

Article

Climate Change and Climatic Water Balance in Brandenburg (Germany): Seasonal Drying and Hydro-Climatic Stress Under Multi-Model Climate Projections to 2100

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Abstract

Climate change is expected to alter hydro-climatic conditions and water availability across Central Europe, with important implications for vegetation and land-use systems. This study assesses projected changes in climatic water balance (CWB), hydro-climatic stress indicators, and their relationship with root-zone soil moisture in Brandenburg, Germany. Four regional climate model realizations under RCP4.5 and RCP8.5 were analyzed for 2006–2100. Air temperature (tas), precipitation (pr), reference evapotranspiration (ET₀), and CWB were evaluated together with indicators describing drought frequency, water-deficit magnitude, aridity, and standardized CWB anomalies. All model realizations project substantial warming, exceeding +2 °C under RCP8.5 by the late century. While annual precipitation remains relatively stable, vegetation-period precipitation decreases and evaporative demand increases, resulting in increasingly negative growing-season CWB. Projected vegetation-period CWB changes range from −22 to −139 mm between near-future and far-future periods. Hydro-climatic stress indicators consistently show increasing seasonal water limitation. Comparisons between CWB and root-zone soil moisture reveal significant positive relationships ($p < 0.001$), although explanatory power remains low ($R^2 < 0.14$). Despite differences in the magnitude of projected changes, all model realizations agree on the direction of change, indicating a robust signal of increasing growing-season drying. These findings highlight the importance of seasonal hydro-climatic indicators for assessing future drought risk and ecosystem water availability.

Keywords: climatic water balance; hydro-climatic stress; drought; soil moisture; evapotranspiration; vegetation period; climate change; regional climate models; Brandenburg; Central Europe



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1. Introduction

Climate change is increasingly altering hydro-climatic conditions across Europe through rising temperatures, changing precipitation regimes, and increasing atmospheric evaporative demand, with important implications for ecosystem functioning, water availability, and land-use systems [1–3]. In Central Europe, recent decades have been characterized by recurrent drought events, including the exceptional 2018–2020 drought, which significantly affected vegetation productivity, forest ecosystems, and regional water resources [4–6]. Climate projections consistently indicate continued warming throughout the

twenty-first century, accompanied by increasing evaporative demand and seasonal shifts in precipitation patterns [1,7,8].

In Germany, particularly in the northeastern regions, climate change is expected to intensify seasonal contrasts in water availability, with wetter winters and increasingly warm and dry growing seasons [9–11]. These seasonal changes are particularly relevant, as vegetation-period water availability is a key control on plant productivity, ecosystem functioning, and land–atmosphere interactions [12–14]. Rising temperatures further increase atmospheric evaporative demand, thereby intensifying seasonal water limitation even under relatively stable annual precipitation totals [3,15].

Brandenburg, located in northeastern Germany, is particularly vulnerable to hydro-climatic change due to relatively low precipitation, sandy soils with limited water-holding capacity, and extensive forest and agricultural land use [11,12,16]. Observational records show increasing temperatures, recurrent drought episodes, and strong interannual variability in water availability across the region [17–19]. As one of the driest federal states in Germany, Brandenburg frequently experiences growing-season water deficits driven by the combined effects of limited precipitation and increasing evaporative demand [20].

Previous studies in Germany and Central Europe have mainly focused on drought indices, individual climate variables, or sector-specific impacts on agriculture and forestry [21–23]. However, comparatively fewer studies have investigated seasonal hydro-climatic conditions using physically based indicators in combination with high-resolution regional climate projections, particularly for northeastern Germany. In addition, the combined assessment of atmospheric water balance and root-zone soil moisture remains limited.

To address this gap, this study applies a physically based framework to quantify seasonal hydro-climatic change in Brandenburg. The climatic water balance (CWB), defined as the difference between precipitation and reference evapotranspiration (ET_0), is used as the primary indicator of atmospheric water availability. CWB integrates both water supply and atmospheric evaporative demand in physical units (mm), enabling a process-based assessment of hydro-climatic conditions. Unlike standardized drought indices such as SPI or SPEI, which are designed for relative anomaly characterization, CWB provides an absolute measure of water surplus and deficit [3,24,25]. Accordingly, CWB is used here to analyze changes in atmospheric water availability rather than drought classification.

High-resolution regional climate simulations are essential for capturing spatially heterogeneous climate signals that cannot be resolved by global climate models alone [26–28]. This study uses the official, bias-corrected regional climate ensemble for Brandenburg, which forms the basis for regional climate impact assessments and adaptation planning. This dataset provides a consistent framework for evaluating future seasonal hydro-climatic conditions and associated uncertainties.

The overarching objective of this study is to assess projected seasonal hydro-climatic changes and vegetation-period water limitation in Brandenburg using high-resolution regional climate projections. Specifically, the study aims to:

1. Quantify projected changes in air temperature (t_{as}), precipitation (pr), reference evapotranspiration (ET_0), and climatic water balance (CWB) over the twenty-first century;
2. Assess temporal and spatial variations in growing-season hydro-climatic conditions under different emission scenarios;
3. Relate projected CWB dynamics to modelled root-zone soil moisture conditions in order to evaluate regional water availability;
4. Assess hydro-climatic stress indicators and associated uncertainties using a multi-model regional climate ensemble.

2. Data and Methods

This study uses high-resolution regional climate projections and modelled soil moisture data to assess future hydro-climatic conditions in Brandenburg, Germany. The methodological framework includes climate and soil moisture datasets, derivation of climatic water balance (CWB) and related indicators, and analysis of seasonal and inter-model variability.

2.1. Study Area

The study area is the federal state of Brandenburg, northeastern Germany (51.9–53.6° N, 11.3–14.5° E), surrounding Berlin (Figure 1). It covers approximately 29,500 km² within the North German Plain and is characterized by low-relief glacial landscapes, including moraines, outwash plains, and kettle lake systems. Elevation ranges from near sea level to approximately 200 m a.s.l. [29].

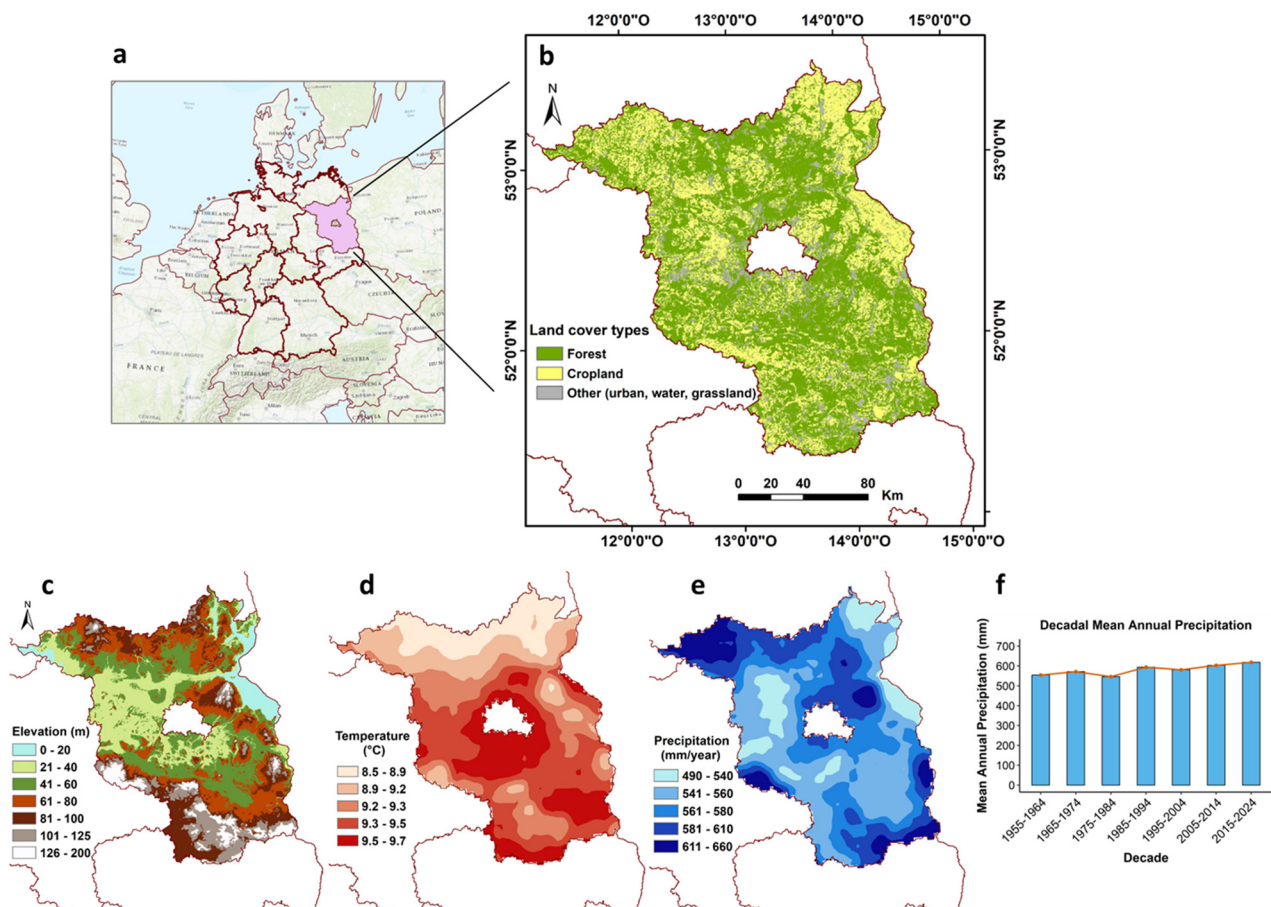


Figure 1. Study area of Brandenburg, Germany: (a) location within Germany; (b) land cover (Sentinel-2, 2020); (c) elevation (DGM 5 m; [29]); (d) mean annual air temperature (1991–2020); (e) mean annual precipitation (1991–2020); (f) precipitation variability (1955–2024; [20]). The apparent central gap corresponds to Berlin (city-state), which is excluded due to its urban climate. Climate variables are based on gridded observational datasets; ArcGIS version 10.8.2 was used for map preparation [30]. All map panels were created by the authors using data from the cited sources.

Brandenburg is located in a temperate transitional climate zone influenced by both maritime and continental air masses. Mean annual precipitation exhibits a pronounced west–east gradient, ranging from less than 500 mm in the southeast to more than 600 mm in the northwest, while mean annual air temperature is approximately 8.5–10 °C [31]. In recent decades, the region has experienced increasing temperatures and more frequent summer drought conditions, reflecting increasing seasonal water limitation [11].

Soils are predominantly sandy and derived from Quaternary glacial deposits, resulting in low water-holding capacity and limited plant-available soil moisture [32]. Combined with relatively low precipitation and increasing atmospheric evaporative demand, these conditions strongly constrain water availability during the growing season.

Land cover is dominated by forests, croplands, and grasslands, with forests largely composed of Scots pine (*Pinus sylvestris*) [33]. The combination of climatic conditions, soil characteristics, and land-use structure makes Brandenburg particularly sensitive to seasonal water limitation and drought-related impacts.

2.2. Data

2.2.1. Climate Data

Climate projections were obtained from the Brandenburg State Office for the Environment (LfU) within the official regional climate projection framework used for climate adaptation and environmental planning in Brandenburg [34]. The dataset consists of four regional climate model chains (Table 1) derived from global climate simulations of the Coupled Model Intercomparison Project Phase 5 (CMIP5), driven by the Representative Concentration Pathways (RCP4.5 and RCP8.5).

Table 1. Regional climate model chains used in this study, including driving global climate models, downscaling methods, emission scenarios, and spatial resolution. Information compiled from the climate projection dataset provided by the Brandenburg State Office for the Environment (LfU Brandenburg) [34].

Global Model	Regional Model	Abbreviation	Downscaling Method	RCP Scenarios	Spatial Resolution
MOHC-HadGEM2-ES	KNMI-RACMO22E	HadGEM2-KNMI	Dynamical	RCP4.5, RCP8.5	3 km
MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17	MPI-CLMcom	Dynamical	RCP4.5, RCP8.5	3 km
CCCma-CanESM2	DWD-EPISODES2018	CanESM2-DWD	Statistical	RCP4.5, RCP8.5	3 km
MPI-M-MPI-ESM-LR	DWD-EPISODES2018	MPI-DWD	Statistical	RCP4.5, RCP8.5	3 km

The ensemble combines both dynamically and statistically downscaled climate projections. Dynamical downscaling is based on EURO-CORDEX and related regional climate modelling initiatives and provides data at a spatial resolution of 3×3 km. Statistical downscaling approaches were applied within national climate service frameworks and regional modelling systems [34].

All simulations were bias-corrected using high-resolution observational reference datasets, including HYRAS and E-OBS, to improve the representation of regional climate conditions and ensure consistency with observed climatology [34–36]. The ensemble was additionally evaluated against historical observations for the reference period 1951–2005 by the German Weather Service (Deutscher Wetterdienst, DWD) and LfU as part of the quality-control procedure underlying the operational climate projection framework used for climate impact assessments and adaptation planning in Brandenburg [34].

The objective of this study is not to compare different CMIP generations, but to assess projected hydro-climatic changes using a consistent and regionally validated climate projection dataset. All model chains were processed within a harmonized framework, ensuring methodological consistency across the ensemble [34].

All climate model outputs are provided in NetCDF format at daily temporal resolution for the period 1951–2100. Variables include near-surface air temperature (tas), maximum and minimum temperature (tasmax and tasmin), precipitation (pr), relative humidity (hurs), surface wind speed (sfcWind), surface downwelling shortwave radiation (rsds), and surface

pressure (psl). These variables were used to derive reference evapotranspiration (ET_0), climatic water balance (CWB), and all hydro-climatic indicators analyzed in this study.

2.2.2. Modelled Soil Moisture Data

Modelled root-zone soil moisture data were obtained from the DWD Climate Data Center [37]. The dataset provides daily values at 1 km resolution expressed as percent usable field capacity (% nFK), derived using the LWF-Brook90 hydrological model driven by meteorological forcing, soil, and land-use data [37].

The dataset covers 1991–2025 and represents modelled estimates rather than direct observations. It is widely used to characterize plant-available water and hydro-climatic stress. Root-zone soil moisture (0–60 cm) is a key indicator of vegetation water availability [38,39], although groundwater influence may locally decouple soil moisture from atmospheric forcing.

2.3. Methodology

A multi-step hydro-climatic assessment framework was applied to quantify seasonal water availability and hydro-climatic variability in Brandenburg using regional climate model simulations and derived hydro-climatic indicators (Figure 2).

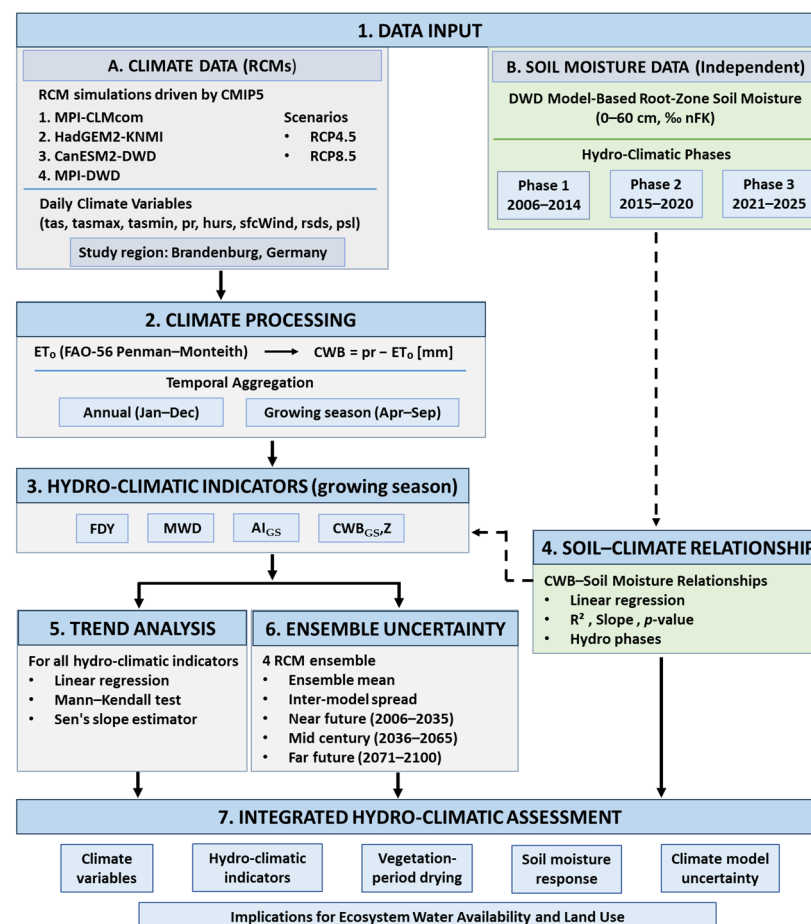


Figure 2. Conceptual and methodological workflow of the study. Processing of climate model data, calculation of climatic water balance (CWB) and hydro-climatic indicators, soil moisture comparison, and ensemble-based uncertainty analysis.

The analysis is based on physically derived variables, including precipitation, reference evapotranspiration, climatic water balance (CWB), and root-zone soil moisture, enabling a process-based assessment of seasonal hydro-climatic conditions [3,40,41].

