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Agro-climatic Analysis for Agricultural Adaptation in Hungary

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Abstract

Both globally and in Hungary, agriculture is one of the industries that is most vulnerable to weather and climate extremes. Intense temperature rises, spatial and temporal variations in precipitation, and significant changes in extreme climatological and weather parameters have contributed to changes in the conditions of cropland, crop losses, and impacts on crop quality in recent years. This paper depicts the transformation of the domestic agricultural sector due to the extreme drought shock of 2022, as well exploring the adaptation strategies applied. The research is based on official agro-climate database and crop data, and the temperature, precipitation, and radiation during the growing season are all examined. The agro-meteorological properties in Hungary had to be investigated for the entire year and all four of its seasons, with indicator analysis projected onto the ever-increasing and dormant seasons. Long-term climate analysis is necessary to understand the historic drought of 2022 and the success of future adaptation and mitigation techniques. The results can help smallholders effectively reduce the adverse impacts of drought conditions, thereby increasing their adaptation to similar shocks.

Keywords

drought, shock, agro-climate, agriculture, precipitation

1 Introduction

Climate change and its extremes are one of the most significant challenges of the 21st century (Bouramdane, 2023; Laporta et al., 2023; Liu and Zhang, 2023). The intense rise in temperature and the spatial and temporal changes in precipitation in the Northern Hemisphere's middle latitudes are increasingly disrupting the traditional and usual variety-climate-soil balance (Bujdosó et al., 2019; Muehe et al., 2019; van Leeuwen et al., 2019). Already in the 1980s, researchers drew attention to the fact that increasing emissions of GHGs will induce irreversible processes in the atmospheric system at the beginning of the 21st century (EPA, 2011; Gasser et al., 2020). One of the signs of this was in Europe in 2021 and 2022; significantly, the agricultural sector was adversely affected (Bonaldo et al., 2023). The adaptability of sectors to a given climate stress event, such as drought, is defined by the vulnerability and adaptability of society (Szendrő et al., 2014). A study examined the impact of climate change on the road transport sector in Hungary, and the Sectoral Adaptive Capacity Index was developed (Szendrő et al., 2014). Extreme weather events threaten all sectors, including agriculture and transport, and therefore the assessment of the adaptive capacity is crucial to protect against weather events. Buzási and Csete (2016) developed indicators for the future adaptive capacity assessment using the scorecard model. Biró and Szalmáné Csete (2021) examined the climate-oriented activities in the Hungarian agricultural sector, and the results of content analyses showed that agribusiness in general is trying to reduce the impacts of climate change through adaptation strategies. The positive and negative impacts of climate change can be observed simultaneously in different sub-sectors of agriculture, e.g., in the western wine regions of Hungary (Kovacs et al., 2017). In 2022, a drought warning came into effect in nearly two-thirds of Europe (Toreti et al., 2022). The 2022 European drought was the worst in at least 500 years (Ripple et al., 2022). Europe's average temperature in both August and June–August 2022 was the highest ever recorded on the continent (Copernicus, 2022; Kempf, 2023). The weakening of the jet stream simultaneously caused the dry period of the last 20–24 months, the persistently negative phase of ENSO (La Niña), the persistent strengthening of block-

