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Increasing available water capacity as a factor for increasing drought resilience or potential conflict over water resources under present and future climate conditions

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ABSTRACT

The close relationship between the onset and severity of agricultural and hydrological drought is considered self-evident, yet relatively few studies have addressed the effects of applying agricultural drought adaptation to hydrological drought characteristics. The present study applies a model cascade capable of simultaneously considering the interactions between agricultural and hydrological droughts. The study area covers all river basins in the Czech Republic and includes the periods of 1956–2015 (baseline) and 2021–2080 (future). The model cascade was shown to explain 91% of the variability in the seasonal and annual accumulated runoff and allows for the analysis of increasing/maintaining/decreasing available water capacity (AWC) across the 133 defined basins with a total area of *c.* 78,000 km^2. The study reports that the probability and extent of agricultural drought increased over the entire period with higher AWC scenario showing slower pace of such increase especially from April to June. The trends in the extent or severity of hydrological droughts were of low magnitude. The future climate has been projected through the use of ensembles of five global (CMIP5) and five regional (EURO-CORDEX) climate models. The results showed a significant increase in the duration of agricultural drought stress and in the area affected throughout the year, particularly in July–September. The hydrological drought response showed a marked difference between areas with a negative and positive climatic water balance, i.e., areas where long-term reference evapotranspiration exceeds long-term precipitation (negative climatic water balance) and where it does not (positive climatic water balance). The overall results indicate that increasing soil AWC would decrease the frequency and likely also impact of future agricultural droughts, especially during spring. This result would be especially true if the wetter winters predicted by some of the models materialized. Hydrological droughts at the country level are estimated to become more pronounced with increasing AWC, particularly in catchments with a negative climatic water balance.

1. Introduction

Drought is a major threat among natural hazards as it impacts people's livelihood and socioeconomic development and is considered a multifaceted phenomenon (e.g., Wilhite and Pulwarty, 2017). Compared to hazards such as floods, drought tends to occur less

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frequently, but when it does occur, it generally affects a broad region for seasons or years (UNISDR, 2009). The drought episodes in Russia in 2010 (Trenberth and Fasullo, 2012; Shmakin et al., 2013), the USA in 2011–2012 (Hoerling et al., 2014), China in 2013 and Brazil in 2014 were, for each particular year, among the 10 natural disasters with the highest recorded damage worldwide (Munich Re, 2015). The most recent 2015–2020 drought episode significantly affected agriculture, forest and water resources across much of central Europe e.g. European drought observatory, https://www.copernicus.eu/en/european-drought-observatory(EDO, 2021).

Meteorological drought originates from a deficiency of precipitation over an extended period of time and can result in impacts within weeks in the case of agricultural drought or within longer time periods in the case of hydrological drought (e.g., Brázdil and Trnka, 2015; van Loon, 2015; Wilhite and Pulwarty, 2017). The deficiency can result in water shortages for some activities, groups, or environmental sectors (e.g., Blauhut et al., 2016). In this study we understand agricultural droughts as a deficit of soil moisture (mostly in the root zone), reducing the supply of moisture to vegetation (similar to "soil moisture drought" as understood e.g. by van Loon, 2015). As hydrological drought we understand negative anomalies in surface and subsurface water flow and storage that result into below-normal groundwater levels or water levels in lakes, declining wetland area, and decreased river discharge.

In recent years, severe drought events with different degrees of intensity affected more than 800,000 km^2 of the EU's territory (37%) and at least 100 million inhabitants (20%). The EU countries, Austria, Belgium, the Czech Republic, Cyprus, Finland, France, Germany, Hungary, Italy, Lithuania, Malta, the Netherlands, Norway, Portugal, Spain and the United Kingdom have been hit with the economic impacts of drought, with estimated losses of 60 billion Euros over the 1980–2017 period (EC, 2018). The single most damaging drought and heat event across EU countries was the summer of 2003, with estimated damage of 15 billion Euros, which were mostly uninsured (EC, 2018), i.e., the financial impacts on various sectors were not mitigated beyond ad hoc assistance from individual EU member states.

The water shortage in Europe is an important problem in many regions (Vogt and Somma, 2000), and estimates for the 21st century show increasing drought occurrence and severity across most of the European continent (e.g., Samaniego et al., 2018; Grillakis, 2019), including central Europe (e.g., Dai, 2013; Trnka et al., 2013). The first sector affected by drought is usually agriculture, which is particularly sensitive to changes in drought occurrence during the early growing season, i.e., April–June in central Europe (Hlavinka et al., 2009). This is crucial for both the productivity of managed ecosystems (e.g., rain fed field crops) and the net primary production of ecosystems as a whole. This period was usually wet due to snow melt saturating the soil profile just prior to the beginning of the growing season. This condition allowed for the maximum use of the soil storage capacity in the following months and provided vegetation with significant reserve buffering for the naturally high rain variability. However, this is no longer the case due to both the observed and expected decline in snow cover (Trnka et al., 2011) coupled with a marked decrease in the soil water holding capacity during recent years (e.g., Trnka et al., 2016a). In particular, the latter process has intensified the impact of the increasing frequency of meteorological droughts (Trnka et al., 2016b). The increases in temperature, solar radiation, water vapor pressure deficit and stagnating precipitation (Trnka et al., 2015) have contributed to the drying of the soil across the Czech Republic. At the same time, the soil available water capacity (AWC) decreased due to chronic erosion and soil compaction, exacerbating the problems caused by climatic trends (Trnka et al., 2016a). This phenomenon could help explain the marked increase in the sensitivity of agriculture to drought observed over the past century (e.g., Trnka et al., 2012, 2016c) and is a reason for concerns for the coming decades due to the expected increasing frequency of droughts (e.g., Hanel et al., 2012; Hanel and Vizina, 2013; Trnka et al., 2013). As a result, efforts to restore the AWC of agricultural soils have been initiated to at least partly alleviate the problem of agricultural drought. Changing the water holding capacity and retaining water to be evaporated by or transpired through agricultural crops might, however, significantly alter other elements of the landscape water balance. Existing studies in a number of catchments in central Europe project relatively small annual changes in the reference evapotranspiration (ETo) and the precipitation despite considerable changes in the seasonal distribution of precipitation and overall increase in ETo. This situation corresponds to high impact scenarios (e.g., Hanel et al., 2012, 2013a). This finding suggests that increasing of water accumulation capacity is the best adaptation strategy to maintain sufficient river flow, as it could store excess water from generally wet winter months for summer when water availability is decreasing. Any formulation of the national policies aimed at mitigating agricultural and hydrological droughts should consider key processes in both the soil profiles as well as the surface and underground reservoirs. The need for such integrated analysis was pointed out in a recent survey and was indicated as priority research by Trnka et al. (2018).

This study aims to test the hypothesis that increasing the soil water holding capacity will enhance landscape resilience to agricultural drought without making worse the frequency, duration and area affected by the hydrological droughts. In this paper, we (i) introduce modelling cascade simultaneously considering agricultural and hydrological drought, (ii) test the new tool during the 1956–2015 baseline period, (iii) use a bias-corrected ensemble of regional climate models (RCMs) and global climate models (GCMs) to estimate the consequences of mitigating agricultural drought via increased soil water holding capacity on the future frequency and severity of hydrological droughts, and finally (iv) test the initial hypothesis defined above.

2. Data and methods

2.1. Meteorological data

Daily precipitation, temperature, sunshine duration, global radiation, air humidity and wind speed data from 268 climatological and 787 rain-gauge stations over the Czech Republic (CR) were quality controlled and homogenized for the 1956–2015 period. The daily data were interpolated by the regression kriging method using geographical coordinates, elevation and other terrain characteristics as predictors. In the CR, the mean minimal distance between two neighboring stations is approximately 17 km for the elements measured at climatological stations and approximately 10 km for rain gauges (Fig. 1). The daily global radiation balance accounts for the slope, aspect and horizon obstruction using the methodology proposed and tested by Schaumberger (2005).

2.2. Soil moisture

The soil moisture content expressed as relative available water (AWR) was estimated using the SoilClim model (Hlavinka et al., 2011), which is principally based on the modeling approach suggested by Allen et al. (1998). AWR values were constrained by the wilting point i.e. water content at -1500 kPa suction pressure (AWR = 0) and field capacity i.e. water content at -33 kPa suction pressure (AWR = 1). The SoilClim model was applied for each 500 m x 500 m grid and accounted not only for the maximum AWC within the grid but also for the type of vegetation cover, phenology development, root growth or snow cover accumulation/melting (Trnka et al., 2010). The module for actual evapotranspiration (*ETa*) and soil water content estimates considers two soil layers: the topsoil layer (from the ground surface to 0.4 m depth) and the subsoil layer (between 0.41 and 1.0 m). The cascading approach for transferring water from the topsoil to subsoil layers is used when the topsoil is more than 50% saturated. In the case of higher than 50% saturation in the topsoil, seepage to the subsoil is allowed, mimicking macropores and preferential water transport (Hlavinka et al., 2011).