Four complementary indicators were calculated for the growing season (April–September): Frequency of Deficit Years (FDY), Magnitude of Water Deficit (MWD), Growing-Season Aridity Index (AI_{GS}), and standardized climatic water balance anomalies (CWB_{GS,Z}).

2.3.1. Climate Data Processing and Ensemble Framework

Daily climate variables (Table 1) were processed in the R environment [42] using standard geospatial workflows for NetCDF data. Preprocessing included spatial harmonization to a common reference grid, derivation of secondary variables (ET₀ and CWB), and temporal aggregation to growing-season (April–September) and annual (January–December) scales. The growing-season definition follows the climatologically active vegetation period in Central Europe, during which evapotranspiration and atmospheric water demand reach their annual maxima [43,44].

All analyses were based on four regional climate model realizations (CanESM2-DWD, HadGEM2-KNMI, MPI-CLMcom, and MPI-DWD), representing both dynamical and statistical downscaling approaches. The MPI-CLMcom realization served as the primary reference dataset for detailed spatial and temporal analyses based on its validated performance in Central Europe [7,45]. This selection does not imply universal superiority; the remaining three realizations were retained specifically for ensemble-based uncertainty assessment (Section 2.3.6).

The following daily variables were used as input: near-surface air temperature (tas), maximum/minimum temperature (tasmax and tasmin), precipitation (pr), relative humidity (hurs), wind speed (sfcWind), shortwave radiation (rsds), and surface pressure (psl).

2.3.2. Reference Evapotranspiration and Climatic Water Balance

Reference evapotranspiration (ET₀) was estimated using the FAO-56 Penman–Monteith formulation [46]. Daily climatic water balance (CWB) was then calculated as the difference between precipitation and ET₀:

$$\text{CWB}_t = \text{pr}_t - \text{ET}_{0,t} \quad (1)$$

Positive CWB values indicate water surplus; negative values indicate that atmospheric evaporative demand exceeds precipitation supply. CWB provides a physically transparent, mass-balance-based representation of the atmospheric water supply–demand relationship [25,47], though it does not explicitly include soil moisture storage or hydrological buffering (see Section 2.3.5).

2.3.3. Future Climate Periods and Scenarios

Projected time series (2006–2100) for temperature, precipitation, ET₀, and CWB were analyzed under RCP4.5 and RCP8.5 based on the MPI-CLMcom simulation (Section 2.3.1). Following WMO guidelines (2017) [48], three 30-year periods were compared (near future: 2006–2035; mid future: 2036–2065; far future: 2071–2100) to reduce the influence of internal climate variability. Temperature variables were averaged over each period, while precipitation and ET₀ were aggregated as cumulative sums to reflect their flux-based nature.

2.3.4. Indicators of Hydro-Climatic Stress

Hydro-climatic stress was assessed using four complementary indicators derived from the growing-season climatic water balance (CWB_{GS}), following the vegetation-period definition in Section 2.3.1 [25,47]. For each year *i*, the growing-season climatic water balance was calculated as:

$$CWB_{gs} = \sum_{\{t \in GS\}} (pr_t - ET_{0,t}) \quad (2)$$

where pr_t is daily precipitation and $ET_{0,t}$ is daily reference evapotranspiration during April–September.

Hydro-climatic stress indicators include:

- Frequency of Deficit Years (FDY) is defined as the proportion of years with a negative growing-season climatic water balance ($CWB_{GS,i} < 0$). Increasing FDY indicates more frequent seasonal water deficits and reduced atmospheric water availability during the vegetation period [49,50].
- Magnitude of Water Deficit (MWD) is defined as the negative value of $CWB_{GS,i}$ when $CWB_{GS,i} < 0$, with more negative values indicating stronger atmospheric water limitation and hydro-climatic stress [3,47,49].
- Growing-Season Aridity Index (AI_{GS}) was calculated as:

$$AI_{GS,i} = \frac{\sum_{t \in GS} ET_{0,t}}{\sum_{t \in GS} pr_t} \quad (3)$$

Values greater than 1 indicate that atmospheric evaporative demand exceeds precipitation, reflecting enhanced atmospheric dryness [4,51].

- Standardized CWB Anomaly ($CWB_{GS,Z}$) was computed as:

$$Z_i = \frac{(CWB_{GS,i} - \mu)}{\sigma} \quad (4)$$

where μ and σ are the mean and standard deviation of CWB_{GS} over the full simulation period. Negative values indicate drier-than-average conditions [4,40]. Moderate and severe drought frequencies were defined as the proportion of years with $Z < -1$ and $Z < -2$, respectively, calculated for each 30-year period [1,40].

For visualization, sequential colour schemes were applied to frequency-based indicators (FDY and drought frequencies), while diverging colour schemes were used for magnitude- and anomaly-based indicators (MWD, AI_{GS} , and $CWB_{GS,Z}$). Diverging blue–white–red palettes were used to represent transitions from wetter/less stressful to drier/more stressful conditions, with white indicating near-average conditions. For drought frequency metrics derived from $CWB_{GS,Z}$ thresholds ($Z < -1$ and $Z < -2$), sequential red colour schemes were applied to represent increasing drought occurrence.

2.3.5. Comparison with Observed Soil Moisture

The relationship between modelled growing-season CWB from the reference realization (MPI-CLMcom; Section 2.3.1) and observed root-zone soil moisture (SM, % nFK, 0–60 cm) from DWD was evaluated for 2006–2025. CWB data (3 km resolution) were spatially resampled to the SM grid (1 km) using bilinear interpolation [52]. The DWD soil moisture product is model-derived and does not explicitly resolve groundwater-influenced sites, which should be considered when interpreting the CWB–SM relationship.

To assess soil moisture responses under contrasting hydro-climatic conditions, the analysis period was subdivided into three a priori defined phases based on documented regime shifts in Central Europe [3,53,54]: (i) 2006–2014 (baseline), (ii) 2015–2020 (extended drought period), and (iii) 2021–2025 (post-drought recovery). The relationship between CWB and SM was quantified separately for each phase using linear regression:

$$SM = a \cdot CWB + b \quad (5)$$

where a and b are regression parameters. The coefficient of determination (R^2) was used to quantify the strength of the relationship across hydro-climatic phases.

2.3.6. Trend and Uncertainty Assessment

Temporal trends were evaluated using the non-parametric Mann–Kendall test and Sen’s slope estimator [55–57], with statistical significance assessed at $p < 0.05$.

Projection uncertainty was assessed from three complementary sources. Inter-model uncertainty was quantified using four regional climate model (RCM) realizations (CanESM2-DWD, HadGEM2-KNMI, MPI-CLMcom, and MPI-DWD). Ensemble statistics included the multi-model mean, standard deviation, interquartile range (IQR), and minimum–maximum range. Scenario uncertainty was evaluated by comparing results from RCP4.5 and RCP8.5 across three future periods: near-future (2006–2035), mid-century (2036–2065), and far-future (2071–2100). Internal climate variability was represented by temporal variability within each 30-year climatological period, consistent with World Meteorological Organization (WMO) climate normal definitions [48].

All analyses were performed on spatially harmonized grids and consistent temporal aggregation periods to ensure comparability across variables, scenarios, and model realizations.

3. Results

Projected changes in hydro-climatic conditions and water availability in Brandenburg are presented below. Results are first shown for the representative MPI-CLMcom simulation (Sections 3.1–3.4), followed by a comparison across all four regional climate model realizations to evaluate inter-model variability and uncertainty (Section 3.5).

3.1. Projected Changes in Climate Variables

Projected changes in annual and growing-season climate variables (MPI-CLMcom) are shown in Figures 3 and 4. Historical simulations (1951–2005) are provided in Appendix A, Figure A1.

Temperature increases consistently across both temporal scales and scenarios. By 2071–2100, annual mean temperature rises by +1.05 °C (RCP4.5) and +2.17 °C (RCP8.5) relative to 2006–2035. Growing-season temperature increases by +0.94 °C (RCP4.5) and +2.46 °C (RCP8.5).

Precipitation shows a seasonal divergence. Annual precipitation increases slightly (+12.5 mm under RCP4.5; +44.6 mm under RCP8.5), whereas growing-season precipitation decreases (−9.3 mm and −33.3 mm, respectively), indicating a seasonal redistribution toward the non-growing season.

Reference evapotranspiration (ET_0) increases annually (+23.9 mm under RCP4.5; +26.1 mm under RCP8.5). Growing-season ET_0 increases under RCP4.5 (+14.8 mm) but shows a slight decrease under RCP8.5 (−10.6 mm), reflecting scenario-dependent changes in atmospheric demand.

Climatic water balance (CWB) exhibits contrasting signals. Annual CWB changes from −2.7 mm (RCP4.5) to +18.4 mm (RCP8.5). In contrast, growing-season CWB consistently decreases under both scenarios (−21.7 mm under RCP4.5; −22.8 mm under RCP8.5), indicating increasing seasonal water limitation.

Historical simulations (Appendix A, Figure A1) show a clear long-term temperature increase, while precipitation exhibits high interannual variability with no clear growing-season trend.

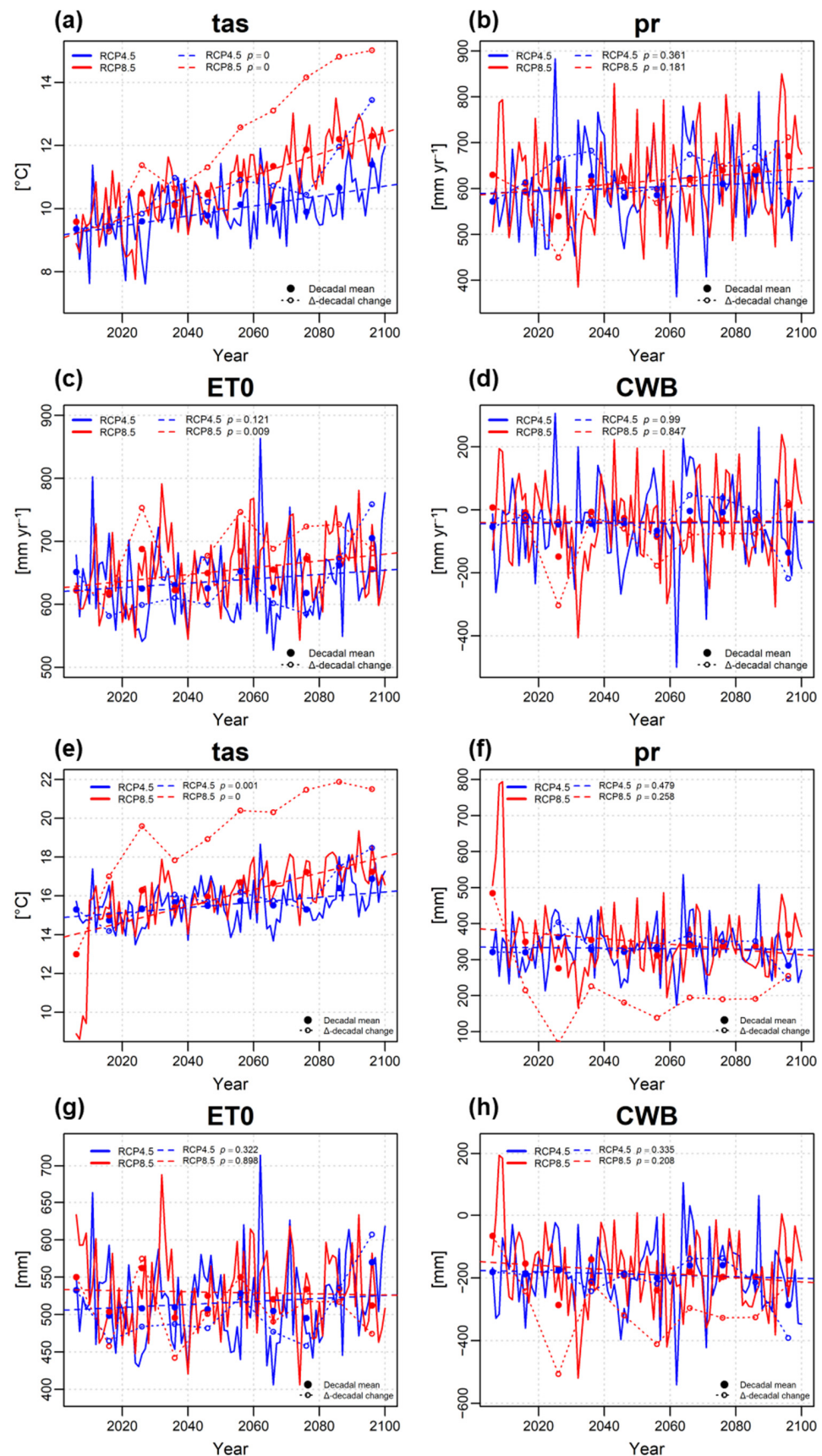


Figure 3. Projected annual and growing-season climate variables in Brandenburg (2006–2100). MPI-CLMcom simulations under RCP4.5 (blue) and RCP8.5 (red). Panels (a–d): annual tas, pr, ET₀, and CWB. Panels (e–h): growing-season (April–September) values. Dashed lines indicate long-term means. Note the divergence between annual and growing-season CWB responses.

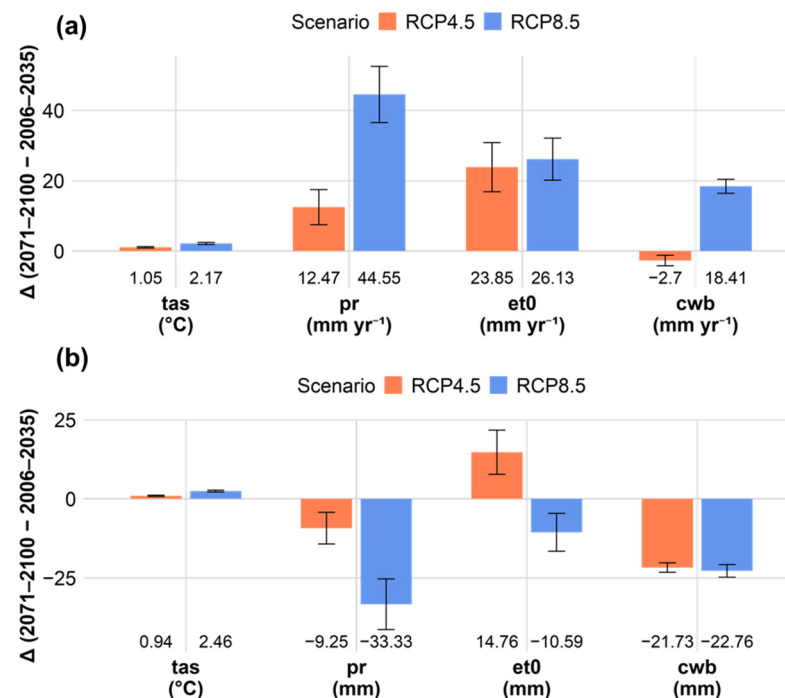


Figure 4. Projected climate variable changes between future periods. Differences between 2071–2100 and 2006–2035 under RCP4.5 and RCP8.5. (a) Annual conditions; (b) growing-season conditions. Positive values indicate increases.

3.2. Climatic Water Balance Dynamics

Annual and growing-season CWB dynamics (2006–2100) are shown in Figure 5, with period changes in Figure 6 and spatial patterns in Appendix A, Figure A2.

Annual CWB exhibits strong interannual variability (range: -499 to $+307$ mm under RCP4.5; -406 to $+239$ mm under RCP8.5; Figure 5) but no statistically significant long-term trend (RCP4.5: slope = 0.04 mm yr^{-1} , $p = 0.930$; RCP8.5: slope = 0.05 mm yr^{-1} , $p = 0.929$; Mann–Kendall τ near zero, $p > 0.8$). Thirty-year means confirm relative stability: annual CWB changes from -45.1 mm (2006–2035) to -47.8 mm (2071–2100) under RCP4.5 ($\Delta = -2.7$ mm), and from -49.4 mm to -31.0 mm under RCP8.5 ($\Delta = +18.4$ mm) (Figure 6).

Growing-season CWB, in contrast, shows persistently negative values throughout the period, indicating that evaporative demand generally exceeds precipitation during the vegetation period. Although trends are statistically non-significant (RCP4.5: slope = -0.26 mm yr^{-1} , $p = 0.523$; RCP8.5: slope = -0.66 mm yr^{-1} , $p = 0.145$), climatological means reveal a consistent shift toward more negative conditions. Under RCP4.5, mean growing-season CWB declines from -180.6 mm (2006–2035) to -202.3 mm (2071–2100; $\Delta = -21.7$ mm). Under RCP8.5, it declines from -168.8 mm to -191.5 mm ($\Delta = -22.8$ mm). Decadal means reach as low as -286 mm under both scenarios in specific decades.

Spatial patterns (Appendix A, Figure A2) were heterogeneous for annual CWB but uniformly negative for growing-season CWB. Annual changes showed small regional means but large spatial variability (-2.7 ± 9.6 mm under RCP4.5; $+18.4 \pm 12.7$ mm under RCP8.5). Growing-season changes were consistently negative across Brandenburg (mean: -21.7 ± 8.3 mm under RCP4.5; -22.8 ± 10.3 mm under RCP8.5), with fifth percentile values of -35.7 mm and -37.6 mm, respectively, indicating stronger drying in the lower tail of the spatial distribution.