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ing anticyclones, and the absence of tropical cyclones (Rousi et al., 2022). This resulted in low saturated water vapour arriving in the northern hemisphere, deficient in atmospheric moisture, so precipitation could not form. Most of the water vapour was unsaturated in the atmosphere, resulting in a secondary greenhouse effect. Together, these cause heat and lack of precipitation, which may become more frequent (Ciric et al., 2016; Tuinenburg et al., 2020). Events like last year's record drought in terms of volume and intensity may become the new norm (Caloiero et al., 2018). No scenario currently presents an optimistic forecast for the 21st century (IPCC, 2021). Evaporation, the water cycle, and macro-circulation processes increase and change with climate change, which is why droughts, storms, and floods will become more frequent and intense at the same time in Europe (Kron et al., 2019). Farmers worldwide are trying out different methods in an effort to adapt to changing climatic conditions. Drought is a severe threat to agricultural production, including livestock numbers. The death of livestock also harms food security. A study assessed households' strategies in livestock production during food security shocks (Bahta, 2022). Life cycle assessment has been used to investigate the environmental impacts of livestock production to propose an effective solution for sectoral adaptation to climate change (Ndue and Pál, 2022). Agriculture depends mainly on water availability; therefore, the pressure on water resources is increasing worldwide (Hussain et al., 2019). There are regions (e.g., the Mediterranean area, Hungarian and Romanian lowlands) where surface and soil water resources have already sunk below a critical level in the long term (Pinke et al., 2020). Irrigation helps protect farmers from climate extremes and increases crop yields, but it also puts significant pressure on water resources (Nikolaou et al., 2020). Despite this, no significant relationship has yet been shown between the modern irrigation technologies appearing in field crop production and water saving, and according to the FAO study, these lead to an increase in water consumption (Perry et al., 2017).

In Europe, the agricultural production of nations is significantly affected by the fact that 60% of water catchment areas are in global regions, which makes effective cross-border cooperation essential (Baranyai, 2020). More than 10% of the water resources of 20 European countries depend on other countries, and more than 75% of the water resources of five countries come from rivers from abroad (EEA, 2021). The annual water runoff of rivers decreases in Central, Southern, and South-Eastern Europe and increases in Northern and North-Eastern Europe due to climate change (Skoulikaris et al., 2020). The falling and growing precipitation and changing water flows and groundwater levels affected the yield difference in the European agro regions (Nistor, 2020). While crop production increased in Northern Europe, it decreased significantly in Southeastern Europe – several assessments of climate change impact on crop yields. At more intense global warming, substantial yield losses are predicted in lower latitudes especially (Deryng et al., 2011). Czibolya et al. (2020) examined the dependence of yields of maize, wheat, barley and rye on precipitation and temperature in Hungary. They found that maize yields were the most sensitive to precipitation among the cereals studied.

2 Materials and methods

In this paper, the shock effects of droughts are approached from two directions. First, the agro-climatological features of Hungary (temperature, precipitation, radio thermal index, etc.) are analysed within a 30-year data series. Secondly, the analysis of the effects of the changing climate and increasing droughts focuses on three selected varieties (wheat, corn, and grape wine). The agro-climatological data come from the National Meteorological Service (OMSZ) and their measurements. Each private station was calibrated annually. The results of the RegCM regional climate model, the HUCLIM, and CARPATCLIM databases were used for the climatological study. During the research, temperature, and precipitation were examined annually during the growing and dormancy periods. With the help of the literature, the most crucial extreme climate parameters were collected, which are calculated from temperature and precipitation. These are important for the climatological examination of the threshold values (Table 1).

Table 1 The most common general climatic parameters (Sensoy et al., 2011)

Appellation	Definition
Summer days	$T_{max} > 25$ °C
Heat days	$T_{max} > 30$ °C
Hot days	$T_{max} \geq 35$ °C
Tropical nights	$T_{min} > 20$ °C
Frost days	$T_{min} < 0$ °C
Winter days	$T_{max} < 0$ °C
Days with heavy rainfall	$R_{day} > 20$ mm
The maximum length of dry spells	$R_{day} < 1$ mm
Rainfall intensity	mm/h

In all cases, a statistically cleaned, long-term data set is required for indicator analysis. To analyse the indicators, most domestic plants react sensitively to changes in the climate, as even minor changes pose a qualitative and quantitative risk to the crop. The relationship between radio thermal index (including temperature and radiation effects) and the length of the main crops and growing season were analysed based on several year-long meteorological and phenological data series. The calculation of radio thermal index (R) is as follows (Dunkel et al., 1981):

$$R = \left(A \frac{G}{n} \right) \times 10^{-2}, \quad (1)$$

where:

- A is the active heat sum of the vegetation period (°C),
- G is the global radiation during the vegetation period (J/cm^2),
- n is the length of the vegetation period per year (Dunkel et al., 1981).