The SoilClim estimates of the soil moisture content are affected by AWC for both soil layers in each grid. The AWC value was estimated

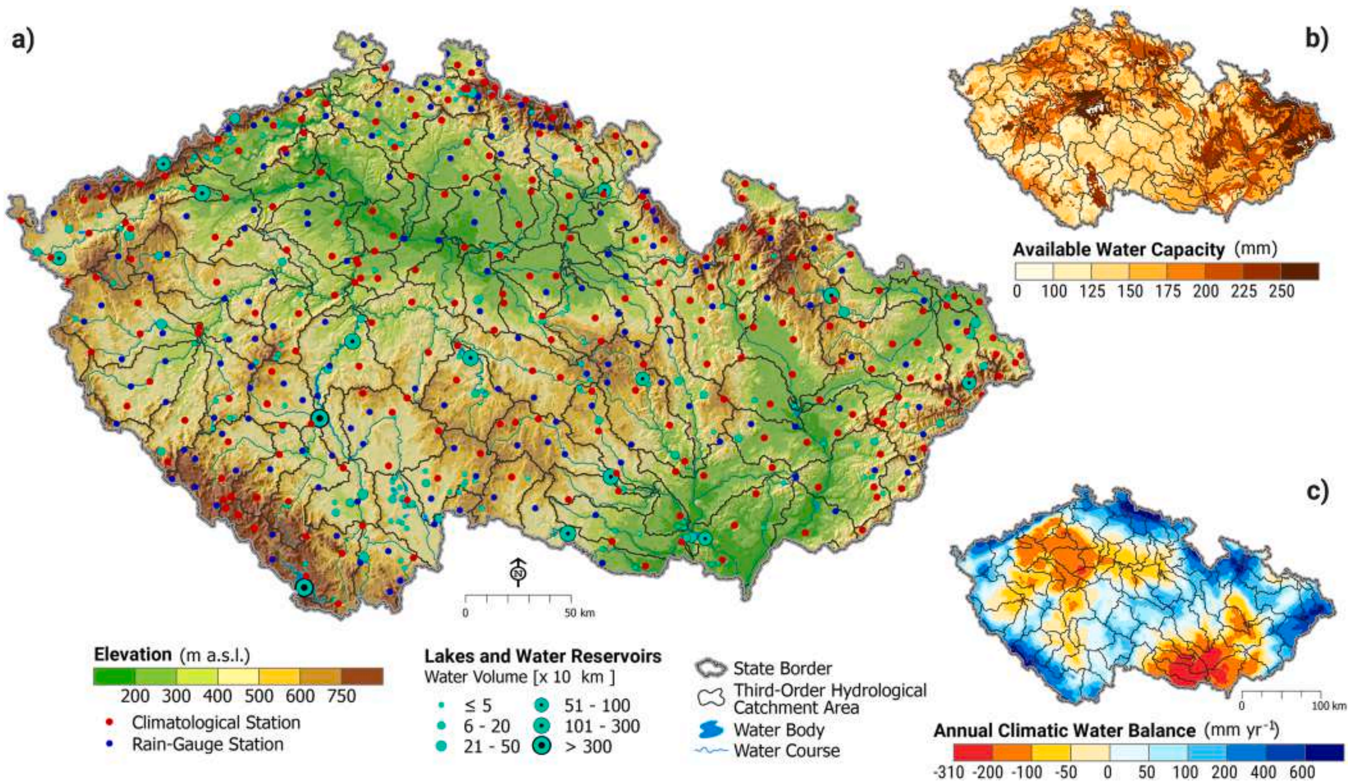

Fig. 1. a) The physical-geographical map of the Czech Republic with the network of climatological and rain-gauge stations and with lakes; b) the map of the available water capacity (AWC) in the first 1 m of the soil used in the SoilClim modeling; c) climatic water balance expressed as the mean difference between annual mean precipitation and reference evapotranspiration during the 1961–2015 period.

through a combination of digital soil maps and detailed soil physics data from 1073 soil pits collected by the Czech National Soil Survey (more details in Trnka et al., 2015). The AWC was calculated assuming a 1.0 m soil profile unless the soil database indicated a shallower soil depth. The topsoil (0–0.4 m) and subsoil (0.41–1.0 m or maximum rooting depth when it was shallow) layers had their properties defined separately based on the available soil data. In addition, grids in which at least some part of the vegetation season was influenced by high underground water tables (that are likely to be reached by roots for natural subsurface irrigation) and therefore respond to drought differently (in terms of both the stress magnitude and timing) were compared to other grids. The soils with an observed gleyic process, which were within close proximity (and at the same altitude) to water bodies and peat and bog areas, had their soil moisture depletion rate slowed significantly compared to neighboring grids without such influence (Trnka et al., 2015).

SoilClim has dynamically simulated vegetation cover that changes the parameters of the canopy (e.g., root depth or crop height) during the vegetation season based on the thermal time and vernalization requirement (in case of winter crops and perennials). Therefore, the crop parameter *Kc* (Allen et al., 1998), as well as root growth dynamics, vary for individual vegetation covers and throughout the year (or growing season). To account for the seasonally changing crop cover composition on grids of arable land (which dominate the landscape), a fixed proportion of crops on each arable grid was considered. In these grids, the soil moisture contents using spring and winter C_3 crops (based on present spring barley and winter wheat cultivars) and spring C_4 crops (maize) were calculated and then averaged for the three considered crops.

The information about the land cover relied on the CORINE land cover (CLC2006) 100 m product (version 12/2009). The following proportion of the individual land-use classes was found for the CR territory: (i) arable land (46.2%), (ii) permanent grasslands (7.6%), (iii) conifer forest (20.3%), (iv) deciduous forest (3.1%), (v) mixed forests (6.0%), and (vi) other agricultural areas (8.7%). Areas where no realistic SoilClim calculation was possible, i.e., urbanized areas (7.0%) and water bodies (1.1%), were still considered by the Bilan hydrological model through a simplified internal procedure. The land-use cover was considered static over the analyzed period, as our study focuses on agricultural and hydrological drought interactions.

2.3. Hydrological balance

Hydrological balance was assessed by the Bilan conceptual hydrological model (Van Lanen et al., 2004; Vizina et al., 2015). This model has been widely used in the CR for evaluation of water balance with monitoring applications by the Czech Hydrometeorological Institute (CHMI) and for assessment of climate change impacts (e.g., Hanel et al., 2012, 2013b). The structure of the model is defined by a system of relationships describing the basic principles of water balance in the hydrological basin in the aeration zone. For calibration of the key model parameters, a runoff series at the outlet of the basin was used. For calibration of the Bilan hydrological model, we used a database on observed monthly runoff and water use maintained by the T. G. Masaryk Water Research Institute that contained records for 631 hydrologic stations over the 1961–2015 period. In addition to total runoff, the model simulates soil and ground water storage and snow water equivalent. The Bilan model has been calibrated with a focus on the reproduction of drought characteristics. Moreover, the available soil moisture content simulated by the SoilClim model (having spatially distributed soil parameters) was also considered within the calibration, i.e., the AWC of the Bilan model was forced to mimic the variation in the soil water content from the SoilClim model. The Bilan model was set up for 133 basins (with areas ranging from 620 to 1925 km^2) covering the CR (see Fig. 1).

2.4. Water balance of reservoirs and available water resources

The balance of reservoirs was simulated by the Wateres model (available as an R package at https://github.com/tgmwri/wateres WATERES, 2021), which simulates the balance of individual reservoirs and reservoir networks in daily time steps and provides reservoir performance characteristics (yield, reliability, deficit volume, etc.). The balance is calculated considering the reported water use together with the estimated runoff, precipitation and evaporation from the water surface of the reservoirs, which are shown in Fig. 1a. In the CR, water use exceeding 500 m^3/month or 6000 m^3/year has to be approved and reported to the water authority, and all water uses above these thresholds were considered in the study.

2.5. Drought definition and statistical analysis

Agricultural drought is defined for the purposes of this study as conditions that cause adverse crop responses because plants usually cannot meet reference transpiration as a result of too high atmospheric demands and/or limited soil moisture. The decrease in transpiration occurs whenever the available water within reach of the roots is not freely available, i.e., whenever readily available water becomes scarce in the soil. The readily available water represents approximately half of the AWC (Allen et al., 1998). Therefore, the moment when the AWR reached or dropped below 0.5 was considered the onset of agricultural drought. Agricultural drought ends when AWR increases above this threshold. We also considered drought duration as the number of days when AWR $\leq$ 0.5.

Hydrological drought is defined by considering a threshold level through the so-called deficit index (Tallaksen and Van Lanen, 2004; Van Loon, 2015). A drought event starts when the index drops below a threshold (here, the minimum residual flow as defined in the decree of the Ministry of Environment of the CR) and ends when it rises above the threshold. The deficit index for an event (also called deficit volume), representing drought severity, equals a cumulative deviation from the threshold. The number of months for which the runoff does not reach the minimum residual flow is considered the drought duration.

The Mann-Kendall test was used to determine if the slope of the estimated linear regression line was different from zero (Hirsch et al., 1982) with the p-value provided. The statistical analysis has been done with the use of AnClim and ProClimDB software packages http://www.climahom.eu/software-solution/anclim (AnClim, 2021) developed specifically for the analysis of meteorological, climatological and hydrological data (e.g. Štěpánek et al., 2009). The performance of the models in comparison with the observed data have been assessed through mean bias error, root mean square error, the Nash–Sutcliffe model efficiency coefficient and Theil-Sen estimator.

2.6. Future climate simulations

The analysis of future climate conditions used a set of RCM simulations that were carried out within the European part of the global Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX, 2021 www.euro-cordex.net). The EURO-CORDEX experimental design is based on the utilization of state-of-the-art RCMs forced by multiple GCMs from the Coupled Model Intercomparison Project (CMIP5) ensemble. EURO-CORDEX RCM simulations deliver new insight into European climate development at two spatial scales for three greenhouse gas emission scenarios from representative concentration pathways (RCPs) (Van Vuuren et al., 2011). From all available EURO-CORDEX simulations, we chose the following five GCM/RCM pairs that were performed for RCP4.5 at a 0.11° spatial resolution (Clarke et al., 2007): CNRM-CM5/ALADIN53, EC-EARTH/RACMO22E, EC-EARTH/RCA4, MOHC-HADGEM2-ES/RCA4, and MPI-ESM-LR/CCLM4.8.17. This choice was influenced by the availability of the EURO-CORDEX data within the time of preparation of this study and by the effort to capture a variety of the different RCMs and their driving GCMs.

All climate model simulations were subject to bias correction by applying the Distribution Adjusting by Percentiles (DAP) method (Štěpánek et al., 2016). This method relies on the quantile mapping bias correction approach. The CHMI dataset of 787 stations with daily precipitation observations and 268 stations with daily air temperature, humidity and wind speed observations within the 1981–2010 period was used for bias correction. As a part of the DAP method, the RCM data from the several nearest grids were first recalculated into station locations, and then the bias correction itself was performed on the daily data within the 1981–2005 period.