In summary, annual CWB remains relatively stable throughout the century, whereas growing-season CWB shows a gradual shift toward more negative values under both emission scenarios.

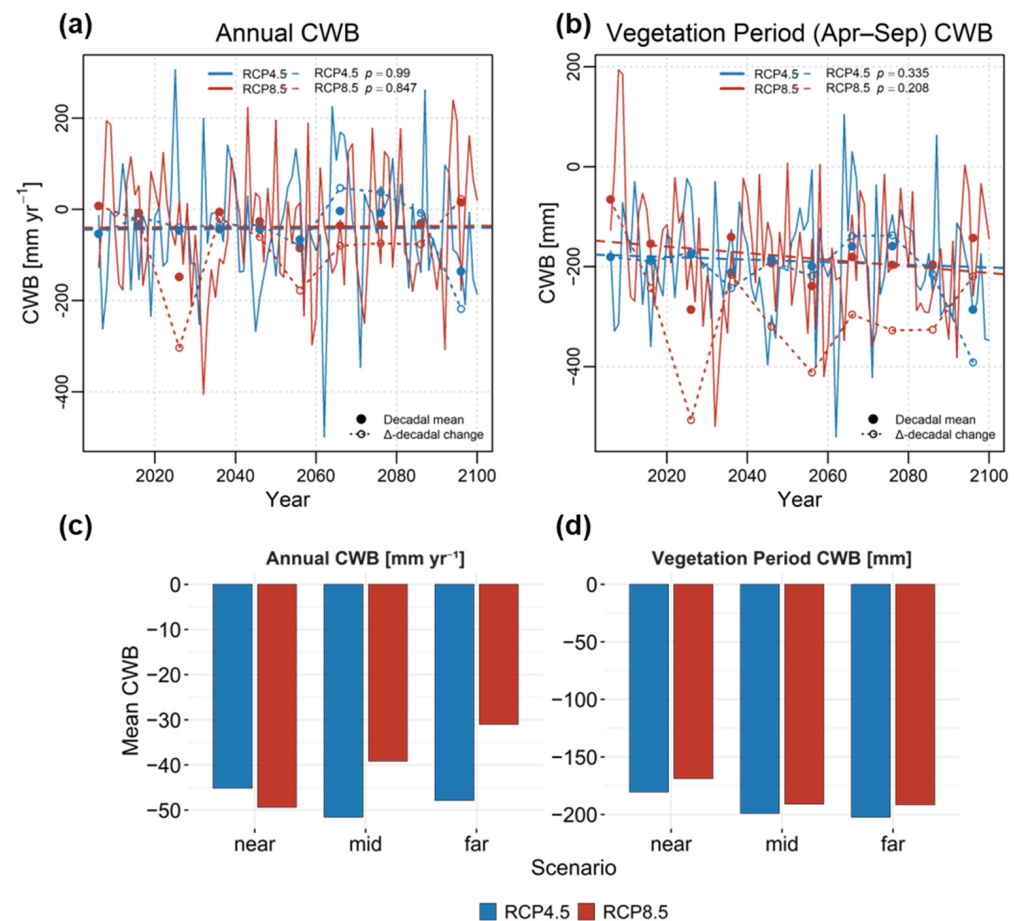


Figure 5. Projected climatic water balance (CWB) in Brandenburg under RCP4.5 (blue) and RCP8.5 (red) for 2006–2100. (a) Annual CWB time series; (b) growing-season (April–September) CWB time series. Decadal means are shown as points, and solid lines indicate linear trends (Mann–Kendall significance indicated in panels). (c) Thirty-year mean annual CWB for the near (2006–2035)-, mid (2036–2065)-, and far (2071–2100)-future periods; (d) corresponding growing-season CWB. Different y-axis scales are used for annual and growing-season values.

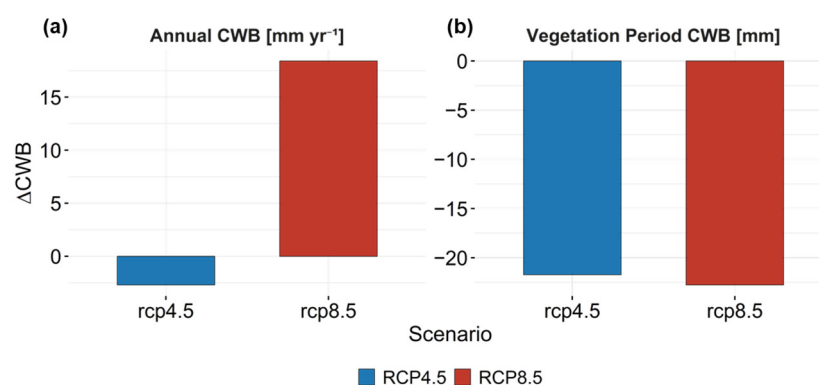


Figure 6. Changes in climatic water balance between future periods. Spatially averaged Δ CWB (2071–2100 minus 2006–2035) under RCP4.5 and RCP8.5. (a) annual; (b) Growing season. Negative values indicate increasing deficits.

3.3. Hydro-Climatic Stress Indicators

To assess future hydro-climatic stress during the vegetation period (April–September), four complementary indicators derived from growing-season climatic water balance (CWB_{GS}) were evaluated: (i) FDY, (ii) MWD, (iii) AI_{GS}, and (iv) CWB_{GS,Z}. Together, these

indicators characterize different dimensions of hydro-climatic stress, including deficit frequency, deficit magnitude, atmospheric dryness, and drought anomalies.

3.3.1. Frequency of Deficit Years (FDY)

FDY values remained consistently high throughout the twenty-first century under both emission scenarios, indicating persistent seasonal water limitation across Brandenburg (Figure 7). Under RCP4.5, the mean fraction of the study area affected by negative growing-season climatic water balance changed only slightly from 0.954 in the near future (2006–2035) to 0.964 in the far future (2071–2100). Under RCP8.5, lower values were projected for the near future (0.890), followed by a gradual increase to 0.950 by the end of the century, converging toward RCP4.5 conditions.

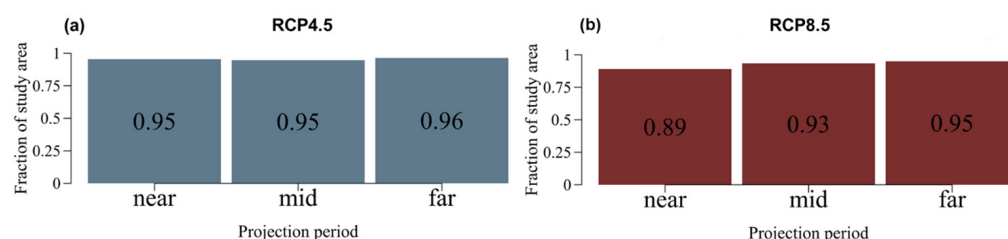


Figure 7. Evolution of growing-season deficit conditions. Mean fraction of the study area affected by negative growing-season climatic water balance ($CWB_{GS,i} < 0$) under (a) RCP4.5 and (b) RCP8.5 for the near-future (2006–2035), mid-century (2036–2065), and far-future (2071–2100) periods.

Despite considerable interannual variability (Appendix A, Figure A3), deficit conditions affected nearly the entire study area in most years. Spatial differences between scenarios were generally small, although RCP8.5 showed slightly higher frequencies across most regions (Figure 8). Localized exceptions occurred in parts of southern Brandenburg, reflecting regional differences in the balance between precipitation and atmospheric evaporative demand.

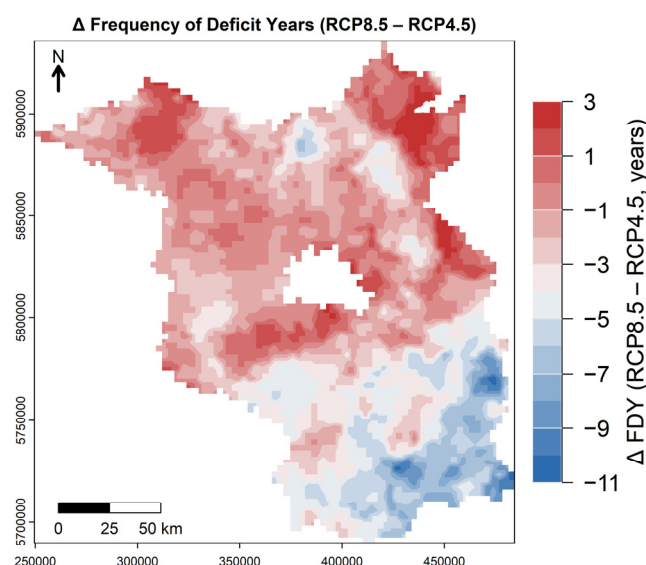


Figure 8. Difference in deficit-year occurrence between scenarios. Difference in the cumulative number of years with negative growing-season climatic water balance ($CWB_{GS,i} < 0$) between RCP8.5 and RCP4.5 during 2006–2100. Positive values indicate more deficit years under RCP8.5, whereas negative values indicate fewer deficit years relative to RCP4.5.

3.3.2. Magnitude of Water Deficit (MWD)

The Magnitude of Water Deficit (MWD)—represented by the growing-season climatic water balance (CWB_{GS})—remained negative throughout the twenty-first century under both emission scenarios, indicating persistent seasonal atmospheric water deficits across Brandenburg (Figure 9). Under RCP4.5, spatially averaged MWD decreased from -694 mm (2006–2035) to -714 mm (2036–2065) and -730 mm (2071–2100). Under RCP8.5, mean values were -708 mm, -715 mm, and -720 mm for the same periods, respectively. Differences between scenarios were small (≤ 14 mm) relative to interannual variability.

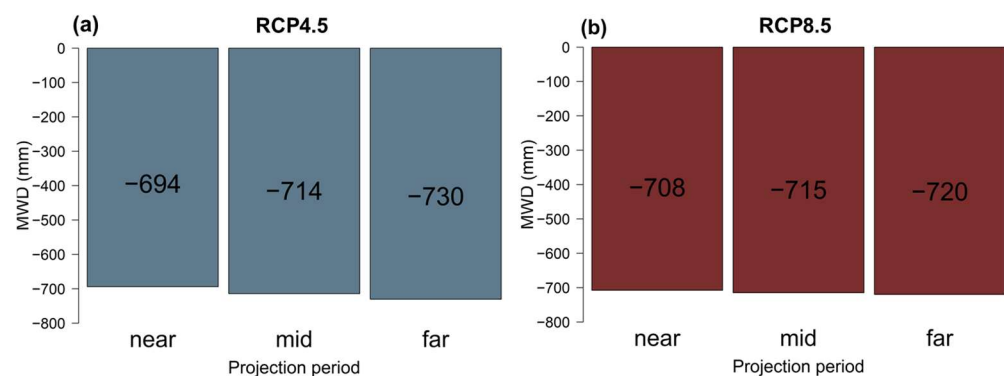


Figure 9. Magnitude of Water Deficit (MWD) across future periods. Spatially averaged growing-season climatic water balance (CWB_{GS}), used as the Magnitude of Water Deficit (MWD), for the near-future (2006–2035), mid-century (2036–2065), and far-future (2071–2100) periods under (a) RCP4.5 and (b) RCP8.5. More negative values indicate stronger seasonal atmospheric water deficits.

Spatial patterns (Appendix A, Figure A5) showed widespread negative CWB_{GS} values across Brandenburg, with the strongest deficits occurring in the southern and central parts of the study area. Considerable interannual variability was evident (Appendix A, Figure A6), yet seasonal water deficits remained persistent throughout the simulation period.

Trend analyses indicated weak long-term declines under both scenarios (Appendix A, Figure A6). Sen's slopes were approximately -1.2 mm yr^{-1} (RCP4.5) and -1.8 mm yr^{-1} (RCP8.5), although neither trend was statistically significant at $p < 0.05$ due to high interannual variability.

Overall, MWD remained consistently negative across all projection periods, highlighting persistent growing-season atmospheric water limitation in Brandenburg. Scenario differences were small compared with internal variability.

3.3.3. Growing-Season Aridity Index (AI_{GS})

Across all projection periods and emission scenarios, spatially averaged AI_{GS} remained consistently above 1, indicating persistent atmospheric moisture limitation during the growing season in Brandenburg (Figure 10). Under RCP4.5, mean AI_{GS} increased from 1.64 (2006–2035) to 1.74 (2036–2065), followed by a slight decrease to 1.72 (2071–2100). Under RCP8.5, values remained comparatively stable at 1.66, 1.70, and 1.67, respectively. Overall, inter-scenario differences were small relative to inter-period variability.

Spatial variability in AI_{GS} was pronounced (Appendix A, Figure A7), with consistently higher aridity levels in central Brandenburg, indicating stronger atmospheric moisture limitation compared to northern and southern regions. However, spatial gradients were stable across scenarios and time periods, suggesting limited structural change in spatial aridity patterns.

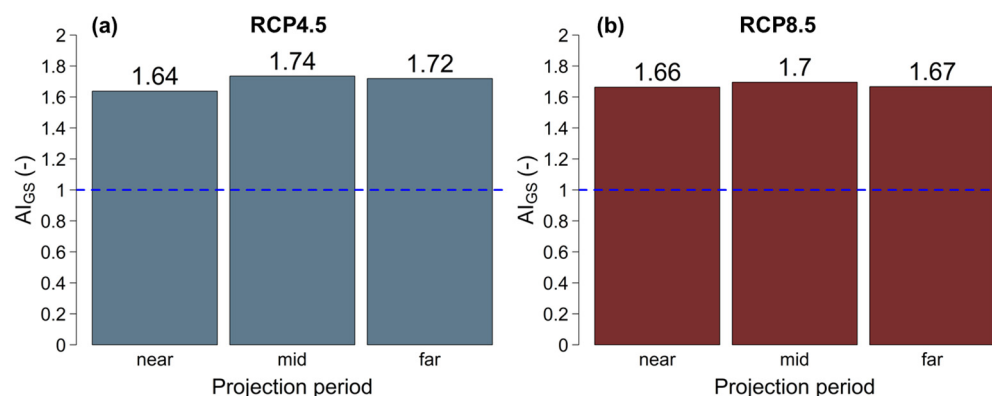


Figure 10. Changes in growing-season aridity (AI_{GS}) across future periods under (a) RCP4.5 and (b) RCP8.5 for the near-future (2006–2035), mid-century (2036–2065), and far-future (2071–2100) periods. The blue dashed line indicates the aridity threshold ($AI_{GS} = 1$), where precipitation equals atmospheric evaporative demand. Values above this threshold indicate increasingly arid conditions during the growing season.

The annual time series exhibited strong interannual variability (Appendix A, Figure A8), with several extreme years characterized by $AI_{GS} > 4.0$ (e.g., 2062 under RCP4.5 and 2032 under RCP8.5), reflecting episodic but pronounced atmospheric moisture deficits. These extreme values highlight that short-term variability dominates over long-term directional change.

Trend analysis confirmed only weak positive tendencies in AI_{GS} over time. Sen's slopes were 0.00149 yr^{-1} (RCP4.5) and 0.00191 yr^{-1} (RCP8.5). However, Mann–Kendall tests indicated that these trends were not statistically significant (RCP4.5: $\tau = 0.065$, $p = 0.351$; RCP8.5: $\tau = 0.081$, $p = 0.247$), confirming the absence of robust monotonic trends over the simulation period.

Overall, AI_{GS} remained persistently above the aridity threshold throughout the twenty-first century. While interannual variability and occasional extremes were substantial, long-term changes were weak and statistically non-significant, and differences between emission scenarios remained limited.

3.3.4. Standardized Growing-Season Climatic Water Balance Anomaly ($CWB_{GS,Z}$)

Spatially averaged $CWB_{GS,Z}$ values remained close to zero over the full simulation period, while spatial patterns showed pronounced heterogeneity (Appendix A, Figure A9), with persistent negative anomalies in central and northern Brandenburg.

Thirty-year mean anomalies showed a weak shift toward drier-than-average conditions over time (Figure 11). Under RCP4.5, values declined from +0.07 (2006–2035) to −0.05 (2036–2065) and −0.15 (2071–2100). Under RCP8.5, a similar but weaker change occurred, from +0.02 to −0.02 and −0.05, respectively. The magnitude of change remained small relative to interannual variability.

Trend analysis showed weak negative tendencies in both scenarios. Sen's slopes were -0.0030 yr^{-1} (RCP4.5) and -0.0041 yr^{-1} (RCP8.5). Mann–Kendall tests were not statistically significant (RCP4.5: $\tau = -0.062$, $p = 0.375$; RCP8.5: $\tau = -0.073$, $p = 0.295$), confirming that long-term changes were not robust relative to internal variability (Appendix A, Figure A10).

Extreme anomalies highlighted strong interannual variability, with pronounced negative values (e.g., −3.38 in 2062 under RCP4.5; −2.94 in 2032 under RCP8.5) and positive anomalies exceeding +2 in both scenarios, confirming high hydro-climatic volatility throughout the simulation period.

