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Spatial and temporal analysis of drought-related climate indices for Hungary for 1971–2100

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Abstract

The lack of precipitation may cause severe damage in different sectors, especially in agriculture and forestry, therefore, its analysis is a key element of adaptation strategies in the changing climate. In the present study, we selected different climate indices as important indicators for forests to investigate the current and future wet and dry conditions in summer in Hungary. For the historical period (from 1971), the observation-based HuClim dataset is used, which already shows a slight drying trend in the past 50 years, especially in June. For the future, regional climate model simulations from the EURO-CORDEX program are used, taking into account two different RCP scenarios (a business-as-usual scenario and an intermediate mitigation scenario, i.e., RCP8.5 and RCP4.5, respectively). Since mitigation starts to affect the climate system after about 20 years, results do not differ substantially for the two scenarios until 2060, however, the simulated changes highly depend on the applied RCP scenario in the late 21st century. Based on the De Martonne Index, a large expansion of semi-arid conditions is projected for the future in July and even more in August. The analysis of the Forestry Aridity Index shows that the steppe category will become dominant in 2081–2100, while the category optimal for beech may disappear entirely from Hungary according to the RCP8.5 scenario.

Keywords*:* De Martonne Index, Forestry Aridity Index, climate change, summer, HuClim, precipitation

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Introduction

Climate change is not only the future generations' problem; its effects can already be detected, and their consequences are able to cause losses and damages in the natural ecosystems as well as in socio-economic issues. An increase of hot extremes has been detected since the 1950s in almost every region of the world, including Europe, and there is high confidence in the anthropogenic contribution to this observed change. Furthermore, precipitation extremes and droughts have become more frequent and more intense over most land areas (IPCC, 2021).

Water plays a key role in our lives, as it is essential for plants, animals and humans. Global warming affects the water cycle on a regional and global level. Both the excess and lack of water may cause severe problems, meanwhile, water has a high potential in managing climate change effects (e.g., in the case of agriculture, forestry, health or energy sector; WMO, 2021). On the one hand, devastating floods or inland water, flash floods, and landslides may emerge because of intense rainfall. On the other hand, precipitation deficit and drought is a critical factor that already causes problems regarding agriculture or water supply. Moreover, the compound effects of irregularly distributed precipitation and higher daily temperatures may have severe consequences.

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In 2022 (from January to September), substantially less than the usual rainfall occurred in many regions, including Europe (WMO, 2022). The summer was exceptionally hot and dry in Northern America, China and Europe. These conditions favoured wildfires, which caused serious damages, e.g., in Portugal and in France; the total burned area was 110,000 ha in 2022 until 15th October. In August, several European rivers (e.g., Danube, Rhine, Loire) fell to critically low levels. The summer of 2022 was drier in the European continent compared to the 1991–2020 reference period in terms of soil moisture, precipitation and relative humidity as well, except for the south-eastern areas (Copernicus Climate Change, 2022). In Hungary, water restrictions were applied to certain regions, and even drinking-water supply difficulties emerged in some settlements in June and July. In addition, these extremely hot and dry conditions negatively affected agricultural production: yield losses occurred, especially in the case of maize.

Because of the importance and severe consequences of precipitation deficiency, which can be worsened by concurrent high temperatures, our study focuses on drought in the summer half-year, characterized by different indices. Beside severe drought, the De Martonne Index, and the Forestry Aridity Index is analysed, as the climate is a determining factor in the distribution of different tree species. Climatological, hydrological and soil characteristics are often considered unchanged in forestry, however, in the last few decades, climate change has intensified, so climate classification regarding forestry should be revised (Führer, E. 2017). Water availability is a critical factor for the different species, if it is aggravated by extremely high temperature, then it can have severe impacts on the health of forests. The main objectives of this study include a detailed analysis of the above-mentioned indices. Namely, we address the following questions: (i) How did/will the spatial extension of the different categories of these indices change? (ii) In which month(s) is the greatest the projected drought change? (iii) What is the difference between the simulations under the RCP4.5 and RCP8.5 scenarios?

Next, data and methods are described, and then our results are presented with a discussion. Finally, the main conclusions are drawn.

Data and methods

Observations and climate model simulations

The present study focuses on Hungary for the period 1971–2100. Hungary lies in Central Eastern Europe (~45.7–48.6°N; 16–23°E), its territory is about 93,000 km^2. For the analysis of the past 50 years (i.e., 1971–2020), the high-quality, observational database of HuClim (https://odp.met.hu/) is used. The daily data are homogenized and interpolated to a regular 0.1° grid.

As for the investigation of the future, climate model simulations can be used. We selected six simulations from the EURO-CORDEX database (Jacob, D. *et al.* 2014) with 0.11° horizontal resolution. Since the choice of global climate models (GCMs) shows greater uncertainty in the simulation results than the choice of regional climate models (RCMs) over Central Europe (Szabó, P. and Szépszó, G. 2016), four GCMs (EC-EARTH, CNRM-CM5, IPSL-CM5A-MR and NorESM1-M) provided the necessary initial and boundary conditions for the selected RCA4 RCM. Furthermore, another RCM was chosen, namely, the RACMO22E model, which was driven by two GCMs (EC-EARTH and CNRM-CM5). Beside internal climate variability and model physics, the third greatest source of climate model simulations' uncertainty is the applied scenario (Hawkins, E. and Sutton, R. 2009). Therefore, two different RCP scenarios are taken into account in the present study, namely, a scenario with starting mitigation from around 2040, RCP4.5, and a business-as-usual scenario, with no mitigation in the 21st century, RCP8.5 (van Vuuren, D.P. *et al.* 2011). In order to use the same horizontal resolution, HuClim data were interpolated to the same grid as the RCM simulations by the bilinear method. In addition, the area of Hungary was masked in the simulations' fields.

The analysed indices

Three different indices are analysed in this study, describing dry climatic conditions. Depending on the indicators, they were calculated for every grid point for the entire time period (1971–2100), on a monthly, half-year and annual basis. The necessary basic variables for calculating the selected indices were daily precipitation and mean temperature for every grid point.

Severe droughts particularly affect forests and cultivated plants in summer and autumn. We selected a drought indicator, which is simple yet powerful. As a basis, we calculated dry days (DD, when daily precipitation is below 1 mm) first since it correlates moderately or highly with other simple and more complex drought indicators, and precipitation (e.g., Zhuang, Y. *et al.* 2020; Hansel, S. *et al.* 2022). Note that this 1 mm threshold eliminates the drizzle effect (e.g., Polade, S.D. *et al.* 2011), which may have caused a problem in the simulations otherwise. Then, we selected the dry half-years (DHF) of spring and summer together (MAMJJA), when the number of dry days was above the median value of 1971–2020 separately for both spring (MAM) and summer (JJA). Then, the values above the mean value of dry half-years in 1971–2020 were defined as severe droughts (SD), as follows:

$$SD = DHF \mid DHF > mean\ (DHF^{1971–2020}),$$

where $DHF = DD_{MAM} + DD_{JJA} \mid DD_{MAM} > median\ (DD_{MAM}{}^{1971–2020})\ \&\ DD_{JJA} > median\ (DD_{JJA}{}^{1971–2020})$.