In addition, five GCMs were considered through the delta approach method as used by Trnka et al. (2016a) and were applied to obtain daily data for each 500 m x 500 m grid for future climate (2021–2080). GCMs were used as representations of ensemble central estimates (IPSL – model of Institute of Pierre Simone Laplace, France) and for the best capture of the variability in the expected changes in precipitation and temperature (BNU – Beijing Normal University, China; MRI – Meteorological Research Institute, Japan; CNMR – National Centre for Meteorological Research, France; HadGEM – Hadley Centre Global Environment Model, UK). These models were selected from 40 climate models available in the CMIP5 database (Taylor et al., 2012). We followed the methodology developed by Dubrovsky et al. (2015) and used the RCP4.5 and a climatic sensitivity of 3.0 °C.

2.7. Scenarios of soil water holding capacity

In addition to the climate change scenarios, we introduced perturbations in the parameters influencing the soil AWC within the SoilClim simulation and Bilan models. We considered scenarios where the soil AWC remained constant at the baseline levels (AWC+0) and improved or reduced by 40% (AWC+40 and AWC-40, respectively) and varied with a 7% reduction in soil AWC per decade (AWC-7). The AWC+0 value of water holding capacity was based on the National Soil Survey and corresponds to the AWC in the early 1970′s, as a more recent national survey has not been carried out. Therefore, we used a 7% reduction in AWC per decade as an approximation of the deterioration of the soil AWC in the CR through a combination of soil erosion, soil compaction and loss of organic matter (Šarapatka and Bednář, 2015). This decrease in AWC is only an approximation, but it has been occurring at a faster pace since the 1960′s than that in neighboring countries such as Austria (Devátý et al., 2019). The selection of the lower limits of the AWC change, i.e., –40%, was based on the estimated decrease in the AWC from the observed data from the CR caused by soil erosion, compaction and loss of soil structure and organic matter (e.g., Vopravil, 2009; Vopravil, 2011) over the past 50 years. On the other hand, the increase in the AWC by +40% over the baseline value is considered to be the theoretical upper limit that could theoretically be achieved by considerable and long-term efforts that completely change the soil management, crop and landscape structure. These efforts would constitute (i) adjusting tillage to improve infiltration and soil structure (e.g., Blanco-Canqui and Ruis, 2018); (ii) introducing no-till practices while building up layers of organic mulch from intercrops and/or using intercrops but also extensive use of soil amendments such as biochar. The latter approach was found to be capable of significantly boosting AWC values (e.g., Yu et al., 2013), while the debate still continues if extensive biochar introduction is realistic (e.g., Atkinson, 2018).

3. Results

3.1. Validation of SoilClim and Bilan models

Fig. 2 shows the mean annual runoff over all basins analyzed for the observed data (1981–2015) and data simulated by the Bilan model (1956–2017). Soil moisture in the Bilan model was provided by the SoilClim simulations at 500 m x 500 m grids. Overall, the Bilan model was able to explain more than 90% of the seasonal and annual

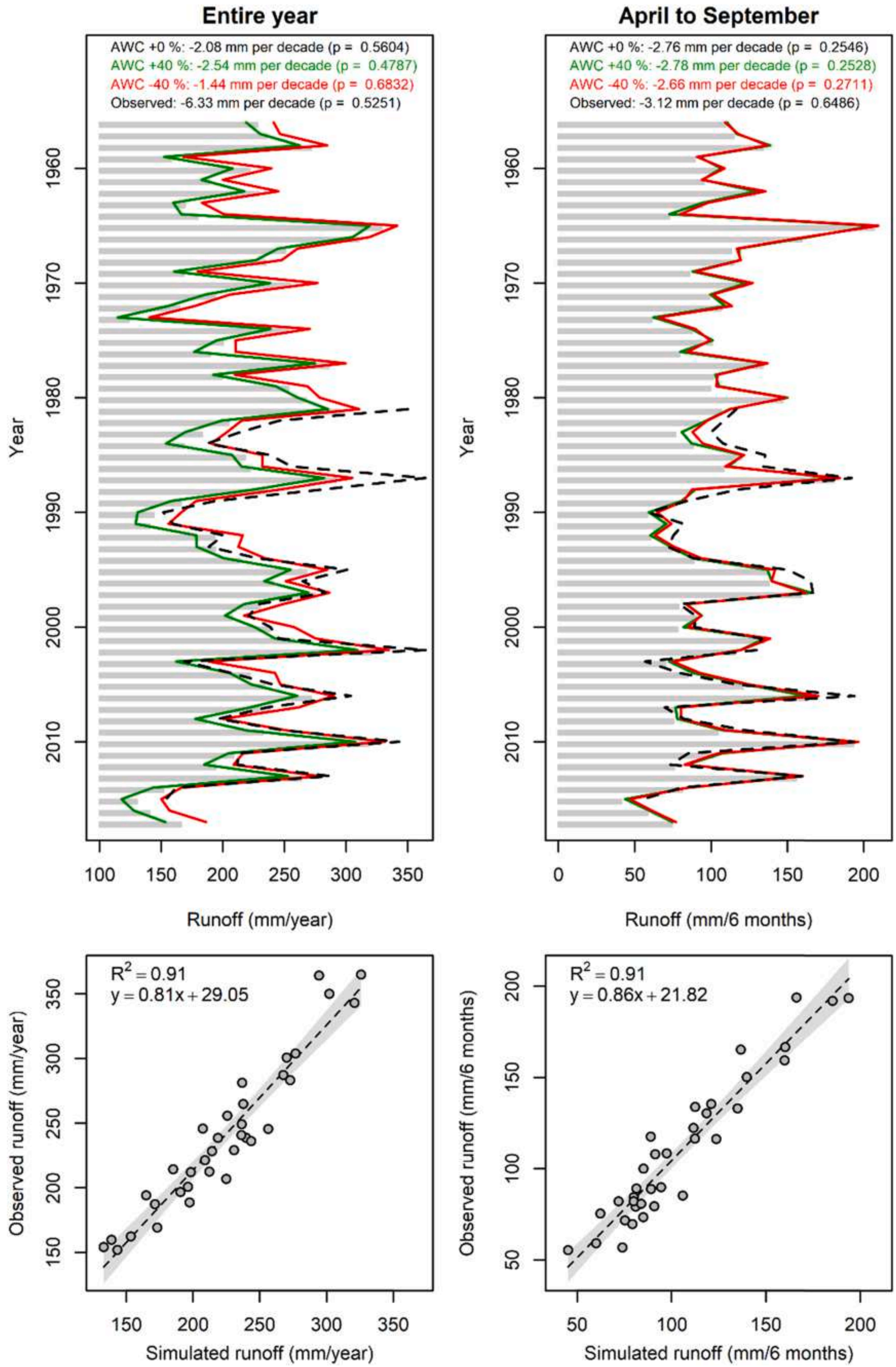

Fig. 2. Mean annual runoff in the 1981–2015 period (dashed line) and simulated by the Bilan model for the 1956–2017 period with baseline available water capacity (AWC+0; black bars), assuming 40% increased soil retention capacity (AWC+40; green line) and 40% decreased soil retention capacity (AWC-40; red line).

variability in runoff in comparison with the observed data. The minimum annual runoff corresponded to *c.* 120 mm, while the maxima exceeded 330 mm, and the model was able to capture these large fluctuations well. Fig. 2 also demonstrates the simulation results for AWC+40 and AWC-40. An increase in AWC leads to decreased runoff and vice versa.

3.2. *Trends in agricultural drought during the 1956–2015 period*

There is a general increase in the area with the soil water content below 50% of the AWC (Fig. 3) and in the area with the soil water content (SWC) below the significant water stress threshold, i.e., 30% of AWC (Supplement Fig. 1) especially in the low-pass filter charts. The increase in SWC during the 1956–2015 period is statistically significant ($p < 0.05$) for April–June for all considered AWC alternatives (Fig. 3c–d). This increase is particularly pronounced when soil AWC is decreased by 40% or when the gradually decreasing AWC emulating soil degradation is considered. However, even if the soil AWC would increase by 40%, the climate signal is sufficient to significantly increase the duration and extent of the area affected by agricultural drought. This means that the climate signal may outweigh even very ambitious soil retention improvement programs. The positive effect of high AWC is most pronounced during years with normal or above-normal precipitation, as this allows for the accumulation of the water reserves in the soil typically prior to the peak of