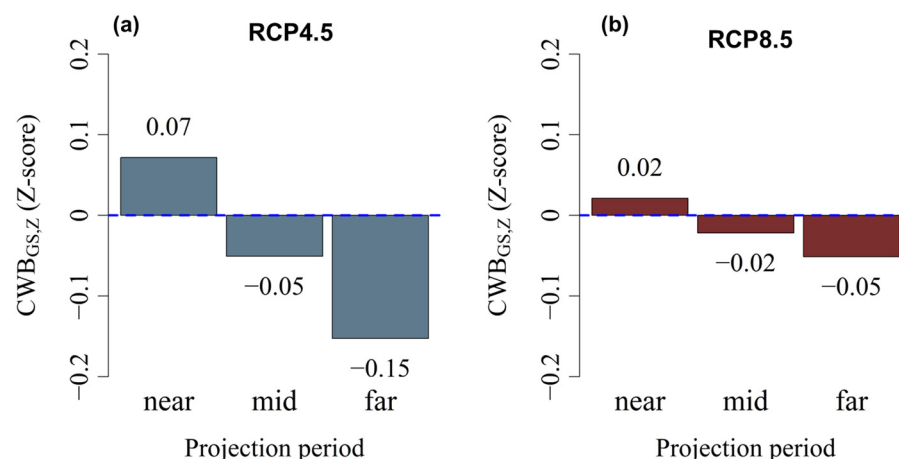


Figure 11. Changes in standardized growing-season moisture anomalies ($CWB_{GS,Z}$) across future periods under (a) RCP4.5 and (b) RCP8.5 for the near future (2006–2035), mid-century (2036–2065), and far future (2071–2100). Positive values indicate wetter-than-average conditions, while negative values indicate drier-than-average conditions relative to the reference climatology. The blue dashed line indicates the zero line ($CWB_{GS,Z} = 0$).

Drought frequency patterns (Appendix A, Figures A11 and A12) showed that moderate drought ($Z < -1$) occurred frequently across large parts of Brandenburg under both scenarios, whereas severe drought ($Z < -2$) was spatially restricted, primarily in northern and northeastern regions. Severe drought remained rare overall, as indicated by the predominance of zero-frequency values.

In summary, the $CWB_{GS,Z}$ analysis showed only a weak shift toward more negative growing-season conditions. This signal was spatially heterogeneous and statistically non-significant, with interannual variability representing the dominant component of hydro-climatic variability under both emission scenarios.

3.4. Relationship Between Climatic Water Balance and Soil Moisture

The relationship between vegetation-period climatic water balance (CWB) and observed root-zone soil moisture (SM, % nFK) was analyzed for three hydro-climatic phases: Phase 1 (2006–2014), Phase 2 (2015–2020), and Phase 3 (2021–2025) (Figure 12).

Across all phases and both emission scenarios, statistically significant positive relationships were identified between CWB and soil moisture ($p < 0.001$). However, explanatory power varied substantially among phases, with consistently low coefficients of determination ($R^2 = 0.004$ – 0.139), indicating that CWB explains only a limited proportion of soil moisture variability.

Under RCP4.5, the relationship strengthened during the drought phase (Phase 2), as indicated by an increase in slope (0.72 to 0.82) and R^2 (0.044 to 0.067), before weakening markedly in Phase 3 (slope = 0.16; $R^2 = 0.004$). Under RCP8.5, a similar pattern was observed, with the strongest relationship in Phase 2 (slope = 0.61; $R^2 = 0.139$), compared to weaker relationships in Phase 1 (slope = 0.41; $R^2 = 0.024$) and Phase 3 (slope = 0.38; $R^2 = 0.035$).

Despite statistically significant associations, the low R^2 values across all phases indicate substantial unexplained variability in soil moisture dynamics, suggesting that factors beyond climatic water balance contribute to root-zone soil moisture variability.

Overall, the strongest CWB–SM relationships were observed during the drought period (2015–2020) under both scenarios, with weaker relationships during the pre-drought and post-drought phases.

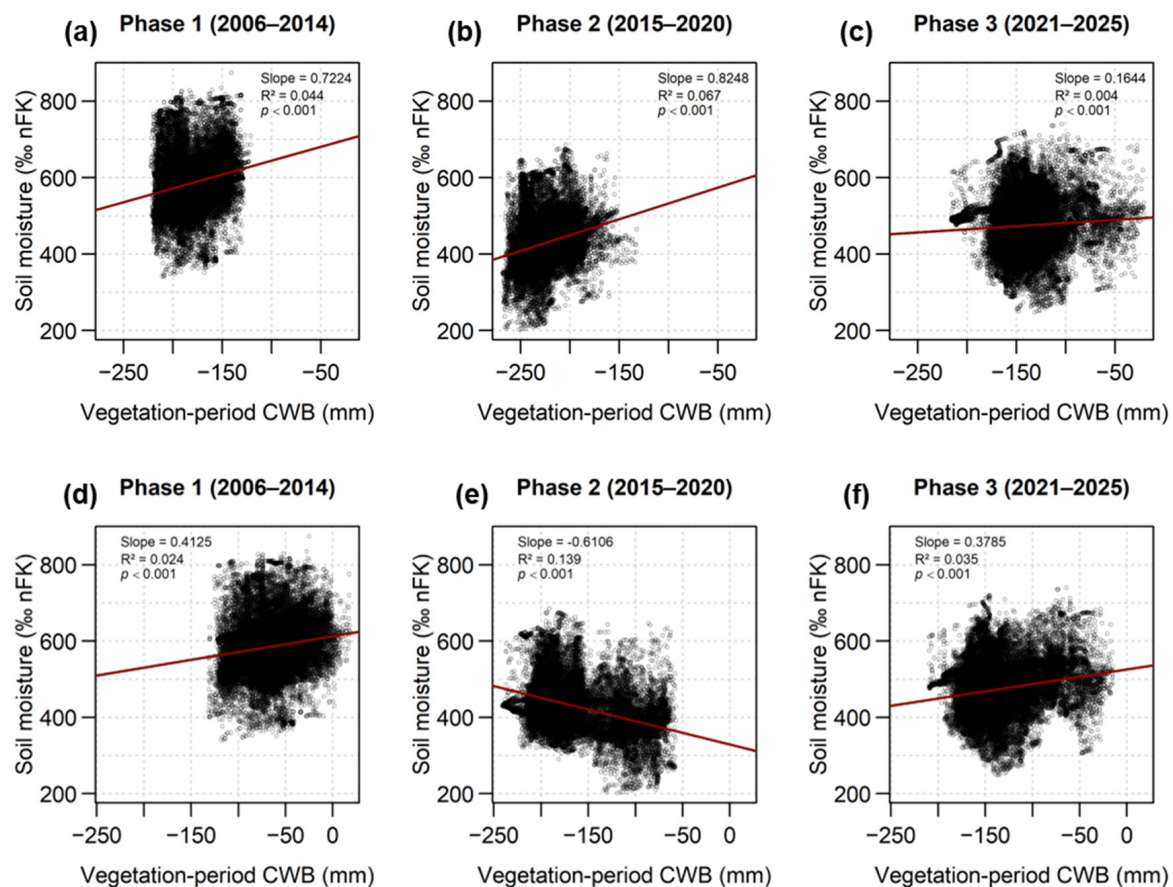


Figure 12. Relationship between growing-season climatic water balance (CWB) and root-zone soil moisture (SM, % nFK) across three hydro-climatic phases. Panels (a–c) show RCP4.5 and panels (d–f) show RCP8.5 for Phase 1 (2006–2014), Phase 2 (2015–2020), and Phase 3 (2021–2025). Black dots represent individual grid cells, and red lines indicate linear regression fits (all $p < 0.001$). The inset statistics report regression slope and coefficient of determination (R^2).

3.5. Ensemble-Based Uncertainty Assessment

3.5.1. Inter-Model Variability of Key Hydro-Climatic Variables

Inter-model uncertainty was assessed using the four RCM realizations (Section 2.3.6). Projected growing-season temperature (tas), precipitation (pr), reference evapotranspiration (ET_0), and climatic water balance (CWB) were compared for the near-future (2006–2035) and far-future (2071–2100) periods (Figure 13; Appendix A, Figure A13).

All model realizations consistently project increasing vegetation-period temperatures, indicating a robust warming signal. Under RCP4.5, ensemble warming ranges from approximately 0.9 to 1.8 °C, while under RCP8.5 it increases to 2.5–3.9 °C. Inter-model spread is relatively small for temperature, indicating strong agreement on both the direction and magnitude of change.

Precipitation shows substantially higher inter-model uncertainty, with simulated changes ranging from −17 to +34 mm under RCP4.5 and from −34 to +49 mm under RCP8.5. The occurrence of both positive and negative changes across models indicates a lack of agreement on precipitation direction, highlighting precipitation as the dominant source of structural uncertainty.

Evapotranspiration increases in most realizations but shows considerable spread, particularly under RCP8.5 (−11 to +104 mm), reflecting differences in model sensitivity to atmospheric demand and temperature-driven feedback.

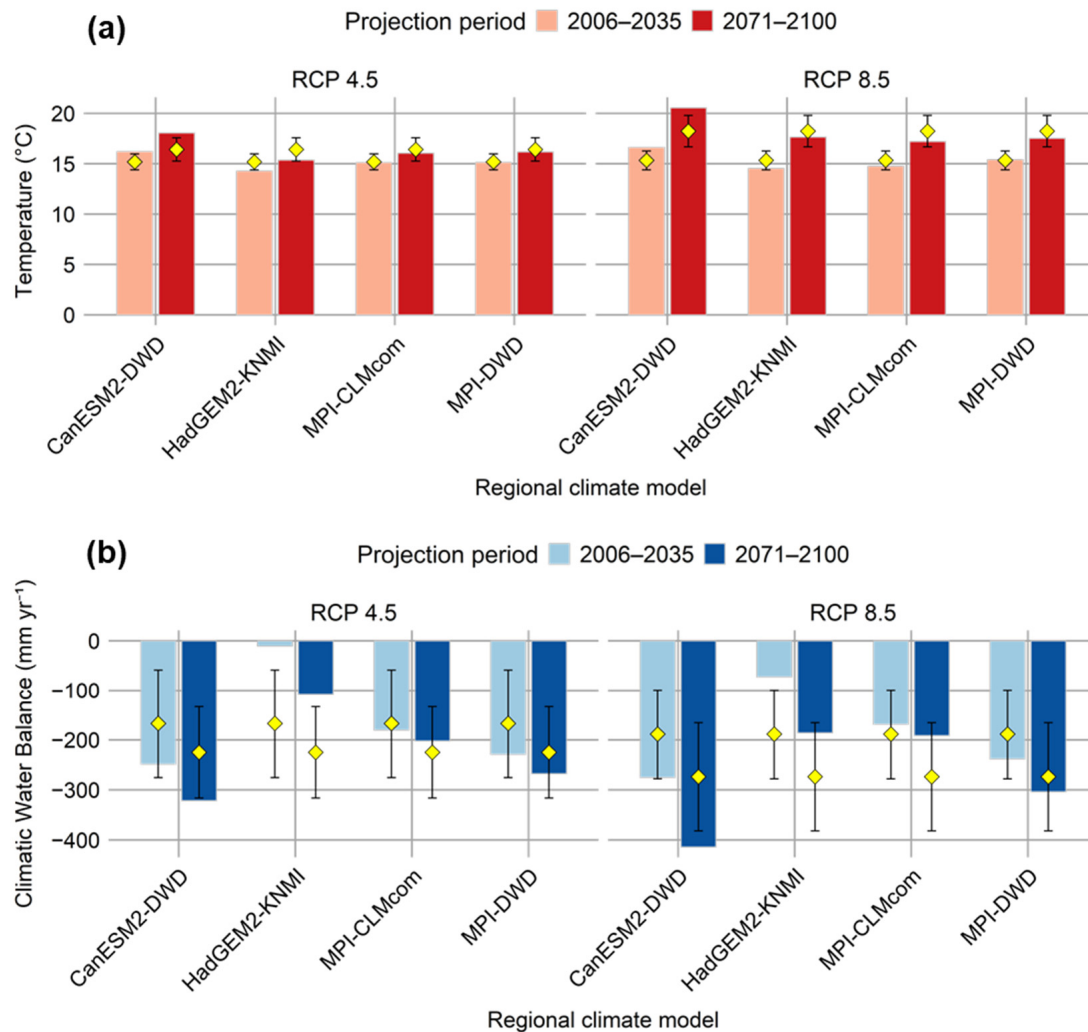


Figure 13. Inter-model projections of growing-season (a) air temperature (tas) and (b) climatic water balance (CWB) derived from four regional climate model realizations under RCP4.5 and RCP8.5. Bars indicate the near-future (2006–2035) and far-future (2071–2100) periods, while yellow markers represent ensemble mean values across models.

Climatic water balance exhibits the largest ensemble spread among all variables. Under RCP4.5, far-future CWB ranges from −109 to −321 mm, and under RCP8.5, it ranges from −186 to −414 mm. Despite this spread, all realizations consistently simulate negative CWB values, indicating full agreement on the direction of future water deficits.

Overall, inter-model variability is smallest for temperature, larger for precipitation and evapotranspiration, and largest for CWB. Nevertheless, all models consistently project warming and decreasing growing-season water availability.

3.5.2. Inter-Model Variability in Climatic Water Balance Change

Projected changes in vegetation-period climatic water balance (ΔCWB), defined as the difference between 2071–2100 and 2006–2035, show a consistent drying signal across all regional climate model realizations under both emission scenarios (Figure 14).

Under RCP4.5, ΔCWB ranges from −21.7 to −98.6 mm, with an ensemble mean of −57.9 mm and a standard deviation of 34.5 mm. Under RCP8.5, the magnitude of drying increases, ranging from −22.8 to −138.6 mm, with a mean of −85.2 mm and a standard deviation of 51.5 mm. The larger ensemble spread under RCP8.5 indicates increasing uncertainty under stronger radiative forcing.

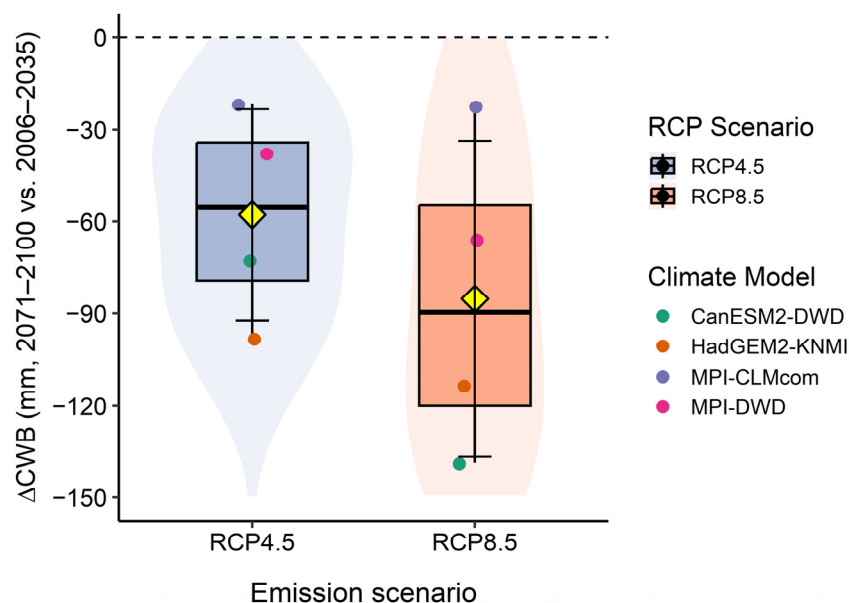


Figure 14. Inter-model variability in projected changes in growing-season climatic water balance (ΔCWB) between the far-future (2071–2100) and near-future (2006–2035) periods under RCP4.5 and RCP8.5. Boxplots show the interquartile range across four regional climate model realizations, with medians indicated by central lines. Individual model results are shown as colored circular symbols, and yellow diamonds indicate ensemble means. The dashed line indicates the zero line ($\Delta\text{CWB} = 0$).

All models project negative ΔCWB , indicating full agreement on the direction of change. Thus, while uncertainty in magnitude remains substantial, uncertainty in sign is absent, indicating a robust ensemble consensus on decreasing growing-season water availability.

4. Discussion

The results indicate a systematic shift toward increasing growing-season hydro-climatic stress in Brandenburg despite comparatively small changes in annual water balance. This divergence reflects the increasing importance of seasonal atmospheric water limitation under climate change. Comparison with root-zone soil moisture provides additional insights into the strengths and limitations of climatic water balance as an indicator of ecosystem water availability. The following sections discuss the underlying drivers, ecological implications, and associated uncertainties of the projected changes.

4.1. Drivers of Seasonal Drying and Climatic Water Balance Changes

The results reveal a pronounced divergence between annual and growing-season hydro-climatic conditions in Brandenburg. While annual climatic water balance (CWB) changes only moderately throughout the twenty-first century, growing-season CWB shows a consistent decline under both emission scenarios. This indicates that seasonal processes rather than annual water-balance totals dominate future hydro-climatic change in the region.

The relative stability of annual CWB results from partially compensating effects of precipitation and atmospheric water demand. However, this compensation does not occur during the vegetation period (April–September), when increasing temperatures substantially enhance evapotranspiration while projected precipitation changes are insufficient to offset the resulting increase in atmospheric water demand. Consequently, seasonal water deficits intensify despite relatively small changes in annual precipitation totals. Similar patterns have been reported for Central Europe, where climate warming is projected to increase summer drying and alter the seasonal distribution of water availability [4,58,59].