We kept this threshold of dry days for the future as well. The resulting time series corresponds well with the lack of precipitation and other drought indices: when there is a high number of dry days, the total precipitation is usually low, while evaporation is high for the MAMJJA period, which is important for the cultivated summer and autumn plants and forests.

The De Martonne Index (DMI) can be determined for different time scales, i.e., years, seasons or months (Gavrilov, M.B. *et al.* 2019). In general, it is applied to a yearly scale, but in this study, a monthly scale was chosen instead, as there are substantial differences between June and August, for instance. The index is calculated for the three summer months separately using the following formula:

$$DMI = \frac{12\,P}{10 + T},$$

where *P* means the monthly precipitation total (mm), and *T* indicates the monthly mean temperature (°C). The results are categorized on the basis of the following thresholds (Milovanovic, B. *et al.* 2022): arid (DMI < 10), semi-arid (10 ≤ DMI < 20), Mediterranean (20 ≤ DMI < 24), semi-humid (24 ≤ DMI < 28), humid (28 ≤ DMI < 35), very-humid (35 ≤ DMI < 55) and extremely humid (55 < DMI). If DMI is greater than 30, the conditions are optimal for forests, moreover, ideal DMI values for beech are between 35 and 40 (Satmari, A. 2010).

Furthermore, the simplified Forestry Aridity Index (FAI – Führer, E. *et al.* 2011) was determined for Hungary, which represents the climate marker species. It can be calculated by the following formula:

$$FAI = 100 \cdot \frac{T_{VII-VIII}}{\Sigma P_{V}^{VII} + \Sigma P_{VII}^{VIII}},$$

where $T_{VII\text{-}VIII}$ means the average temperature in July and August, and indicate the precipitation total from May to July and from July to August, respectively. Five categories can be defined based on different threshold values: beech (FAI < 4.75), hornbeam-oak (4.75 ≤ FAI < 6), sessile oak and Turkey oak (6 ≤ FAI ≤ 7.25), forest-steppe (7.25 < FAI < 8.5), and steppe (8.5 < FAI).

As absolute threshold values are used to distinguish the different categories, bias-correction of the RCM simulations has an important role. In order to eliminate the systematic errors emerging from climate model simulations (Christensen, J.H. *et al.* 2008), a simple bias-correction method was applied to the raw results, based on the relative delta-method. We used the following formula:

$$Index_{corrected}^{future} = \frac{Index_{model}^{future}}{Index_{model}^{past,mean}} \cdot Index_{observation}^{past,mean},$$

where *"past"* refers to the period 2001–2020 regarding the calculation of DMI and FAI, and 1971–2020 regarding severe droughts, *"mean"* indicates the temporal mean, *"model"* denotes the selected individual climate simulation, and *"observation"* is the HuClim database. The correction is executed for each index, each grid point, each RCM simulation and each month (for DMI only) separately. The simple bias correction is applied to the indices instead of the raw simulation output variables in order to avoid possible inconsistency that may emerge if we correct temperature and precipitation separately. Similar approach is widely used in the literature, e.g., Casanueva, A. *et al.* (2014), Rocheta, E. *et al.* (2014).

The study investigates the changes in the past, for which two 20-year-long historical periods, 1971–1990 and 2001–2020, are compared. In order to analyse the projected future changes, the average values for four 20-year-long time periods (2021–2040, 2041–2060, 2061–2080, 2081–2100) are calculated. We used 20-year-long periods instead of the usual 30-year-long periods, hence we could make a comparison within the observation period as well. We note that Wilks, D.S. and Livezey, R.E. (2013) found that using alternative periods is appropriate in the case of temperature, while for precipitation, Kis, A. and Pongrácz, R. (2023) found that the 15-year-long period is capable to represent the variability of the 50-year-long data. We focused only on the summer months (June, July and August) or the spring + summer half-year (from March to August), as water deficit is the most critical in these seasons for cultivated plants and forests. Temperature is higher, evaporation is more enhanced, and at the same time, water is a key mitigation factor, e.g., in the case of heatwaves. Furthermore, several crops need appropriate water supply at this time of the year in order to grow properly.

Results

In the following subsections, our results are presented for each index separately. Maps show the spatial distribution of the indices, averaging the analysed 20 years and all of the selected model simulations, i.e., they present a multi-model mean. However, in order to show the uncertainty emerging from the choice of the model, diagrams are also included, which present the range of the projected changes, indicating the individual climate model simulations and the different scenarios.

Validation

As climate model simulations usually show biases compared to the reference data, a bias-correction method was applied to eliminate the systematic errors for all indicators in this study. In this section, we compare the calculated indices with and without bias-correction, for which HuClim serves as a reference.

Considering the spatial extent of the different DMI categories, we can conclude that raw simulations usually show biases *(Figure 1)*. For example, the very-humid category is well represented in July and August, but an overestimation occurs in June (26% vs. 5%). Raw simulations underestimate the spatial extent of the semi-humid and the humid categories in all three summer months. The Mediterranean category is well represented in July, while an overestimation occurs in June and an underestimation in August. Raw climate model simulations greatly overestimate the spatial extent of the semi-arid category, especially in June and July, when, according to HuClim, no grid point falls to this category.

