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Drought risk in Moldova under global warming and possible crop adaptation strategies

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Abstract

This study analyzes the relationship between drought processes and crop yields in Moldova, together with the effects of possible future climate change on crops. The severity of drought is analyzed over time in Moldova using the Standard Precipitation Index, the Standardized Precipitation Evapotranspiration Index, and their relationship with crop yields. In addition, rainfall variability and its relationship with crop yields are examined using spectral analysis and squared wavelet coherence. Observed station data (1950–2020 and 1850–2020), ERA5 reanalysis data (1950–2020), and climate model simulations (period 1970–2100) are used. Crop yield data (maize, sunflower,

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grape), data from experimental plots (wheat), and the Enhanced Vegetation Index from Moderate Resolution Imaging Spectroradiometer satellites were also used. Results show that although the severity of meteorological droughts has decreased in the last 170 years, the impact of precipitation deficits on different crop yields has increased, concurrent with a sharp increase in temperature, which negatively affected crop yields. Annual crops are now more vulnerable to natural rainfall variability and, in years characterized by rainfall deficits, the possibility of reductions in crop yield increases due to sharp increases in temperature. Projections reveal a pessimistic outlook in the absence of adaptation, highlighting the urgency of developing new agricultural management strategies.

KEYWORDS
climate change, crop yields, drought, global warming, Republic of Moldova

INTRODUCTION

The sensitivity of food production to climate variability and change is a critical issue,[1–3] with several studies raising concern for crop yield failures in response to drought.[4–7] Crop yields are commonly affected by soil water availability,[7–9] which is ultimately determined by precipitation and evapotranspiration,[10,11] but also by the variability of other meteorological variables that affect photosynthesis (e.g., radiation, temperature) and plant physiology (vapor pressure deficit [VPD] and temperature).[12–15]

The influence of temperature on plant physiology is complex. On the one hand, higher temperatures can promote more photosynthesis, which may increase the biophysical capacity of crops and overall crop yields. On the other hand, temperature increase drives enhanced VPD, which regulates leaf stomatal closure and reduces photosynthesis and carbon uptake.[16–18] Moreover, higher temperature is also a driver of atmospheric evaporative demand, which under low soil moisture increases plant water stress, potentially triggering plant mortality under hydraulic failure.[19–21] Finally, in situations of extreme heat, leaf tissues are damaged, with associated hydraulic consequences.[22]

There is a general consensus that, as a consequence of these different mechanisms, temperature rise is accelerating the damage associated with low water availability[23,24] and that projected future temperature increases will enhance negative impacts on crop yields.[25–28] Although fertilizing CO_2 effects could counteract the negative effects of climate change on crops,[29–31] this is still a subject of an ongoing scientific debate, with the literature supporting a secondary role of this factor in comparison to the primary importance of soil moisture deficits and increased VPD and heat.[32–35]

The identification of climate change impacts on crop yields is not an easy task as there are several technological and socioeconomic aspects that play a fundamental role in mitigating or amplifying the effects. Nevertheless, efficient management and identification of successful adaptation options require guidance on possible crop yield decreases or failures caused by climate change. This is particularly critical in world areas where agriculture plays an important role in the economy and society. This is the case in large regions of central and South America, Africa, and Asia, where agriculture is the main economic activity. There are also regions of Europe that are predominantly agrarian and highly vulnerable to a decline in crop potential as a consequence of climate change. In the Republic of Moldova, located in Eastern Europe, more than 80% of land is covered by nonirrigated crops (Figure 1) and agriculture employs more than 30% of the population. This region has been frequently affected by droughts,[36] with large negative consequences on crop yields.[36,37] Drought in 2020 was particularly serious, with crop yields decreasing by 30% on average, causing a reduction of 20% in employment in the sector and a decline of 8% in gross domestic product (GDP).[38]

Given such vulnerability to droughts in Moldova, it is necessary to investigate the climate mechanisms that have caused this strong decline in crop yields in recent years. It is also necessary to assess possible future climate scenarios that may drive changes in crop yields to identify potential crop management strategies that might limit future declines in crop yields. In this study, we analyze the evolution of crop yields in Moldova over the last 170 years and assess climate drivers and possible future drought scenarios.

Study area

Moldova experiences a temperate continental climate, characterized by hot summers and mild to cold winters. The average temperatures vary significantly across the seasons, with summer temperatures ranging from 20°C to 25°C, often peaking above 30°C during heatwaves.[39,40] Winters are generally cold, with average temperatures ranging between −4°C and −1°C in January, the coldest month. Snowfall is common, especially in the northern regions, but it is typically light and does not linger for long periods.

Precipitation in Moldova averages about 400–600 millimeters annually and is characterized by strong interannual variability.[36] The

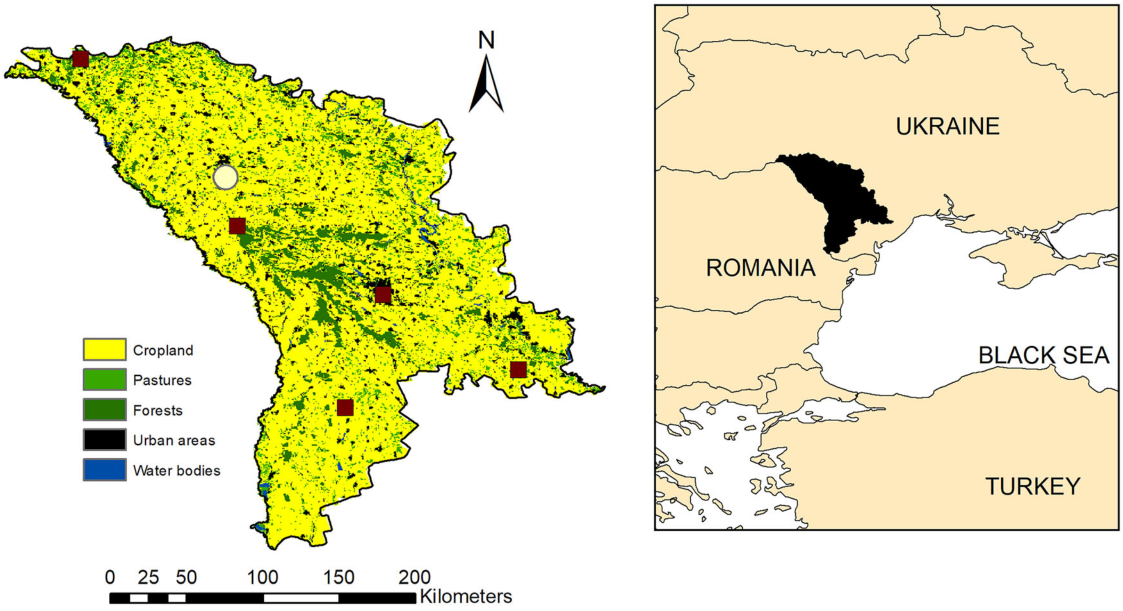

FIGURE 1 Land cover characteristics of Moldova. The location of the meteorological stations used in this study is shown by squares. The white circle shows the location of the experimental fields of the Selectia Research Institute for Crop Research.

wettest months are typically June and July, coinciding with the summer season, when thunderstorms are frequent. Winter and early spring are generally drier. The southern regions tend to receive less precipitation compared to the north.[40]

Overall, the climate of Moldova supports a diverse range of agricultural activities, including viticulture and cereals.[41] The agricultural sector has great importance in the economy of Moldova, playing a crucial role in both employment and exports.[38] The country benefits from fertile soil, which supports the cultivation of a variety of crops, including cereals, fruits, vegetables, and notably, grapes for wine production.[42] Viticulture and winemaking are particularly significant, with Moldova being one of the world's top wine producers and exporters. Agriculture accounts for a substantial portion of the GDP and employs a significant percentage of the workforce, and since it is affected by the enormous challenges related to climate-related risks,[39,43] ongoing reforms and investments aim to modernize agricultural practices, enhance productivity, and ensure sustainable growth.