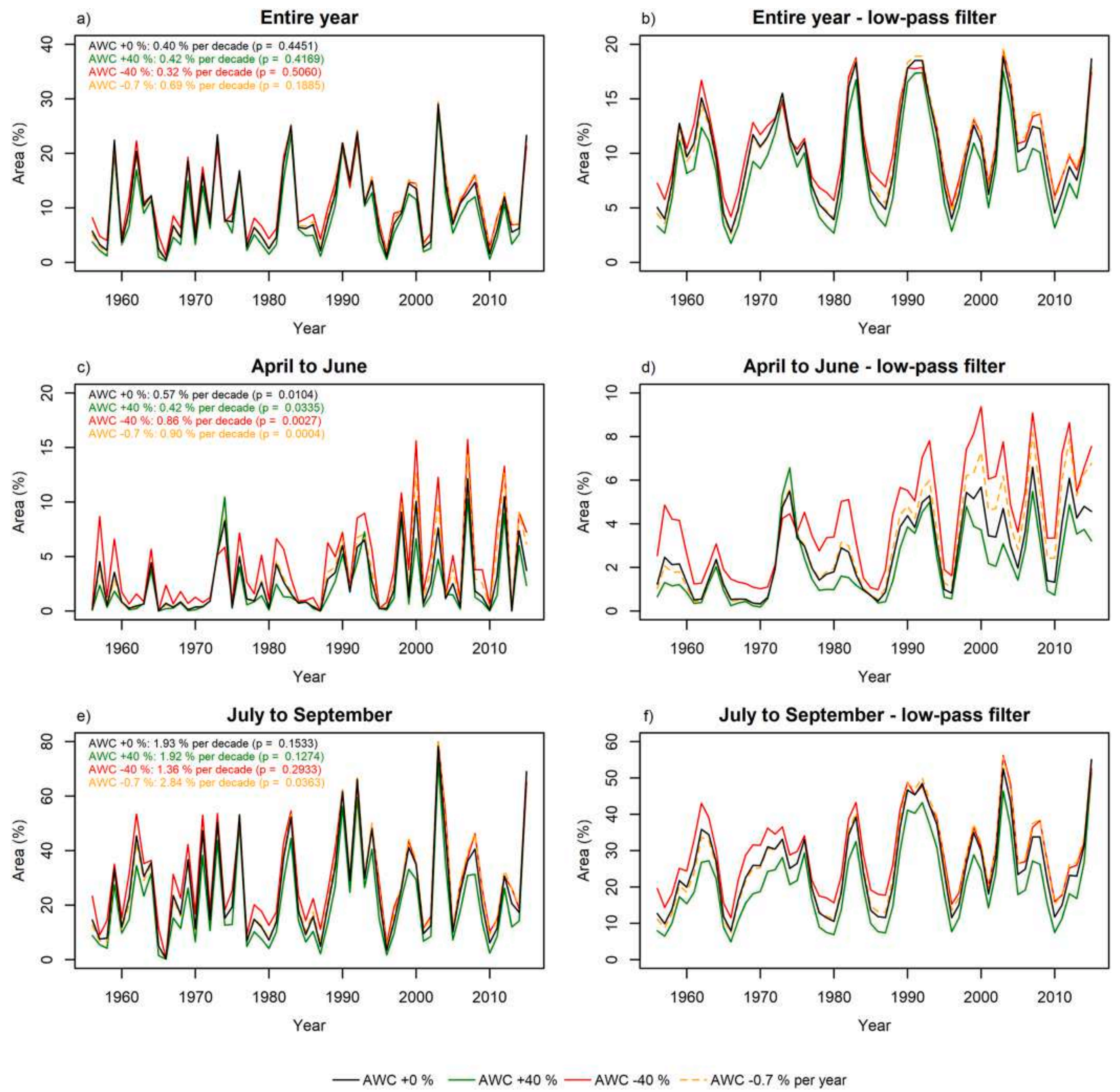

Fig. 3. Trends in agricultural drought were defined as periods with available water content below 50% of its maximum. The analysis assumed a constant maximum soil water holding capacity (black), reduced AWC by 40% (red), increased AWC by 40% (green) and decreased AWC by 7% (orange) per decade in the 1956–2015 period. The trends (% per decade) and p-values are provided. In the left column, the annual values are plotted. The right column depicts values smoothed by a 5-year Gaussian filter to highlight long-term tendencies.

the vegetation season (i.e., during winter and early spring). In the AWC+40 scenario, the soil water accumulated over winter can last longer and reduce the area affected by drought, especially during April–June. The differences among soil AWC scenarios are smallest during dry years for July–September (e.g., 2003 or 2015), as the reserves of the soil moisture are already depleted prior to drought, even in soils with high AWC. On the other hand, the highly positive effect of soil AWC can be illustrated for early season droughts (e.g., 2000 or 2012), for which increased soil AWC can significantly decrease the extent of drought events. The AWC-40 scenario strengthens the impact of the climate signal. First, the decreased AWC markedly worsens the impact of drought in April–June (Fig. 3c–d) but also notably increases the affected area in July–September (Fig. 3e–f). In line with that, the decreased AWC also considerably increases the area affected by drought stress (Supplement Fig. 1) during both April–June and July–September.

3.3. Trends in hydrological drought during the 1956–2015 period

The perturbations in the soil AWC exhibit an opposite effect on runoff (Fig. 2) as well as on other hydrological drought characteristics (Fig. 4) compared to their effects on agricultural drought. In general, there is a negative non-significant trend in runoff (–2.29 mm/decade) over the 1956–2015 period. The AWC+40 scenario leads to a steep overall decrease in runoff, while the AWC-40 scenario leads to a reduction in the negative trend.

The trends in drought duration and area affected increase for

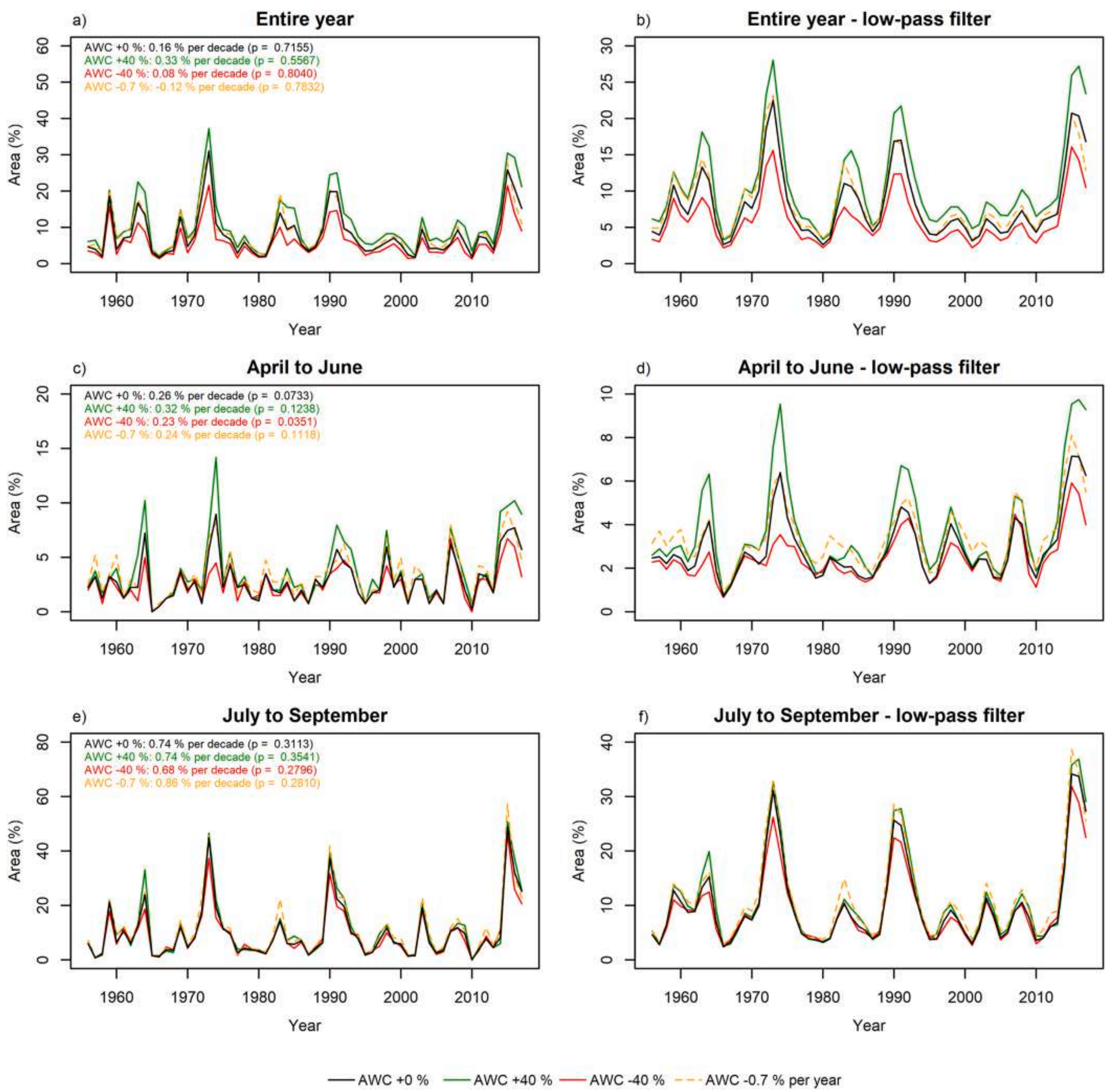

Fig. 4. The area affected by hydrological drought between 1956 and 2015 assuming constant AWC (AWC+0; black), reduced AWC by 40% (AWC-40; red), increased AWC by 40% (AWC+40; green) and decreasing AWC at a rate of 7% per decade (AWC-7; orange). In the left column, the annual values are plotted. The right column depicts the values smoothed by a 5-year Gaussian filter to highlight long-term tendencies.

April–October, but statistically significant trends are observed in only June. The available water resources decrease for April–September, but the decrease is statistically significant for only June and August. This condition may negatively influence, for example, the availability of water for irrigation. Soil AWC also has a significant impact on drought characteristics. In particular, the most severe droughts (e.g., 1973, 1991 and 2015) are on average 0.64 months longer for AWC+ 40 and 0.77 months shorter for AWC-40 as can be deduced from Fig. 6. In addition, the area affected by hydrological drought increases with increasing soil AWC and vice versa. In the case of April–June, AWC+40 caused almost doubling of the drought-affected area, while AWC-40 decreased to approximately one-half compared to AWC+ 0.

Fig. 5 shows the spatial distribution of mean annual runoff for the CR for constant and perturbed AWCs. There are two large areas (Fig. 5c) with low runoff: south Moravia (runoff < 50 mm) and northwest Bohemia (runoff < 75 mm). The runoff coefficient (ratio of runoff to precipitation) in these areas ranges from 0.08 to 0.15. According to the Bilan model simulation, these areas are the most sensitive to soil AWC perturbations: the AWC-40 leads to an increase in runoff on the order of tens of millimeters, while the AWC+40 results in a further decrease in the already low runoff. The effect of the AWC+40 scenario can be attributed to an increase in actual evapotranspiration in the investigated basins.