The indicator was developed for grapes but can be used successfully for all domestic plant varieties.

The research also assessed Hungary's drought sensitivity using the Atmospheric Drought Index (LSZI) (Table 2). Physiological changes occur in plants due to atmospheric dryness, which can often destroy certain parts of the plant (flowers, shoots, clusters, stems). The temperature must rise above 25 °C, and the air humidity must fall below 40% (Kovács, 2018). The formula for the LSZI is as follows (Lakatos et al., 2005; Lakatos et al., 2012):

$$\mathrm{LSZI} = \frac{T_{átl}}{25} \times \frac{40}{RT_{13\mathrm{h}}}, \quad (2)$$

where:

- $T_{átl}$ is the daily mean temperature (°C),
- $RT_{13\mathrm{h}}$ is the relative air humidity measured at 13 hours (1 pm) (%).

Table 2 Values of LSZI and water supply level (Source: Kovács, 2018)

Values of LSZI	Water supply for plants
0.0 < LSZI < 0.2	Favourable water supply
0.2 < LSZI < 0.4	Satisfactory water supply
0.4 < LSZI < 0.6	Moderately unfavourable, intermittent water supply
0.6 < LSZI < 0.8	Strong atmospheric dryness
0.8 < LSZI < 1	Severe atmospheric drought, disruption of plant water balance
1 < LSZI	Extreme atmospheric dryness, plant death, water stress

Not only the atmospheric dryness but also the soil-air dryness should be examined, for which the Palfai Drought Index (PaDI) was used (Palfai, 1990), which is:

$$\mathrm{PaDI} = \frac{t_{\mathrm{IV-VIII}}}{P_{\mathrm{X-VIII}}} k_t k_p k_{gw}, \quad (3)$$

where:

- PaDI is the drought index °C/100 mm;
- $t_{\mathrm{IV-VIII}}$ is the mean temperature of the period between April and August;
- $P_{\mathrm{X-VIII}}$ is the weighted sum of precipitation (mm) between October and August;
- k_t, k_p, k_{gw} are temperature, precipitation, and the correction factor for soil humidity.

The analysis of the quantity and quality of the crops was based on official data from the Hungarian Chamber of Agriculture, village farmers, and the Hungarian Central Statistical Office. The statistical data sets were checked by t-test, mean, median, standard deviation, and Mann-Kendall (MK) trend test.

3 Results

3.1 Agroclimatology aspects focused on precipitation and drought

Based on the evaluation of long-term and short-term data, climate change and its extremes have a negative and, to a lesser extent, a positive impact on Hungarian agriculture. Precipitation is a very variable meteorological element in space and time, both in the Carpathian Basin and in Hungary. The country's average annual precipitation is around 620 mm, usually between 550 and 700 mm. Values above 800 mm also occur in the wettest years, while the driest years, which tend to occur in recent decades, have been below 430 mm over the last 30 years. In the long term, a slight decrease in annual precipitation is observed but not significant (Fig. 1).

In Hungary, a drier or wetter year occurs on average every two years during the 1991–2020 climate standard period. Drier (avg. prec. −15%) or wetter (avg. prec. +15%) years also occur irregularly, a region feature. On average, the southwestern part of Hungary receives 150–200 mm more precipitation falls than the south-eastern part. According to meteorological station data, the difference is less than 300 mm. In some cases, even more, significant differences, up to 600–700 mm, can occur within the country, e.g., in 2022. In the last 30 years, there have been prolonged permanently dry periods, for example, between 1992 and 1994, as well as in 2011 and 2012. The most severe drought began in 2021 and ended in the early fall of 2022.

