Future global water scarcity partially moderated by vegetation responses to atmospheric CO_2 and climate change

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Abstract. Accurate water scarcity projections are essential for effective adaptation strategies. Most existing studies rely on hydrology models that often neglect the effects of plant physiological responses to rising CO_2 on the water cycle, such as reduced stomatal opening, which can decrease transpiration and enhance water availability over large scales. To evaluate how physiological and structural plant responses to rising CO_2 and subsequent climate change affect water scarcity in typical impact studies, we replicate their experimental design by driving an offline land surface model with Earth system model output. Under a high-emission climate scenario, our simulations suggest that the combined effects of these plant responses partially alleviate the Water Scarcity Index (WSI) for most regions, largely due to CO_2-induced stomatal closure, although CO_2- and climate-induced vegetation changes do exacerbate water scarcity in some places, particularly arid regions. For the period 2076–2095, incorporating all plant responses to CO_2 and climate change reduces global median WSI by approximately 12%. Furthermore, across 291 river basins, 138 basins show lower median WSI (by 10-70%), representing 80% of the global population, while 11 basins show higher WSI (by 10-60%), representing 0.2% of the population. These model results highlight the potential for plant responses to CO_2 to somewhat moderate water scarcity, noting water scarcity is still projected to worsen in many regions, including highly populated areas. There is an urgent need to gather empirical evidence on the strength of plant responses to CO_2 at large scales to address modelling uncertainties.

Short summary. Plants typically transpire less with rising atmospheric carbon dioxide, leaving more water in the ground for human use, but many future water scarcity assessments ignore this effect. We use a land surface model to examine how plant responses to carbon dioxide and climate change affect future water scarcity. Our results suggest that including these plant responses increases overall water availability for most people, highlighting the importance of their inclusion in future water scarcity studies.

1 Introduction

Throughout this manuscript, we use the following terminology:

- **Stomatal response** – changes in stomatal conductance (i.e., stomatal opening and closure)

- **Structural response** – changes in vegetation structure (leaf area and canopy coverage)
- **Physiological response (or forcing)** – CO_2-induced changes encompassing both stomatal behaviour and vegetation structure (leaf area and canopy coverage)

Water scarcity, where water demand exceeds available supply, is one of the greatest challenges of our time (FAO, 2017). Nearly half of the global population already faces severe water scarcity at some point each year, and as both population and consumption rates rise, water demand is escalating (Caretta et al. 2022). From 1992 to 2015, global freshwater resources per capita declined by over 25% (Ripple et al., 2017). Water availability, crucial for meeting this rising demand, depends on the balance between land precipitation and evapotranspiration, both of which are strongly affected by human activities, including climate change. Climate change is altering precipitation patterns and near-surface meteorological conditions, driving more frequent hydrological extremes and higher evaporative demand (Seneviratne et al., 2021). Human interventions—such as groundwater over-abstraction, dam construction, and water diversion—further disrupt water supply, while pollution threatens the availability of clean water. Accurately forecasting future water supply and demand remains a complex but vital task for informing long-term adaptation strategies (Caretta et al., 2022). Current impact studies on future water scarcity are typically based on output from hydrology models driven by climate model outputs (e.g., Dolan et al., 2021; Gosling and Arnell, 2016; Greve et al., 2018; Haddeland et al., 2014). While hydrology models are powerful tools for understanding, managing, and planning water resources, they often lack a representation of vegetation response to rising levels of CO_2 and climate change. In this study, we investigate the influence that vegetation responses to atmospheric CO2 and climate change have on water scarcity projections.

Vegetation is crucial to the global water cycle and therefore to water availability for humans. Large-scale changes in vegetation type and coverage are already occurring due to climate change and human activities, such as deforestation. Vegetation plays a key role in precipitation generation, with approximately 60% of terrestrial precipitation originating from land via evapotranspiration – primarily through plant transpiration (Schneider et al., 2017; Wei et al., 2017). Vegetation also influences other hydrological processes, including infiltration, interception, and runoff (Caretta et al., 2022). Climate change continues to alter vegetation types and coverage globally, as regions experience more or less favourable conditions. Increased vegetation growth has been observed in many areas (Xu et al., 2017; Yu et al., 2018; Zhu et al., 2016), while droughts and heatwaves have heightened plant stress and mortality (Parmesan et al. 2022).

Rising atmospheric CO_2 concentrations also impact the water cycle by altering plant physiology. Plants continuously adjust the widths of their stomatal openings to maximise photosynthesis while minimising water loss (Cowan, 1978). Under higher atmospheric CO_2, plants typically reduce their stomatal openings, as they can maintain higher rates of photosynthesis at increased leaf-level water-use efficiency, thereby decreasing transpiration (Battipaglia et al., 2013; Field et al., 1995; Norby and Zak, 2011). As less water is lost through transpiration, more water remains in the soil and at the surface, contributing to

increased runoff and soil moisture levels (Fowler et al., 2019; Gedney et al., 2006). However, higher CO_2 generally enhances photosynthesis, known as the CO_2 fertilisation effect, leading to increased vegetation growth and thus overall canopy transpiration due to a higher number of stomata, even as individual stomatal openings are reduced (Betts et al., 1997). At the canopy-level, this effect can offset or even reverse the increase in runoff from reduced stomatal openings (Cowling and Field, 2003; Piao et al., 2007; Ukkola et al., 2016). The net effect on canopy transpiration thus depends on the balance between these two opposing factors, which varies greatly between different plant species and climatic biomes (Norby and Zak 2011).

Better understanding of vegetation-water-atmosphere interactions, in both historical observations and under future climate change scenarios (e.g., Betts et al., 2007; Gedney et al., 2006) has been made possible with the introduction of Land Surface Models (LSMs). LSMs simulate complex interactions between the atmosphere, land surface, and sub-surface, including energy and water fluxes, carbon cycling, and soil processes. Dynamic vegetation schemes in LSMs have been made increasingly realistic over the past few decades (Fisher and Koven, 2020). They typically simulate vegetation coverage, canopy height and leaf area index for a limited number of generalised plant functional types, driven by carbon fluxes and vegetation competition. Including dynamic vegetation in climate models is essential for capturing critical changes in land surface and plant physiology that influence the climate system and hydrological cycle. Yet, these schemes are still absent from many hydrology models.