DATA AND METHODS

Data

We use data from five meteorological stations in Moldova (Figure 1) provided by the Moldovan meteorological service. The data contain monthly precipitation and maximum and minimum temperature with no gaps. Four station records contain data from 1950 to 2020, with the Chisinau station data containing precipitation data since 1850. The data were quality controlled and homogeneity tested using meteorological stations available from Ukraine and Romania through the Global Historical Climatology Network.[44,45] Homogeneity testing was based on HOMER (Homogenization in R),[46] and no temporal inhomogeneities were found, so corrections to the raw data were not needed. Regional series were calculated for precipitation and temperature for the whole Republic of Moldova by averaging the station data. Data for solar radiation and relative humidity were also used to calculate atmospheric evaporative demand according to the FAO-56 Penman-Monteith equation.[47] Data for these variables were obtained from the ERA5 Reanalysis.[48]

National annual crop yield data for maize, sunflower, and grapes from 1950 to 2020 were obtained from the Ministry of Agriculture of the Republic of Moldova. They reflect important long-term fluctuations that may be related to socioeconomic issues (Figure S1). For example, crop yields increased from the 1950s to 1990 but the creation of the Republic of Moldova as an independent country was followed by an economic collapse, with a decrease in yields of the three crops. Since 2000, crop yields have increased again. In addition to these long-term trends, there are important interannual variations, which can be mostly related to climate, particularly drought variability.[9,37] We removed the long-term trends associated with external nonclimate factors. Given the temporal complexity of the fluctuations, it was not possible to apply a linear model for this purpose. Instead, we used a simple approach to obtain anomalies by calculating the difference between annual yields and the average yields of the current year and the previous 5 years. This approach removes the long-term trend and allows a homogeneous series of interannual yield anomalies to be obtained that may be related to climate variability.

Time series of vegetation indices from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellites were used as complementary metrics of crop yields. Vegetation activity was quantified by means of the two-band Enhanced Vegetation Index (EVI2) from the MODIS satellite sensor for the period 2000–2020. EVI2 is more robust than the three-band EVI, which is sensitive to atmospheric disturbances in the blue band. While EVI2 is primarily an indicator of photosynthetic activity, it can also be seen as a proxy of other vegetation parameters (e.g., leaf foliage variations, vegetation coverage, vegetation primary productivity, and carbon uptake).[49] The MODIS reflectance data used for calculating EVI2 were derived from the MCD43A4 product, retrieved from the NASA repository (https://modis.gsfc.nasa.gov/data/dataprod/mod13.php) at a grid interval of 500 m and averaged to a temporal frequency of 16 days. Curve fitting was applied to the 16-day composite data to extract comparable monthly values using the TIMESAT software package.[50]

We also used daily 500 hPa geopotential heights (Z500) in order to identify the atmospheric patterns that cause dry and warm conditions in Moldova, with a particular focus on the 13 months between July 2019 and August 2020. For this purpose, we used the ERA5 reanalysis during the 1950–2020 period.

Climate model simulations for the RCP8.5 scenario were obtained from the Euro-CORDEX project[51–53] for the whole of Moldova. We used a high-emission scenario for the future in order to determine the drought projections for the worse possible situation. We retrieved the series of monthly precipitation and maximum and minimum temperature from 43 regional climate model simulations (RCMs; see Table S1) from 1970 to 2100. Given the relatively small size of the Republic of Moldova (33,844 km^2) and the homogeneity of landscape and climate in the country, average series over the whole country were used to assess drought projections in the region.

Finally, wheat crop yields from the experimental plots of the Selectia Research Institute for Crop Research located in Bălți were available for the period 1980–2020. The experiments include one crop rotation where winter wheat is sown after two different predecessors, an early- and a late-harvested one. A mixture of winter rye and winter vetch for green mass (for feeding cattle) was used as the early-harvested predecessors, and corn for grain was used as the late-harvested predecessor.[54]

METHODS

We quantified drought severity by means of two drought indices, the Standardized Precipitation Index (SPI),[55] which is based on monthly precipitation anomalies, and the Standardized Precipitation Evapotranspiration Index (SPEI),[56,57] which is based on the difference of precipitation and the atmospheric evaporative demand. The SPI was calculated for the entire 1851–2020 period for the meteorological station at Chisinau, but also for the period 1950–2020 for the other meteorological stations and also for the regionally averaged precipitation series. SPEI was also calculated from the averaged precipitation series and atmospheric evaporative demand for the period 1950–2020. We used two methods to calculate the atmospheric evaporative demand using the ERA-5 data: the FAO-56 Penman-Monteith equation mentioned above and the Hargreaves—Samani equation,[58] which is based only on maximum and minimum temperature. As observed in other regions of Europe,[59] both methods provide similar temporal variability and trends (Figure S2), and considering that the main driver of global trends in atmospheric evaporative demand is the temperature increase,[60] we decided to calculate the atmospheric evaporative demand using the Hargreaves and Samani method for the period of observations and for the future projections since station data for wind speed, relative humidity, and solar radiation were not available and the model simulations from RCMs only contain data of maximum and minimum temperature. SPI and SPEI were also calculated for regional series of precipitation and atmospheric evaporative demand for each climate model projection for the period 1970–2100. We calculated the evolution of SPI and SPEI over the period of the year showing the highest correlation with the crop yields over the period of observations. We also calculated the duration of drought events considering a threshold of 1 in 20 years (−1.65) according to the normal distribution that characterizes SPI and SPEI in each model and calculated the annual average of the drought duration from the different models.

Changes in precipitation were analyzed by means of a temporal spectral analysis to determine possible cycles and short- and long-term periodicities. For this purpose, we focused on the long-term series for Chisinau that can be considered as representative of the general precipitation variability over the whole country. We use the continuous wavelet transform[61] to localize in both time and periodicity the transient patterns embedded in the precipitation time series. Thereby, we obtain information about the dominant timescales of underlying processes and hence sources of variability across timescales. In this research, we make use of the Morlet wavelet, which has been successfully used to analyze hydrological time series.[62–64] Time series were standardized (zero mean, unit standard deviation) before applying the continuous wavelet transform.

The relationship between the climate variability and the interannual variability of different crop yields was assessed by means of correlation analysis. For this purpose, we used the complete period of record, and the correlation was calculated considering different periods of accumulation of the precipitation, temperature, and the atmospheric evaporative demand. This allowed us to determine the periods of the year that most affect the interannual variability of crop yields. The same approach was followed to analyze the relationship between vegetation activity by means of the EVI2 and the climate variables for the period 2000–2020. For comparison, correlations between the annual crop yields and climate variables were also analyzed for the period 2000–2020. To identify possible temporal changes and correlations in the relationship between precipitation and crop yields, we used squared wavelet coherence, following the approach of Grinsted et al.[65] (i.e., a direct correlation between the wavelets of both precipitation and crop yields), and moving-window correlations between precipitation and crop yields considering intervals of 15 years.

To characterize the atmospheric circulation over Eastern Europe, we define six weather regimes (WRs) based on daily anomalies of Z500 (defined as departures of the daily fields from the 1981 to 2010 daily climatology computed using a 15-day centered running mean) over the domain [0°E – 55°E, 30°N – 65°N] during the period 1950–2020. Following previous studies,[66,67] WRs were computed by applying a