Projected temperature increases represent the primary driver of these changes. All climate simulations consistently indicate substantial warming, particularly under RCP8.5, resulting in increased atmospheric evaporative demand and higher reference evapotranspiration (ET_0). Consequently, even modest precipitation changes can translate into pronounced reductions in climatic water balance. This finding is consistent with studies highlighting the increasing importance of atmospheric evaporative demand as a key driver of drought intensification under climate change [3,15,60].

These results also emphasize the limitations of annual climate indicators for evaluating ecosystem-relevant water availability. Annual precipitation and annual water-balance metrics may mask substantial intra-annual shifts in hydro-climatic conditions that directly affect vegetation and land-use systems. Similar limitations of annual indicators have been reported across temperate regions where seasonal climate changes exert stronger ecological impacts than changes in annual means [1,61].

Overall, the results indicate that future hydro-climatic change in Brandenburg is primarily driven by increasing atmospheric water demand during the growing season rather than by strong reductions in annual precipitation. The projected increase in seasonal water limitation is consistent with broader projections of enhanced summer drying and increasing hydro-climatic stress across Central Europe [1,59].

4.2. Soil Moisture Response to Climatic Water Balance

The relationship between climatic water balance and root-zone soil moisture demonstrates a statistically significant but variable coupling across hydro-climatic phases. Although all relationships are significant ($p < 0.001$), the low explanatory power indicates that CWB captures only a limited fraction of soil moisture variability.

The strength of the coupling is strongly state-dependent, with the highest correlation observed during the drought phase (2015–2020). During this period, reduced precipitation and elevated atmospheric demand increase the direct control of atmospheric forcing on soil moisture dynamics, resulting in stronger CWB–soil moisture coupling. Similar drought-amplified coupling has been reported across Europe [3,54].

In contrast, weaker relationships during pre- and post-drought phases indicate that soil moisture is more strongly regulated by internal system properties under non-extreme conditions. These include soil texture, rooting depth, vegetation characteristics, groundwater influence, and hydrological buffering processes. Temporal lags between atmospheric forcing and soil moisture response further reduce instantaneous correlations [52,54].

Overall, the results suggest that climatic water balance is a robust indicator of atmospheric water availability but not a direct predictor of soil moisture dynamics. Instead, soil moisture integrates both atmospheric forcing and subsurface storage processes, making it a more complex system variable. The observed phase dependency highlights that atmospheric controls become increasingly dominant under drought conditions.

4.3. Implications for Vegetation and Land Use

The projected increase in growing-season hydro-climatic stress has important implications for vegetation and land-use systems in Brandenburg. The region's predominantly sandy soils and limited water-holding capacity make ecosystems particularly sensitive to seasonal water deficits and increasing evaporative demand [11,31].

Across all indicators, results consistently show an intensification of growing-season water limitation. Increasing CWB deficits, higher FDY, stronger MWD, and rising AI_{GS} collectively indicate a coherent signal of worsening seasonal hydro-climatic conditions. Importantly, this signal emerges despite a relatively stable annual water balance, emphasizing the ecological relevance of seasonal processes.

Model agreement further strengthens confidence in these findings. Although uncertainty exists in the magnitude of change, all simulations consistently project declining growing-season water availability. This consistency suggests that seasonal drying represents a robust regional climate signal rather than a model-dependent artefact.

Ecologically, increasing water deficits during the growing season can reduce stomatal conductance, constrain photosynthesis, and lower biomass production, thereby reducing ecosystem productivity [1,3]. Forest ecosystems may be particularly vulnerable due to cumulative drought impacts on tree growth, carbon uptake, and mortality risk [47,62].

The projected increase in drought frequency is particularly relevant for Scots pine-dominated forest systems in Brandenburg. Although drought-tolerant, these ecosystems have shown increasing sensitivity to repeated drought events in recent years [11]. The combination of higher evaporative demand and more frequent seasonal deficits may therefore challenge long-term forest stability.

Agricultural systems are similarly exposed, as crop productivity depends strongly on water availability during the vegetation period. Increasing seasonal deficits may reduce yield stability and increase irrigation demand, consistent with findings from Central European drought impact studies [1,3,63].

These results highlight the need for adaptation strategies that explicitly target growing-season water availability rather than annual averages. Measures such as drought-adapted crops, diversified forest stands, improved soil-water conservation, and enhanced landscape water retention may become increasingly important under future climate conditions.

4.4. Uncertainty, Limitations, and Future Research

Several limitations should be considered when interpreting the results of this.

First, the climate projections are based on four regional climate model realizations driven by CMIP5 boundary conditions. Although CMIP6 projections are increasingly used in climate impact studies, the CMIP5 ensemble applied here represents the official high-resolution climate projection framework currently used by the Brandenburg State Office for the Environment for regional climate adaptation planning. Previous studies have shown that CMIP5-driven regional climate simulations provide robust estimates of future changes in temperature, evapotranspiration, and drought-related variables across Central Europe [7,45,64]. While CMIP6 projections may differ in the magnitude of projected changes, both model generations consistently indicate increasing temperatures, enhanced atmospheric evaporative demand, and increasing drought risk across Europe [1,15,65]. Accordingly, the applied CMIP5-based ensemble provides a consistent and policy-relevant basis for assessing future hydro-climatic changes in Brandenburg.

Second, this study uses climatic water balance (CWB) as an indicator of atmospheric water availability. Alternative drought metrics such as SPI and SPEI are widely used for drought monitoring and inter-regional comparison. However, for the purpose of this study—assessing changes in the physical water balance rather than classifying drought events—CWB was considered more appropriate because it directly quantifies the balance between precipitation and evaporative demand in physical units (mm). This allows process-based interpretation of seasonal water surplus and deficit conditions relevant to vegetation and land-use systems. Nevertheless, CWB does not explicitly represent soil-water storage, groundwater processes, runoff generation, or hydrological buffering, and should therefore be interpreted primarily as an indicator of atmospheric drought conditions [3].

Third, uncertainty arises from multiple sources, including emission scenarios, climate model structure, and internal climate variability. Temperature projections show relatively high agreement across ensemble members, whereas precipitation exhibits substantially larger variability. Consequently, uncertainty in future climatic water balance is mainly

driven by precipitation uncertainty. Despite these uncertainties, all simulations consistently indicate increasingly negative growing-season CWB values, suggesting robust agreement regarding the direction of future seasonal drying.

Finally, the soil moisture dataset used in this study is model-derived rather than based on direct observations. Although the DWD soil moisture product is among the most comprehensive datasets available for Germany, uncertainties related to model structure, parameterization, rooting depth assumptions, and groundwater representation remain. These factors likely contribute to the relatively weak statistical relationships observed between climatic water balance and root-zone soil moisture.

Future research should extend this analysis using larger CMIP6 ensembles, investigate drought propagation between atmospheric and subsurface compartments, explicitly consider groundwater–soil moisture interactions, and evaluate vegetation-specific responses to projected hydro-climatic change. Such approaches would further improve understanding of ecosystem vulnerability and future water availability in Brandenburg and comparable regions of Central Europe.

5. Conclusions

This study shows a consistent divergence between relatively stable annual water balance conditions and increasingly negative growing-season hydro-climatic conditions in Brandenburg under future climate scenarios. Seasonal water deficits intensify across all indicators, indicating a robust seasonal drying signal.

Growing-season conditions are substantially more sensitive to climate change than annual averages, with increasing climatic water balance (CWB) deficits, higher drought frequency, and rising aridity across the twenty-first century.

While CWB shows a statistically significant relationship with root-zone soil moisture, the explained variability is limited, reflecting the influence of soil properties and hydrological storage processes not explicitly represented by atmospheric indicators.

Despite uncertainties in magnitude, all climate model realizations consistently project increasing seasonal water limitation, indicating a robust seasonal drying trend in Brandenburg.

Overall, the results highlight that future hydro-climatic impacts in Brandenburg will be primarily driven by seasonal water deficits rather than annual precipitation changes, with important implications for ecosystems, agriculture, and water resource management in regions with low water-holding capacity.

Author Contributions: Conceptualization, M.A.M., W.R. and R.H.; methodology, M.A.M.; software, M.A.M. and R.H.; validation, M.A.M., R.H. and W.R.; formal analysis, M.A.M.; investigation, M.A.M.; data curation, M.A.M.; writing—original draft preparation, M.A.M.; writing—review and editing, R.H. and W.R.; visualization, M.A.M.; supervision, W.R. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The climate projection data used in this study were provided by the Brandenburg State Office for the Environment (LfU Brandenburg) and are available upon reasonable request from the corresponding author, subject to permission from the data provider. The root-zone soil moisture data are publicly available from the DWD Climate Data Center [37].

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Figures A1–A13 provide supplementary information on historical reference conditions, projected climate variables, hydro-climatic stress indicators, spatial patterns, and uncertainty analyses to complement the results in the main text.

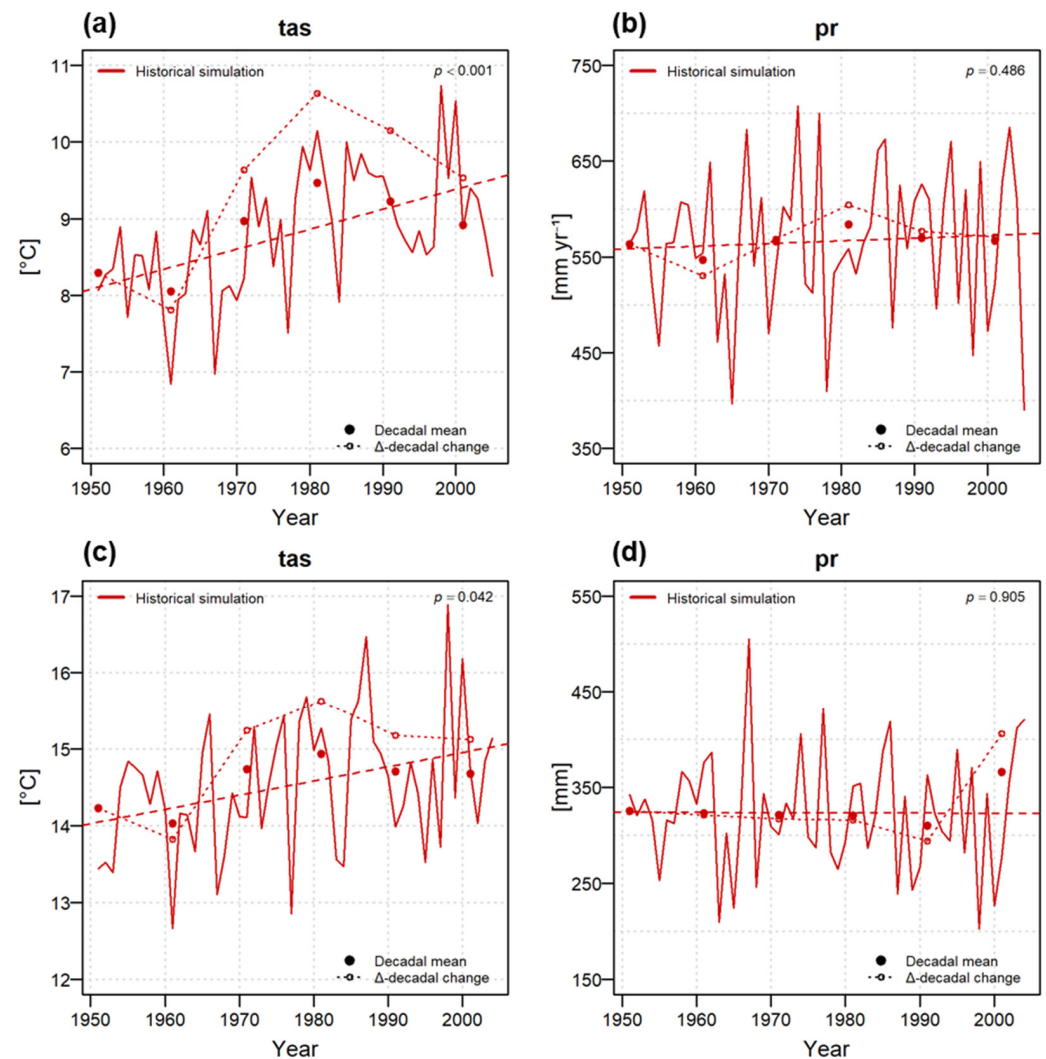


Figure A1. Historical climate conditions in Brandenburg (1951–2005). MPI-CLMcom historical simulation. (a,b) Annual tas and pr; (c,d) growing-season tas and pr. A single time series is shown (identical forcing before 2006). The solid line shows the annual time series, the dashed lines indicate decadal mean and Δ -decadal change, and the dotted line shows the linear trend.

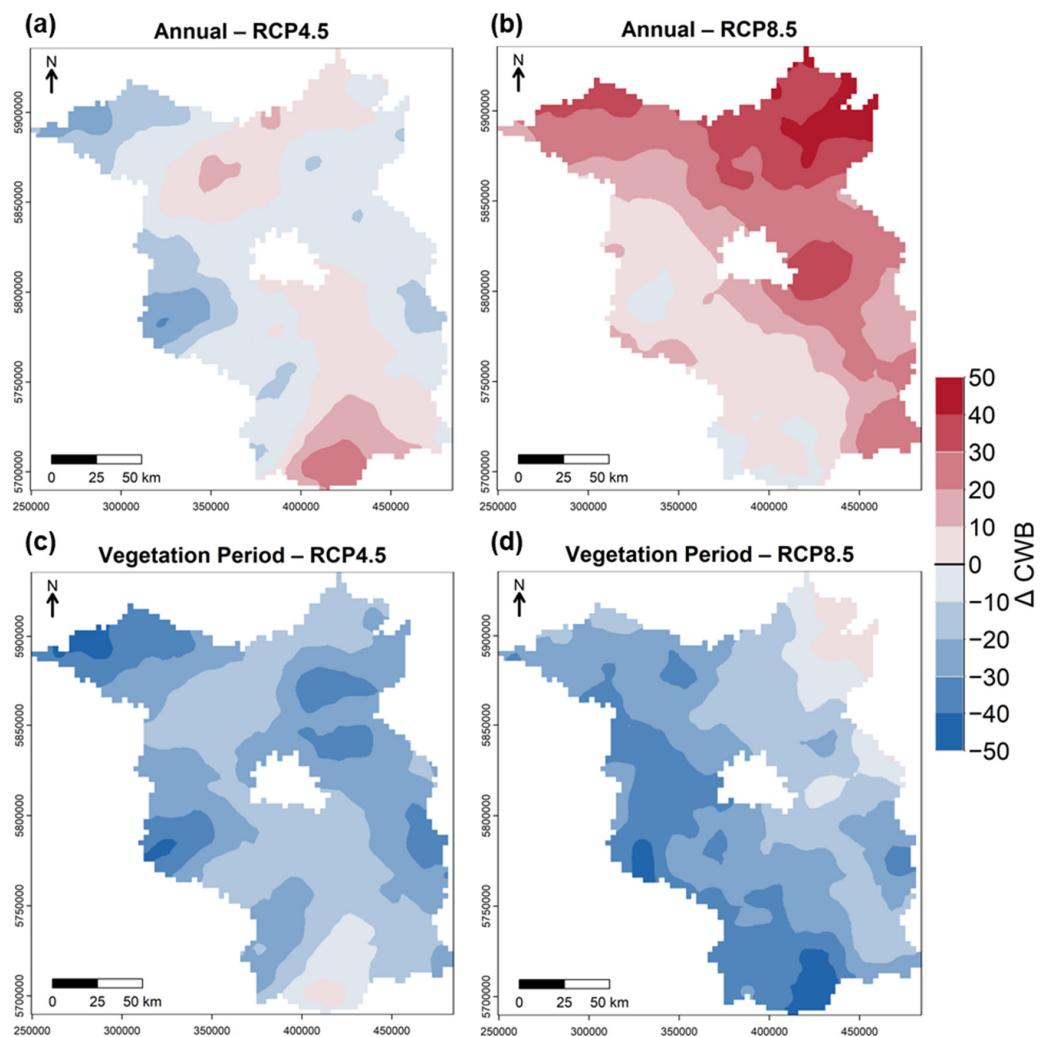


Figure A2. Spatial patterns of climatic water balance change (ΔCWB). Differences between 2071–2100 and 2006–2035. (a,b) Annual conditions; (c,d) growing-season conditions. Negative values (blue shades) indicate increasing water deficits; positive values indicate decreasing water deficits (red).