Advances in LSMs have improved understanding of how plant physiological responses to rising CO_2, herein 'physiological forcing' (which, in this study also refers to changes in vegetation coverage and leaf area) impact the water cycle. An early study by Wigley and Jones (1985) was one of the first to link CO_2-driven changes in plant evapotranspiration (ET) to runoff. As land surface and climate models have advanced, effects of CO_2-induced vegetation growth on the water cycle have also been analysed alongside stomatal closure. Betts et al. (1997) projected that increased vegetation cover could partially offset the projected reduction in ET. Gedney et al. (2006) attributed rising historical continental river runoff records to CO_2-induced stomatal closure. However, Piao et al. (2007) suggested that physiological forcing *reduced* global runoff when CO_2-induced leaf area increases were also considered from 1901 to 1999. Subsequent modelling studies have also concluded that CO_2-induced stomatal closure and leaf area increases together generally *increase* projected global runoff in the current generation of models. For instance, doubling CO_2 in climate models led to global mean runoff increases of 6% (Betts et al., 2007) and 8-9% (Cao et al., 2010) relative to preindustrial; comparable to the impact of radiative forcing. Further studies have suggested that physiological responses to rising CO_2 affect the hydrological cycle differently around the globe, although generally suggest increased runoff, especially in the tropics (Davie et al., 2013; Fowler et al., 2019; Lemordant et al., 2018; Yang et al., 2019), reduced drought severity (Swann et al., 2016) and increased flood risk (Kooperman et al., 2018). Conversely, runoff reductions are suggested in more arid locations, including the mid-latitudes in model projections (Mankin et al., 2019) and parts of Australia in observations (Ukkola et al., 2016). Moreover, a recent study by Wei et al. (2024) suggested physiological forcing had limited effect on observed global streamflow. However, the consensus between most studies currently suggests that the

stomatal response to CO_2 has a dominant effect over the structural responses at the global scale, particularly in future climate projections.

Water scarcity is a complex and multifaceted issue influenced by water availability, demand, and quality. Many future water scarcity projections rely on standalone hydrology models driven by global climate model outputs (e.g., Dolan et al., 2021; Gosling and Arnell, 2016; Greve et al., 2018; Haddeland et al., 2014; Schewe et al., 2013). These studies have generally projected worsening water scarcity in many regions due to both climate change and rising demand, with the most affected areas including parts of northern and southern Africa, south and southeast Asia, Australia, parts of Europe, the Middle East and the western United States. However, these hydrology models often do not account for vegetation responses to atmospheric CO_2 and climate change.

Few studies have explored the influence of physiological forcing on water scarcity-related variables. Wiltshire et al. (2013a, b) suggested that when both climate change and CO_2 effects are considered, the number of people experiencing water stress decreases. Notably, Wiltshire et al. (2013a) projected that physiological forcing could reduce the population under high water stress by approximately 200 million by the end of the century, an impact comparable to that of climate change alone. However, while their water stress indicator accounted for population growth, it did not consider varying water demands due to different living standards. Wang and Sun (2023) also examined socioeconomic exposure to drought under various Shared Socioeconomic Pathways finding that physiological forcing could increase extreme drought frequency by around 2% in the 2030s, particularly in arid and semi-arid regions, but this influence shifted to a decrease by the 2050s. However, their study only used fully coupled models and did not replicate the experimental setup typically used in hydrology studies—such as driving standalone hydrology models with climate model outputs—and therefore did not directly address the impact of physiological forcing in hydrological studies.

Understanding the extent to which dynamic plant processes affect metrics like water scarcity remains a critical research gap for the climate and hydrology impacts community. This study is the first to address this by replicating the experimental design of typical hydrology impact studies, i.e., running a standalone hydrology model without dynamic vegetation driven by climate model output, while adjusting plant responses to rising CO_2 and climate change through a land surface model. This approach allows us to estimate how vegetation's physiological and structural responses affect global water scarcity projections.

2 Methodology

2.1 Experimental design

The setup of the experiment has been carefully designed to best replicate the process used in water-related impact studies, i.e., a hydrology model run standalone and driven by climate model output. Here we use the Joint UK Land Environment

Simulator (JULES; Best et al., 2011; Clark et al., 2011) as the offline impact model. JULES has been driven by the bias-adjusted (following Lange, 2019) Earth system climate model HadGEM2-ES (Hadley Centre Global Environment Model version 2; Jones et al., 2011) resampled to 0.5 x 0.5 degrees horizontal resolution as part of the bias correction. We use the historic simulation from 1861 to 2005 and the "future" period 2006 to 2100 using Representative Concentration Pathway (RCP) 6.0. The earth system configuration JULES-ES is used following the setup for the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; https://www.isimip.org/) version 2b; details of the setup can be found in Mathison et al. (2023).

JULES is a suitable model for this study as it includes both a global hydrological cycle and dynamic vegetation scheme (Cox, 2001), enabling isolation of different vegetation structural and physiological processes to investigate their influence on the hydrological cycle. For our experiments, we use a combination of fixing the following two components in JULES:

(1) the **plant physiological response to rising CO_2 by** fixing CO_2 in JULES to 277ppm (representing preindustrial levels following protocol of the TRENDY project; Sitch et al., 2024).
(2) **vegetation spatial and temporal structural changes**, including Leaf Area Index (LAI; the ratio of leaf to ground area), by fixing the dynamic vegetation scheme in JULES to that at the start of the simulation.

Using a combination of fixing CO_2 and dynamic vegetation in JULES gives four simulations, all driven by identical climate model output. Taking the difference between two different simulations enables us to investigate the influence of different plant responses. Table 1 outlines the name of the simulations and which vegetation responses they include. A more expansive table can be found in Table A1. Note the naming conventions used in this study for each simulation and isolated factor follow the generic format: <Forcing factor(s)>: <Responding factor(s)>. The following acronyms have been used: 'CLIM' represents climate changes, 'CO2' represents the atmospheric CO_2 changes, 'VEG' represents vegetation cover and LAI responses and 'STOM' represents stomatal responses.