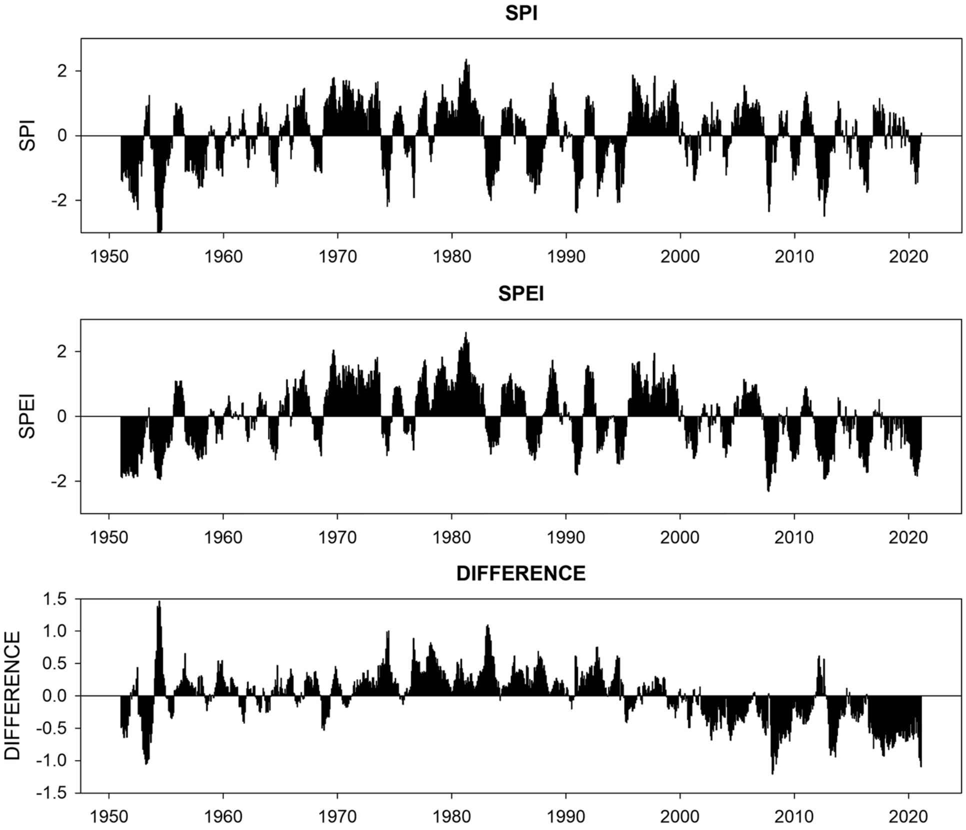

FIGURE 2 Evolution of the SPI and SPEI from the national average series for Moldova and the difference between them.

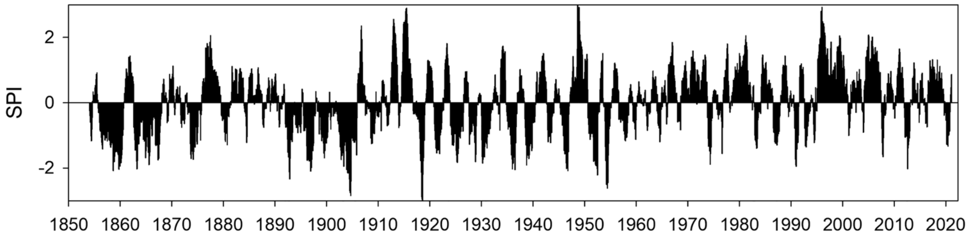

FIGURE 3 Evolution of the 12-month SPI for Chisinau from 1850 to 2020.

k-means clustering algorithm to area-weighted Z500 anomalies after their reconstruction by means of an empirical orthogonal function analysis. The choice of the final number of clusters has been made as a reasonable compromise between the anomaly correlation coefficient and the sum of squares (not shown).

RESULTS

Evolution of drought severity

The long-term evolution of meteorological droughts in Moldova does not show a declining trend over the last decades (Figure 2). Thus, considering the long-term period 1850–2020 in Chisinau (Figure 3), the evolution of SPI shows a positive long-term trend, indicative of a decrease in the severity of drought events, which were particularly strong in the 1890s and 1900s, in agreement with the pattern observed in neighboring areas of Ukraine.[68] Precipitation in Moldova does not show clear cycles over the long term (Figure S3), with no relevant temporal differences in periodicities over the last 170 years (Figures S4 and S5 and Table S2). This stresses the random character of drought events in the region and the difficulties of establishing long-term drought forecasting approaches.

Relationship between the drought indices and crop yields

The evolution of SPI from 1950 to 2020 for the different meteorological stations available in Moldova shows a strong correlation

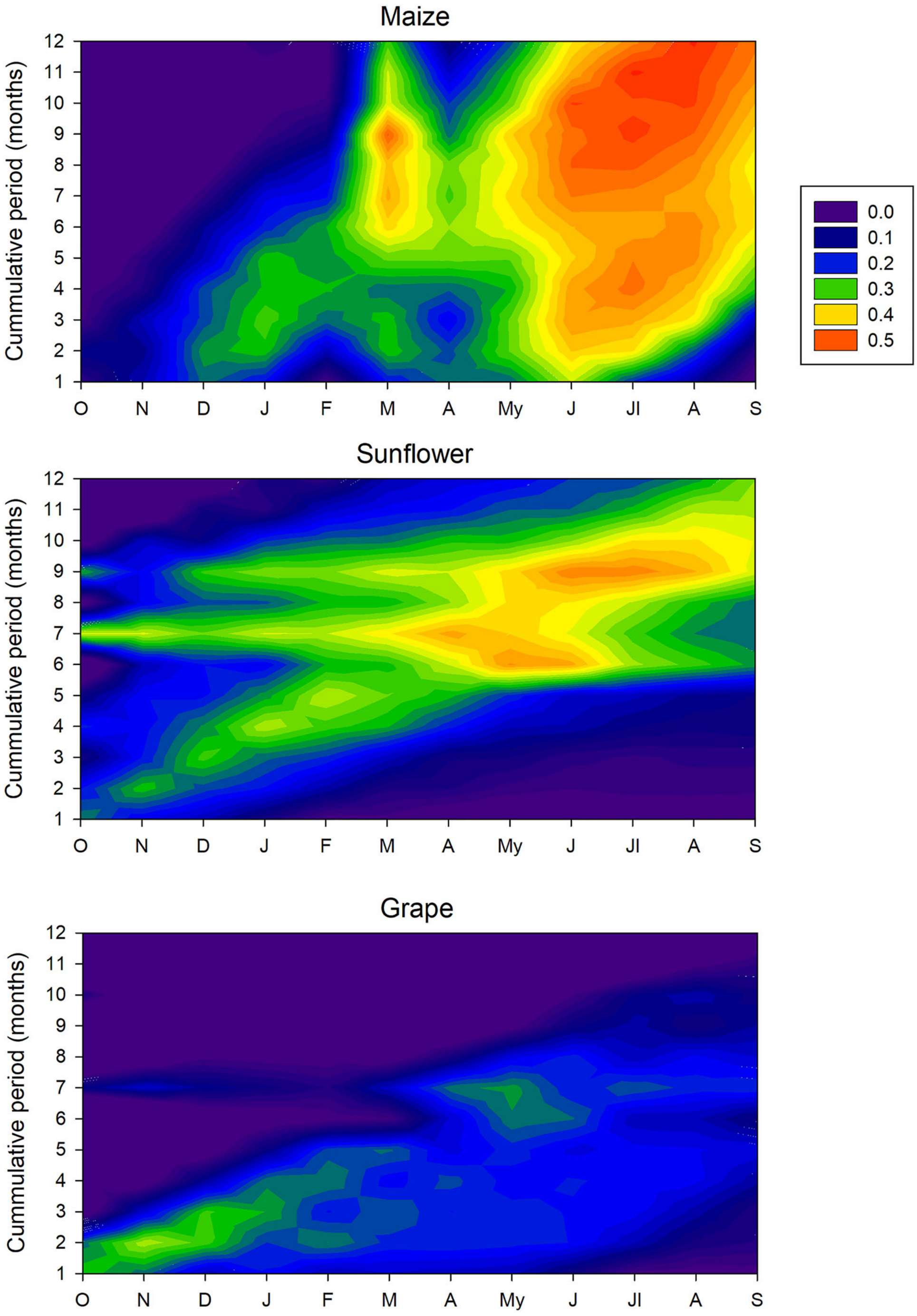

FIGURE 4 Monthly correlations between precipitation accumulated over different temporal scales and the crop yields of maize, sunflower, and grape in Moldova. Significant correlations ($p > 0.05$) correspond to Pearson's $r = 0.23$.

($r > 0.8$) with similar duration and severity of meteorological droughts. The average SPI obtained for the whole country shows the most severe drought events in the decade of the 1950s. The 1980s, 1990s, and 2010s were also characterized by some severe meteorological droughts, particularly in 2012 (Figure S6). The drought that affected Moldova in 2020 and caused a strong decline in crop yields was not as severe as previous droughts from a meteorological point of view.