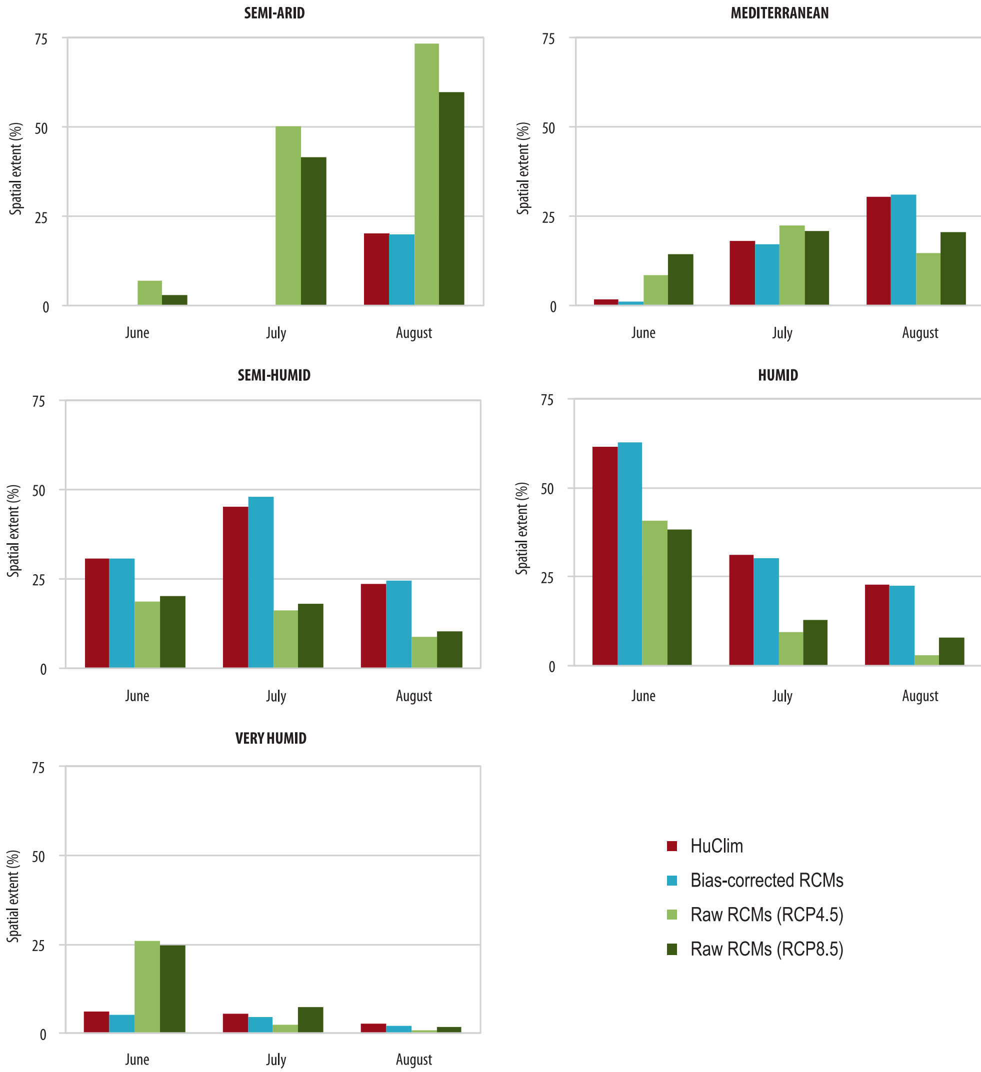

Fig. 1. Validation results of the spatial extent (in %) of DMI for Hungary, 2001–2020, separately for the three summer months, based on the multi-model means of the bias-corrected and the raw climate model simulations compared to the HuClim database.

In the case of FAI, raw climate model simulations overestimate the dry categories, i.e. steppe and forest-steppe (*Figure* 2). At the same time, the sessile-oak and Turkey-oak category is substantially underestimated, namely, the raw simulations show ~20 percent spatial extent, while HuClim and the bias-corrected simulations show ~45 percent.

Severe drought

First, severe droughts in Hungary are presented. Generally, in the last two decades, more precipitation occurred in Hungary over the course of consecutive spring and summer than in 1971–1990, but rain fell on fewer days, which resulted in higher precipitation

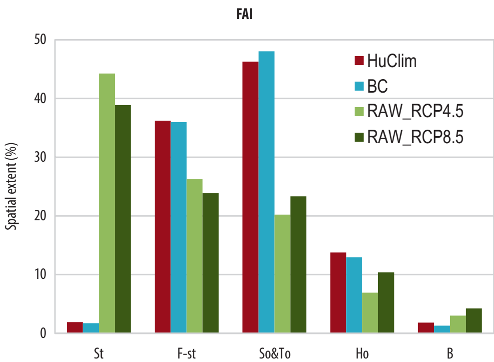

Fig. 2. Validation results of the spatial extent (in %) of the FAI index for Hungary, 2001–2020 based on the multi-model mean of the bias-corrected and the raw climate model simulations compared to the HuClim database. St = Steppe; F-st = Forest-steppe; So&To = Sessile oak and Turkey oak; Ho = Hornbeam oak; B = Beech.

intensity, lower number of wet days, and higher number of dry days. These changes may be unfavourable for plants, as a less intense rainfall infiltrates into the soil more effectively, compared to a very intense precipitation event. Additionally, a substantial increase can be detected in the number of severe droughts if we compare the periods 1971–1990 and 2001–2020 *(Figure 3).* Severe droughts occurred the most often in the north-eastern and western parts of Hungary in the last 20 years, while in 1971–1990, the northern regions were more exposed to the lack of precipitation or higher evaporation. Drought means high risk to forestry and agriculture, as yield losses or even plant destruction may emerge due to water scarcity.

According to the multi-model mean, if the RCP4.5 scenario is followed until the end of the 21st century, a further increase of severe droughts can be avoided, moreover, the frequency of severe droughts may even decrease compared to the observations. In the case of RCP8.5, slightly (significantly) more frequent severe drought is likely to occur in 2041–2060 (2081–2100) compared to the RCP4.5 scenario with intermediate mitigation. Frequency values are the highest in the southern and eastern parts of the country (with currently mostly agricultural areas) in 2041–2060 following the RCP8.5 scenario, while severe droughts occur in the south-western areas (with more forests in this region) in 2081–2100. One may note that the maps based on observations show higher spatial variability than the model means, and that even if we follow the high-emission scenario by the end of the 21st century, frequency values may not be higher than the observations of 2001–2020. This is the consequence of (i) averaging several model means instead of selecting one

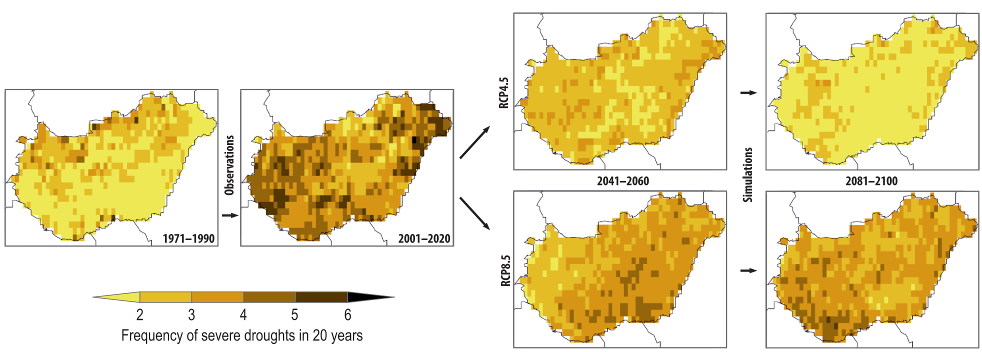

Fig. 3. Spatial distribution of severe drought frequency in Hungary in 1971–1990 and 2001–2020 based on HuClim, and in 2041–2060 and 2081–2100 according to the multi-model mean of the selected climate model simulations, taking into account the RCP4.5 and RCP8.5 scenarios.

particular model simulation, and (ii) the high internal variability of precipitation.

If we analyse the frequency of severe droughts based on the individual model simulations *(Figure 4)*, it can be seen that particularly by 2081–2100 in the case of RCP8.5 the model selection has a great role: the model uncertainty is greater than the model mean itself. In general, the variability between the model simulations is somewhat smaller for the RCP4.5 scenario than RCP8.5. The number of years when severe drought occurs can reach 5, 6 or even 8 within 20 years according to several simulations under the RCP8.5 scenario – this is higher than the mean value for the observed 2001–2020. All in all, there is a high uncertainty in the projection results, but 5 out of 6 models project higher values for RCP8.5 than for RCP4.5 after 2040, and only 1 or 2 models simulate lower values after 2060 than the observations in 2001–2020.

De Martonne Index

In this chapter, results based on the De Martonne Index are shown. We note that the two tails of the categories, which are introduced in Section 2, namely, the arid and the extremely humid categories, cannot be found in Hungary (or only in 1–2 grid points) in the investigated time period.