Simulation 1 (S1) CLIM: STOM includes climate-induced stomatal changes only and is closest to a typical hydrology study with fixed vegetation coverage/LAI and physiological forcing. Simulation 2 (S2) CLIM: STOM+VEG includes climate-induced stomatal and vegetation coverage/LAI responses. Simulation 3 (S3) CLIM+CO2: STOM includes CO_2- and climate-induced stomatal responses. Simulation 4 (S4) CLIM+CO2: STOM+VEG includes all CO_2- and climate-induced stomatal and vegetation coverage/LAI responses and is closest to fully coupled Earth System Model. Different "isolated factors" are combined by taking the differences between simulations. CLIM: VEG (S2 – S1) represents climate effects on vegetation coverage/LAI. CO2: STOM (S3 – S1) represents CO_2 effects on stomata. CO2: STOM+VEG (S4 – S2) represents CO_2 effects on stomata and vegetation coverage/LAI. CO2: STOM & CLIM+CO2: VEG (S4 – S1) represents CO_2 effects on stomata and climate plus CO_2 effects on vegetation coverage/LAI and indicates the differences between a typical offline hydrology study

and the fully coupled ESM. Relative differences, as displayed in Figs. 2, 4, 8 and 9, are calculated by dividing the difference by the initial value, following the formula: $\frac{b-a}{a}$. Note that we do not analyse the influence of climate change alone in this study.

Table 1: Details of dynamic processes included in each of the simulations and isolated factors.

Simulation	Name	Climate-induced stomatal changes	Climate-induced veg. changes	CO_2-induced stomatal changes	CO_2-induced veg. changes
S1	CLIM: STOM	✓			
S2	CLIM: STOM+VEG	✓	✓		
S3	CLIM+CO2: STOM	✓		✓	
S4	CLIM+CO2: STOM+VEG	✓	✓	✓	✓
S2 - S1	CLIM: VEG		✓		
S3 - S1	CO2: STOM			✓	
S4 - S2	CO2: STOM+VEG			✓	✓
S4 - S1	CO2: STOM & CLIM+CO2: VEG		✓	✓	✓

For all simulations, the atmospheric CO_2 and meteorological input variables such as radiation, temperature, precipitation and windspeed, are identical, since they come from the driving climate model HadGEM2-ES output, as would be the case for a typical hydrology study. Furthermore, all simulations use atmospheric CO_2 concentrations from the driving climate model (RCP 6.0), noting that, in the preindustrial CO_2 simulation, atmospheric CO_2 has been fixed in JULES only and not the driving climate input data. Note that anthropogenic disturbance of land is not included in any of the simulations, so vegetation can be affected by changes in climate and CO_2 only. Some of the meteorological inputs from HadGEM2-ES are shown in Fig. 1.

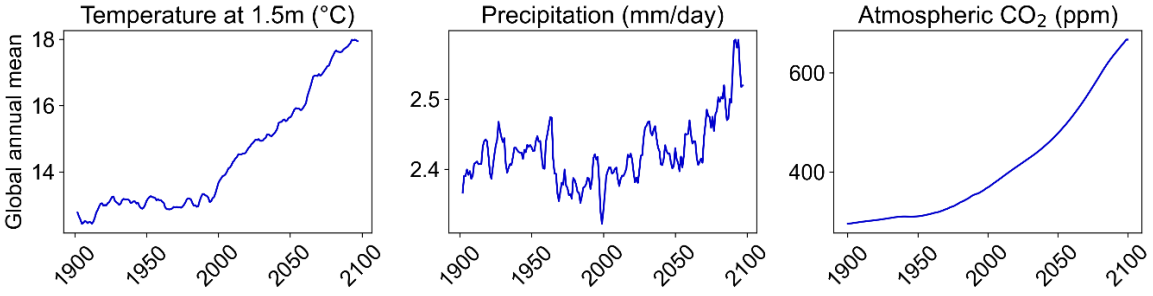

Figure 1a: Global annual mean timeseries for a) 1.5m temperature, b) precipitation and c) atmospheric CO_2 from driving climate model HadGEM2-ES used as input to JULES simulations (rolling 5-year mean for precipitation and temperature).

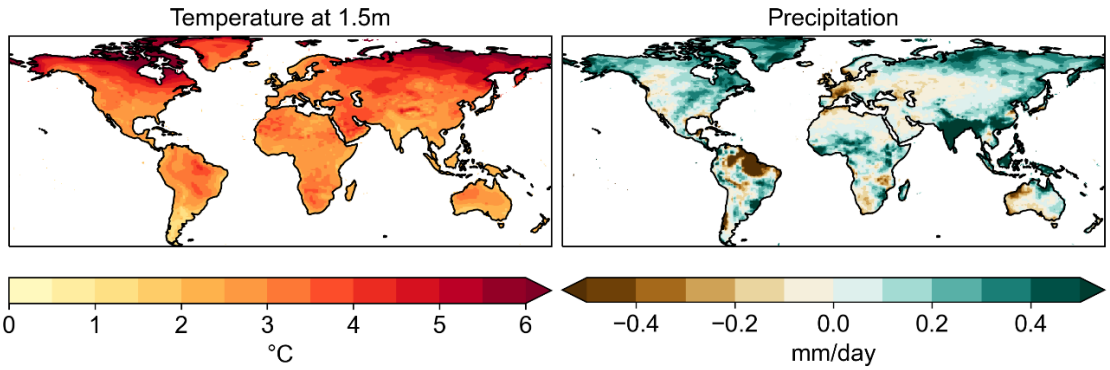

Figure 1b: Mean changes from present (2006-2025) to future (2076-2095) for precipitation (left) and 1.5m temperature (right) from driving climate model HadGEM2-ES used as input to JULES simulations.

Using the output from the four simulations in Table 1, we investigate the influence of physiological forcing and vegetation structural changes on global water scarcity. We calculate the Water Scarcity Index (WSI) to be the ratio of water demand to water supply (Falkenmark et al., 1989). The WSI is chosen as it is a simple and widely used indicator of water scarcity. We use a WSI of 0.2-0.4 to indicate mild or emerging water scarcity, and WSI ≥ 0.4 for severe water scarcity, in line with Raskin and Gleick (1997) and Greve et al. (2018). Runoff is used as a proxy for water supply because it represents the fraction of precipitation that is not lost to evapotranspiration and is therefore available for water resources. Total runoff is taken from the output of the simulations and includes both surface (overland flow generated when precipitation exceeds infiltration capacity or soil saturation) and sub-surface runoff (lateral drainage through the soil column) at the grid box scale. Water demand has been downloaded from the ISIMIP database (https://data.isimip.org/), specifically ISIMIP2b from the global water sector (Gosling et al., 2023). The hydrology model used is H08 (Hanasaki et al., 2008a, b, 2018) driven by HadGEM2-ES, RCP 6.0 and shared socioeconomic pathway SSP2, which represents population and gross domestic product for the 'middle of the road' scenario (Riahi et al., 2017). Total water demand is represented by summing water withdrawal for irrigation (assuming unlimited water supply), domestic use and manufacturing.