Maize and sunflower annual yields show significant correlations with the precipitation recorded between November and December of the previous year and July of the current year. Correlations are stronger for maize yields than for sunflower (Figure 4). On the other hand, there is a weak correlation between precipitation and grape yields, indicating the insensitivity of this crop to precipitation variability. Maize and sunflower annual yields also show a negative relationship with temperature and the atmospheric evaporative demand for the majority of months of the year (Figures S7 and S8). Thus, high temperatures and atmospheric evaporative demand during the entire growing season show a negative correlation with annual yields,

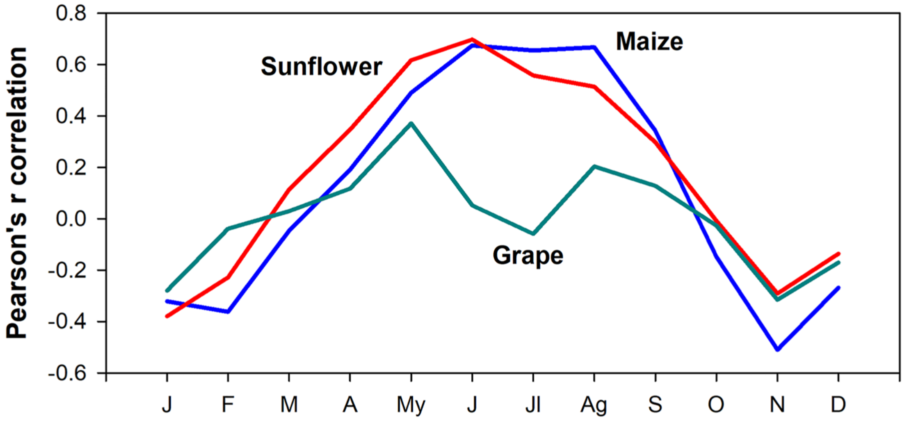

FIGURE 5 Correlation between the monthly EVI in crop lands and the annual crop yields of maize, sunflower, and grape for the period 2000–2020.

suggesting that the hydraulic stress caused by temperature is more relevant than its role in promoting photosynthesis. Again, grape yields show a low sensitivity to the interannual variability of these climate variables.

The correlation dynamics between MODIS vegetation indices and crop yields

For the period 2000–2020, there is a strong correlation between the maize and sunflower crop yields and the MODIS vegetation indices, particularly during the summer months (Figure 5). Thus, the correlation between the different climate variables and the monthly EVI2 series shows patterns coherent with the relationship found between the maize and sunflower yields and climate. There is a positive correlation between EVI2 and summer precipitation, with maximum correlation for the period between November and July (Figure 6). In addition, there are negative correlations with summer temperature and atmospheric evaporative demand, the strongest for the latter. Moreover, the magnitude of these correlations is stronger than that recorded between crop yields and climate variables for the study period 1950–2000. Nevertheless, these results do not mean that vegetation activity shows a stronger response than crop yields to the climate variability. Analyzing the correlations between crop yields and climate variables for the same period of the EVI2 data (2000–2020), we also find stronger correlations than those found for the whole period of analysis (Figures S9–S11). Moreover, the patterns of correlation with the different precipitation accumulations are equivalent to those obtained with the EVI2 data for this period. This suggests a reinforcement of the relationship between climate variability and crop yields during the last two decades in relation to what was observed in previous decades. The evolution of crop yields clearly shows a stronger relationship with precipitation for maize and sunflower from the 2000s onwards (Figure 7). Nevertheless, the crop yield decrease of 2020 was stronger than expected from the observed reduction of precipitation. The years 2007 and 2012 showed lower precipitation but these years were not affected by such a large crop yield decrease.

Changes in the relationship between crop yields and precipitation

There is a clear change in the relationship between precipitation variability and maize and sunflower yields in the last two decades (Figure 8). This is clearly observed with the wavelet coherence between precipitation and maize and sunflower yields showing the dominance of a relationship between both variables at long periods (8 years) between 1950 and 2000 but after 2000 the relationship is recorded at higher frequencies, with a maximum considering 1 year. In addition, analysis of moving-window correlations between precipitation and crop yields with periods of 15 years shows a clear positive trend toward higher correlations in the three crops, indicating that crop yields became more sensitive to the precipitation variability in the last two decades.

We further explore the factors that may drive the reinforcement of the role of precipitation variability in explaining annual crop yields. We observe a strong increase in temperature that starts in 2000 (Figure 9). From 2000 to 2020, the average annual temperature has increased by 2°C, which is a very strong trend for such a short period. The warming is mostly concentrated in the summer. This strong temperature increase has caused a noticeable increase in the atmospheric evaporative demand, which has reinforced the severity of drought events. Analyzing the difference between the evolution of SPI and SPEI, it is observed that the drought events that affected Moldova from 2000 onwards were clearly reinforced by the drying effect of enhanced atmospheric evaporative demand, which was particularly acute during the 2020 drought (Figure 2). The evolution of the negative departure of SPEI from SPI shows a clear negative trend and strong reinforcement of the severity of drought events from 2000 driven by evaporative demands from rising temperature.

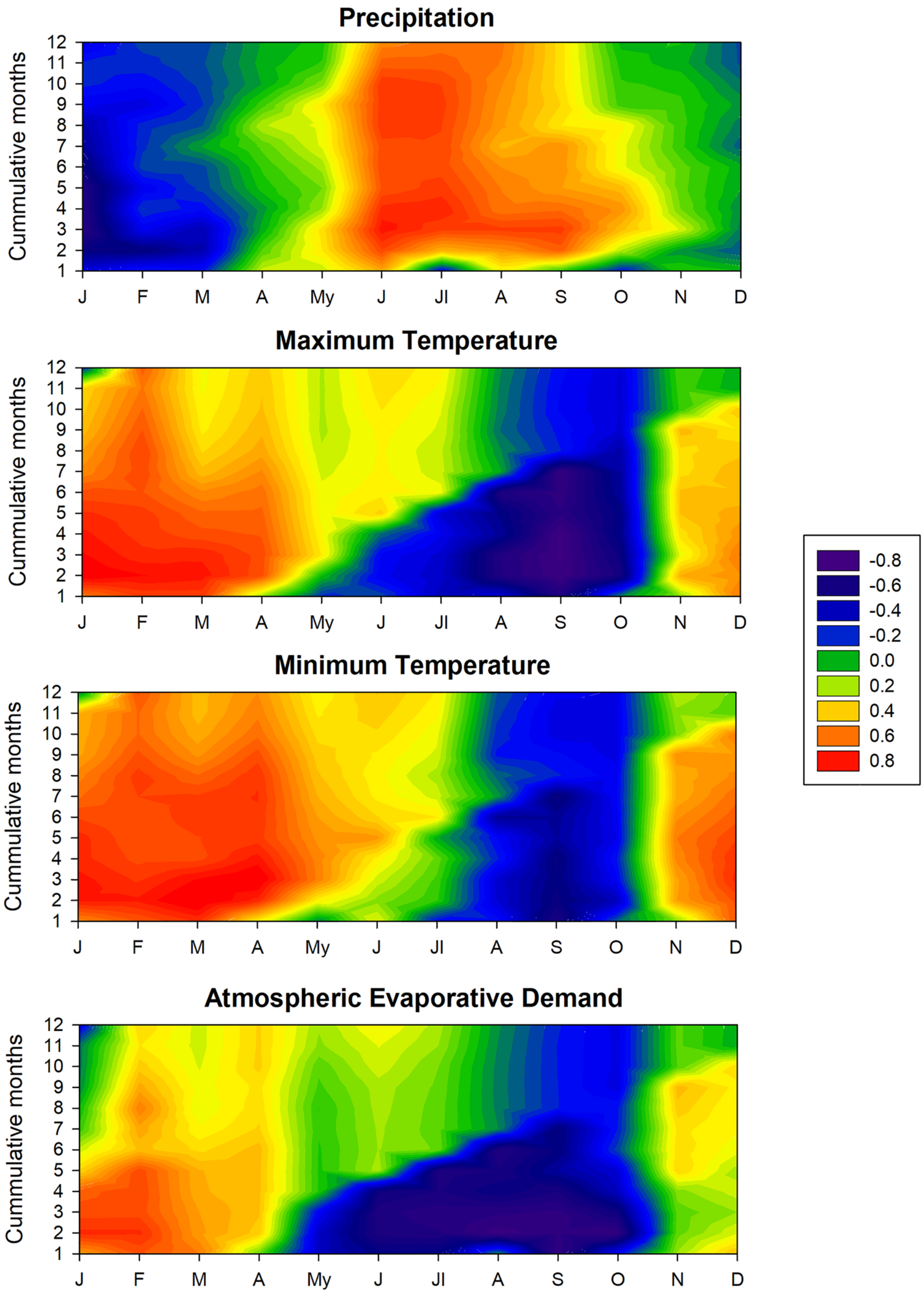

FIGURE 6 Pearson's *r* correlations between the monthly EVI2 and the monthly meteorological variables accumulated over different temporal scales for the period 2000–2020.