3.4. Climate conditions for the 2021–2080 period

According to five RCMs, the mean temperature between the 1981–2010 and 2021–2080 periods should increase by 1.5 °C. The highest warming of 2.0 °C is projected by MOHC-HADGEM2-ES_RCA4, and the lowest warming of 0.9 °C is projected by MPI-ESM-LR_CLM4.8.17. The CNRM-CM5_ALADIN53 and MOHC-HADGEM2-ES_RCA4 models indicate the highest temperature increase in winter (2.0–2.7 °C). In contrast, the EC-EARTH model shows the highest positive change in spring (1.8–2.1 °C), and the MPI-ESM-LR_CLM4.8.17 model shows the highest positive change in summer (1.3 °C). The precipitation will increase by approximately 10% for the whole 2021–2080 period compared to the reference 1981–2010 period according to five RCMs, but they provide very different results. The CNRM-CM5_ALADIN53 and MOHC-HADGEM2-ES_RCA4 models project the highest precipitation increases, 15.4% and 13.4%, respectively, while the EC-EARTH_RACMO22E model predicts an increase of only approximately 3.5%. A remarkable increase in precipitation is indicated, especially for spring (14.5%) and winter (12.8%). The summer precipitation should be nearly the same as that in the current climate according to most models; only CNRM-CM5_ALADIN53 provides much higher totals.

When the projections based on five GCMs are considered, the results are slightly different from the RCM simulations. The increase in the annual mean temperatures in the 2021–2080 period compared to the baseline period is expected to be 1.8 °C and ranges from 1.4 °C (MRI model) to 2.1 °C (HADGEM model). While the CNRM, IPSL and MRI models predict the largest warming in winter, ranging from 1.7 °C (MRI) to 2.7 °C (CNRM), the remaining two GCMs indicate the largest warming during summer (BNU: 2.2 °C) or even autumn (HADGEM: 2.6 °C). On the other hand, all GCMs agree with the lowest warming in spring, ranging from 1.1 °C to 1.6 °C. Unlike the RCMs, the GCMs project high variability in terms of precipitation totals. The three models (BNU, IPSL and HADGEM) show decreases in annual precipitation by 1 or 2%, while the two models (MRI and CNRM) indicate increases of 4% and 9%, respectively. The CNRM model shows precipitation increases across all seasons. Except for BNU, all models project an increase in winter precipitation between 5.1% and 10.0%. Three models show a decrease in precipitation during autumn, and two models always indicate about 6% decrease in precipitation during spring and summer months, one model shows no change and remaining two indicate increase of about 5–7% of the baseline precipitation.

3.5. Impact of climate change on agricultural drought

For agricultural drought, Fig. 6 shows its changes with respect to the changing climate simulated by RCMs and GCMs and to the sensitivity of the duration and spatial extent of the drought with regard to AWC.

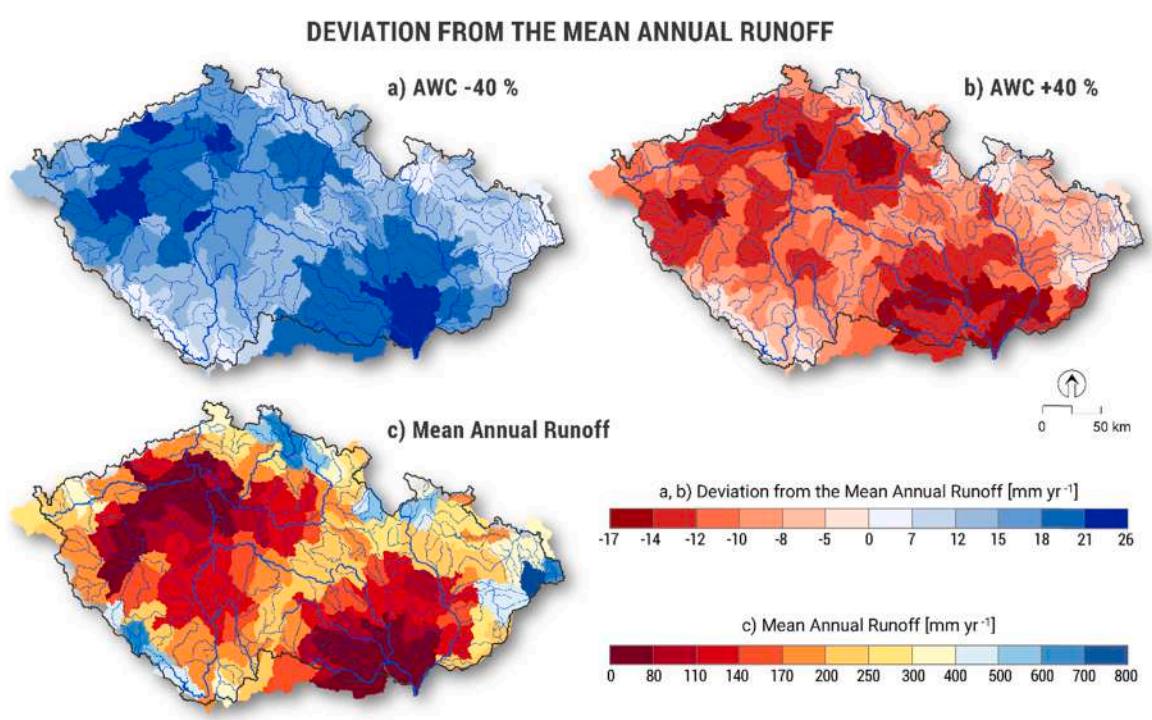

Fig. 5. Mean annual runoff for the 1956–2015 period assuming a constant maximum soil water holding capacity (c) and changes in annual runoff for reduced AWC by 40% (a) and increased AWC by 40% (b).

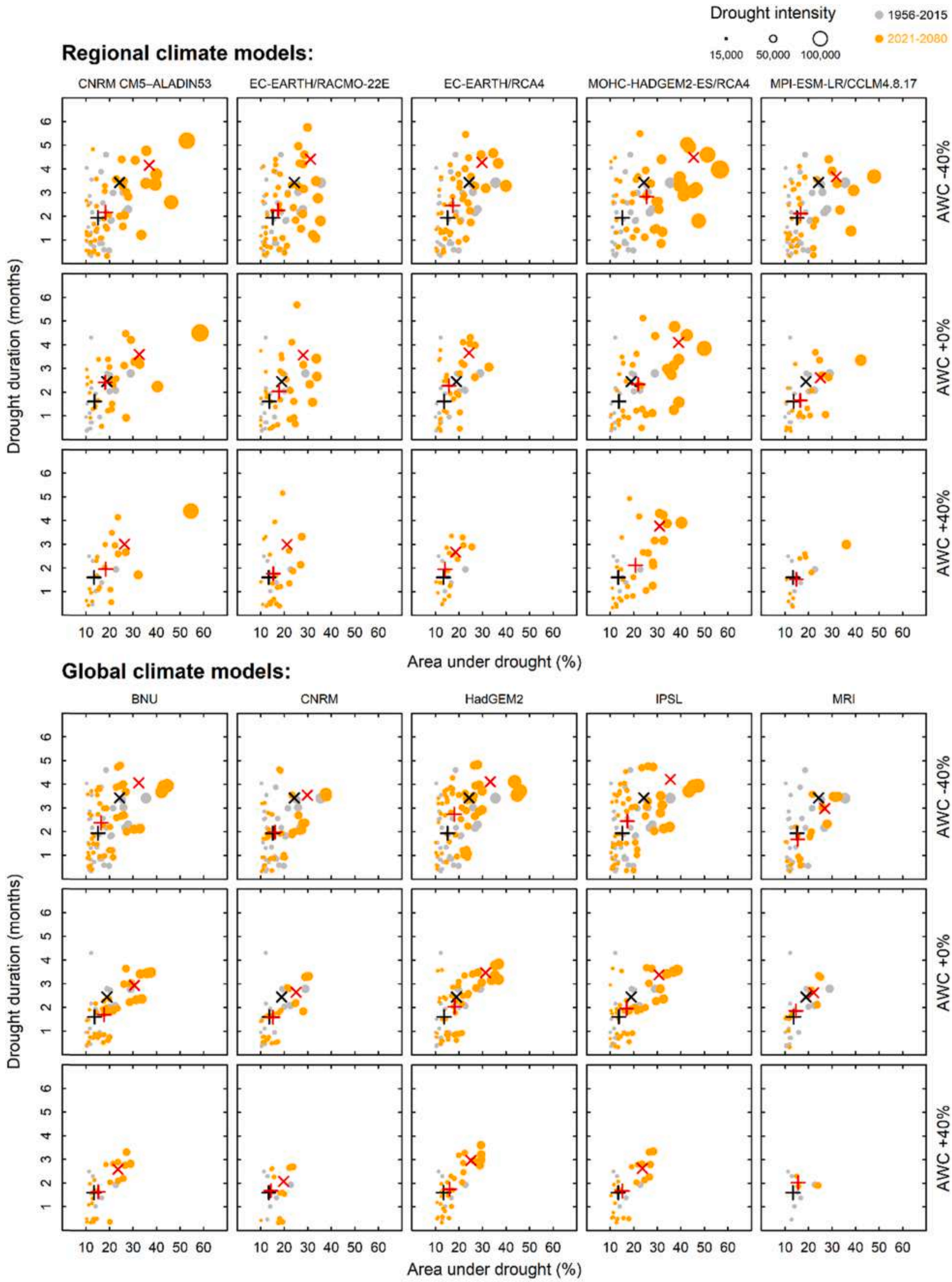

Fig. 6. Comparison of the severity of agricultural droughts (combination of drought duration and affected area) for the 1956–2015 baseline and 2021–2080 periods for RCP 4.5 and five RCMs (upper panel) and five GCMs (lower panel). Drought was defined as a soil water content below 30% of the maximum water holding capacity, and the duration was defined as the continuous period below this threshold. Soil AWC was kept at the current levels (0%) or increased/decreased by 40%. The "+" sign indicates the mean value of drought severity over the whole period, while "x" shows the mean drought severity of the ten most severe droughts.

Under all projections, climate change leads to an increased duration of drought episodes as well as their spatial extent. The results of all models used show a coherent tendency to increased areas hit by agricultural drought. Additionally, the duration and extent of the ten most severe droughts is increasing, indicating not only an increase in the overall drought occurrence but also in its intensity.