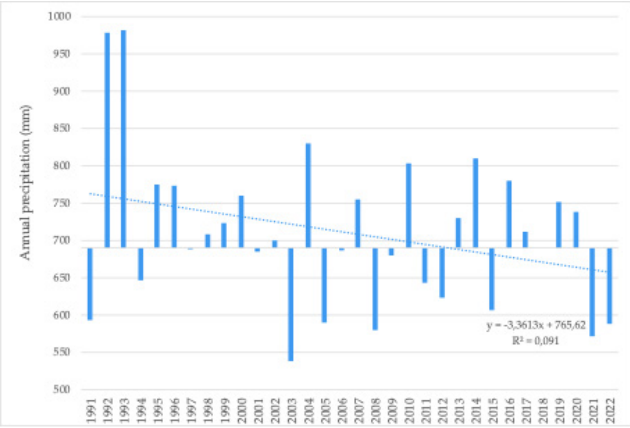

Fig. 1 Annual precipitation – based on homogenised and interpolated data (Source: own editing)

The change in precipitation is not significant if only examined on an annual basis. Where climate change is concerned, predicting and observing changes in precipitation is the most uncertain factor. Therefore, the measurement and evaluation of precipitation amounts is of great importance. The differences in precipitation indicators measured between 1991 and 2020 are not significant in most cases. The amount of precipitation during the growing season decreased significantly ($p < 0.05$), from 387 mm to 321 mm (standard deviation: 68.87).

However, it can already be seen as significant changes from season to season. In the climate period between 1991–2020, it decreased significantly between May and September (−15–20%), while it increased by 16–18% from October to April. The results of the climate simulations predict further significant precipitation patterns comparable to this for Hungary until 2100.

Hungary's exposure to climate change is very significant, reflected in the number, duration, and intensity of heat waves. In the case of heat waves, there is a shift towards early onset, but there are also examples of the heat period starting in August and extending into the first days of September or an independent heat period forming at the beginning of autumn. In the climate period between 1991–2020, the number of summer and early autumn heat wave days increased by more than 100 percent. The steepest increase occurred in August, nearly 300 percent compared to the period between 1961–1990 (Table 3). In the last 30 years, 2019 and 2022 had the most heatwave days in Hungary. It had 150–200% more heatwave days in both years than the 30-year average. In the summer, the country's heat and radiation supply continues to improve due to the increasing number and intensity of anticyclones, decreasing cloud cover, and intense warming. While

Table 3 The occurrence of days above 27 °C between 15 May and 15 September in 2022 (Σ day/3 decades) (Source: own editing)

Climate normal	June	July	August	September
1901–1930	5	41	26	0
1931–1960	3	64	40	0
1961–1990	0	51	28	0
1991–2020	18	128	115	3
2022	6	8	17	0

previously the western half of the country was not ideal in terms of heat and radiation supply for some varieties, today the region's capabilities have improved, but based on all climate simulations, from the middle of the century due to temperature extremes, the eastern and southern thirds of the country will become less and less suitable for agricultural activities in the current form.

3.1.1 Drought assessment based on LSZI and PAI data

Based on the data for 1991-2022, every second year is below 1, which means that every second year was a drought. The LSZI value for the 2010 decade is 0.5–0.6. Different grades of dryness can be observed, among which 2003, 2007, 2012, 2021, and 2022 stand out. In these years, a particularly severe drought was typical. According to the drought indices, the most extreme drought was standard in 2009 and 2022. The correlation matrix of the available 30-year crop series and the drought indices produced for the growing season is shown in Table 4.

A strong correlation was observed between drought indices and the average yield of each plant. The correlation is strong for corn ($r = 0.71$), barley ($r = 0.62$), and apples ($r = 0.61$). The correlation is weak for wheat ($r = 0.19$). The statistical correlations indicate that drought and aridity particularly impact late-season varieties.

3.2 Drought Shock 2022

According to data from official institutions and domestic

Table 4 Correlation matrix of drought indices for each plant (Source: own editing)