Frequency of different atmospheric circulation patterns in 2020

The July 2019–August 2020 period was particularly dry as a consequence of anomalous atmospheric conditions that favored both low precipitation and high temperature. Figure 10A shows the dominant atmospheric configurations in Eastern Europe, which were selected according to a WR cluster analysis (see Methods). The fact that none of the six WRs shows a frequency of occurrence within the climatological interquartile range proves that the atmospheric circulation was especially uncommon during this period (Figure 10B). In particular, WR1 leads to lower precipitation (Figure 10C) and higher temperature (Figure 10D) than the other WRs due to the associated anticyclonic anomaly over central and eastern Europe. Therefore, the high occurrence of WR1 (above the 90th percentile) explains the low precipitation (below the 5th percentile) and the very extreme temperatures (above the 99th percentile) that characterized the 2020 drought.

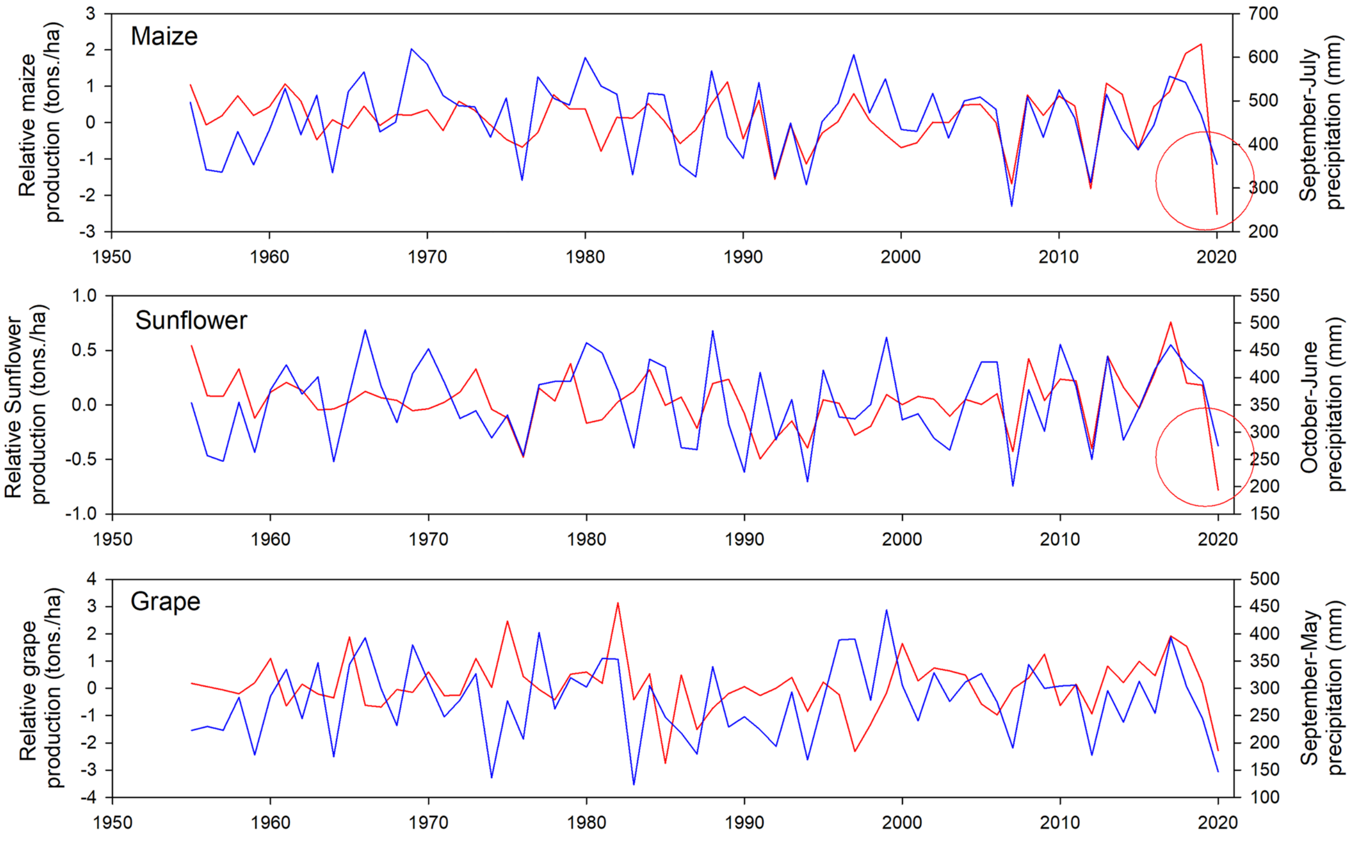

FIGURE 7 Evolution of the temporal variability of precipitation during the period of higher correlation with the anomalies in crop yield and the annual yields of the three crops. The yield for 2020 is marked for maize and sunflower.

Projected changes in the drought patterns

Observations show that increasing temperatures are negatively affecting crop yields in Moldova. Future projections based on climate change scenarios show that this situation will continue to worsen crop yields in the region, in the absence of adaptation. Figure S12 shows the simulations of temperature and precipitation for Moldova from 43 CORDEX models for the period 1970–2100, according to the emission scenario RCP8.5. During the historical period between 1970 and 2005, there is high agreement between the long-term average of observations and the ensemble mean simulations. While the observed values of minimum temperature tend to be higher than those simulated by the models, both series reproduce very well the strong temperature increase observed in the last two decades. Precipitation shows static behavior between 1970 and 2005, while the future evolution from the models does not show notable precipitation changes during the twenty-first century. On the other hand, temperature is projected to increase substantially, with maximum temperature projected to increase more than 4°C in the period 2070–2100 relative to 1970–2020. Summer would be the most affected season (Figure S13). The climate projections of drought severity do not show changes in the duration of the extreme drought events (1 in 20 years) based on the SPI (Figure 11), but do show strong increases in the duration of droughts based on SPEI, particularly from 2070 to 2100. These longer droughts are also characterized by more negative SPEI values during summer, which is presently the period most strongly correlated with annual crop yields.

Strategies for adaptation under a warmer climate

Given the increasing effect of temperature on crop yields in Moldova and its projected future increase, it is necessary to consider possible strategies of crop management in the region to deal with new climate conditions. Here, we focus on wheat production. Crop rotation experiments managed by the Selectia Research Institute for Crop Research from the 1980s allow the evaluation of two different strategies to improve crop yields in response to droughts. The results show that wheat production in rotation after rye and vetch are statistically significantly different from the wheat yields after corn rotation (Figure 12). Yield differences between both crop management practices are higher in dry years, in which the wheat yields after corn rotation strongly decrease in comparison to normal and humid years. On the other hand, wheat yield after rye vetch rotation shows a smaller decrease. This response during extreme dry conditions seems to be related to the availability of soil moisture and is clearly observed in the dry years of 2007, 2012, and 2020. Average crop yield in these 3 years was 76.8% for the wheat after rye and vetch in relation to the long-term mean,