Different approaches can be used to calculate the average WSI over space and time, which can considerably influence the results. Mostly, we have chosen to calculate WSI at the most granular spatial and temporal scale, which is monthly and by grid-box. The exception is when analysing by river basins in Figs. 8 and 9, where the sum of total supply and demand is computed for each basin before calculating WSI. The rationale is that, generally, all water within a river basin could ideally be used for all the population within that basin, noting in real life this is not always the case.

Since WSI is calculated as water demand divided by water supply, it can yield extremely high values where supply values are very low relative to demand. To moderate the impact of these extreme values, the *median* WSI is used for spatial and temporal

averaging in this study, as it provides a more robust measure less influenced by outliers. Additionally, median WSI is calculated over larger spatial areas. Firstly, by the climate regions outlined in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), consisting of 46 land regions based on a combination of geographic, climatic, and socio-economic criteria (Fig. S2; Iturbide et al., 2020). Secondly, by Hydrosheds river basins (https://www.hydrosheds.org/products/hydrobasins; Lehner and Grill, 2013).

Finally, population projections are for SSP2 from the ISIMIP2b data library (Piontek and Geiger, 2017), plotted in Fig. S1, which are gridded at 0.5 x 0.5-degree resolution. These have been used to calculate projected population numbers by river basin in Table 2 and Fig. 8.

2.2 The Joint UK Land Environment Simulator (JULES)

JULES is a process-based model simulating fluxes of carbon, water, energy and momentum between the land surface and atmosphere. JULES is used as either an integral part of an Earth System Model such as UKESM1 (Sellar et al., 2019) or as an independent land surface model driven by input data from observations or atmospheric models; in this study it is used in the latter manner. Within JULES, the dynamic vegetation model predicts changes in leaf area and the fractional coverage of 13 different Plant Functional Types (PFTs; Harper et al., 2016) where each PFT is categorised by specific physiological traits, and surface fluxes are calculated separately for each PFT. JULES uses a coupled canopy conductance and photosynthesis model (Cox et al., 1998), based on Luening (1995), and TOPMODEL-type scheme to calculate soil moisture and runoff; more details on both are in Appendix B.

3. Results

3.1 Vegetation and water cycle variables

The global-mean time series for water-cycle and vegetation variables (Fig. 2) reveal substantial divergence among simulations. The largest relative differences are associated with the CO_2-induced stomatal response, as indicated by simulations including CO2: STOM, whose influence strengthens throughout the 21st century. In the climate-only simulation (S1), which reflects typical hydrological modelling approaches, soil moisture declines over the century while transpiration increases slightly (Fig. 2d,i), likely driven by rising temperatures (Fig. 1a).

In contrast, when the CO_2-induced stomatal response is represented (S3 and S4), the projected soil-moisture decline is substantially muted, coincident with ~20% reductions in both transpiration and stomatal conductance by 2100 (Fig. 2l,m). Despite decreasing soil moisture, total runoff in S1 shows a modest increase in the latter half of the century (Fig. 2a). This increase becomes ~10–12% larger when CO_2-induced stomatal closure is included (Fig. 2e).

CO_2-driven stomatal closure also dominates over the drying effect of CO_2-driven increases in leaf area. In CO2: STOM+VEG, runoff continues to rise even with a ~30% increase in LAI (Fig. 2e,n). In contrast, climate-driven vegetation structural changes alone (CLIM: VEG) reduce LAI by ~20% (Fig. 2n), leading to a modest 3–5% reduction in transpiration (Fig. 2l) and only a slight enhancement in runoff (Fig. 2e).