Varieties	LSZI	PAI	Level of significance (α)
Wheat	0.19	0.05	NS
Corn	0.71	0.68	$p < 0.001$
Barley	0.62	0.70	$p < 0.001$
Sugar beet	0.23	0.42	$p < 0.01$
Apple	0.61	0.58	$p < 0.1$
Grapevine	0.23	0.09	NS
Sunflower	0.60	0.63	$p < 0.001$
Potato	0.18	0.11	NS

agriculture participants, the 2022 drought caused considerable damages and crop losses in the Carpathian Basin. The most significant yield losses are observed in late-ripening varieties such as corn, apple, grapevine, etc. The main reason is that the extreme drought occurred in July and August, so cell development was delayed in these crops due to lack of rain. The decline in fodder crops has also negatively affected the livestock sector. Hungarian agriculture was not prepared for such an extraordinary drought. The soils of agricultural areas are overused, and organic matter replacement needs to be improved in many cases. Another problem is that 90% of the former floodplains have disappeared from the country, and in some regions, groundwater has sunk by 100–200 cm (own observation). The new technological solutions must be found as soon as possible for targeted surface and groundwater storage and utilising stocks for agricultural and drinking water supply. Both surface and soil water reservoirs are still waiting to be established in the country. Since 2010, more than 18 rainwater reservoirs have been built in the country, but due to the changing climate, at least three or four times as many would be needed, especially in the Hungarian Great Plain, which is prone to aridity. In ungary, 4.3–4.4 million hectares are currently under cultivation, of which slightly over 2%, roughly 100.000 hectares are irrigated – based on the regional database of the Hungarian Central Statistical Office. The most ambitious plans would increase the ratio to two or three times, which means 200–300 thousand hectares, more than that could not realistically be included. Therefore, the soil's water demand is handled by precipitation and groundwater.

4 Discussion and conclusions

The increasingly extreme effects of global warming and climate change pose more significant challenges for Hungarian agriculture, and with present cultivation technologies, it will be impossible to grow crops efficiently. The combination of a warming atmosphere, a significant decrease in summer rainfall, and an increase in drought are causing more frequent droughts in the country. The peak of this so far occurred in 2022.

Field cultivation must be shifted from drought regions to less arid ones, e.g., from the Hungarian Great Plain to the Little Plain or the Transdanubia region. In the case of current industrial crops, re-establishing less productive but more stress-tolerant varieties with a short growing season brings a "renaissance" (e.g., short breeding season soybean, buckwheat, etc.). Corn is currently grown in 6–8% of Hungarian fields. As this crop is susceptible to precipitation and the number of rainy days in the country decreases significantly in summer, it will increasingly decline in Hungary. In arid regions (e.g., Homokhátság, Kiskunság), sorghum can be one of the main alternatives to corn, as it is much better able to tolerate heat and drought stress. It was widespread in the country until the 1920s and 1930s, but its production area has shrunk in the last 50–60 years.

The success of July and later crop varieties (corn, sunflower, barley, apples, wine grapes) is of fundamental importance in the crop production of growing plants. In the future, the hybrid portfolio in Hungary will offer farmers and growers an extraordinarily abundant and wide-ranging opportunity to choose the most suitable hybrids for a given area and a given technological level.

In the future, it will be necessary to clone and create crop varieties that can withstand the extreme heat and dryness of the summer and then the high humidity and the overfilling of the summer groundwater in the following wet periods. It should be noted here that the peculiarity of the Carpathian Basin is that a wet one always follows a dry period. However, variety selection is only partially successful; the technological system needs to be transformed from soil cultivation to intelligent farm management and crop protection. The key is the soil: if it can retain water, plants can survive periods of rainfall deficit with less damage. Although Hungary's soils are still of relatively good quality for successful cultivation, one of the keys to future success is the provision of precision nutrients and water supply. This requires a complete change of attitude in domestic agriculture. Robotisation and digitisation are keys to future cultivation from dormant to harvest. In the era of climate change and environmental protection, the whole of agriculture in Hungary must strive to ensure that mitigation and adaptation are balanced simultaneously.

Technological developments and digitalisation achievements must be brought closer to farmers so they can manage changes flexibly and support them in investing in sustainable innovation and its practical application. To achieve sustainable agricultural and rural development in Hungary, preparing for the expected impacts of climate change, including the transformation of the agricultural sector, is crucial and strongly supports EU climate policy objectives and national recovery and resilience-building plans. Changing climatological conditions will require a complete transformation of agriculture, from growing conditions to digitalisation and crop varieties. We expect a new agricultural revolution to begin in Hungary, driven by climate change rather than technological progress.