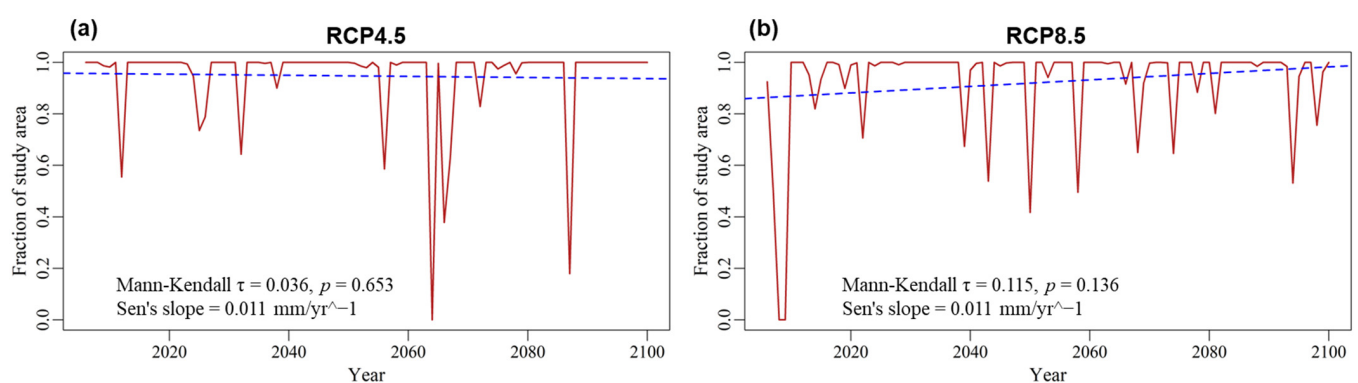


Figure A3. Interannual variability of deficit area fraction. Annual fraction of Brandenburg affected by negative growing-season climatic water balance ($\text{CWB}_{\text{CS},i} < 0$) during 2006–2100 under (a) RCP4.5 and (b) RCP8.5. These annual values form the basis of the period averages shown in Figure 7. The blue dashed line indicates the linear trend.

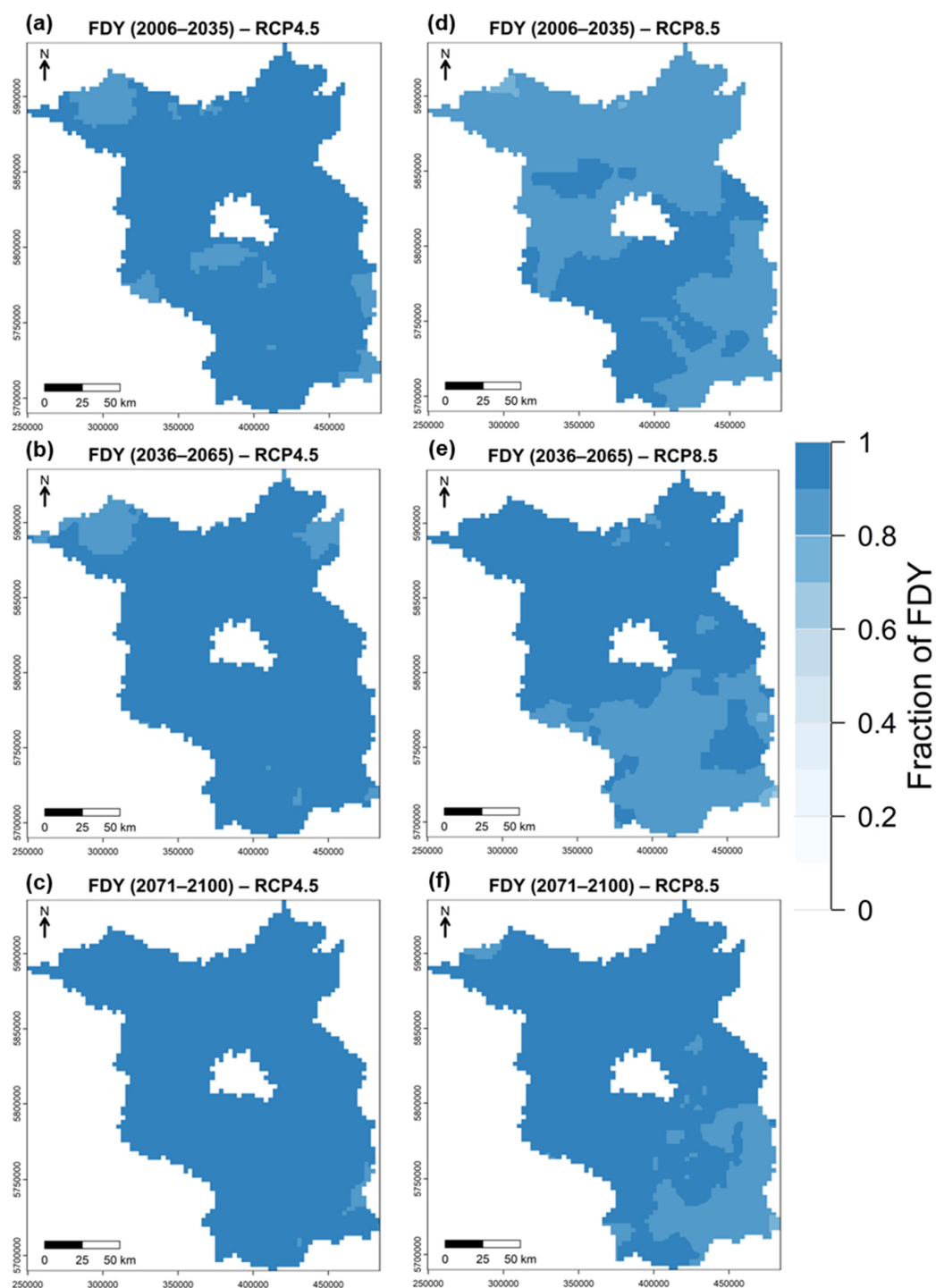


Figure A4. Spatial distribution of Frequency of Deficit Years (FDY). Frequency of years with negative growing-season climatic water balance ($CWB_{GS,i} < 0$) for RCP4.5 (a–c) and RCP8.5 (d–f) during the near-future (2006–2035), mid-century (2036–2065), and far-future (2071–2100) periods.

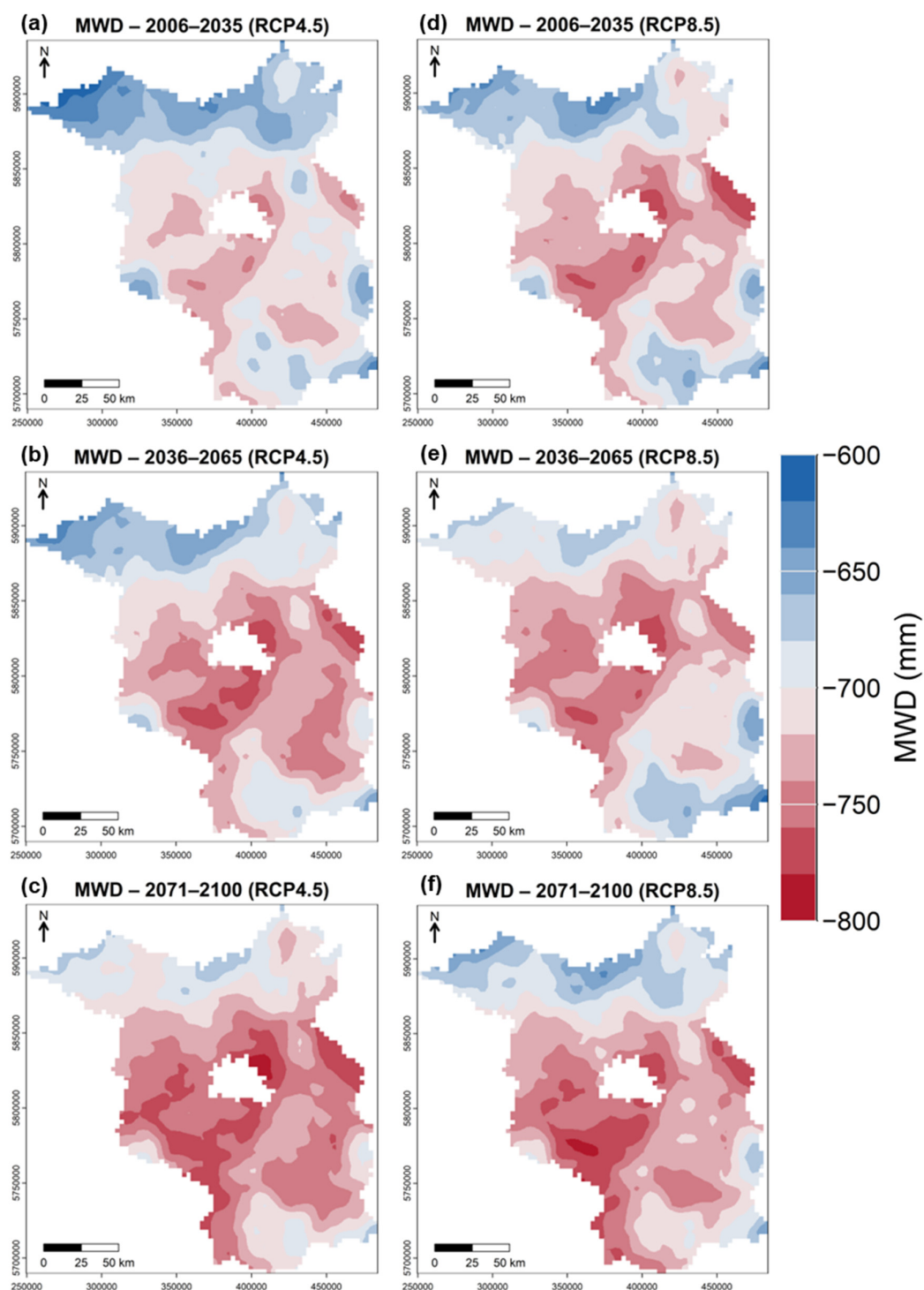


Figure A5. Spatial patterns of growing-season Magnitude of Water Deficit (MWD), expressed as CWB_{GS} , under RCP4.5 (a–c) and RCP8.5 (d–f) for the near-future (2006–2035), mid-century (2036–2065), and far-future (2071–2100) periods. More negative values indicate stronger seasonal atmospheric water deficits.

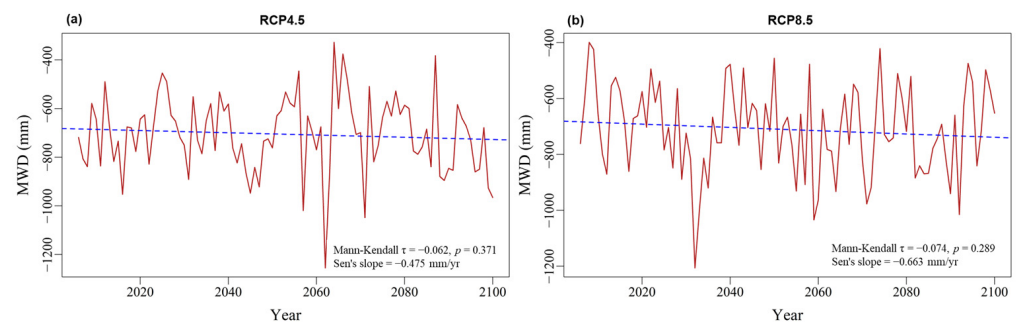


Figure A6. Temporal evolution of growing-season Magnitude of Water Deficit (MWD) under (a) RCP4.5 and (b) RCP8.5 from 2006 to 2100. Dashed lines indicate linear trends.

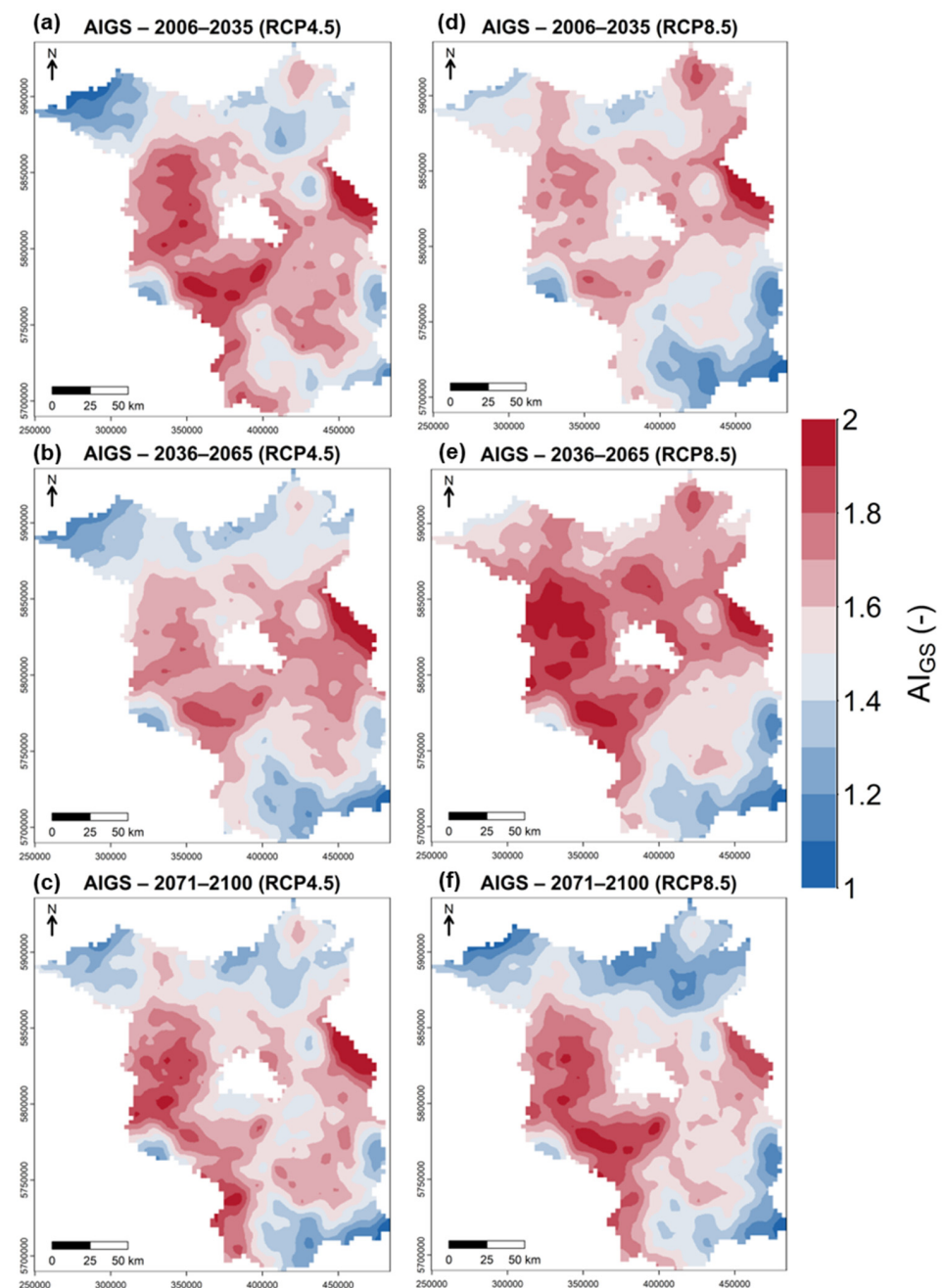


Figure A7. Spatial patterns of growing-season aridity (AI_{GS}) under RCP4.5 (a–c) and RCP8.5 (d–f) for the near-future (2006–2035), mid-century (2036–2065), and far-future (2071–2100) periods. Higher values indicate stronger atmospheric moisture limitation.

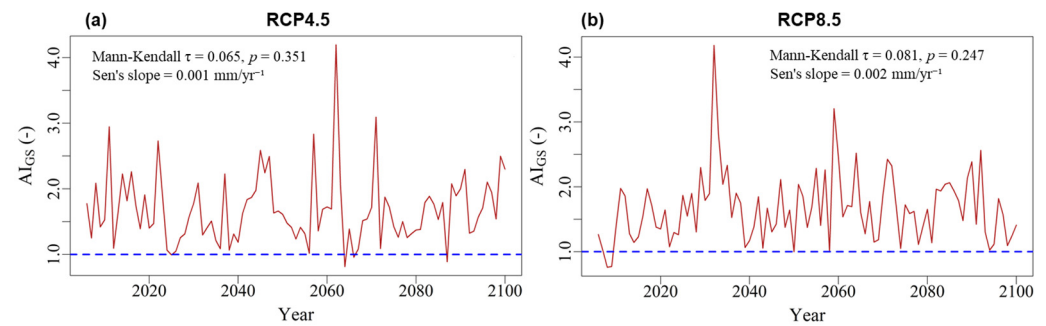


Figure A8. Temporal evolution of growing-season aridity (AI_{GS}) under (a) RCP4.5 and (b) RCP8.5 during 2006–2100. The blue dashed line indicates the aridity threshold ($AI_{GS} = 1$).