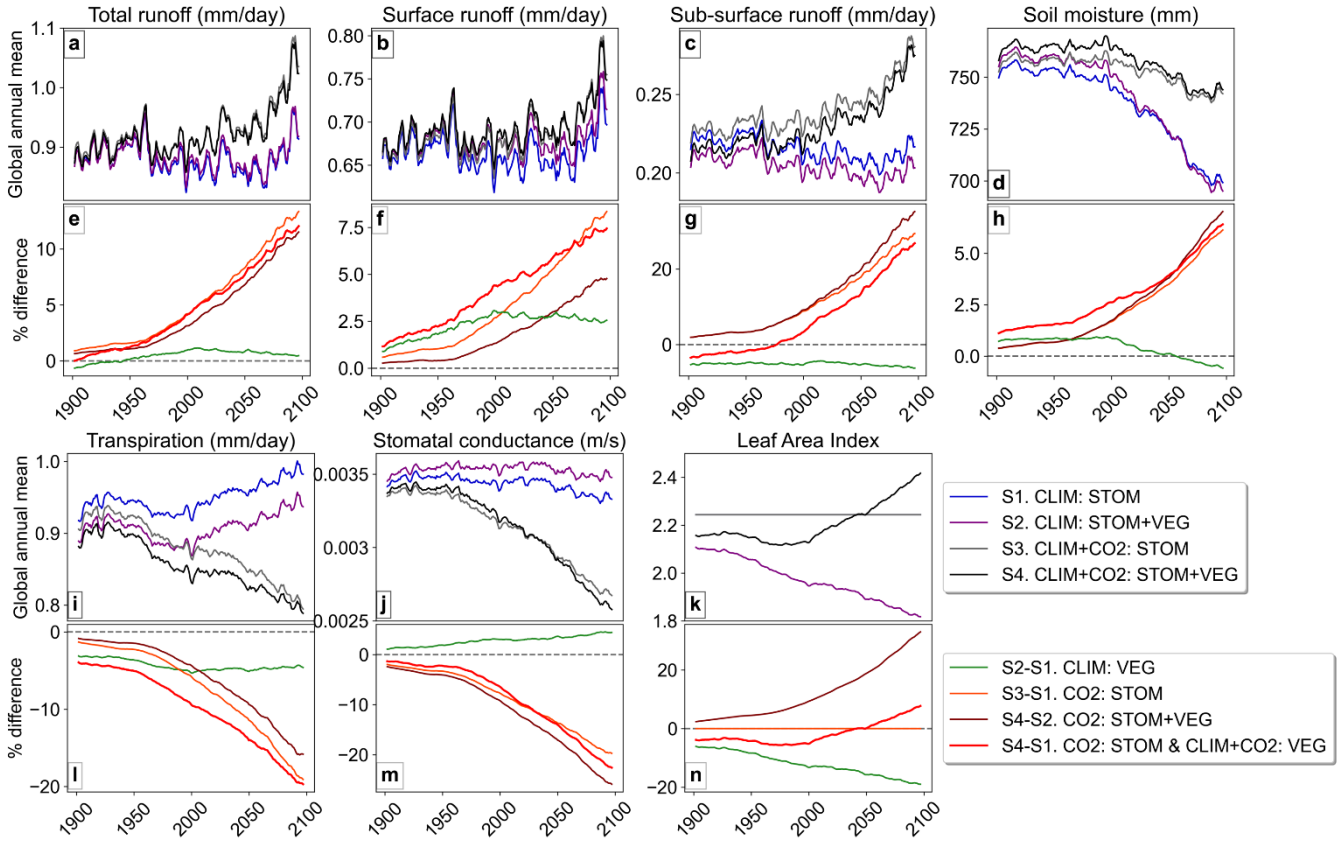

Figure 2: Global annual mean timeseries (rolling 5-year mean) in water cycle and vegetation variables in each simulation and the relative (%) difference between simulations.

While the CO_2-induced stomatal response contributes to overall surface wetting at the global scale (Fig. 2), its influence exhibits considerable spatial heterogeneity. Climate-driven runoff changes from the present (2006–2025) to the future (2076–2095) period are highly variable in both magnitude and direction (Fig. 3a) generally aligning with precipitation changes (Fig. 1b; right). When all vegetation and physiological changes are included in S4, the overall runoff and soil moisture pattern remain broadly similar to the climate-only simulation S1 (Fig. 3a,b,e,f) though increases are more evident in some regions, particularly the tropics, largely due to CO_2-induced stomatal closure. For instance, in CO2: STOM+VEG, runoff increases are projected in many regions (Fig. 3i), especially the tropics and high northern latitudes, corresponding with transpiration

decreases (Fig. 3k). In areas with projected runoff decreases under climate forcing alone (Fig. 3a), such as in the Amazon, parts of the USA, northern and eastern Europe, the stomatal response mitigates drying and, in places such as central Africa, even *reverses* runoff decreases to increases (Fig. 3e).

In many regions, physiological forcing is driving runoff increases (Fig. 3i) despite CO_2-induced LAI increases (Fig. 3l), suggesting that stomatal closure outweighs the drying effect of enhanced leaf area. However, CO_2-induced LAI increases appear to drive slight runoff reductions across some areas, particularly in semi-arid and arid climates such as the Middle East and western USA (Fig. 3i,l). Although considerably smaller than the increases, these small runoff reductions could cause significant impacts in already water-stressed areas. In contrast, climate-driven vegetation structural changes (CLIM: VEG) have relatively limited impact on runoff, transpiration, and stomatal conductance, despite notable LAI changes in parts of the tropics and high latitudes (Fig. 3m-p).

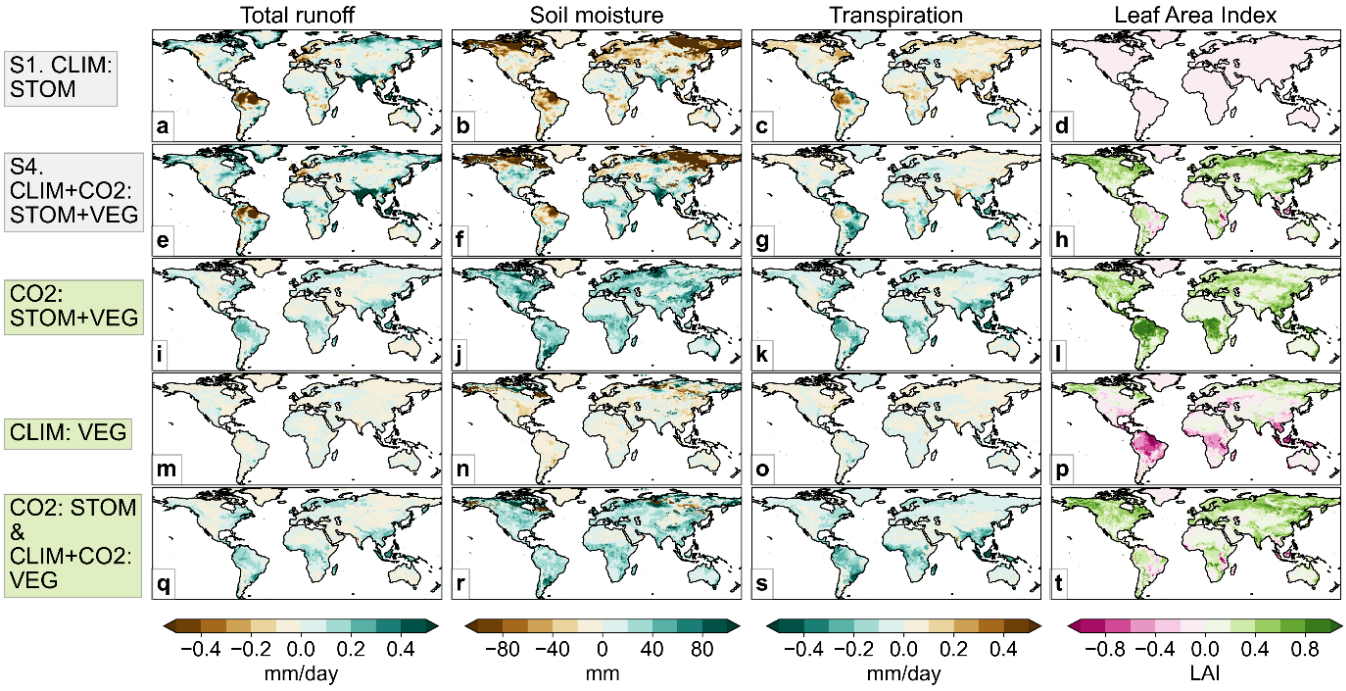

Figure 3: Global mean changes from present (2006-2025) to future (2076-2095) period in the climate-only simulation (top row), and the absolute difference when the various isolated factors are included.