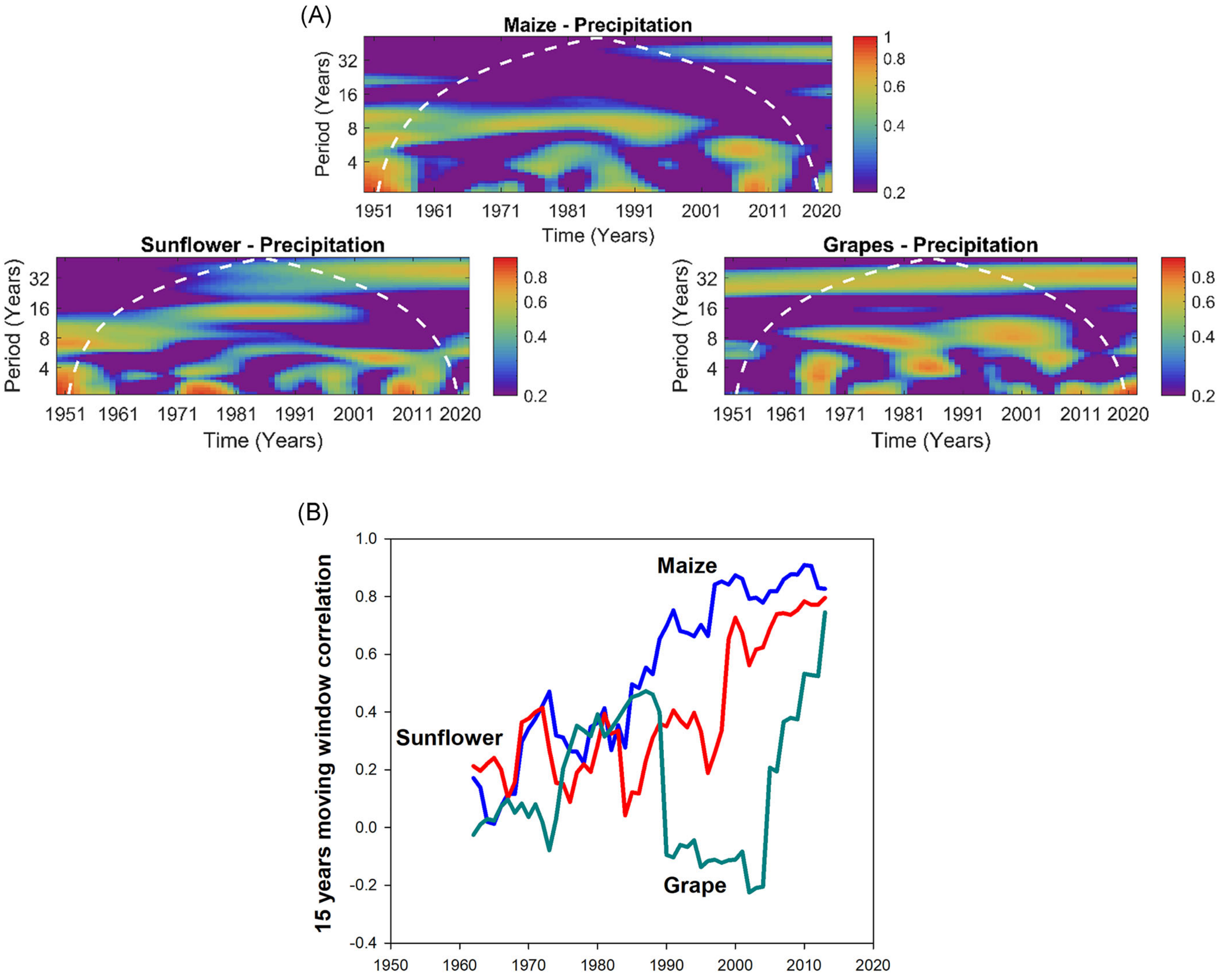

FIGURE 8 (A) Squared wavelet coherence between the three selected agricultural yields and precipitation time series during the period 1951–2020. The vertical axis is the time scale and the horizontal axis is the time position. The dashed curve depicts the cone of influence within which the edge effects are negligible.[61] The shaded contours indicate the strength of the coherence. Regions where coherence is significant above the 60% level are plotted with warm colors. (B) Moving-window correlations between annual crop yield of maize, sunflower, and grape and the precipitation for the period with stronger correlation.

but only 59.1% for the average of wheat after corn. The mixture of rye and vetch for green mass is harvested in June, but corn for grain in September. Consequently, the consumption of soil moisture in the corn rotation is significantly higher, reducing the soil moisture storage, which could explain the subsequent reduction of wheat yields. This is particularly critical during years characterized by low precipitation. Also, water availability in the soil after harvesting is maintained better during dry years by the wheat rotation after rye and vetch since in these three extreme drought years the water storage in the soil was 40.0% relative to the soil moisture at the date of planting, but only 22.3% in the case of wheat and corn rotation. This suggests that the rotation of wheat after rye and vetch optimizes soil water saving and improves crop yields, particularly in dry years.

DISCUSSION AND CONCLUSIONS

This study analyzed observed long-term drought evolution and future drought projections for the Republic of Moldova, with a specific focus on crop yield impacts. Previous studies have shown the strong influence of climate variability and drought on crop yields in Moldova.[9,36,37] Here, we have found similar results, which are strongly dependent on the crop type. While the severity of pluvial droughts (SPI) has decreased in the last 170 years, the impact of precipitation deficits on yields has increased in the last two decades. We associate this behavior with the strong warming trend observed in recent decades.

Precipitation trends in Moldova are consistent with other studies analyzing trends in precipitation deficits and pluvial droughts in the

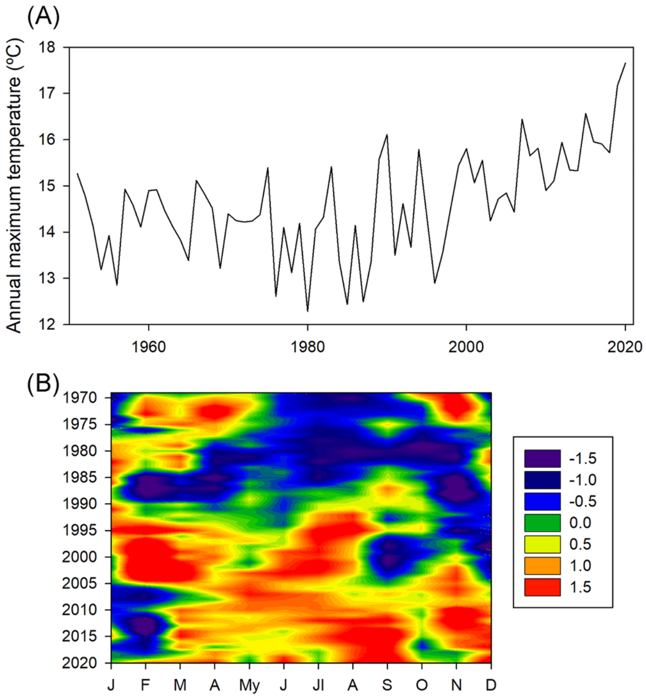

FIGURE 9 (A) Evolution of annual maximum temperature in Moldova. (B) Magnitude of the linear trend of monthly temperature in periods of 30 years. The end year of the period is indicated in the vertical axis.

Mediterranean area and southeastern Europe that do not show trends associated with anthropogenic forcing but rather are dominated by natural variability.[69,70] Given this temporal pattern, it is not possible to associate stronger drought severity and impacts on crop yields to larger precipitation deficits. Thus, it could be considered that given the bioclimatic conditions of the Republic of Moldova, with annual average precipitation close to 600 mm, a strong reduction of precipitation as recorded in 2012 or 2019 (430 and 450 mm, respectively) would not cause a strong decrease of crop yields given current crop water requirements.[71]

However, the current climate in Moldova is not static. Air temperature shows a very strong increase, particularly for the last two decades, and more intense than the pattern observed worldwide as a consequence of anthropogenic forcing.[72] According to our results, this strong and rapid increase in maximum temperature during summer has endangered the capacity of crops to cope with years characterized by extreme water deficits. This is supported by the fact that precipitation deficits recorded in some years in the last two decades, particularly in 2020, have not been sufficiently severe to explain the large decrease of crop yields. More severe pluvial drought events have been recorded since the 1950s but have not caused such a dramatic decline in crop yields as those recorded in the last two decades.