In general, the wettest month in summer is June in Hungary (~70 mm/month). In this month, the spatial extensions of very-humid and humid categories are reduced for 2001–2020 compared to the period 1971–1990 *(Figure 5)*. Further reductions are projected for 2041–2060 and 2081–2100, according to both RCP scenarios. As a result of these changes, the very-humid category is limited to the western and northernmost parts of Hungary in future time periods. Note that these categories are ideal for forests

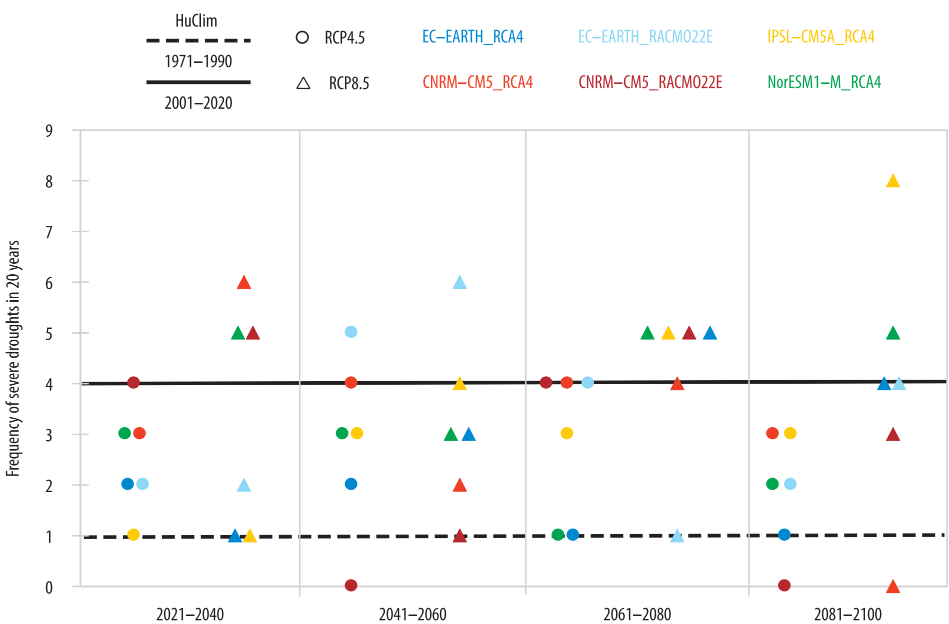

Fig. 4. Projected frequency of severe droughts in Hungary according to the individual RCM simulations (indicated by different colours) taking into account the RCP4.5 (circle) and RCP8.5 (triangle) scenarios. The reference values based on observations are indicated by a dashed (1971–1990) and a solid (2001–2020) black line.

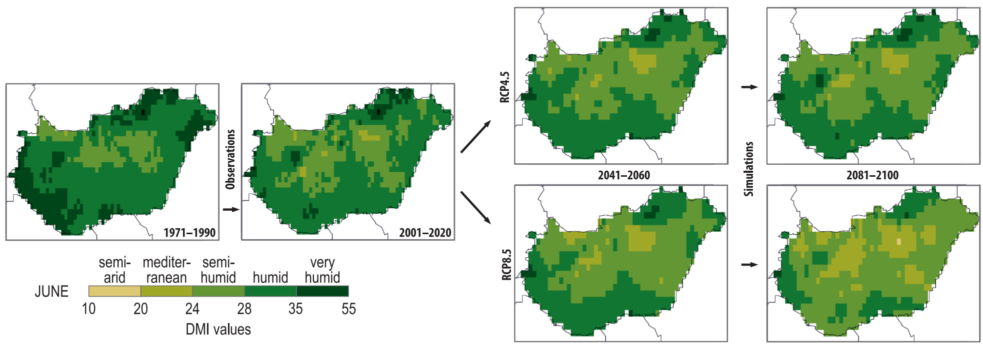

Fig. 5. Spatial distribution of DMI categories in June in Hungary in 1971–1990 and 2001–2020 based on HuClim, and in 2041–2060 and 2081–2100 according to the multi-model mean of the selected climate model simulations, taking into account the RCP4.5 and RCP8.5 scenarios.

(30 < DMI), and climatic conditions are appropriate for beech within the very-humid category (DMI: 35–40). In general, DMI is greater than 24 in June, however, the Mediterranean category appears in more grid cells in the future time periods, especially in the case of RCP8.5 by the end of the 21st century in the lowland areas. Moreover, even the semi-arid category (which was not present at all earlier) appears in one grid cell.

July is generally warmer and drier in Hungary than June. Consequently, dominantly lower DMI values occurred in July in 1971–1990 in the central parts of Hungary, while DMI was greater than 20 in 2001–2020 in every grid point *(Figure 6).* So on the basis of the observations, substantial changes can be recognized within the historical period, namely, the spatial extent of humid categories increased. In the future, similar values and spatial patterns are projected for 2041–2060 to 2001–2020 regardless of the applied scenario: humid and very-humid conditions in the north-eastern and westernmost parts of Hungary, the Mediterranean category occurring in the southern and north-western areas, and semi-humid grid cells in the central regions. However, there are likely to appear substantial differences by 2081–2100 between the simulations under RCP4.5 and RCP8.5. More specifically, in the case of the RCP4.5 scenario, the spatial distribution of the categories of DMI are very similar to 2001–2020, but if RCP8.5 is taken into account, semi-arid category appears in the south-eastern, central-eastern parts of Hungary and in the north-western lowland region. Furthermore, the Mediterranean category expands substantially, while humid and very-humid grid cells will be found only in the westernmost and northernmost regions.

In August, in the Great Hungarian Plain the dominant DMI category is semi-arid in 1971–1990, and it will be in the whole country in the future time periods *(Figure 7).* However, in 2001–2020 a small reduction appears in this drier category, while the Mediterranean category occupies a greater area. A west-east gradient can be identified in all of the investigated periods, namely, there are higher DMI values in the western parts of the country (humid and very-humid), and heading towards the east, DMI decreases, until it reaches the semi-arid category. So, the spatial distribution of DMI categories is very similar for the two different scenarios, however, there are differences in the spatial extent of each category: in the case of RCP8.5, the area of the humid category is very limited, while semi-arid expands to the northern and western regions.

Figure 8 summarizes the future spatial extent of the different DMI categories for each of the three summer months, based on the individual climate model simulations.

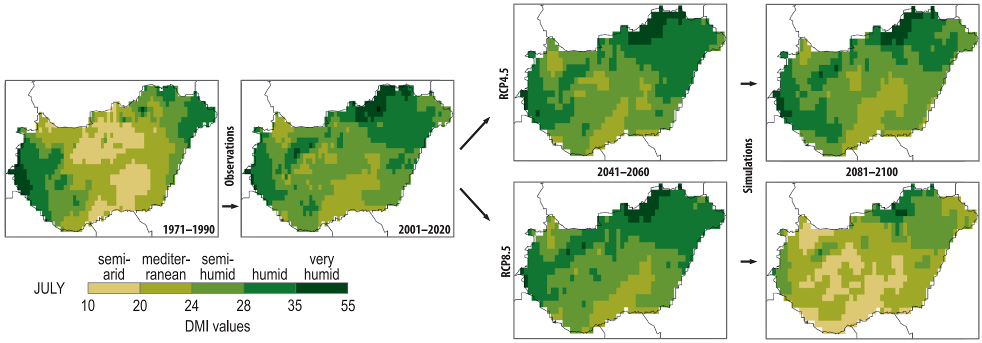

Fig. 6. Spatial distribution of DMI categories in July in Hungary in 1971–1990 and 2001–2020 based on HuClim, and in 2041–2060 and 2081–2100 according to the multi-model mean of the selected climate model simulations, taking into account the RCP4.5 and RCP8.5 scenarios.