3.2 Water demand, supply and the Water Scarcity Index

Global median water demand, supply, and WSI are projected to increase over the coming decades under SSP2 and RCP 6.0 (Fig. 4a-c). However, while water demand and WSI peak and subsequently decline later in the century, JULES projects a

continued rise in global water supply, particularly in simulations S3 and S4 that include CO_2 effects on stomata (Fig. 4b). When the isolated effect of increased CO_2 on plant stomata is included (CO2: STOM), global median water supply is approximately 30% higher by 2100; even when CO_2-induced structural changes are also included (CO2: VEG+STOM), supply is around 20% higher by 2100. In contrast, the climate effects on vegetation have a comparatively small influence on global median water supply, and this influence diminishes further in the coming decades (Fig. 4d; CLIM: VEG).

These water supply increases correspond with consistent projected reductions in global median WSI throughout the century (Fig. 4c,e). The CO_2-induced stomatal response appears to ameliorate WSI by 15-20% toward the century-end shown by CO_2: STOM (Fig. 4e). However, when CO_2-induced LAI increases are also allowed in CO_2: STOM+VEG, the reduction in WSI is notably less at 8-10% in the second half of the century. Climate-induced vegetation changes also reduce global median WSI by around 5%, remaining consistent throughout the period. When all processes are included, the combined influence shown by S4 – S1 (Fig. 4e) results in a 10-15% reduction in WSI throughout the century.

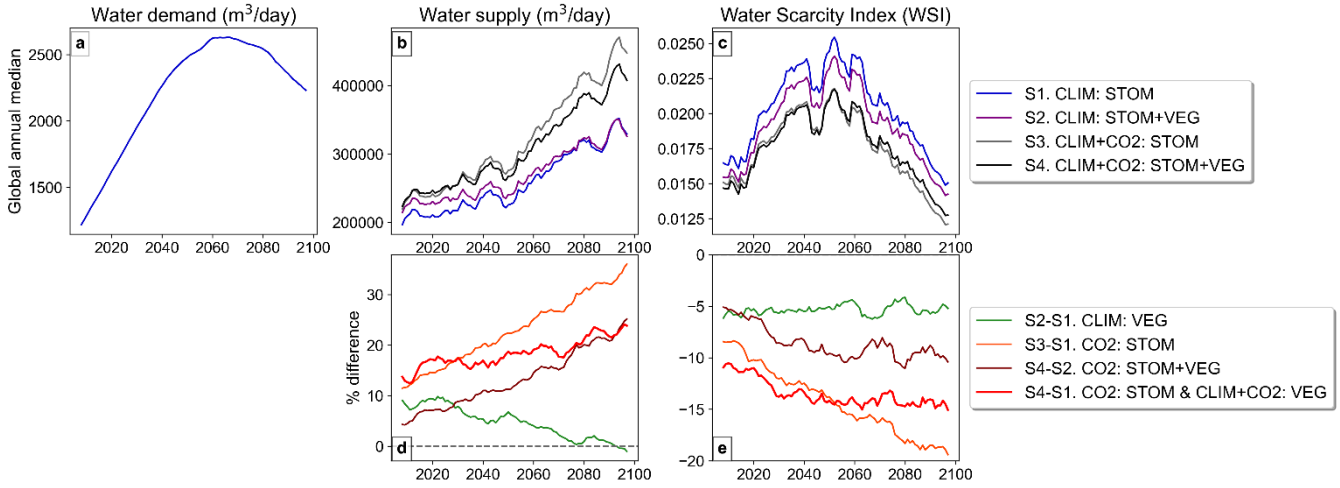

Figure 4: Annual global-median timeseries (rolling 5-year mean) of a) water demand, b) water supply, c) WSI in the four simulations and the % difference in d) supply and e) WSI due to the various isolated factors. Note, water demand is the same across all simulations.

Under RCP 6.0 and SSP2, water demand for the present period is high in much of Europe, South and Southeast Asia and the USA (Fig. 5a). Water demand increases for most places, especially in the highly populated and developing regions of South Asia, as well as parts of Africa, but decreases are also seen for parts of Europe and China (Fig. 6a). Regions experiencing severe water scarcity (WSI ≥ 0.4; Raskin, et al., 1997) in the present period (2006 - 2025), include most of India, the Middle East, eastern China and parts of South Africa, USA, and Europe (Fig. 5c). Large swathes of northern Africa are also experiencing severe water scarcity despite low demand (Fig. 5a). Even though global median WSI reduces later this century

in Fig. 4c, many of the already water scarce regions are projected to become even more water scarce by the future period (2076-2095; Fig. 6c), as the demand grows, including in highly populated regions such as India.

The plots comparing the change in median WSI from the present (2006-2025) to the future (2076-2095) under scenarios with and without plant processes (Fig. 6c,e) appear quite similar, suggesting that water demand and meteorological factors driving water supply are the primary influences on WSI. Interestingly, the changes in supply between the S1 and S4 simulations (Fig. 6b,d) show greater difference than those for WSI, since the supply differences mainly occur in areas with low levels of water scarcity, and therefore have less impact on WSI.

Despite the visual similarities between simulations with (Fig. 6e) and without (Fig. 6c) plant responses to CO_2 and climate, the effect of plant responses on WSI is not negligible. The CO_2-induced stomatal response increases water supply in most regions, especially in the tropics (Fig. 6f), resulting in corresponding reductions in WSI (Fig. 6g). When CO_2-induced vegetation structural changes are also included in the CO2: STOM+VEG simulations (Fig. 6h,i), overall supply still increases, as the supply reductions associated with CO_2-driven structural vegetation expansion are relatively small and less apparent in the plots. However, these modest reductions translate into substantial increases in WSI in arid regions such as the Middle East and northern and southern Africa (Fig. 6i), where baseline water supply is already low. Climate-induced vegetation changes shown in CLIM: VEG appear to have minimal impact on supply (Fig. 6j), yet there are substantial changes in WSI in some areas, with increases in some places, including western India, although parts of southern and northern Africa show some reductions (Fig. 6k). Finally, when all processes are combined in CO2: STOM & CLIM+CO2: VEG, supply predominantly increases (Fig. 6l), even though WSI increases in many arid and semi-arid regions.