The soil AWC+40 scenario should not only shorten the mean duration of agricultural drought but also markedly limit the duration of the ten longest drought episodes and limit their areal extent. While increasing soil AWC would especially influence the most pronounced drought episodes during 1956–2015, the AWC-40 should significantly prolong the duration and area affected by drought in general, and the top ten droughts should be markedly more severe. While understanding past droughts and the AWC role is critically important, Fig. 6 provides a clear indication that AWC values are even more important for assessments of future agricultural drought impacts. For AWC+0, the mean duration of drought events would significantly increase according to four of the five RCMs and three out of the five GCMs, and the areal extent would increase according to all of them. The extent and duration of the ten worst events would increase almost twofold. The situation with soil AWC-40 would be much worse, for example, as a result of continuing large-scale degradation. While the climate signal would still be dominant, the decreased ability of soil to hold water would result in drought episodes that would be twice as long and twice as large than those in the recent period.

On the other hand, increased soil AWC could, at least according to three out of the five RCMs, more or less maintain the current agricultural drought severity and duration. Similar outcomes were derived from the five GCMs (Fig. 6), which showed considerable benefit of increased soil AWC on maintaining the spatial extent and duration of future droughts within the order of intensity of the recent droughts. However, in the case of the top ten drought events, even such an increase in AWC would not be enough to prevent a significant increase in the drought extent and duration. The beneficial effect of increased AWC stems from the increased precipitation totals during the winter half-year (October–March) that can be stored for the following part of the year (later part of the season). While the increasing AWC seems to be critical for controlling future droughts, it would not be enough to prevent increased drought damage in the case of the most severe droughts.

3.6. Impact of climate change on hydrological drought

For hydrological drought, Fig. 7 shows the relation between hydrological drought length and the available water resources. In contrast to agricultural drought, the RCM signal has only a weak impact on the hydrological drought duration and available water resources, but one projection showed even a considerable decrease in drought duration and increase in available water resources. In the case of the GCM simulations, all consistently indicated a decrease in available water resources and an increase in drought duration.

The soil AWC perturbations have only limited effects on the overall mean duration of drought and the available water resources in the RCM simulations. This result is likely due to increasing precipitation, which is projected by all RCMs, leading to increasing direct and hypodermic runoff and sustaining reservoir storage. This is not the case for the GCM simulations showing a considerable decrease in available water resources and an increase in drought duration for the improved and reduced soil AWC, respectively, due to limited precipitation.

For the ten worst hydrological drought events, the inverse proportionality between soil AWC and available water resources is clear in all RCM and GCM simulations and is more pronounced than for the overall mean characteristics. However, the signal is again weaker for the RCM simulations than for the GCM simulations. While the variation in drought duration due to soil AWC perturbations is up to 0.5 (RCM simulations) and 1 (GCM simulations) months for the overall mean, for the ten worst events, these values are 1.5 (RCM) and 2 (GCM) months. The changes in estimated available water resources show similar patterns of variation. The AWC+40 scenario effect on maximum and mean deficits is 50–80% of the shifts caused by the changing climate (in the case of simulations showing an increase in deficit). This result means that the efficiency of any measure compensating for the decrease in available water resources will need to carefully consider any major changes in the AWC of the basins.

3.7. Changes in the dynamics of agricultural and hydrological droughts from 2021–2080

The temporal dynamics of the projected area that could be affected by agricultural drought are demonstrated in Fig. 8 (based on RCMs) and Supplement Fig. 2 (based on the GCMs). The mean area, which is based on the RCM simulations affected by water contents below 50% of the AWC indicating drought stress onset and by the presence of pronounced water stress for plants (relative saturation of the soil below 30% of AWC), exhibits statistically significant increases for the entire year, particularly for July–September. The decadal trends double and are pronounced for April–June when the future climate is directly projected by GCMs (Supplement Fig. 2). The mentioned figures also show how the scenario of a stepwise increase in the AWC would affect drought frequencies after 2020. Improvements to the soil AWC by 0.5 or even 1.0% per year would not be enough to counter the overall climate-driven trend and would only moderate the extent of the area affected by drought. However, especially in seasons when agricultural drought follows after a relatively wet period, the effect and benefit of improved AWC on mitigating agricultural drought would be considerable.

Fig. 9 shows the temporal distribution of the area affected by hydrological drought according to RCM and GCM simulations. There is a difference in the hydrological drought response between areas with a negative and positive climatic water balance (Fig. 1c), i.e., areas where ETo exceeds precipitation (negative balance) and where it is opposite (positive balance). With a positive balance, the runoff and drought characteristics are mostly controlled by available precipitation. This control is reflected by the considerable temporal and spatial variability in the area under drought and drought severity. In such regions, 3–5% of catchments are under drought, the most severe droughts cover 20–25% of catchments, and usually, at least some of the catchments are under drought for most of the years (95–99%). In areas with a positive balance, runoff is strongly affected by ETo, and therefore, the variability in drought is much smaller. Although the catchments are naturally dry, hydrological drought occurs less frequently (70–80%) for RCMs and GCMs. On average, 1–3% of the area is under drought each year; for extreme droughts, the fraction increases to 18–23%.

Figs. 8 and 9 taken together indicate that increasing soil AWC should decrease the frequency and likely also impact of agricultural drought compared to the baseline soil AWC, especially during April–June. Improvement is primarily driven by an increased ability to store water from winter precipitation, as predicted by some of the climate models. Hydrological drought in the CR becomes more pronounced with increasing AWC, particularly in catchments with negative climatic water balance. On the other hand, strengthening the soil AWC in regions with a positive water balance leads to only marginal worsening of the hydrological droughts. This result indicates that the adaptation measures need to have different priorities according to the regional specifics.

To sumarize, we have found differences in the hydrological drought response between areas with annual precipitation total exceeding reference evapotranspiration and those where precipitation is lower than ETo. In the former, the water resources are limited by available precipitation. This situation leads to considerable spatial and temporal variation in the area under drought, with drought being experienced in some of the catchments every year. For the basins where the reference evapotranspiration does not exceed total precipitation, there are years completely without drought. These basins are then more sensitive to soil AWC perturbations, especially in combination with strong climate

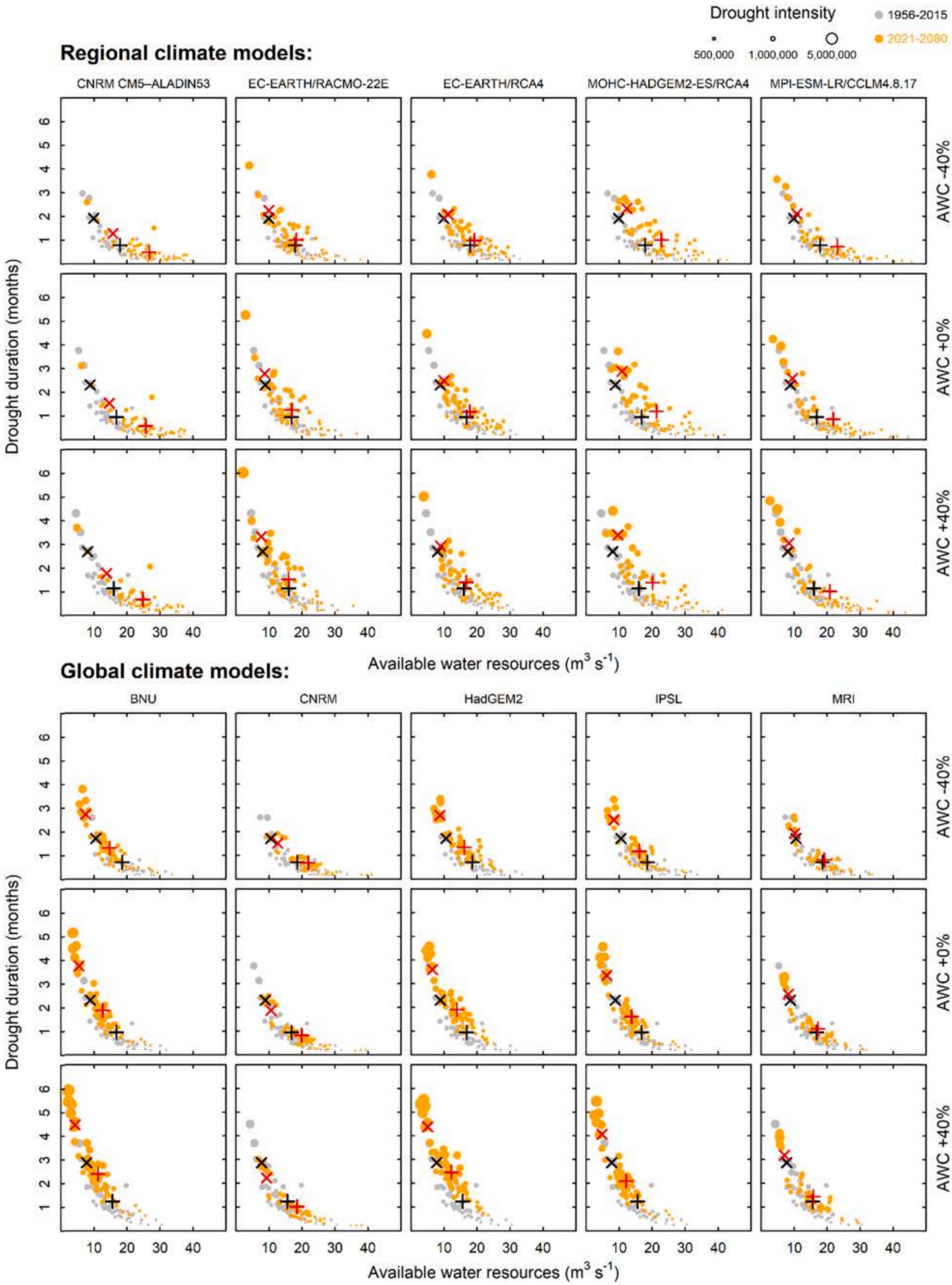

Fig. 7. Comparison of the severity of hydrological drought (combination of drought duration and available water) for the 1956–2015 baseline and 2021–2080 periods for RCP 4.5 and five RCMs (upper panel) and five GCMs (lower panel). Drought was defined as discharge below the 90% quantile and expressed as available water resources $m^3.s^{-1}$. Soil AWC was kept as today (0%) or increased/decreased by 40%. The "+ sign indicates the mean value of drought intensity over the whole period, while "x" shows the mean drought severity of the ten most severe droughts.