References

Bahta, Y. T. (2022) "Nexus between Coping Strategies and Households' Agricultural Drought Resilience to Food Insecurity in South Africa", Land, 11(6), 893.
https://doi.org/10.3390/land11060893

Baranyai, G. (2022) "Transboundary Water Governance in the European Union", In: European Water Law and Hydropolitics: An Inquiry into the Resilience of Transboundary Water Governance in the European Union, Springer, pp. 79–112. ISBN 978-3-030-22540-7
https://doi.org/10.1007/978-3-030-22541-4_8

Biró, K., Szalmáné Csete, M. (2021) "Corporate social responsibility in agribusiness: climate-related empirical findings from Hungary", Environment, Development and Sustainability, 23(4), pp. 5674–5694.
https://doi.org/10.1007/s10668-020-00838-3

Bonaldo, D., Bellafiore, D., Ferrarin, C., Ricchi, A., Sangelantoni, L., Vitelletti, M. L. (2023) "The summer 2022 drought: a taste of future climate for the Po valley (Italy)?", Regional Environmental Change, 23(1), 1.
https://doi.org/10.1007/s10113-022-02004-z

Bouramdane, A.-A. (2023) "Assessment of CMIP6 Multi-Model Projections Worldwide: Which Regions Are Getting Warmer and Are Going through a Drought in Africa and Morocco? What Changes from CMIP5 to CMIP6?", Sustainability, 15(1), 690.
https://doi.org/10.3390/su15010690

Bujdosó, G., Magyar, L., Hrotkó, K. (2019) "Long term evaluation of growth and cropping of sweet cherry (*Prunus avium* L.) varieties on different rootstocks under Hungarian soil and climatic conditions", Scientia Horticulturae, 256, 108613.
https://doi.org/10.1016/j.scienta.2019.108613

Buzási, A., Csete, M. (2016) "Modified Scorecard Method for Evaluating Climate Aspects of Urban Transport Systems", Periodica Polytechnica Social and Management Sciences, 24(1), pp. 65–73.
https://doi.org/10.3311/PPso.7991

Caloiero, T., Veltri, S., Caloiero, P., Frustaci, F. (2018) "Drought Analysis in Europe and in the Mediterranean Basin Using the Standardized Precipitation Index", Water, 10(8), 1043.
https://doi.org/10.3390/w10081043

Ciric, D., Stojanovic, M., Drumond, A., Nieto, R., Gimeno, L. (2016) "Tracking the Origin of Moisture over the Danube River Basin Using a Lagrangian Approach", Atmosphere, 7(12), 162.
https://doi.org/10.3390/atmos7120162

Copernicus (2022) "Copernicus: Summer 2022 Europe's hottest on record", Sept. 8. [online] Available at: https://climate.copernicus.eu/copernicus-summer-2022-europes-hottest-record [Accessed: 09 March 2023]

Czibolya, L., Makra, L., Pinke, Z., Horváth, J., Csépe, Z. (2020) "Dependence of the Crop Yields of Maize, Wheat, Barley and Rye on Temperature and Precipitation in Hungary", Carpathian Journal of Earth and Environmental Sciences, 15(2), pp. 359–368.
http://doi.org/10.26471/cjees/2020/015/136

Deryng, D., Sacks, W. J., Barford, C. C., Ramankutty, N. (2011) "Simulating the effects of climate and agricultural management practices on global crop yield", Global Biogeochemical Cycles, 25(2), GB2006.
https://doi.org/10.1029/2009GB003765

Dunkel Z., Kozma F., Major, G. (1981) "Szőlőültetvényeink hőmérséklet- és sugárzásellátottsága a vegetációs időszakban" (Temperature and radiation in our vineyards during the growing season), Időjárás, 85(4), pp. 226–234. (in Hungarian)

EPA (2011) "Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990–2030", Office of Atmospheric Programs, Climate Change Division, U.S. Environmental Protection Agency, Washington, DC, USA, Rep. EPA 430-R-12-006.