The first evident effect of temperature increases that we found is a reinforcement of the sensitivity of crop yields to precipitation variability. In the period between 1950 and 2000, the yield of annual crops (sunflower and maize) showed in general low sensitivity to interannual variations in annual precipitation. Nevertheless, the increase of temperature recorded in the last decades has caused a strong increase in atmospheric evaporative demand in Moldova,[73] which is consistent with observations in other regions of Europe.[59,69,74,75] This increase has two main effects; the first is related to the reinforcement of plant transpiration and direct soil evaporation. If precipitation is high and sufficient moisture is available in the soil, it is not expected that plants are affected negatively over the short term.[60] Thus, during periods of high evaporative demand, temperature and radiation are usually high, and if moisture is available in the soil, this usually reinforces photosynthesis and plant growth. However, during periods of precipitation deficits when leaf stomatal conductance is determined by soil water availability, and also during periods of very high temperatures, an increase in atmospheric demand reduces photosynthesis in response to higher VPD[16,17,20,76] and, in addition, increases the risk of plant hydraulic failure as a consequence of xylem embolism.[19,77]

Moreover, even if precipitation deficits are modest, enhanced plant transpiration and soil evaporation in response to higher atmospheric evaporative demand reinforces soil moisture deficits[78] and may also cause land–atmospheric feedbacks that contribute to additional atmospheric drying by altering the partitioning between sensible and latent heat fluxes from the surface to the atmosphere.[79] Moreover, plant physiology is also strongly affected by the increasing frequency and magnitude of extreme temperatures, particularly during summer, since they may contribute to the additional loss of water from leaves and damage the leaf tissues.[22] All these mechanisms caused by temperature rise that negatively affect plant development are consistent with the observations of crop yield and vegetation activity in Moldova, since temperature and atmospheric demand show strong negative correlations with these crop variables. It is, therefore, reasonable to consider that enhanced temperature has negatively affected crop yields in the region, which is consistent with assessments by several studies that have observed a decline in the crop yield potential in response to global warming in other regions or at the global scale.[23,80–82]

Projections by climate change models for the region are alarming for the agricultural sector. Precipitation projections do not suggest substantial changes at the end of the century, even for scenarios of high greenhouse gas concentrations, although all models show that precipitation will have an important interannual variability consistent with the behavior observed from historical observations. This is consistent with recent studies that show that this region of eastern Europe is not a hotspot in relation to precipitation changes.[83] Nevertheless, it is expected that the atmospheric conditions favorable to generate precipitation deficits, characterized by the dominant atmospheric stability in eastern Europe, as observed in 2020, will be also observed in the future as a consequence of natural climate variability.[84–86] The real problem is that climate change projections show with high confidence a strong temperature increase of more than 4°C in the Republic of Moldova at the end of the century. This increase is very consistent among the different models and particularly severe during the summer.[87] Moreover, studies focusing on the projections of extreme temperature have also shown that the frequency and severity of heatwaves will increase in the future in this region of Europe.[88] These projections suggest that during periods of precipitation deficits that

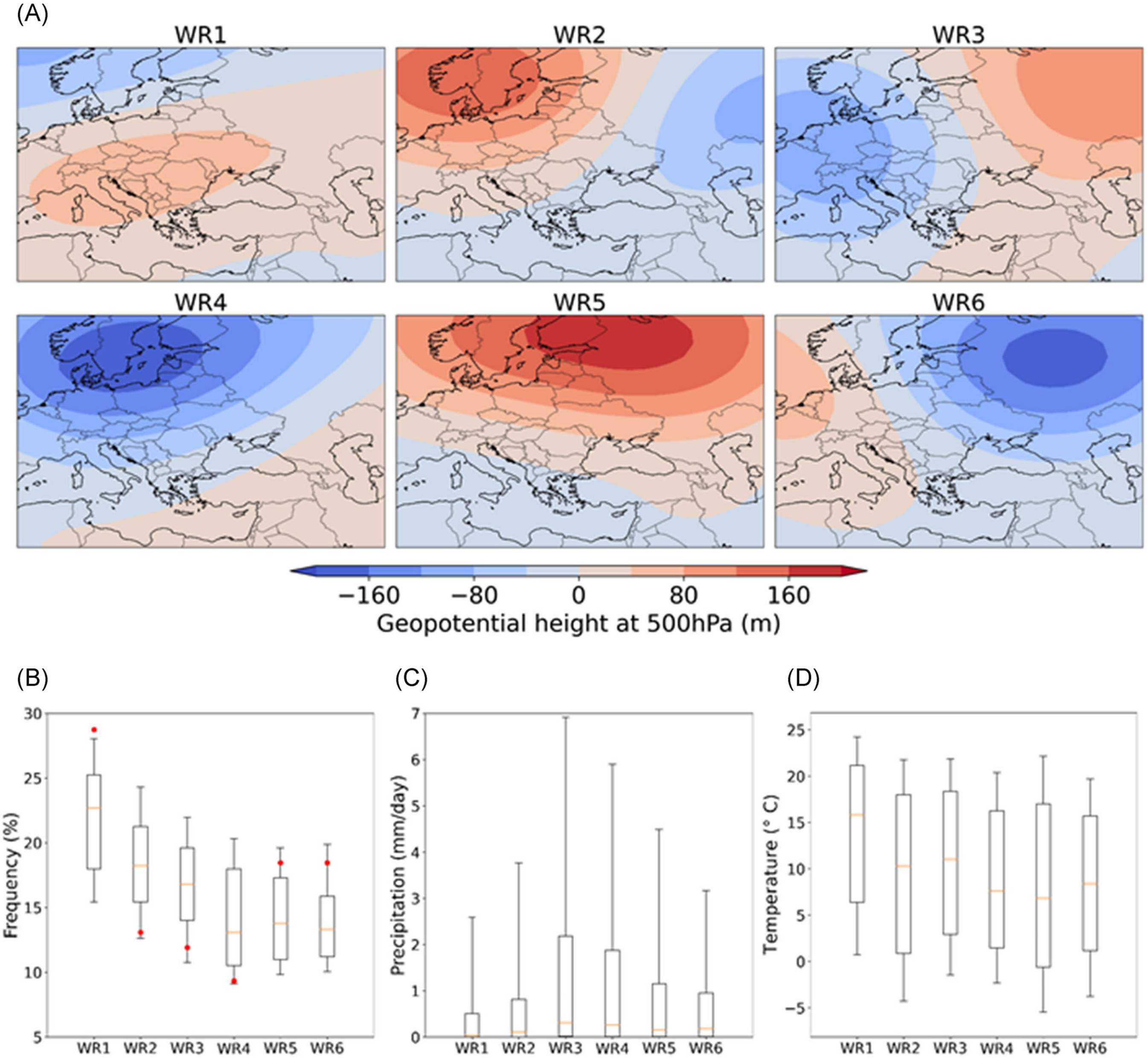

FIGURE 10 (A) Main patterns of atmospheric circulation in Eastern Europe derived from the ERA5 reanalysis for the period 1950–2020. Colors show the 500 hPa geopotential height anomalies (in m). (B) Frequency distribution of days in each pattern of atmospheric circulation for the 13-month July–August 1950–2020 climatology (boxes). Red circles correspond to the July 2019–August 2020 period. The boxes extend from the lower (Q1) to the upper (Q3) quartile values of the data, with the horizontal line indicating the position of the median (Q2). The whiskers extend from the boxes to show the range of the data between the 10th and 90th percentiles. (C) Distribution of daily precipitation in Moldova (considering the closest grid cell to Chisinau) corresponding to the different atmospheric circulation patterns. (D) Distribution of temperature in Moldova corresponding to the different atmospheric circulation patterns.

are expected to be observed in the future as a consequence of natural climate variability, the limitations for crop growth will increase even more. Moreover, the stronger evaporation that is expected during normal or wet periods may reinforce soil moisture depletion not exclusively determined by precipitation deficits.[78,89–91] Thus, the inclusion of atmospheric evaporative demand in the assessment of drought conditions for future scenarios shows a clear increase in the severity of droughts at the end of the twenty-first century in the Republic of Moldova, which is consistent with assessments in other regions of Europe based on metrics that consider atmospheric evaporative demand[92–95] or directly the land evapotranspiration.[96]

Moldova possesses extensive experimental field datasets on three strategic crops, enabling effective comparison with drought climatology. These datasets demonstrate the efficacy of crop rotation in mitigating agricultural risks associated with drought. Integrating crop rotation with drought-resistant crop varieties and soil conservation