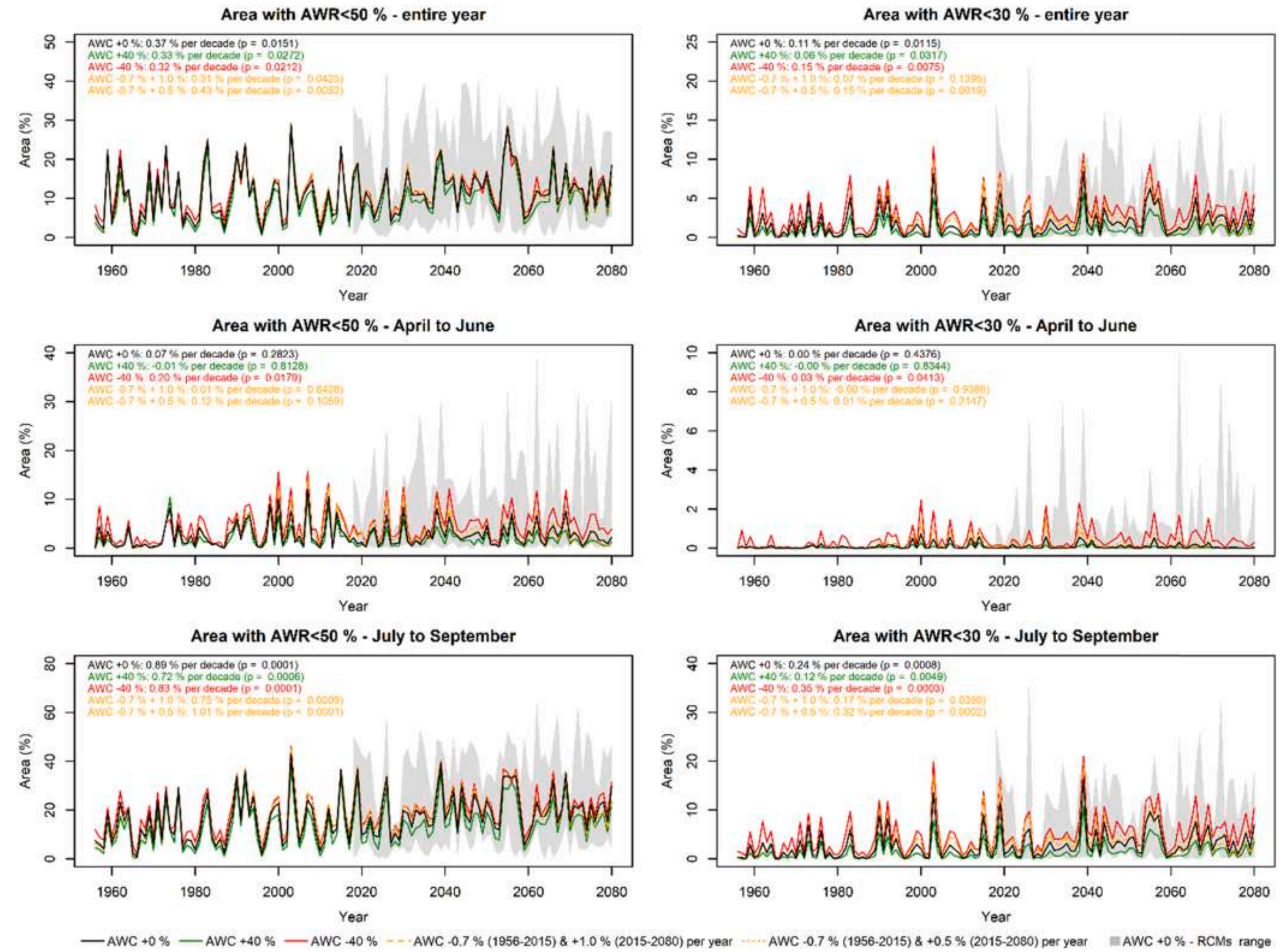

Fig. 8. Trends in the area affected by decreased soil water content below the point of decreased availability (AWR<50%) and water stress (AWR<30%). The analysis is based on the observed data between 1956 and 2015 and projections for the rest of the 21st century based on the five RCMs used in this study. The estimates were made assuming constant available water holing capacity (AWC+0; black), reduced AWC by 40% (AWC-40; red) and increased AWC by 40% (AWC+40; green). In addition, two dynamic scenarios considering the first decreasing AWC at a rate of 7% per decade (1956–2015) followed by an increase of 5%/10% per decade in the 2020–2080 period are shown. The trends in % per decade and p-values are provided.

forcing (i.e., GCM simulations).

4. Discussion

The absence of a general definition of drought led to the development of drought types specified according to their related impacts and various methods of drought quantification. Both hydrological and agricultural droughts show good correlation, but hydrological droughts lagged behind agricultural droughts by two months on average. While agricultural drought is characterized by high sensitivity to precipitation in case of the delimitation of the beginning and end of agricultural drought, the decrease in precipitation is not immediately reflected in runoff and hence in the onset of hydrological drought. Wu et al. (2016) showed similar findings with the time lag of the end of hydrological drought reaching at least six months. The close relationships between agricultural and hydrological droughts were pointed out by Vazifehkhah and Kahya (2019) in their evaluation of drought characteristics in a semiarid region. Poor agricultural drought conditions were associated with the regions with high flow rates according to these authors, indicating an inverse relationship between these two drought types, which agrees with the findings of our study.

The results presented in this study indicate that the enhancement of soil AWC can be considered a key factor in reducing vulnerability to agricultural drought. For example, this result was also found by Wilhelmi and Wilhite (2002), who included soil AWC among four key factors in their drought vulnerability index for Nebraska (US). The "high" vulnerability class included non-irrigated cropland and rangeland on sandy soils located in regions with a very high probability of deficiency in seasonal crop moisture. Similarly, Wu et al. (2011) showed that regions with high AWC were characterized by a low degree of vulnerability to agricultural drought while areas with low AWC showed higher drought vulnerability. The role of soil AWC increases if crop growth depends at least partly on the soil water accumulated during the period preceding the vegetation season; this is the case for not only the CR but also the agriculture in temperate zones in general (e.g., Fischer et al., 2012; Trnka et al., 2013). Therefore, attempts focusing on increasing soil AWC and soil retention of the landscape seem to be obvious solutions to drought mitigation. However, as indicated in Fig. 7, the effect of changing the soil AWC on hydrological drought is opposite to the effects on agricultural drought (Fig. 6). When the results of our study are expressed in absolute numbers, the mean maximum deficit per basin in 1956–2015 corresponds to 1.56×10^9 m^3 of water for AWC+ 40, 1.13×10^9 m^3 for AWC+ 0 and 0.97×10^9 m^3 for AWC-40. This result means that the Czech Republic would need to build additional reservoirs with a total volume of *c.* 430 mil. m^3 to compensate the runoff deficit due to improved soil retention. This volume is more than the available

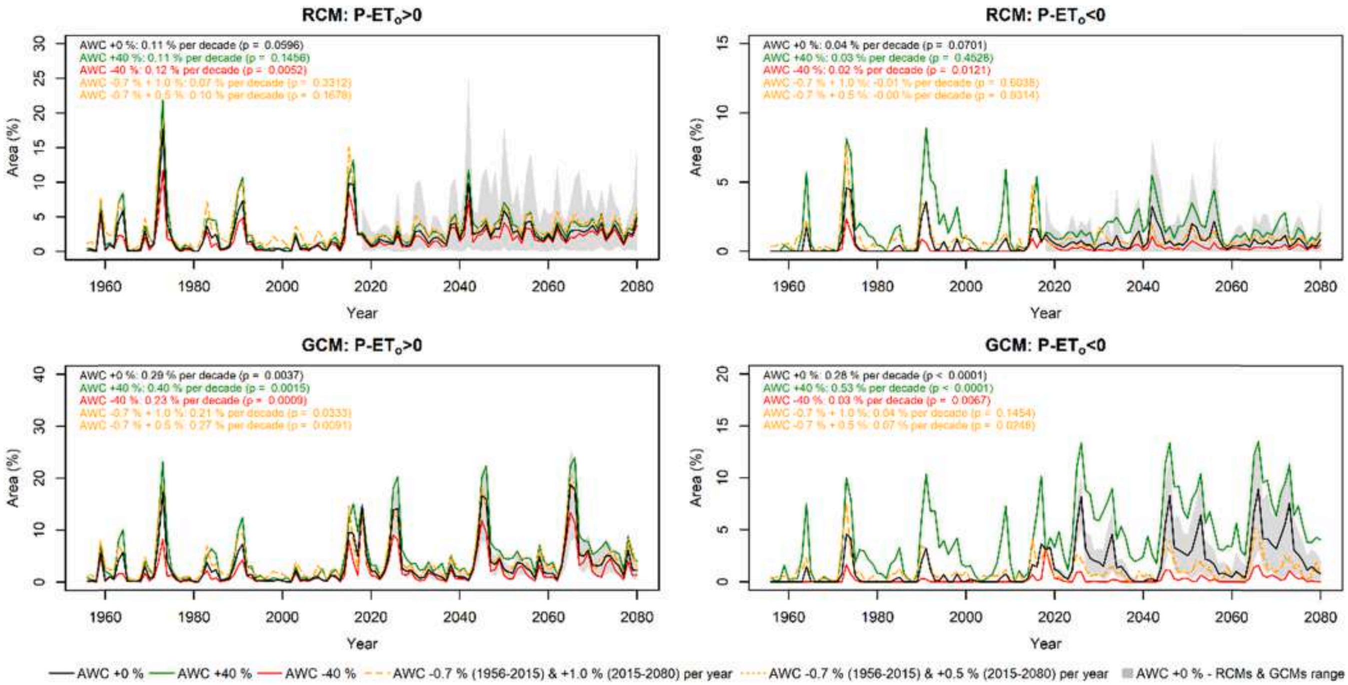

Fig. 9. Trends in area affected by hydrological droughts, in which precipitation totals (P) are higher than reference evapotranspiration (ETo) (1) and vice versa (2) based on the observed data from 1956 to 2015 and projections for 2021–2080 based on five RCMs (above) and five GCMs (below). Three soil water holding scenarios were assumed to have constant AWC (AWC+0; black), reduced AWC by 40% (AWC-40; red) and increased AWC by 40% (AWC+40; green). In addition, two dynamic scenarios considering at first decreasing AWC at a rate of 7% per decade (1956–2015) followed by an increase of 5%/10% per decade are shown (orange).