EEA (2021) "Water resources across Europe – Confronting water stress: an updated assessment", European Environment Agency, Publications Office of the European Union, Luxembourg, Rep. 12/2021.
https://doi.org/10.2800/320975

Gasser, T., Crepin, L., Quilcaille, Y., Houghton, R. A., Ciais, P., Obersteiner, M. (2020) "Historical CO_2 emissions from land use and land cover change and their uncertainty", Biogeosciences, 17, pp. 4075–4101.
https://doi.org/10.5194/bg-17-4075-2020

Hussain, M. I., Muscolo, A., Farooq, M., Ahmad, W. (2019) "Sustainable use and management of non-conventional water resources for rehabilitation of marginal lands in arid and semiarid environments", Agricultural Water Management, 221, pp. 462–476.
https://doi.org/10.1016/j.agwat.2019.04.014

IPCC (2021) "Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis", Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, L., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (eds.)]. In Press.

Kempf, M. (2023) "Enhanced trends in spectral greening and climate anomalies across Europe", Environmental Monitoring and Assessment, 195(2), 260.
https://doi.org/10.1007/s10661-022-10853-8

Kovács, E. (2018) "A Soproni és a Zalai borvidék agroklimatikus jellemzése és a borszőlő (Vitis vinifera L.) fajták fenofázisainak válasza az éghajlat változására" (Agro-climatological characterisation of Sopron and Zala wine-growing regionsand responses of grapevines (Vitis vinifera L.) to climate change), PhD Thesis, ELTE Környezettudományi Doktori Iskola. (in Hungarian)
https://doi.org/10.15476/ELTE.2018.068

Kovacs, E., Puskas, J., Pozsgai, A. (2017) "Positive Effects of Climate Change on the Field of Sopron Wine-Growing Region in Hungary", In: Karacostas, T., Bais, A., Nastos, P. (eds.) Perspectives on Atmospheric Sciences, Springer Atmospheric Sciences, Springer, pp. 607–613. ISBN 978-3-319-35094-3
https://doi.org/10.1007/978-3-319-35095-0_86

Kron, W., Löw, P., Kundzewicz, Z. W. (2019) "Changes in risk of extreme weather events in Europe", Environmental Science & Policy, 100, pp. 74–83.
https://doi.org/10.1016/j.envsci.2019.06.007

Lakatos, L., Karácsony, Z., Racskó, J., Zhong-Fu, S., Yingchun, W. (2005) "The Effect of Atmosperical Aridity on the Changes of Quantitative Parameters of Horticultural and Arable Crops", Acta Agraria Debreceniensis, 18, pp. 40–45.
https://doi.org/10.34101/actaagrar/18/3244

Lakatos, L., Szabó, T., Soltész, M., Szabó, Z., Sun, Z., Nyéki, J. (2012) "The atmospherical drought as a decisive factor of yield in the main sour cherry varieties of Hungary", International Journal of Horticultural Science, 18(2), pp. 121–125.
https://doi.org/10.31421/IJHS/18/2/1047

Laporta, G. Z., Potter, A. M., Oliveira, J. F. A., Bourke, B. P., Pecor, D. B., Linton, Y.-M. (2023) "Global Distribution of *Aedes aegypti* and *Aedes albopictus* in a Climate Change Scenario of Regional Rivalry", Insects, 14(1), 49.
https://doi.org/10.3390/insects14010049

Liu, Y., Zhang, Y. (2023) "Statistical Characteristics of Blocking High in the Ural Mountains during Winters and Relationship with Changes in Sea Surface Temperature and Sea Ice", Atmosphere, 14(1), 129.
https://doi.org/10.3390/atmos14010129

Muehe, E. M., Wang, T., Kerl, C. F., Planer-Friedrich, B., Fendorf, S. (2019) "Rice production threatened by coupled stresses of climate and soil arsenic", Nature Communications, 10(1), 4985.
https://doi.org/10.1038/s41467-019-12946-4