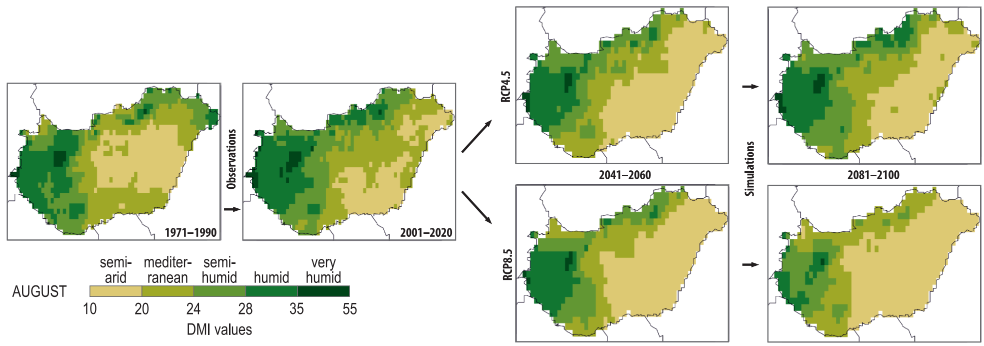

Fig. 7. Spatial distribution of DMI categories in August in Hungary in 1971–1990 and 2001–2020 based on HuClim and in 2041–2060 and 2081–2100 according to the multi-model mean of the selected climate model simulations, taking into account the RCP4.5 and RCP8.5 scenarios.

The semi-arid category is clearly the most dominant in August. According to the majority of the simulations, an increasing trend is projected for the future in the spatial extent of this dominant category, which can reach even 70–80 percent by the end of the 21st century, based on RCP8.5. In July, only a few simulations (under the RCP8.5 scenario) imply an increase compared to the period 1971–1990. In June, the spatial extent of the semi-arid category is almost negligible, but there are some individual simulations that project a substantial increase for 2081–2100.

The simulated changes of the Mediterranean category are different in the three summer months. In general, an increase is projected for June, a decrease for August, and a quasi-stationary state for July (or more precisely, the sign of the change depends on which historical period provides the reference). In the case of the semi-humid category, the range of the model uncertainty is smaller, and there is no discrepancy between the two scenarios. Similar to the Mediterranean category, an increase (decrease) is likely to occur in the spatial extent in June (in August), while the predicted change in July depends on the reference period. The humid category is projected to decrease in June according to almost all the simulations under both scenar-

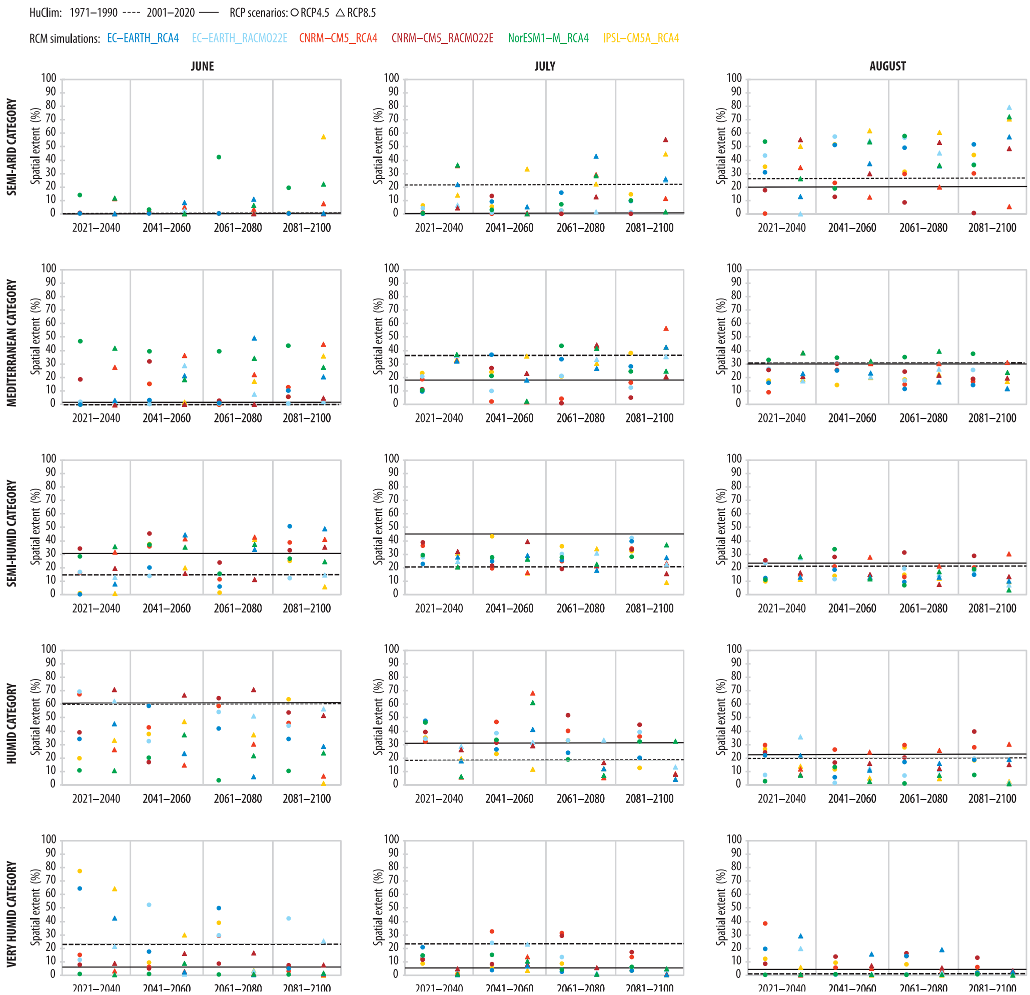

Fig. 8. Projected DMI categories in Hungary in June, July and August, according to the individual RCM simulations (represented by different colours) taking into account the RCP4.5 (circle) and RCP8.5 (triangle) scenarios. The reference values based on observations are indicated by a dashed (1971–1990) and a solid (2001–2020) black line.

ios: in some periods, its spatial extent will become less than 10 percent according to some of the individual simulations. In August, a decrease is projected in general too, but we note that this category has a smaller ratio in the historical periods (~20%), so the relative changes are also smaller. In July, an increase in the spatial extent of the humid category can occur in the middle of the 21st century. The very-humid category's spatial extent is projected to be smaller as we are heading to the future in all three months.