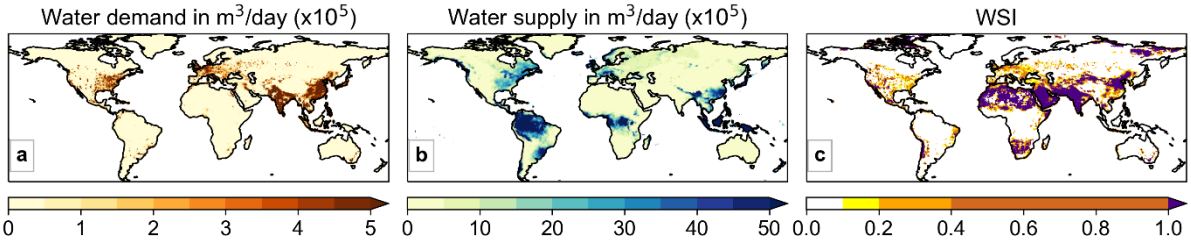

Figure 5: Median a) water demand, b) supply and c) Water Scarcity Index (WSI) for the period 2006-2025 in S1. CLIM: STOM.

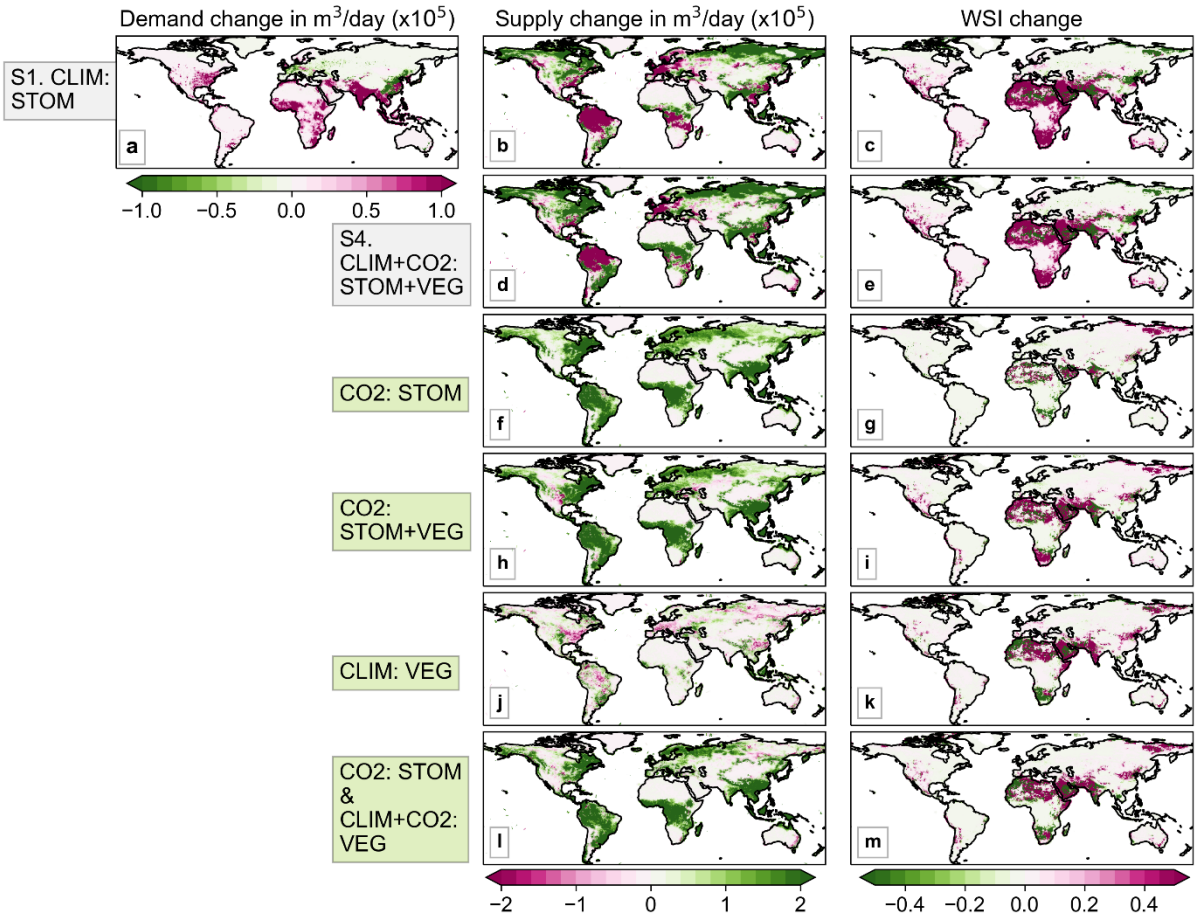

Figure 6: Median water demand, supply and Water Scarcity Index (WSI) change from the present (2006-2025) to future (2076-2095) period in simulations S1 and S4 (a-e), and the difference in supply and WSI when including the various isolated factors (f-m).

The 25 IPCC AR6 climate regions with the highest monthly median WSI between 2076-2095 are shown in Fig. 7. The Arabian Peninsula region is projected to experience the highest median WSI, and South Asia is predicted to have the second highest (Fig. 7; left panel). Comparing with the 2006-2025 present period (Fig. S3), nearly all these regions are projected to increase in median WSI by the end of the century, with the largest increases in the East and West Southern Africa and Western Africa regions.