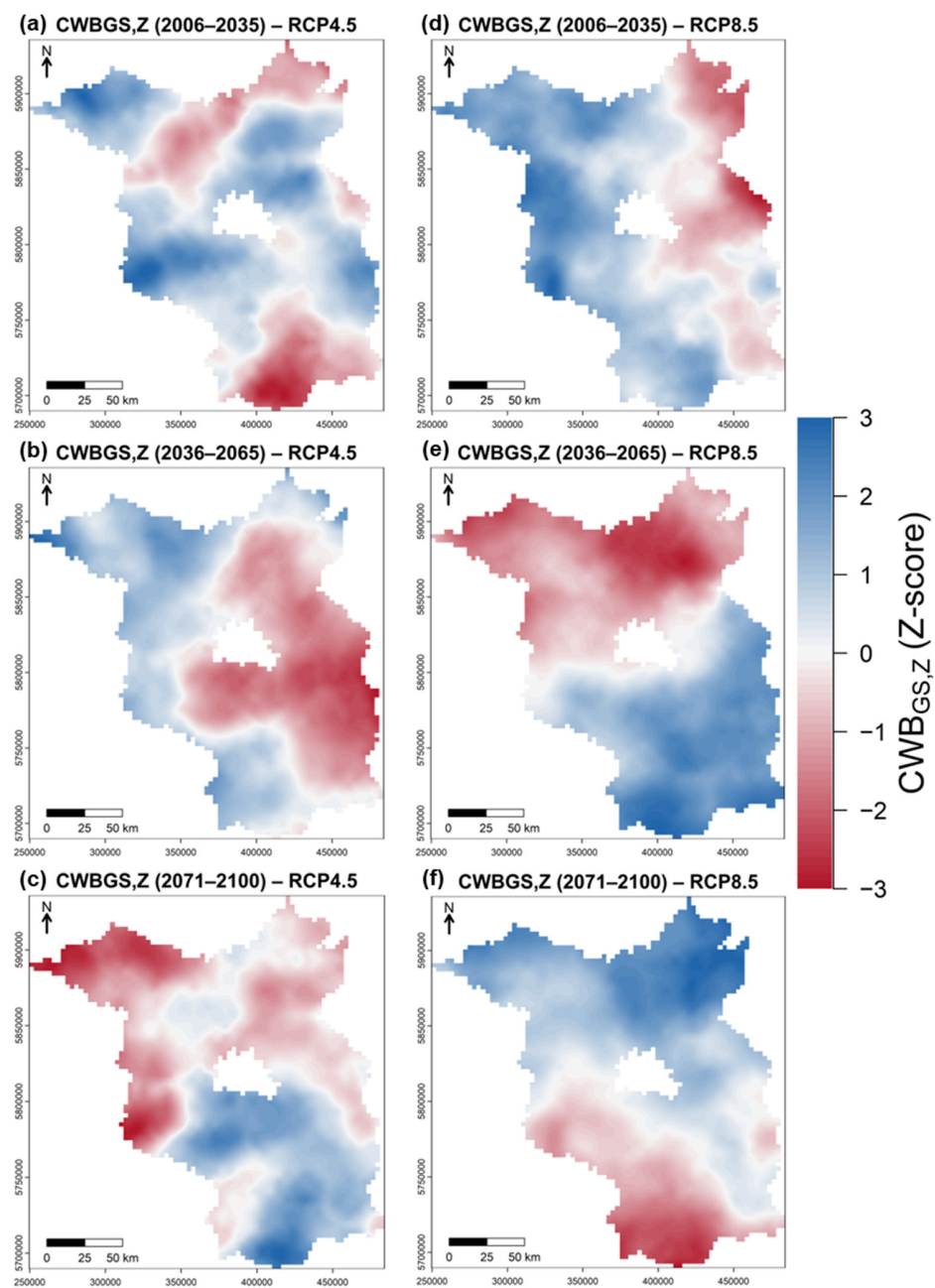


Figure A9. Spatial patterns of standardized growing-season moisture anomalies ($CWB_{GS,Z}$) under RCP4.5 (a–c) and RCP8.5 (d–f) for the near-future (2006–2035), mid-century (2036–2065), and far-future (2071–2100) periods. Negative anomalies are shown in red and positive anomalies in blue.

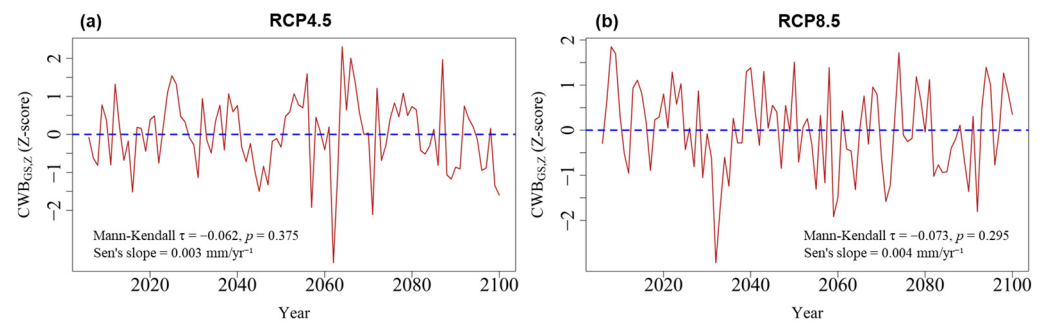


Figure A10. Temporal evolution of standardized growing-season moisture anomalies ($CWB_{GS,Z}$) under (a) RCP4.5 and (b) RCP8.5 from 2006 to 2100. The dashed line indicates the long-term mean ($Z = 0$).

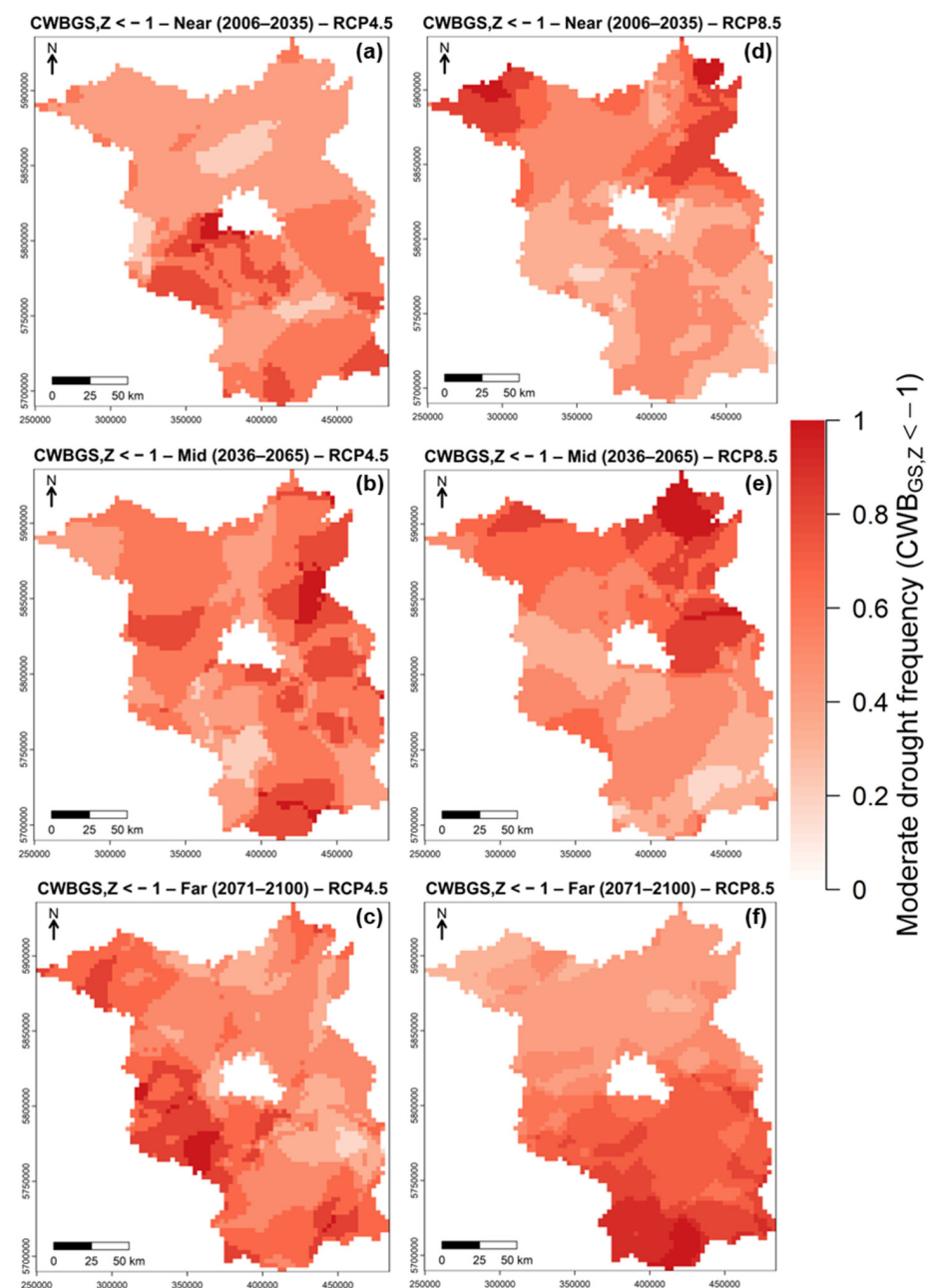


Figure A11. Spatial patterns of moderate drought frequency ($CWB_{GS,Z} < -1$) under RCP4.5 (a–c) and RCP8.5 (d–f) for the near-future (2006–2035), mid-century (2036–2065), and far-future (2071–2100) periods.

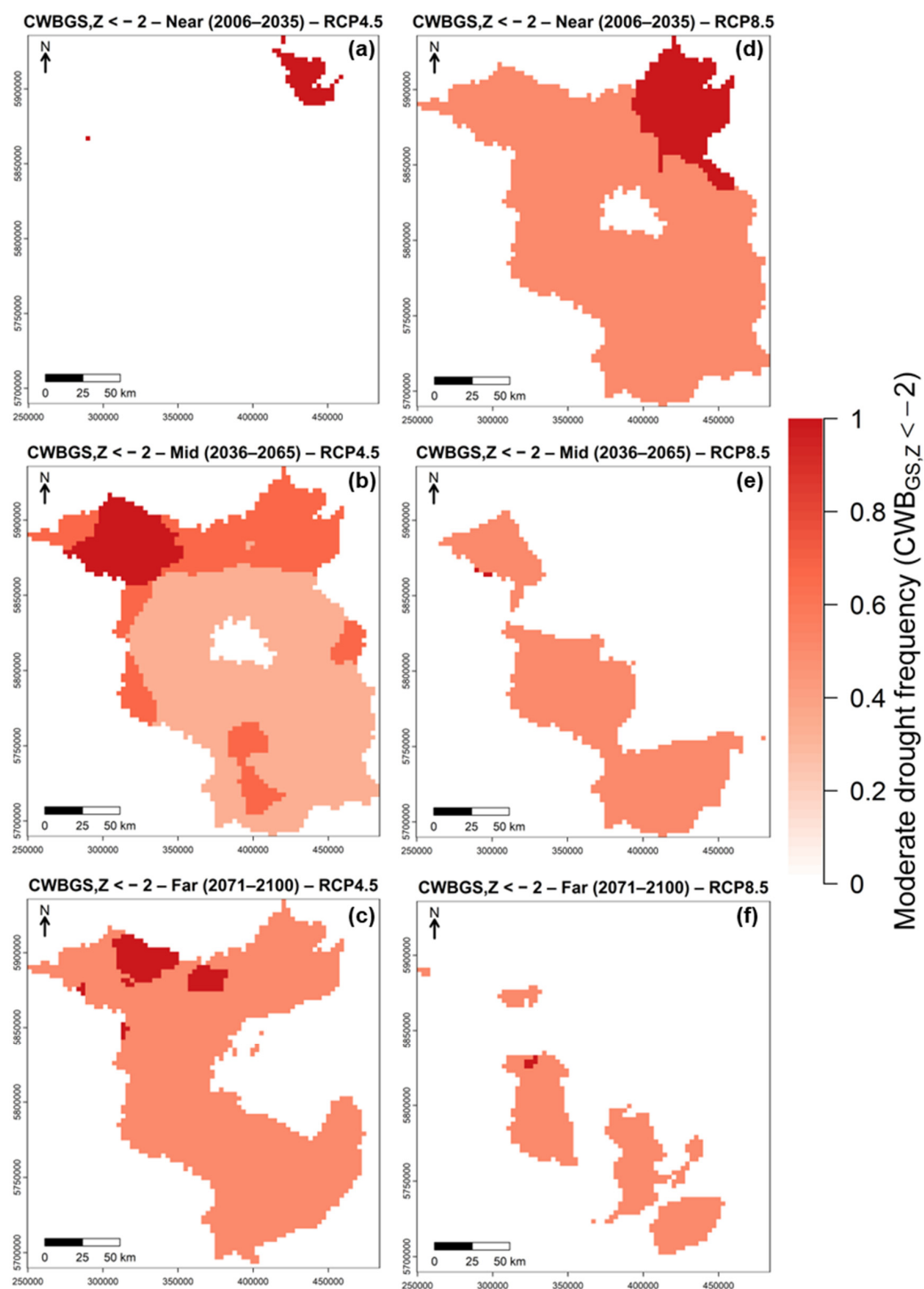


Figure A12. Spatial patterns of severe drought frequency ($CWB_{GS,Z} < -2$) under RCP4.5 (a–c) and RCP8.5 (d–f) for the near-future (2006–2035), mid-century (2036–2065), and far-future (2071–2100) periods.

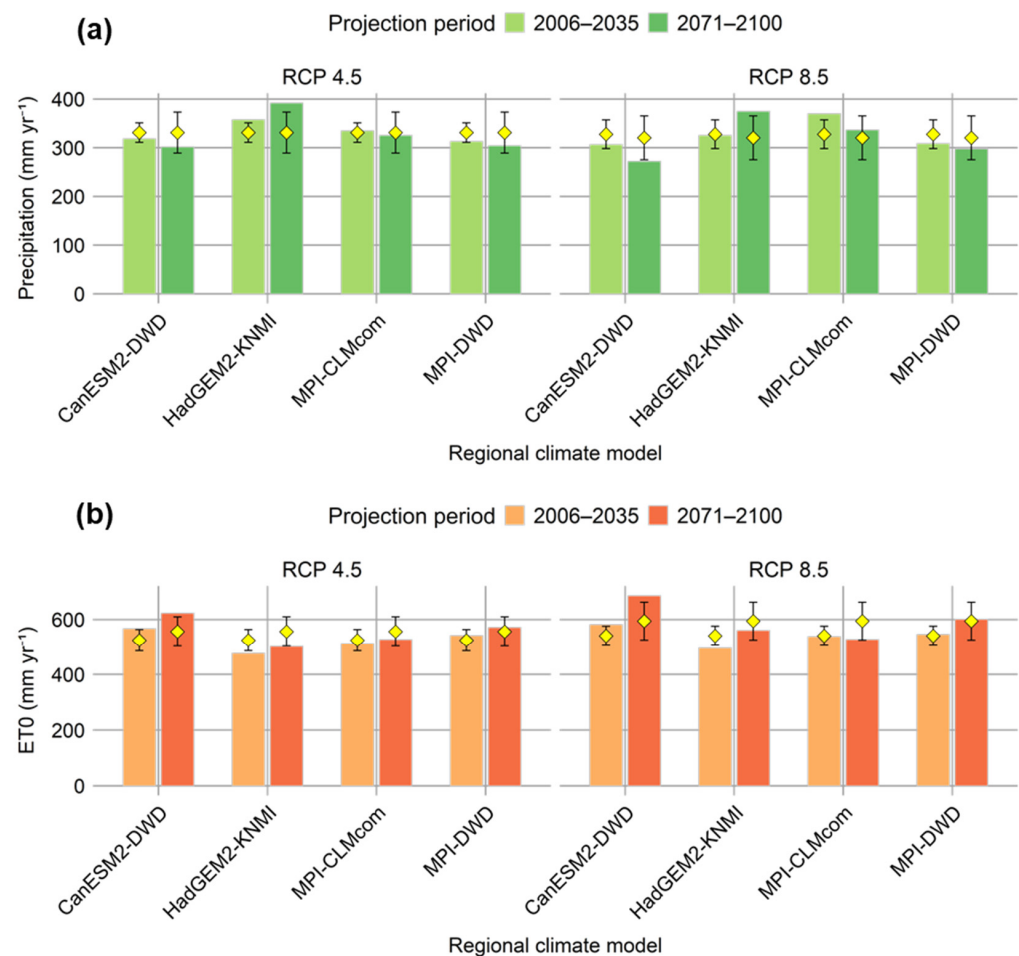


Figure A13. Inter-model projections of growing-season precipitation (pr ; panel (a)) and reference evapotranspiration (ET_0 ; (b)) derived from four regional climate model realizations under RCP4.5 and RCP8.5. Bars represent the near-future (2006–2035) and far-future (2071–2100) periods, while yellow markers indicate ensemble mean values across all model realizations.