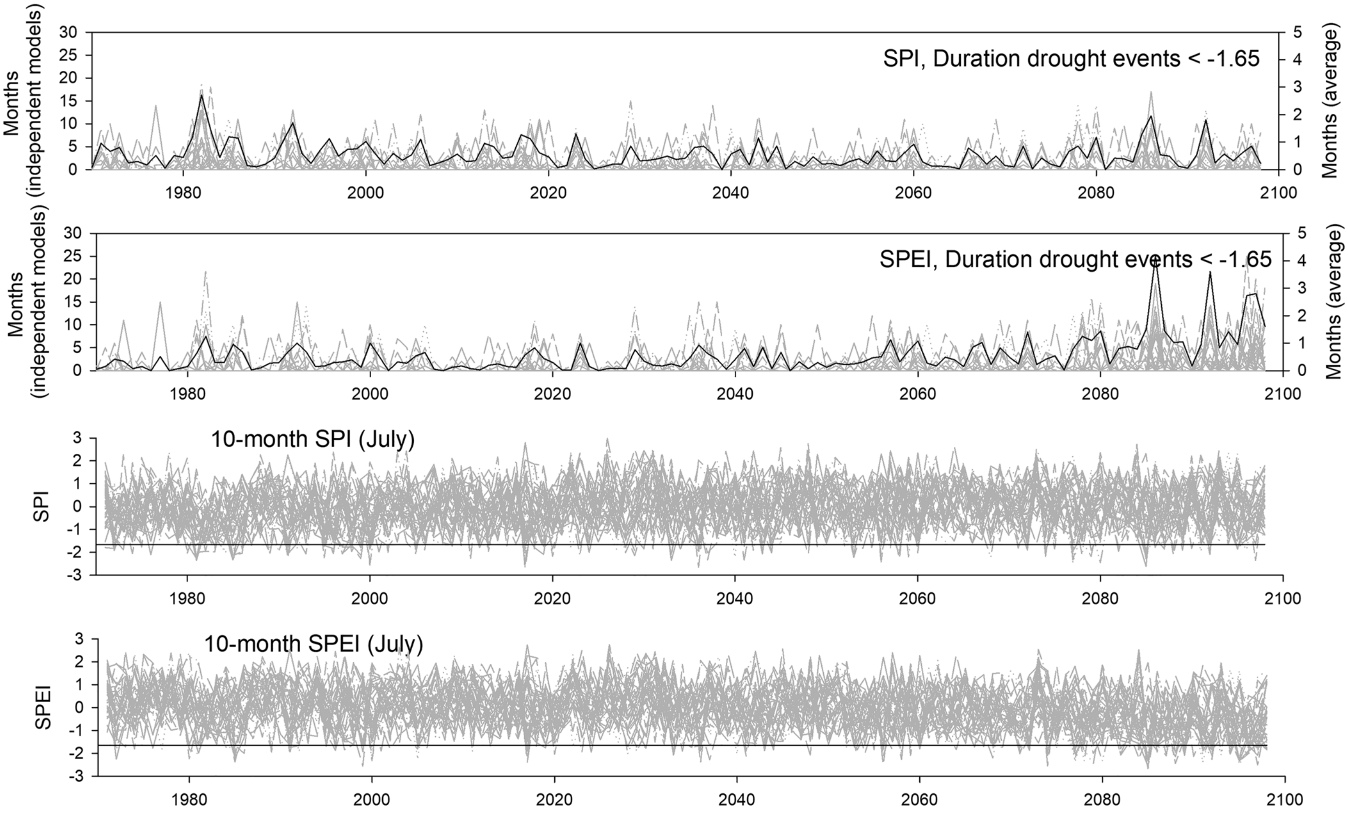

FIGURE 11 Evolution of drought duration from 43 climate change models in Moldova using the SPI and the SPEI. Gray lines show the evolution of each model and black lines represent the average. The two bottom plots show the evolution of the SPI and SPEI at the time scale of 10 months in July. The horizontal black line represents SPI and SPEI values equal to −1.65.

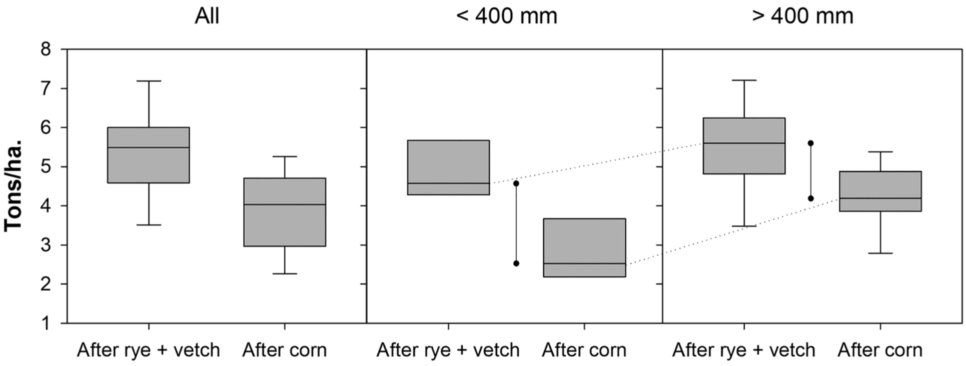

FIGURE 12 Distribution of wheat yields from the Selectia crop research site in Balti for two types of crop rotations: wheat after rye + vetch and wheat after corn. The box plots show the total number of years over the period 1980–2020 and for the dry (<400 mm) and humid (>400 mm) years.

practices such as mulching and minimal tillage constitutes a holistic strategy to mitigate the impact of water scarcity and climate variability on agriculture in Moldova.[42,97]

Given the importance of the agricultural sector to the economy of Moldova and the serious constraints that global warming is imposing on crop yields, it is urgent to advance the development of adaptive agricultural management strategies. One possibility is to increase the importance of grapes in the crop sector. The quality of wines produced in Moldova is renowned[98–100] and this could be a relevant sector to strengthen agricultural activity and eco-tourism. In this study, we have observed that annual grape production in the last seven decades was insensitive to precipitation variability. Grapes are cultivated in other regions of the world characterized by much more limiting climate conditions than those recorded in Moldova, for example, different

Mediterranean climate regions.[101–103] Vineyards show high adaptability to summer dryness as developed root systems allow water to be obtained from deeper layers.[104] This means that although the climate may evolve to more arid conditions in Moldova, vineyards may adapt well to less available water and warmer conditions. Although increased temperatures may enhance the sugar concentration of the fruits and the resulting wine, for example, increasing the degree of alcohol or sweetness, this would not affect the production very much, as the wine produced in much more arid regions usually shows very high quality.[105,106]

There are other possibilities for crop adaptation in the region. The development of more sustainable agricultural management practices based on crop rotation to maintain the quality and carbon content of the soil is one of the main strategies to promote adaptation to climate change.[97,107] In this study, we used crop yield data from a long-term experiment developed at the Selectia Research Institute for Crop Research in Balti in which rotation management practices were compared. We have shown that management characterized by intensive crop cultivation with the rotation of summer maize and winter wheat generates lower wheat yields on average, and this is accentuated during years of precipitation deficits. On the other hand, including early-harvested predecessors in the rotation reduces the vulnerability of the wheat crop yields to drought. This can be explained by two factors. First is that maize is harvested later than the mixture of spring vetch and spring oats for green mass, which means more consumption of water from deeper soil layers. In the rich soils of the Moldovan steppe, the water stored in deeper layers (1–2 meters) plays a more important role under drought conditions than in normal and humid years,[42,97] and the depletion of this layer by the intensive summer maize crops reduces the availability of water for the subsequent winter cereals. Second, winter rye in crop rotations increases carbon accumulation and the capacity of soils to store water,[107,108] which is crucial under drought conditions. Unfortunately, in Moldova, winter wheat is sown mainly after late-harvested predecessors such as maize for grain and sunflower, which could be unsustainable under conditions of more severe droughts.

In summary, we have shown that the vulnerability of crop yields to precipitation variability has noticeably increased during the last 20 years due to the large temperature increase recorded in the region. Climate change projections show a reinforcement of limiting climate conditions for adequate crop yield. For this reason, it is necessary to promote moisture-preserving land management practices, characterized by perennial spring crops and winter cereals to increase the stock of soil moisture and also consider extending the area covered by vineyards that may adapt to more arid and warmer climate conditions, maintaining productivity and grape quality.

AUTHOR CONTRIBUTIONS

S.M.V.-S., C.J., and V.P. designed and performed the research. S.M.V.-S. and C.J. were involved in developing the methodology. S.M.V.-S., C.J., M.I., J.M.G-P., D.P-A., and I.N. participated in figure creation. V.P., B.B., L.E., H.J., R.G-H., and J.M.G. contributed with data. S.M.V.-S. and C.M. drafted the paper and contributed to revising the content of the final version of the manuscript. All authors contributed to the discussion of the results and editing of the manuscript.

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COMPETING INTERESTS

The authors declare no competing interests.

PEER REVIEW

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