storage volume of the largest reservoir Orlík on the River Vltava in the CR (340 mil. m^3). This result was also reported by Mahe et al. (2005), who investigated the possible role of land-use change on soil AWC in producing the counterintuitive change in runoff regime in West Africa since 1970. Despite the reduction in annual rainfall and the increase in reservoir storage and the number of dams in the basin and agricultural areas, the mean runoff and maximum daily discharges increased indicating lowering AWC. The model simulation was improved markedly by using the time-varying values of soil AWC and by accounting factors that lead to decreasing the general capacity to slow water runoff (reduction in natural vegetation and increase in bare soil areas). And this finding is in agreement with our results of hydrological model calibration for the period 1956–2015. When we introduced slowly decreasing AWC value mimicking observed agricultural land degradation especially between 1956 and 2015, the modelling cascade responded by improved results compared to observed river discharges and lake levels.

Our study does not explicitly consider possible soil-atmosphere feedbacks. Increased AWC, water content and evaporation, which increase the water vapor content in the atmosphere, can enhance precipitation. Schär et al. (1999) showed that the enhancement of the hydrological cycle over Europe is to some degree associated with the existing soil moisture–precipitation feedback mechanism. They suggested that the soil moisture–precipitation feedback must rely on some direct and indirect mechanism, in which wet soils increase the efficiency of the convective precipitation process. In most areas, the maximum recycling ratio (i.e., proportion of precipitation originating from the same river basin to the total rainfall over the basin) occurs in summer (Schär et al., 1999; Bisselink and Dolman, 2008). For example, in the inland Iberian Peninsula, the annual precipitation cycle often exhibits a significant peak in May, when the evapotranspiration of moisture stored in soil after the winter accelerates, and the enhanced instability induced by wet soil leads to the triggering of soil–precipitation feedback with increasing rainfall (Rios-Entenza and Miguez-Macho, 2014).

Daniels et al. (2015) showed that land use and land cover also strongly influence the precipitation recycling ratio, suggesting that precipitation is enhanced over wet soils and reduced over dry soils or urban areas. This finding supports the results by Harding and Snyder (2012) that evapotranspiration increased by *c.* 4% and precipitation increased by 1% in irrigated fields. The key role of soil moisture and soil AWC in the modulation of climate over central Europe, especially by the severity of heat waves, has also been shown by Seneviratne et al. (2006) and Manning et al. (2018).

While the above findings indicate plausible mechanisms of soil-atmosphere feedback, the estimated moisture recycling ratios for central Europe are approximately 0.1 (i.e., 10% of regional evaporation contributes to rainfall over the same region), even if large regions are considered, and the ratio decreases with decreasing area (Bisselink and Dolman, 2008; Keune and Miralles, 2019). However, Bisselink and Dolman (2009) report increased significance of local evaporation in dry years, which was not necessarily due to the fraction of rainfall originating from local evaporation but rather due to the considerable contribution to instability of the atmosphere and thus the triggering of precipitation. This means that allowing for increased AWC (i.e. soil water storage) enables modulation of agricultural and, in particular, hydrological droughts (see Figs. 6 and 7), and this effect can be further strengthened by soil-atmosphere feedback. However, this effect cannot be overestimated because evaporation from a particular basin mostly supplies moisture to basins downwind rather than those where the moisture originated (Keune and Miralles, 2019).

An increase in the probability of soil moisture depletion and prolonged events of agricultural drought across much of Europe has been found by many studies (e.g., Trnka et al., 2015; Samaniego et al., 2018; Grillakis, 2019), in which central Europe has been considered a region where a considerable increase in severe drought events is likely (e.g., Eitzinger et al., 2013; Štěpánek et al., 2016). This finding was considered a major threat to the agricultural productivity of the whole region and has been an issue of continuous concern. On the other hand, in terms of hydrological droughts, central Europe has not been considered particularly affected (e.g., Gosling et al., 2017; Marx et al., 2018). However, the CR represents a "sandwiched" region between central and western Europe, where no change in low flows is predicted, and southern Europe, where a marked increase in the severity of hydrological droughts is expected (e.g., Marx et al., 2018). For example, the results of Marx et al. (2018) indicate that the southeastern part of the CR belongs to regions where the shift towards a major decrease in river flows is likely and pronounced under high-end scenarios.

Due to the increasing frequency and severity of drought episodes caused by climate change, it is necessary to reduce drought vulnerability and prepare suitable adaptation strategies for drought mitigation and preparedness (Wilhite et al., 2014; Iglesias and Garrote, 2015). The findings of this study highlight that agricultural drought mitigation measures that would lead to an increase in soil AWC would inevitably result in an increased frequency of low flows, i.e., hydrological drought. These findings need to be communicated to decision makers in the government and to public stakeholders. At the same time, expert opinion in this respect should consider the uncertainties and interdependencies between the hydrological and agricultural aspects of drought (Taylor et al., 2013; Leng et al., 2015; Nam et al., 2015).

Different tendencies of agricultural and hydrological droughts under future climate conditions have been raised, for example, by Wang et al. (2011) and Duan and Mei (2014). Both studies concluded that indicators of agricultural droughts and, to some extent, hydrological droughts are more sensitive than the Standardized Precipitation Index (Vicente-Serrano et al., 2012), which is frequently used as an indicator of meteorological drought. However, the majority of the studies covering different drought types (e.g., Wang et al., 2011; Vicente-Serrano et al., 2012; Duan and Mei, 2014; Wu et al., 2016) used fairly simple indicators of drought or their more elaborate concepts, such as the aggregated drought index (ADI), which considers three levels of drought (from meteorological to hydrological and agricultural) by Keyantash and Dracup (2004), or the multivariate drought index (MDI) by Rajsekhar et al. (2015).

A more process-oriented approach has been used that applies SWAT models (e.g., Tao et al., 2003; Xie and Eheart, 2003; Narasimhan et al., 2005; Srinivasan et al., 2010) in which some required data had to be replaced by proxies mostly based on remotely sensed data. In some cases, the proper calibration of the models was limited by a lack of observed data. Nevertheless, the process-based models showed quite satisfactory predictions of water and crop yield during dry years. As cited by the modeling studies, the presented study required several simplifications of real-world processes given the data availability as well as computational resources. Most likely, the most relevant simplification, which may affect the analysis outcomes for future climate conditions, is connected to the daily time step used in agricultural drought modeling and the monthly time step used in hydrological drought modeling, as well as using the same land-use patterns (CLC2006) for the entire study period.

Assessment of the water balance at the daily time step does not account for changes in the separation of precipitation into direct runoff and infiltration over short time scales. The positive trend in the intensity of rainfall events and negative trend in their duration at sub-daily scales have already been detected for the area of the CR by Hanel et al. (2016); the climate model simulations are generally consistent with these trends (Svoboda et al., 2016). This result suggests that the infiltration ability and thus the soil retention over the basins can be in fact lower (Singh, 1997) than those estimated by daily models. Quantification of these effects is, however, beyond the scope of our study, in which we assumed that the land-use patterns have not changed significantly for the AWC sensitivity tests. This shortcoming should be analyzed in future studies because recent analyses of land-use patterns have shown that such effects are not negligible, particularly for hydrological drought (Van Loon and Laaha, 2015; Ahn and Merwade, 2017).

5. Conclusions

Our results based on the country-wide example demonstrate the relationship between soil and surface water storage, where an increase in the former leads to a decrease in the latter. Therefore the research hypothesis is rejected. In other words, if the compensation measures for the effects of agricultural and hydrological drought rely on the same water resources (such as basin precipitation), then they should not be designed separately to optimize the benefits and minimize potential conflicts.

This result indicates that if the current attempts to increase the overall soil AWC are successful then the agricultural drought severity and duration would indeed be partly alleviated. However even if the soil AWC would increase by 40% (which would require massive long term efforts), the climate signal would still significantly increase the duration and extent of the area affected by agricultural drought. In the same time substantial efforts and costs would be required to compensate for the surface water deficit and prevent increase in the severity and probability of hydrological droughts.

Our study clearly shows not only the need for joint design of adaptation measures against agricultural and hydrological droughts, but also need carefully communicate to policy and decision makers the relatively limited effect of improving soil water holding properties in drought mitigation efforts. The results also demonstrate that the impact of changing soil AWC (or otherwise increasing retention in the landscape) leads to nontrivial interactions between agricultural and hydrological drought frequency, with both types of droughts showing not only different sensitivities to the increase in the soil AWC but also opposite directions of change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2022.107460.

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Web resources

AnClim – statistical software used for the data analysis is available here 〈http://www.climahom.eu/software-solution/anclim〉 (Accessed 20, December 2021).
EDO - European Drought Observatory data on 2015–2020 drought have been documented by the 〈https://www.copernicus.eu/en/european-drought-observatory〉 (Accessed 12 November 2021).
EURO-CORDEX data can be accessed at 〈www.euro-cordex.net〉 (Accessed 13 November 2021).
WATERES model can be found at 〈https://github.com/tgmwri/wateres〉 (Accessed 12 November 2021).