Forestry Aridity Index

Finally, the results related to the FAI are presented. In the historical periods, ideal conditions for hornbeam oak appeared in the western parts of Hungary and in the northern, mountainous areas *(Figure 9).* Beech can be

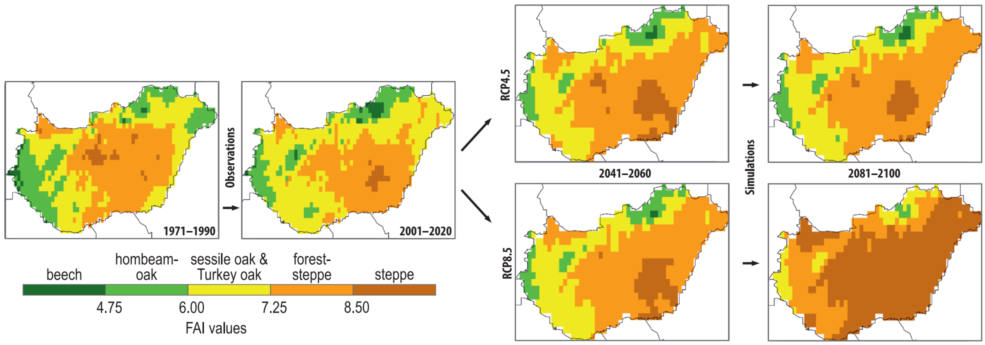

Fig. 9. Spatial distribution of FAI categories in Hungary in 1971–1990 and 2001–2020 based on HuClim, and in 2041–2060 and 2081–2100 according to the multi-model mean of the selected climate model simulations, taking into account the RCP4.5 and RCP8.5 scenarios.

found also in these regions, but its extent is much smaller. Forest-steppe is the dominant category in the central parts of the country and also in the north-western lowlands. The change of the distribution of FAI in the last 50 years in Hungary is unfavourable, and its cause is primarily the increasing temperature (Führer, E. 2017). For 2041–2060, the two applied scenarios show similar changes: beech is likely to disappear from the western regions, while steppe is projected to expand in the south-eastern parts of the Hungarian Great Plain. By the end of the 21st century, in the case of RCP4.5 the simulated changes are very similar to the period 2041–2060. However, if we take into account the RCP8.5 scenario, the spatial distribution of FAI categories is substantially different. Specifically, beech is predicted to disappear entirely from Hungary and hornbeam oak will be limited to a small area in the northern mountains of the country. The extent of sessile oak and Turkey oak reduces, while forest-steppe will appear in the western and northern parts of Hungary. The lowland areas are projected to be steppe, which will be the dominant FAI category in Hungary according to the simulations used in this study.

Figure 10 presents the relative spatial extent of each FAI category based on the individual climate model simulations. The greatest changes can be seen in the case of steppe, for which the spatial extent was smaller than 5 percent in the historical periods, while in 2081–2100, it is 52 percent on average (with one extremely high simulated value, i.e., 93%) under the RCP8.5 scenario. The other substantial change is projected for beech, whose spatial extent was already low in the historical periods (< 2%), but it can even disappear from the area of Hungary by the end of the 21st century under RCP8.5. The projected relative extent of forest steppe varies between 30 and 40 percent according to the multi-model mean, which is similar to the values of the historical period. The number of grid cells, which is suitable for sessile and Turkey oak, generally shows a decreasing trend compared to the historical period, especially in the case of RCP8.5 by 2061–2080 and 2081–2100. The spatial extent of hornbeam oak is also likely to be smaller in the future periods, according to most of the simulations; it is projected to be less than 4 percent in the last two 20-year-long periods in the 21st century if RCP8.5 is taken into account.

Discussion

Raev, I. *et al.* (2015) defined the vulnerability of forests in relation to the value of DMI for Bulgaria, where the current climate is not

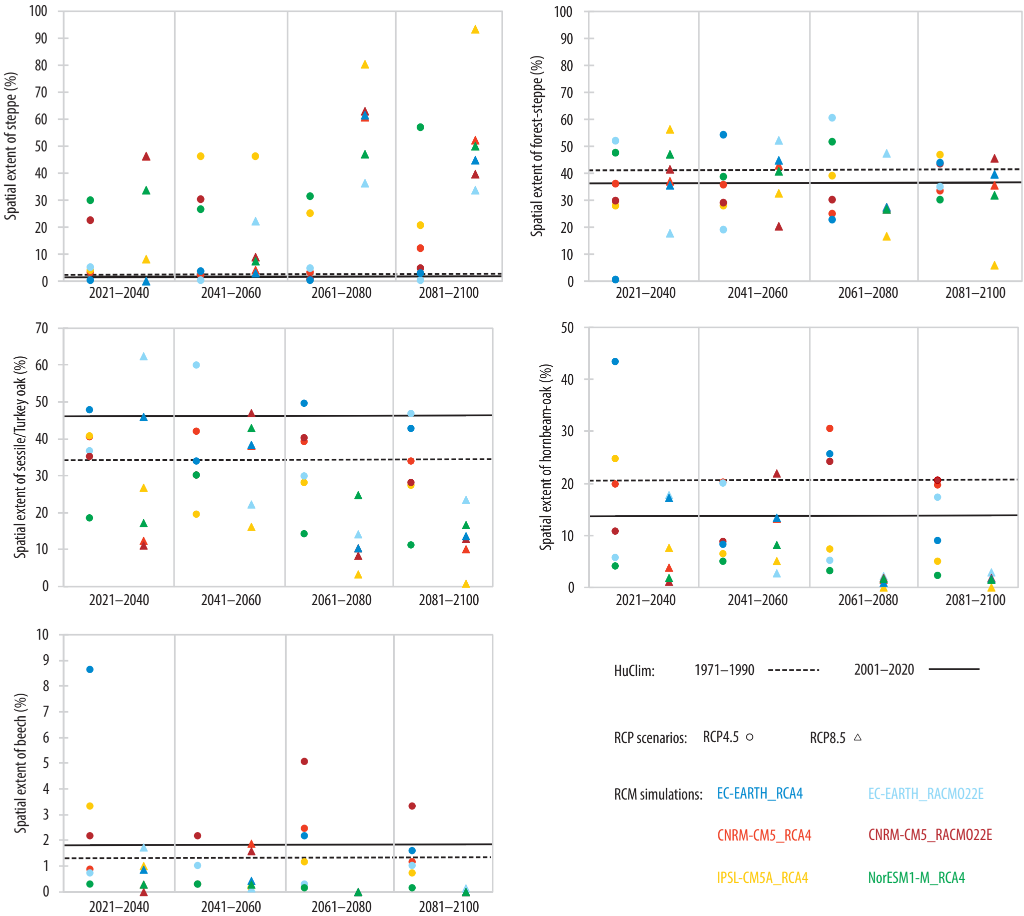

Fig. 10. Projected FAI categories in Hungary according to the individual RCM simulations (indicated by different colours) taking into account the RCP4.5 (circle) and RCP8.5 (triangle) scenarios. The reference values based on observations are indicated by a dashed (1971–1990) and a solid (2001–2020) black line.

very different from Hungary even though the location is somewhat to the southeast relative to Hungary. In the current climate most of the forests fall into the "high" to "medium" vulnerability category (DMI: 25–35), but in the future, the dominant category will be "high" (DMI: 25–30) in the case of RCP2.6 and RCP4.5, and "very high" (DMI: 10–25) if RCP8.5 is taken into account. So similarly to Hungary (based on our results), drier DMI categories are likely to expand in Bulgaria as well, which is unfavourable for forests (DMI < 30). The possible shift of DMI towards drier categories implies that adaptation strategies must be planned in sectors where water is essential, e.g., agriculture. As an example, the study of Paltineanu, Cr. *et al.* (2007) can be mentioned that used DMI values for an agricultural application, namely, the relationship between DMI and irrigation demand is analysed for different crops in Romania. The results show that irrigation is usually needed in those regions, where DMI is below 35. Evidently, the smaller the DMI value, the more water is needed for irrigation. These small values are projected to dominate the majority of the Great Hungarian Plains by the late 21st century, for which stakeholders in agriculture must plan ahead, and develop their own adaptation strategies to handle the changing conditions. This is especially important because the lack of precipitation is already a problem in the region: a questionnaire completed by Biró, K. *et al.* (2021) in Hungary showed that more than 60 percent of the responders experienced decreased productivity due to drought periods. Moreover, according to the analysis of Buzási, A. *et al*. (2021) there are already three counties in Hungary that are highly vulnerable, but poorly prepared for droughts.