Ndue, K., Pál, G. (2022) "Life Cycle Assessment Perspective for Sectoral Adaptation to Climate Change: Environmental Impact Assessment of Pig Production", Land, 11(6), 827.
https://doi.org/10.3390/land11060827

Nikolaou, G., Neocleous, D., Christou, A., Kitta, E., Katsoulas, N. (2020) "Implementing Sustainable Irrigation in Water-Scarce Regions under the Impact of Climate Change", Agronomy, 10(8), 1120.
https://doi.org/10.3390/agronomy10081120

Nistor, M.-M. (2020) "Groundwater vulnerability in Europe under climate change", Quaternary International, 547, pp. 185–196.
https://doi.org/10.1016/j.quaint.2019.04.012

Palfai, I. (1990) "Description and forecasting of droughts in Hungary", In: Proceedings 14th International Congress on Irrigation and Drainage (ICID), Rio de Janerio, Brazil, pp. 151–158. ISBN 81-85068-27-5

Perry, C. J., Steduto, P., Karajeh, F. (2017) "Does improved irrigation technology save water? A review of the evidence", Food and Agriculture Organization of the United Nations (FAO), Cairo, Egypt.
https://doi.org/10.13140/RG.2.2.35540.81280

Pinke, Z., Decsi, B., Kozma, Z., Vári, Á., Lövei, G. L. (2020) "A spatially explicit analysis of wheat and maize yield sensitivity to changing groundwater levels in Hungary, 1961–2010", Science of The Total Environment, 715, 136555.
https://doi.org/10.1016/j.scitotenv.2020.136555

Ripple, W. J., Wolf, C., Gregg, J. W., Levin, K., Rockström, J., Newsome, T. M., Betts, M. G., Huq, S., Law, B. E., Kemp, L., Kalmus, P., Lenton, T. M. (2022) "World Scientists' Warning of a Climate Emergency 2022", BioScience, 72(12), pp. 1149–1155.
https://doi.org/10.1093/biosci/biac083

Rousi, E., Kornhuber, K., Beobide-Arsuaga, G., Luo, F., Coumou, D. (2022) "Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia", Nature Communications, 13(1), 3851.
https://doi.org/10.1038/s41467-022-31432-y

Sensoy, S., Demircan, M., Alan, I. (2011) "Trends in Turkey Climate Extreme Indices from 1971 to 2004", In: BALWOIS 2008, Ohrid, Republic of Macedonia, pp. 1–9. ISBN 978-608-4510-00-0

Skoulikaris, C., Anagnostopoulou, C., Lazoglou, G. (2020) "Hydrological Modeling Response to Climate Model Spatial Analysis of a South Eastern Europe International Basin", Climate, 8(1), 1.
https://doi.org/10.3390/cli8010001

Szendrő, G., Csete, M., Török, Á. (2014) "The Sectoral Adaptive Capacity Index of Hungarian Road Transport", Periodica Polytechnica Social and Management Sciences, 22(2), pp. 99–106.
https://doi.org/10.3311/PPso.7377

Toreti, A., Bavera, D., Acosta Navarro, J., de Jager, A., Di Ciollo, C., Maetens, W., Magni, D., Masante, D., Mazzeschi, M., Spinoni, J., Niemeyer, S., Cammalleri, C.; Hrast Essenfelder, A. (2022) "Drought in Europe August 2022", Publications Office of the European Union, Luxembourg, Rep. EUR 31192 EN.
https://doi.org/10.2760/264241

Tuinenburg, O. A., Theeuwen, J. J. E., Staal, A. (2020) "High-resolution global atmospheric moisture connections from evaporation to precipitation", Earth System Science Data, 12(4), pp. 3177–3188.
https://doi.org/10.5194/essd-12-3177-2020

van Leeuwen, C., Destrac-Irvine, A., Dubernet, M., Duchêne, E., Gowdy, M., Marguerit, E., Pieri, P., Parker, A., de Rességuier, L., Ollat, N. (2019) "An Update on the Impact of Climate Change in Viticulture and Potential Adaptations", Agronomy, 9(9), 514.
https://doi.org/10.3390/agronomy9090514