References

1. IPCC. Climate Change 2021: The Physical Science Basis. In *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2021. Available online: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FullReport.pdf (accessed on 22 March 2026).
2. IPCC. *Climate Change and Land: Summary for Policymakers*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2022. [CrossRef]
3. Vicente-Serrano, S.M.; McVicar, T.R.; Miralles, D.G.; Yang, Y.; Tomás-Burguera, M. Unraveling the influence of atmospheric evaporative demand on drought and its response to climate change. *WIREs Clim. Change* **2020**, *11*, e632. [CrossRef]
4. Spinoni, J.; Naumann, G.; Vogt, J.; Barbosa, P. European drought climatologies and trends based on a multi-indicator approach. *Glob. Planet. Change* **2015**, *127*, 50–57. [CrossRef]
5. Peters, W.; Bastos, A.; Ciais, P.; Vermeulen, A. A historical, geographical and ecological perspective on the 2018 European summer drought. *Philos. Trans. R. Soc. B* **2020**, *375*, 20190505. [CrossRef] [PubMed]
6. Motta, C.; Naumann, G.; Gomez, D.; Formetta, G.; Feyen, L. Assessing the economic impact of droughts in Europe in a changing climate: A multi-sectoral analysis at regional scale. *J. Hydrol. Reg. Stud.* **2025**, *59*, 102296. [CrossRef]
7. Jacob, D.; Petersen, J.; Eggert, B.; Alias, A.; Christensen, O.B.; Bouwer, L.M.; Braun, A.; Colette, A.; Déqué, M.; Georgievski, G.; et al. EURO-CORDEX: New high-resolution climate change projections for European impact research. *Reg. Environ. Change* **2014**, *14*, 563–578. [CrossRef]
8. Seneviratne, S.I.; Corti, T.; Davin, E.L.; Hirschi, M.; Jaeger, E.B.; Lehner, I.; Orlowsky, B.; Teuling, A.J. Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Sci. Rev.* **2010**, *99*, 125–161. [CrossRef]
9. Bat-Enerel, B.; Weigel, R.; Leuschner, C. Changes in the thermal and hydrometeorological forest growth climate during 1948–2017 in northern Germany. *Front. For. Glob. Change* **2022**, *5*, 830977. [CrossRef]

10. Ostermüller, J.; Lorenz, P.; Fröhlich, K.; Kreienkamp, F.; Früh, B. Downscaling and evaluation of seasonal climate data for the European power sector. *Atmosphere* **2021**, *12*, 304. [CrossRef]
11. Ziche, D.; Riek, W.; Russ, A.; Hentschel, R.; Martin, J. Water budgets of managed forests in northeast Germany under climate change—Results from a model study on forest monitoring sites. *Appl. Sci.* **2021**, *11*, 2403. [CrossRef]
12. Wattenbach, M.; Zebisch, M.; Hattermann, F.; Gottschalk, P.; Goemann, H.; Kreins, P.; Badeck, F.; Lasch, P.; Suckow, F.; Wechsung, F. Hydrological impact assessment of afforestation and change in tree-species composition: A regional case study for the federal state of Brandenburg (Germany). *J. Hydrol.* **2007**, *346*, 104–118. [CrossRef]
13. Martínez-Vilalta, J.; Garcia-Forner, N. Water potential regulation, stomatal behaviour and hydraulic transport under drought: Deconstructing the iso/anisohydric concept. *Plant Cell Environ.* **2017**, *40*, 962–976. [CrossRef] [PubMed]
14. Vicente-Serrano, S.M.; Miralles, D.G.; Domínguez-Castro, F.; Azorin-Molina, C.; El Kenawy, A.; McVicar, T.R.; Tomás-Burguera, M.; Beguería, S.; Maneta, M.; Peña-Gallardo, M. Global assessment of the standardized evapotranspiration deficit index (SEDI) for drought analysis and monitoring. *J. Clim.* **2018**, *31*, 5371–5393. [CrossRef]
15. Grillakis, M.G. Increase in severe and extreme soil moisture droughts for Europe under climate change. *Sci. Total Environ.* **2019**, *660*, 1245–1255. [CrossRef] [PubMed]
16. Hofmann, G.; Pommer, U. *Potentielle Natürliche Vegetation von Brandenburg und Berlin*; Eberswalder Forstliche Schriften; Landesforstanstalt Eberswalde: Eberswalde, Germany, 2005. Available online: <https://www.waldkunde-eberswalde.com/pdf/efs24.pdf> (accessed on 21 March 2026).
17. Germer, S.; Kaiser, K.; Bens, O.; Hüttel, R.F. Water balance changes and responses of ecosystems and society in the Berlin–Brandenburg region—A review. *Die Erde* **2011**, *142*, 65–95. [CrossRef]
18. Lindner, M.; Fitzgerald, J.B.; Zimmermann, N.E.; Reyer, C.; Delzon, S.; van der Maaten, E.; Schelhaas, M.J.; van der Maaten-Theunissen, M.; Lasch, P.; Eggers, J.; et al. Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? *J. Environ. Manag.* **2014**, *146*, 69–83. [CrossRef] [PubMed]
19. Ziche, D.; Grüneberg, E.; Hilbrig, L.; Höhle, J.; Kompa, T.; Liski, J.; Wellbrock, N. Comparing soil inventory with modelling: Carbon balance in central European forest soils varies among forest types. *Sci. Total Environ.* **2019**, *647*, 1573–1585. [CrossRef] [PubMed]
20. Deutscher Wetterdienst (DWD). Climate Atlas of Germany—Precipitation (Gridded Climate Data 1961–2020). Available online: https://www.dwd.de/EN/climate_environment/climateatlas/climateatlas_node.html (accessed on 8 June 2026).
21. Pfeifer, S.; Bülow, K.; Gobiet, A.; Hänsler, A.; Mudelsee, M.; Otto, J.; Rechid, D.; Teichmann, C.; Jacob, D. Robustness of ensemble climate projections analyzed with climate signal maps: Seasonal and extreme precipitation for Germany. *Atmosphere* **2015**, *6*, 677–698. [CrossRef]
22. Senf, C.; Seidl, R. Persistent impacts of the 2018 drought on forest disturbance regimes in Europe. *Biogeosciences* **2021**, *18*, 5223–5230. [CrossRef]
23. Schick, J.; Albert, M.; Schmidt, M. A new approach for modeling stand height development of German forests under climate change. *Front. For. Glob. Change* **2023**, *6*, 1201636. [CrossRef]
24. Stephenson, N.L. Actual evapotranspiration and deficit: Biologically meaningful correlates of vegetation distribution across spatial scales. *J. Biogeogr.* **1998**, *25*, 855–870. [CrossRef]
25. Vicca, S.; Luyssaert, S.; Peñuelas, J.; Campioli, M.; Chapin, F.S., III; Ciais, P.; Heinemeyer, A.; Höglberg, P.; Kutsch, W.L.; Law, B.E.; et al. Fertile forests produce biomass more efficiently. *Ecol. Lett.* **2012**, *15*, 520–526. [CrossRef] [PubMed]
26. Hawkins, E.; Sutton, R. The potential to narrow uncertainty in regional climate predictions. *Bull. Am. Meteorol. Soc.* **2009**, *90*, 1095–1107. [CrossRef]
27. Knutti, R.; Furrer, R.; Tebaldi, C.; Cermak, J.; Meehl, G.A. Challenges in combining projections from multiple climate models. *J. Clim.* **2010**, *23*, 2739–2758. [CrossRef]
28. Dietrich, H.; Wolf, T.; Kawohl, T.; Wehberg, J.; Kändler, G.; Mette, T.; Röder, A.; Böhner, J. Temporal and spatial high-resolution climate data from 1961 to 2100 for the German National Forest Inventory (NFI). *Ann. For. Sci.* **2019**, *76*, 6. [CrossRef]
29. Landeskompetenzzentrum Forst Eberswalde (LFE). *Digital Terrain Model (DGM) with 5 m Resolution for Brandenburg (Excluding Berlin); Derived from 2 m DGM Tiles Provided by Landesbetrieb Geobasis Brandenburg, Processed by T. Hass*; Landeskompetenzzentrum Forst Eberswalde: Eberswalde, Germany, 2024. Available online: https://www.brandenburg-forst.de/geoportal/#layer=bg_bm.2.v.0.0bg_dgm.3.t.def.0fgk.101.v.def.0&zoom=5.257&lat=5812530&lon=377622&tools=layer (accessed on 22 March 2026).
30. Esri. ArcGIS Basemap. Available online: <https://www.arcgis.com> (accessed on 22 April 2026).
31. Deutscher Wetterdienst (DWD). Gridded Climate Data for Germany. Climate Data Center (CDC). Available online: https://opendata.dwd.de/climate_environment/CDC/grids_germany/ (accessed on 22 March 2026).
32. Riek, W.; Russ, A. *Waldbodenbericht Brandenburg—Bodenzustandserhebung 2 (BZE II), Band 2*; Landesbetrieb Forst Brandenburg; Landeskompetenzzentrum Forst Eberswalde: Eberswalde, Germany, 2019. Available online: <https://forst.brandenburg.de/sixcms/media.php/9/efs68.pdf> (accessed on 22 March 2026).

33. Ministerium für Landwirtschaft; Umwelt und Klimaschutz (MLUK). *Waldzustandsbericht 2022 des Landes Brandenburg*; MLUK: Potsdam, Germany, 2022. Available online: <https://mleuv.brandenburg.de/sixcms/media.php/9/Waldzustandsbericht-2022.pdf> (accessed on 22 March 2026).
34. Landesamt für Umwelt Brandenburg (LfU). *Ein Klimaprojektionsensemble für Brandenburg*; Referat T14—Luftqualität, Klima, Nachhaltigkeit; Landesamt für Umwelt Brandenburg: Potsdam, Germany, 2021. Available online: <https://lfu.brandenburg.de/sixcms/media.php/9/Klimaprojektionsensemble-Brandenburg.pdf> (accessed on 11 March 2026).
35. Rauthe, M.; Steiner, H.; Riediger, U.; Mazurkiewicz, A.; Gratzki, A. A Central European precipitation climatology—Part I: Generation and validation of a high-resolution gridded daily data set (HYRAS). *Meteorol. Z.* **2013**, *22*, 235–256. [CrossRef]
36. Cornes, R.C.; van der Schrier, G.; van den Besselaar, E.J.M.; Jones, P.D. An ensemble version of the E-OBS temperature and precipitation data sets. *J. Geophys. Res. Atmos.* **2018**, *123*, 9391–9409. [CrossRef]
37. Deutscher Wetterdienst (DWD). Vegetation-Period Soil Moisture Data for Germany—Daily Composites. Climate Data Center (CDC). Available online: https://opendata.dwd.de/climate_environment/CDC/grids_germany/daily/soil_moisture/composite/ (accessed on 11 March 2026).
38. Zang, C.S.; Hartl-Meier, C.; Dittmar, C.; Rothe, A.; Menzel, A. Patterns of drought tolerance in major European temperate forest trees. *Glob. Change Biol.* **2014**, *20*, 3647–3657. [CrossRef] [PubMed]
39. Schaphoff, S.; von Bloh, W.; Rammig, A.; Thonicke, K.; Biemans, H.; Forkel, M.; Gerten, D.; Heinke, J.; Jägermeyr, J.; Knauer, J.; et al. LPJmL4—A dynamic global vegetation model with managed land: Part I. Model description. *Geosci. Model Dev.* **2018**, *11*, 1343–1375. [CrossRef]
40. Vicente-Serrano, S.M.; Beguería, S.; López-Moreno, J.I. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *J. Clim.* **2010**, *23*, 1696–1718. [CrossRef]
41. Orłowsky, B.; Seneviratne, S.I. Elusive drought: Uncertainty in observed trends and short- and long-term CMIP5 projections. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 1765–1781. [CrossRef]
42. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2026. Available online: <https://www.r-project.org/> (accessed on 22 March 2026).
43. Linderholm, H.W. Growing season changes in the last century. *Agric. For. Meteorol.* **2006**, *137*, 1–14. [CrossRef]
44. Menzel, A.; Sparks, T.H.; Estrella, N.; Koch, E.; Aasa, A.; Ahas, R.; Alm-Kubler, K.; Bissolli, P.; Braslavská, O.; Briede, A.; et al. European phenological response to climate change matches the warming pattern. *Glob. Change Biol.* **2006**, *12*, 1969–1976. [CrossRef]
45. Samaniego, L.; Thober, S.; Kumar, R.; Wanders, N.; Rakovec, O.; Pan, M.; Marx, A. Anthropogenic warming exacerbates European soil moisture droughts. *Nat. Clim. Change* **2018**, *8*, 421–426. [CrossRef]
46. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*—FAO Irrigation and Drainage Paper 56; FAO: Rome, Italy, 1998. Available online: <http://www.fao.org/3/x0490e/x0490e00.htm> (accessed on 22 March 2026).
47. Martínez-Vilalta, J.; Poyatos, R.; Aguadé, D.; Retana, J.; Mencuccini, M. A new look at water transport regulation in plants. *New Phytol.* **2014**, *204*, 105–115. [CrossRef] [PubMed]
48. World Meteorological Organization (WMO). *Guidelines on the Calculation of Climate Normals (WMO-No. 1203)*; WMO: Geneva, Switzerland, 2017. Available online: <https://library.wmo.int/idurl/4/55797> (accessed on 22 March 2026).
49. Lévesque, M.; Saurer, M.; Siegwolf, R.; Eilmann, B.; Brang, P.; Bugmann, H.; Rigling, A. Drought response of five conifer species under contrasting water availability suggests high vulnerability of Norway spruce and European larch. *Glob. Change Biol.* **2013**, *19*, 3184–3199. [CrossRef] [PubMed]
50. Cavus, Y.; Stahl, K.; Aksoy, H. Drought intensity–duration–frequency curves based on deficit in precipitation and streamflow for water resources management. *Hydrol. Earth Syst. Sci.* **2023**, *27*, 3427–3445. [CrossRef]
51. United Nations Environment Programme (UNEP). *World Atlas of Desertification*, 2nd ed.; Publications Office of the European Union: Luxembourg, 2018. Available online: <https://wedocs.unep.org/20.500.11822/30300> (accessed on 22 March 2026).
52. Gruber, A.; De Lannoy, G.; Albergel, C.; Al-Yaari, A.; Brocca, L.; Calvet, J.-C.; Wagner, W. Validation practices for satellite soil moisture retrievals: What are the errors? *Remote Sens. Environ.* **2020**, *244*, 111806. [CrossRef]
53. Sheffield, J.; Wood, E.F.; Roderick, M.L. Little change in global drought over the past 60 years. *Nature* **2012**, *491*, 435–438. [CrossRef] [PubMed]
54. Van Loon, A.F.; Gleeson, T.; Clark, J.; Van Dijk, A.I.J.M.; Stahl, K.; Hannaford, J.; Van Lanen, H.A.J. Drought in the Anthropocene. *Nat. Geosci.* **2016**, *9*, 89–91. [CrossRef]
55. Mann, H.B. Non-parametric tests against trend. *Econometrica* **1945**, *13*, 245–259. [CrossRef]
56. Kendall, M.G. *Rank Correlation Methods*, 4th ed.; Griffin: London, UK, 1975. Available online: <https://archive.org/details/rankcorrelationm0000kend> (accessed on 22 March 2026).
57. Sen, P.K. Estimates of the regression coefficient based on Kendall’s tau. *J. Am. Stat. Assoc.* **1968**, *63*, 1379–1389. [CrossRef]

58. Blauhut, V.; Stahl, K.; Stagge, J.H.; Tallaksen, L.M.; De Stefano, L.; Vogt, J. Estimating drought risk across Europe from reported drought impacts, drought indices, and vulnerability factors. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 2779–2800. [[CrossRef](#)]
59. Hänsel, S.; Hoy, A.; Brendel, C.; Maugeri, M. Record summers in Europe: Variations in drought and heavy precipitation during 1901–2018. *Int. J. Climatol.* **2022**, *42*, 6975–6993. [[CrossRef](#)]
60. Disasa, K.N.; Yan, H.; Zhang, J.; Wang, G.; Zhang, C.; Zhang, D.; Wang, B.; Hao, B. Comprehensive review of drought characteristics and intensification under climate change: Implications for agriculture and water resources. *J. Hydrol.* **2026**, *664*, 134571. [[CrossRef](#)]
61. Marx, A.; Kumar, R.; Thober, S.; Rakovec, O.; Wanders, N.; Zink, M.; Wood, E.F.; Pan, M.; Sheffield, J.; Samaniego, L. Climate change alters low flows in Europe under global warming of 1.5, 2, and 3 °C. *Hydrol. Earth Syst. Sci.* **2018**, *22*, 1017–1032. [[CrossRef](#)]
62. Bolte, A.; Ammer, C.; Löf, M.; Madsen, P.; Nabuurs, G.J.; Schall, P.; Spathelf, P.; Rock, J. Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. *Scand. J. For. Res.* **2009**, *24*, 473–482. [[CrossRef](#)]
63. Trnka, M.; Eitzinger, J.; Semerádová, D.; Hlavinka, P.; Balek, J.; Dubrovský, M.; Kubu, G.; Štěpánek, P.; Thaler, S.; Možný, M.; et al. Expected changes in agroclimatic conditions in Central Europe. *Clim. Change* **2011**, *108*, 261–289. [[CrossRef](#)]
64. Kotlarski, S.; Keuler, K.; Christensen, O.B.; Colette, A.; Déqué, M.; Gobiet, A.; Goergen, K.; Jacob, D.; Lüthi, D.; van Meijgaard, E.; et al. Regional climate modeling on European scales: A joint standard evaluation of the EURO-CORDEX RCM ensemble. *Geosci. Model Dev.* **2014**, *7*, 1297–1333. [[CrossRef](#)]
65. Chen, H.; Sun, J.; Lin, W.; Xu, H. Comparison of CMIP6 and CMIP5 models in simulating climate extremes. *Sci. Bull.* **2021**, *66*, 141–143. [[CrossRef](#)] [[PubMed](#)]

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