Although Móricz, N. *et al.* (2013) used a different and only one single climate model to calculate the Ellenberg Index, they also concluded that beech forests are likely to disappear almost entirely from Hungary by the end of the 21st century, moreover, the ideal area for sessile oak is projected to be shrunken. Similarly to these conclusions, our results also show that the extent of sessile oak and Turkey oak reduces, while forest-steppe will appear in the western and northern parts of Hungary.

In our study, newer model simulations and scenarios (RCPs) were taken into account, but the main conclusions are fostered by former results as well. More specifically, based on 12 RCM simulations taking into account the SRES A1B emission scenario (which is between RCP4.5 and RCP8.5), Führer, E. *et al.* (2017) concluded that in the 21st century, forest-steppe will expand, while the other three categories are likely to be shrunken – furthermore, a new category, called steppe (FAI > 8.5), is introduced, which is projected to appear in Hungary in the southern regions. The study of Führer, E. *et al.* (2011) investigated FAI separately for the Transdanubian region in Hungary, and showed that only 10 percent of beech will remain in summer and the relative spatial extent of hornbeam oak will be half as much as in the reference period, while forest-steppe will occupy an area four times greater than in the past few decades.

The potential risk of drought on forests was also highlighted by Hlásny, T. *et al.* (2014), who used 10 RCM simulations taking into account the above-mentioned SRES A1B emission scenario, and projected a warming with drying trend for Hungary. However, such drought risk is present not only in Hungary, but also elsewhere in Central Europe. For instance, the future distribution of forests was analysed for Serbia on the basis of FAI (Stojanovic, D.B. *et al.* 2014). According to their results, more arid conditions are likely to occur in the investigated region in the future, and therefore, the most vulnerable among the currently present tree species is Pedunculate oak due to climate change.

The Hungarian foresters are dominantly aware of the effects of the projected climate change according to an interview-based study (i.e., Jankó, F. *et al.* 2022), however, the number of respondents who have already initiated adaptations is rather low. These applied adaptations so far include changing the composition of the forest area. The study showed that there is an agreement to enhance forest diversity and eliminate monoculture. The international survey of Sousa-Silva, R. *et al.* (2018) also concluded that stakeholders in forestry think that climate change will affect forests, but only 36 percent of foresters modified their management practices.

Conclusions

Different climate indices related to drought are calculated for Hungary, based on the HuClim observations and six climate model simulations, taking into account the RCP4.5 and RCP8.5 scenarios. As water deficit can be critical, especially if it is combined with high temperature values, spring and summer months are investigated. According to our results, the following conclusions can be drawn:

– Generally, more precipitation fell on fewer days in Hungary during spring and summer in the last two decades than in 1971–1990.
– According to the multi-model mean, a further increase of severe droughts can be avoided if we follow the RCP4.5 scenario,

while in the case of RCP8.5 severe droughts are likely to occur more frequently.
- In June, the very-humid category of DMI (which can be ideal for beech) will be limited to the western and northernmost parts of Hungary in the future time periods according to the simulations.
- In July, semi-arid and Mediterranean categories will be dominant by the end of the 21st century under the RCP8.5 scenario.
- In August, the semi-arid DMI category will clearly become the most dominant category, reaching even 70–80 percent spatial extent by the end of the century, based on RCP8.5.
- FAI shows that the steppe category will be the dominant category in Hungary by 2100, while the beech optimum could disappear entirely from around 2060 according to the RCP8.5 scenario.

The overall projected drying trend in Hungary implies that water management should focus on retaining water, as it is critically essential for drinking water supply, agriculture, and therefore, reliable food supply, ecosystems, forests and natural vegetation. If we can store water surplus either from excessive, high-intensity rainfalls or from wet years or during autumn and winter, it can be usefully exploited in drought periods or in periods with higher evaporation. Furthermore, because of the changing climatic conditions, the plantation of drought-tolerant species (both in agriculture and forestry) should be considered in regional/national adaptation strategies. Adaptation could mean a more diverse tree species mixture and the introduction of new species which are more adaptable to the changing climate, but more information on these species would be necessary for better forest management. Irrigation may also be a solution to water scarcity, however, the availability of water may be a limiting factor. Thinning forests can reduce fire risk and increase the health and growth of the remaining trees (Vilá-Cabrera, A. *et al.* 2018).

In the case of agriculture, climate-smart agriculture tools (e.g., bio innovation such as plant breeding, development of new seeds, or precision agriculture by effectively reducing impacts) can foster both adaptation and mitigation (Biró, K. *et al.* 2021). These are key elements for future strategies, since in addition to the necessary adaptation, agriculture also must contribute to global mitigation efforts, as some anthropogenic emissions are associated with agricultural activity.

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REFERENCES

Biró, K., Szalmáné Csete, M. and Németh, B. 2021. Climate-smart agriculture: Sleeping beauty of the Hungarian agribusiness. *Sustainability* 13. 10269. Available at https://doi.org/10.3390/su131810269

Buzási, A., Pálvölgyi, T. and Esses, D. 2021. Drought-related vulnerability and its policy implications in Hungary. *Mitigation and Adaptation Strategies for Global Change* 26. 11(2021). Available at https://doi.org/10.1007/s11027-021-09943-8

Casanueva, A., Frías, M.D., Herrera, S., San-Martín, D., Zaninovic, K. and Gutiérrez, J.M. 2014. Statistical downscaling of climate impact indices: testing the direct approach. *Climatic Change* 127. 547–560. Available at https://doi.org/10.1007/s10584-014-1270-5

Christensen, J.H., Boberg, F., Christensen, O.B. and Lucas-Picher, P. 2008. On the need for bias correction of regional climate change projections of temperature and precipitation. *Geophysical Research Letters* 35. L20709. Available at https://doi.org/10.1029/2008GL035694

Copernicus Climate Change 2022. *Seasonal review: Europe's record-breaking summer*. Climate Change Service, ECMWF. Available at https://climate.copernicus.eu/seasonal-review-europes-record-breaking-summer

Führer, E., Horváth, L., Jagodics, A., Machon, A. and Szabados, I. 2011. Application of a new aridity index in Hungarian forestry practice. *Időjárás* 115. (3): 205–216.

