0.001**	**.39**	**<0.001**
	Buzău	**.30**	**<0.001**	**.48**	**<0.001**	**.23**	**<0.05**	.14	ns
	Teleorman	**.46**	**<0.001**	**.36**	**<0.001**	**.33**	**<0.001**	.14	ns
	Brăila	**.37**	**<0.001**	**.43**	**<0.001**	**.37**	**<0.01**	**.17**	**<0.05**
	Giurgiu	**.19**	**<0.001**	**.19**	**<0.05**	.09	ns	.02	ns
	Ilfov	**.56**	**<0.001**	**.61**	**<0.001**	**.30**	**<0.01**	**.46**	**<0.001**
	Călăraşi	**.47**	**<0.001**	**.47**	**<0.001**	**.31**	**<0.001**	**.27**	**<0.05**
	Ialomiţa	**.44**	**<0.001**	**.39**	**<0.001**	.02	ns	.02	ns
Sunflower	Mehedinţi	.09	ns	.09	ns	.02	ns	**.14**	**<0.05**
	Dolj	.05	ns	**.18**	**<0.05**	.04	ns	.09	ns
	Olt	.14	ns	.12	ns	**.14**	**<0.05**	**.13**	**<0.05**
	Vâlcea	.09	ns	.09	ns	.08	ns	.09	ns
	Gorj	.08	ns	.06	ns	.02	ns	.05	ns
	Argeş	.02	ns	.02	ns	.09	ns	.07	ns
	Dâmboviţa	.07	ns	.10	ns	**.22**	**<0.05**	**.26**	**<0.05**
	Prahova	.07	ns	.07	ns	.12	ns	.02	ns
	Buzău	.13	ns	**.16**	**<0.05**	.07	ns	**.22**	**<0.05**
	Teleorman	.08	ns	.11	ns	.08	ns	.03	ns
	Brăila	.03	ns	.09	ns	.04	ns	.01	ns
	Giurgiu	.02	ns	.02	ns	.01	ns	.01	ns
	Ilfov	.05	ns	.05	ns	.03	ns	**.15**	**<0.05**
	Călăraşi	.07	ns	.07	ns	.04	ns	.06	ns
	Ialomiţa	.06	ns	.05	ns	.01	ns	.02	ns

– Heat stress-maize yield relationship showed most widespread decreases in statistical significance (10 out of the total 15 counties), associated to the predictor referring to the persistent heat stress spells (HSSdurmax). The results of the regression analysis after filtering procedure suggest that this heat stress predictor could produce little detrimental effects on maize yields in Dâmboviţa, Buzău, Brăila, Teleorman and Ialomiţa. An opposite situation was found for the HSDD predictor, for which there were only few counties showing losses in the statistical significance of heat stress-maize crop response (Argeş, Dâmboviţa and Giurgiu).

5. CONCLUSIONS

We have analysed the changes in heat stress characteristics (frequency and duration) in the warming seasonal climate of 1961–2013 and their effects on the annual yield anomalies of three major crops recorded between 1990 and 2013 in the Oltenia and Muntenia cropping regions. Both regions are under a clear and statistically significant summer warming, which was estimated faster and stronger by maximum temperature values (daytime) at rates of over 2.5°C/53 years. The most affected cropping region is Muntenia, especially in some areas in the Danube Floodplain (e.g. Zimnicea, Giurgiu, Călăraşi and Feteşti). July and August were found the largest contributors to seasonal warming by their maximum temperature values (2.7–3.0°C/53 years). The frequency of hot summers (two-to-three standard deviations) in southern Romania amounted 2–4 cases/period: 2012 and 2007 (throughout the study region); and 2000 and 2003 (in some areas). These summers were also among the driest in record in both regions.

In the recent years, persistent episodes of extreme heat have become a common weather feature in summer. The trends analysis of heat stress characteristics over 1961–2013 shows an increase in the frequency and duration of extreme summer heat in both cropping regions, mainly in their southernmost areas. All trends are highly statistically significant ($p<0.01$–0.001). The seasons of significant heat stress by means of all four selected indices, were 2000, 2007 and 2012, also known for their prominent soil water deficits and severe droughts. At monthly scale, increasing trend values were particularly large in July and August (the months of high heat stress sensitivity for maize and sunflower and of peak water demand for maize), threatening the yields of crops with harvesting in fall (maize and sunflower). Here are the counties where the estimated slopes of heat stress trends are in general the largest: Dolj, Olt, Teleorman and Giurgiu.

This analysis shows different and spatially variable crop yield sensitivities to extreme heat. Fitting the statistical relationships between crop production and the four selected heat stress metrics to decompose the detrimental effects of extreme heat, we aimed to estimate the strength and direction of the corresponding relationships at county scale (NUTS3). The main conclusions are summarized below:

– There is a good correspondence between the negative crop yield anomalies and the warm (and dry) character of the extended summer season (May–September), highly visible during the hot and dry years of 2000, 2007 and 2012. The counties which experienced substantial crop yield failures during those years were Mehedinţi, Dolj, Gorj, Olt, Teleorman and Giurgiu;

– *Summer heat stress* is a key yield *limiting factor* in the *crop production of maize* in most counties. Selected heat stress indices allowed explaining 17 to 55% (on average) of the annual variability of yields at county level. Among heat stress indices, HSD and HSDD were found as best predictors (19 up to 61%), followed by HSSfr (18–45%), while HSSdurmax was found to explain 24 up to 36% and only sparsely (in the Mehedinţi, Dolj, Teleorman and Călăraşi);

– During the hot and droughty summers of 2000, 2007 and 2012, the detrimental effect of heat stress on crop yields was worsened by the lack of efficient water compensations through irrigations (generally below 5% in Oltenia and 7% in Muntenia). Rehabilitation of the existing irrigation infrastructure emerges as an important adaptation measure to reduce the vulnerabilities and future impacts of heat stress on national food security;

– There is a strong (good-to-excellent in the case of maize and fair-to-good for sun flower and wheat) and negative relationship between the annual production and seasonal the heat stress over 1990–2013;

– Heat stress could be considered an important predictor of crop yield failures, especially for maize crops. After filtering the data to exclude the influence of the very warm and droughty summers of 2000, 2007 and 2012, the heat stress-maize yield relationship maintained its direction (negative) for all crops and in all counties of the two regions, but decreased in its strength and significance. These changes were particularly obvious for maize crops, mostly by means of HSD and HSDD heat stress predictors. HSSdurmax factor was found to produce the weakest effects on maize yields, especially in Dâmboviţa, Buzău, Brăila, Teleorman and Ialomiţa counties;

– High daytime temperatures showed less detrimental influences on the yields of summer harvesting crops (winter wheat) and good high temperature and drought resistance (sunflower).

Our results confirm previous findings of regional disparities in climate change impacts on crop production. However, as temperature thresholds are well-defined and distinct for each crop plant, further investigations on the mechanisms and processes involved in the key development stages of crops, which could influence statistical correlations between extreme heat and the final crop yield, remain as a perspective work. Further analyses at finer spatial and temporal scales, using longer time-series of crop production and climate data, would be also beneficial to improving our current results, for better distinguishing and decoupling climate change effects from the broad socio-economic context within which the crop yield gains and losses evolved.

Acknowledgements. This study was conducted under the Romanian Academy fundamental research project on the *Climate hazards in the Romanian Plain Region*.

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Received september 20, 2017