Führer, E., Gálos, B., Rasztovits, E., Jagodics, A. and Mátyás, Cs. 2017. Erdészeti klímaosztályok területének várható változása (Expectable changes in the area of forest climate classes). *Erdészeti Lapok* 152. (6): 174–177.

Führer, E. 2017. Az erdészeti klímaosztályok új lehatárolása öko-fiziológiai alapon (New way of separation of forest climate classes on eco-physiological basis). *Erdészeti Lapok* 152. (6): 173–174.

Gavrilov, M.B., Lukic, T., Janc, N., Basarin, B. and Markovic, S.B. 2019. Forestry Aridity Index in Vojvodina, North Serbia. *De Gruyter, Open Geosciences* 11. 367–377. Available at https://doi.org/10.1515/geo-2019-0029

Hansel, S., Hoy, A., Brendel, C. and Maugeri, M. 2022. Record summers in Europe: Variations in drought and heavy precipitation during 1901–2018. *International Journal of Climatology* 42. (12): 6235–6257. Available at https://doi.org/10.1002/joc.7587

Hawkins, E. and Sutton, R. 2009. The potential to narrow uncertainty in regional climate predictions. *Bulletin of the American Meteorological Society* 90. (8): 1095–1108. Available at https://doi.org/10.1175/2009BAMS2607.1

Hlásny, T., Mátyás, Cs., Seidl, R., Kulla, L., Merganicová, K., Trombik, J., Dobor, L., Barcza, Z. and Konopka, B. 2014. Climate change increases the drought risk in Central European forests: What are the options for adaptation? *Lesnicky Casopis / Forestry Journal* 60. 5–18. Available at https://doi.org/10.2478/forj-2014-0001

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*. Eds.: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. and Zhou, B., Cambridge, UK and New York, USA, Cambridge University Press, 3–32. Available at https://doi.org/10.1017/9781009157896.001

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B. and Yiou, P. 2014. EURO-CORDEX: New high-resolution climate change projections for European impact research. *Regional Environmental Change* 14. 563–578. Available at https://doi.org/10.1007/s10113-013-0499-2

Jankó, F., Bertalan, L., Pappné Vancsó, J., Németh, N., Hoschek, M., Lakatos, M. and Móricz, N. 2022. Seeing, believing, acting: Climate change attitudes and adaptation of Hungarian forest managers. *iForest* 15. (6): 509–518. Available at https://doi.org/10.3832/ifor3958-015

Kis, A. and Pongrácz, R. 2023. Analyzing the influences of the selection of the RCP scenario and the reference period on the evaluation results of EURO-CORDEX simulations for Hungary. *International Journal of Climatology* 1–19. Available at https://doi.org/10.1002/joc.8184

Milovanovic, B., Schubert, S., Radovanovic, M., Vakanjac, V.R. and Schneider, C. 2022. Projected changes in air temperature, precipitation and aridity in Serbia in the 21st century. *International Journal of Climatology* 42. (1): 1985–2003. Available at https://doi.org/10.1002/joc.7348

Móricz, N., Rasztovits, E., Gálos, B., Berki, I., Eredics, A. and Loibl, W. 2013. Modelling the potential distribution of three climate zonal tree species for present and future climate in Hungary. *Acta Silvatica & Lignaria Hungarica* 9. (1): 85–96.

Paltineanu, Cr., Tanasescu, N., Chitu, E. and Mihailescu, I.F. 2007. Relationships between the De Martonne aridity index and water requirements of some representative crops: A case study from Romania. *International Agrophysics* 21. (1): 81–93.

Polade, S.D., Pierce, D.W., Cavan, D.R., Gerchunov, A. and Dettinger, M.D. 2014. The key role of dry days in changing regional climate and precipitation regimes. *Scientific Reports* 4. 4364. Available at https://doi.org/10.1038/srep04364

Raev, I., Alexandrov, V. and Tinchev, G. 2015. Assessment of drought related climate change impacts on forests in Bulgaria. *Silva Balcanica* 16. (1): 5–24.

Rocheta, E., Evans, J.P. and Sharma, A. 2014. Assessing atmospheric bias correction for dynamical consistency using potential vorticity. *Environmental Research Letters* 9. 124010. Available at https://doi.org/10.1088/1748-9326/9/12/124010

Satmari, A. 2010. *Lucrări Practice de Biogeografie* (Practical applications of biogeography). Timişoara, Eurobit. Available at: http://www.academia.edu/9909429/05_indici_ecometrici

Sousa-Silva, R., Verbist, B., Lomba, A., Valent, P., Suskevics, M., Picard, O., Hoogstra-Klein, M.A., Cosofret, V-C., Bouriaud, L., Ponette, Q., Verheyen, K. and Muys, B. 2018. Adapting forest management to climate change in Europe: Linking perceptions to adaptive responses. *Forest Policy and Economics* 90. (5): 22–30. Available at https://doi.org/10.1016/j.forpol.2018.01.004

Stojanovic, D.B., Matovic, B., Orlovic, S., Krzic, A., Trudic, B., Galic, Z., Stojnic, S. and Pekec, S. 2014. Future of the main important forest tree species in Serbia from the climate change perspective. *South-east European Forestry* 5. (2): 117–124. Available at http://dx.doi.org/10.15177/seefor.14-16

Szabó, P. and Szépszó, G. 2016. Quantifying sources of uncertainty in temperature and precipitation projections over different parts of Europe. In *Mathematical Problems in Meteorological Modelling: Mathematics in Industry*. Eds.: Bátkai, A., Csomós, P., Faragó, I., Horányi, A. and Szépszó, G., Cham, CH, Springer International Publishing, 207–237. Available at https://dx.doi.org/10.1007/978-3-319-40157-7_12

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J. and Rose, S.K. 2011. The representative concentration pathways: An overview. *Climatic Change* 109. (5): 5–31. Available at https://doi.org/10.1007/s10584-011-0148-z

Vilá-Cabrera, A., Coll, L., Martínez-Vilalta, J. and Retana, J. 2018. Forest management for adaptation to climate change in the Mediterranean basin: A synthesis of evidence. *Forest Ecology and Management* 407. 16–22. Available at http://dx.doi.org/10.1016/j.foreco.2017.10.021

Wilks, D.S. and Livezey, R.E. 2013. Performance of alternative "normals" for tracking climate changes, using homogenized and non-homogenized seasonal U.S. surface temperatures. *Journal of Applied Meteorology and Climatology* 52. 1677–1687. Available at https://doi.org/10.1175/JAMC-D-13-026.1

WMO 2021. *2021 State of Climate Services. Water.* WMO-No. 1278. Geneva, CH, World Meteorological Organization. Available at https://library.wmo.int/doc_num.php?explnum_id=10826

WMO 2022. *WMO Provisional State of the Global Climate 2022*. Geneva, CH, World Meteorological Organization. Available at https://library.wmo.int/doc_num.php?explnum_id=11359

Zhuang, Y., Fu, R. and Wang, H. 2020. Large-scale atmospheric circulation patterns associated with U.S. great plains warm season droughts revealed by self-organizing maps. *Journal of Geophysical Research: Atmospheres*. 125. e2019JD031460. Available at https://doi.org/10.1029/2019JD031460