When all vegetation responses are included in S4, there is a reduction in median WSI for all regions, except for East Central Asia and the Sahara, when compared with S1 (Fig 8; left panel). The CO_2-induced stomatal response appears to be driving the largest reductions in WSI, indicated by CO2: STOM and CO2: STOM+VEG (Fig. 7; right panel). Reductions of 30-40% are projected for Madagascar, East Southern Africa and South-Eastern Africa regions, and 20-30% reductions in Western Africa,

Northeast South America, and South and East Asia. These regions are predominantly in tropical climates, aligning with the areas of increased water supply shown in Fig. 6b. However, CO2: STOM+VEG also indicates increases in median WSI, potentially due to CO_2-induced vegetation growth in regions like North Central America, East Central Asia, and South and East Australia. Climate-induced vegetation changes (CLIM: VEG) appear to drive WSI reductions in almost all regions, perhaps due to decreased leaf area and vegetation coverage requiring less water in these regions. These reductions are considerable in some areas, with ~45% decreases in East and South Australia. When all dynamic vegetation responses are considered in CO2: STOM & CLIM+CO2: VEG, the majority of these most water scarce regions see a 20-40% reduction.

These results are reinforced by alternative WSI measures; both the number of severely water scarce months (Fig. S4a) and % area in severe water scarcity (Fig. S4b), indicate that incorporating dynamic plant processes leads to a reduction in both the temporal and spatial extent of water scarcity for most regions. These reductions are also primarily driven by the CO_2-induced reduction in stomatal aperture, particularly in the tropical regions such as East Asia and South-Eastern Africa.

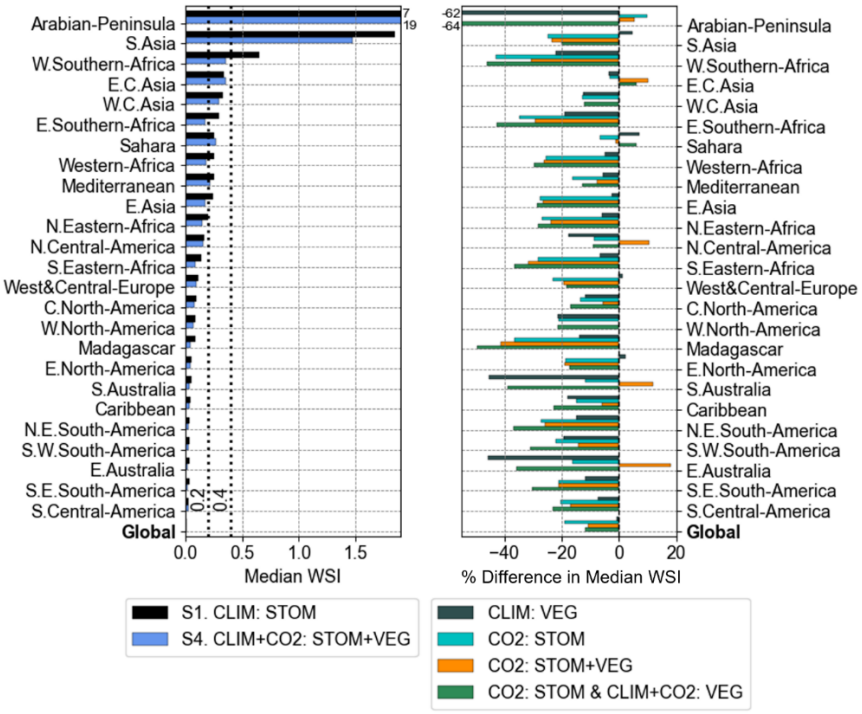

Figure 7: Median monthly WSI in simulations S1 and S4 (left) and % difference of median WSI when including the various isolated factors (right) by IPCC AR6 regions for the future period 2076-2095. The grey dashed lines (left) indicate the thresholds for mild water scarcity (WSI ≥ 0.2) and severe water scarcity (WSI ≥ 0.4). Only the 25 regions with the highest median WSI, according to the S1. CLIM: STOM simulation, are shown, sorted from the most water scarce region (top) to the least (bottom). The global median is also presented at the bottom. Out-of-range values for the Arabian-Peninsula are printed at the top.

When analysing median WSI by river basins for the future period (2076 – 2095; Fig. 8), the findings become clearer compared to the grid-cell analysis in Fig. 6. Similar to the bar plots in Fig. 7, the comparison of median WSI between scenarios S1 and S4 (Fig. 8a, b) suggests that dynamic plant processes results in limited overall changes. However, WSI category shifts are suggested for several basins, including in central, southern, and northern Africa, Southeast Asia, and eastern Australia. Supporting our existing findings, the CO_2-induced stomatal response reduces WSI in many basins (Fig. 8c,d,f); median WSI at least 20% lower in numerous basins, including in Europe, central and southern Africa, and South and East Asia, and at least 40% lower in basins in part of Africa. When CO_2 effects on vegetation structure are also included in CO2: STOM+VEG, median WSI increases by more than 10% in 18 basins (Table 2) including in the Middle East, Australia, Southern and Northwestern Africa, and the western USA (Fig. 8d), potentially due to CO_2-induced vegetation increases enhancing drying. However, the supply increases from stomatal responses due to enhanced CO_2 appear to dominate, resulting in WSI reductions by at least 10% in 122 basins (Table 2).

The effects of climate-induced vegetation structural changes is more varied with modest increases in WSI (<10%) in much of Europe and larger increases (10-30%) in central-northern Africa. However, reductions are more common, particularly around arid and semi-arid regions (Fig. 8e), also supported by Table 2, which suggests more increases than decreases in median WSI across all the thresholds.

Considering all factors combined (CO2: STOM & CLIM+CO2: VEG), decreases in WSI outweigh increases (Fig. 8f). Out of 291 basins, 139 show reductions of at least 10% (maximum 67%), affecting 80% of the global population, while only 11 basins see increases over 10% (maximum 59%), affecting just 0.2% of the population (Table 2). Most of the population are seeing small percentage changes compared with large ones, shown by the higher numbers in the lower thresholds (e.g., 5% and 10%) in Table 2. For example, when all processes are included in CO2: STOM & CLIM+CO2: VEG, median WSI will reduce by at least 5% for 88% of the population compared with reductions of at least 40% for only 2% of the population.

Figure S5 shows the number of months in severe water scarcity (WSI $\geq$ 0.4), with the CO_2-induced stomatal response again driving small reductions of mainly 1 to 2 months in many basins, in similar regions to those seen in Fig. 8f, including southern South America, central and southern Africa southeast Asia and coastal Australia. The results are also consistent when dividing into seasons, which show overwhelming reductions in median WSI across all seasons in the future period (Fig. S6).

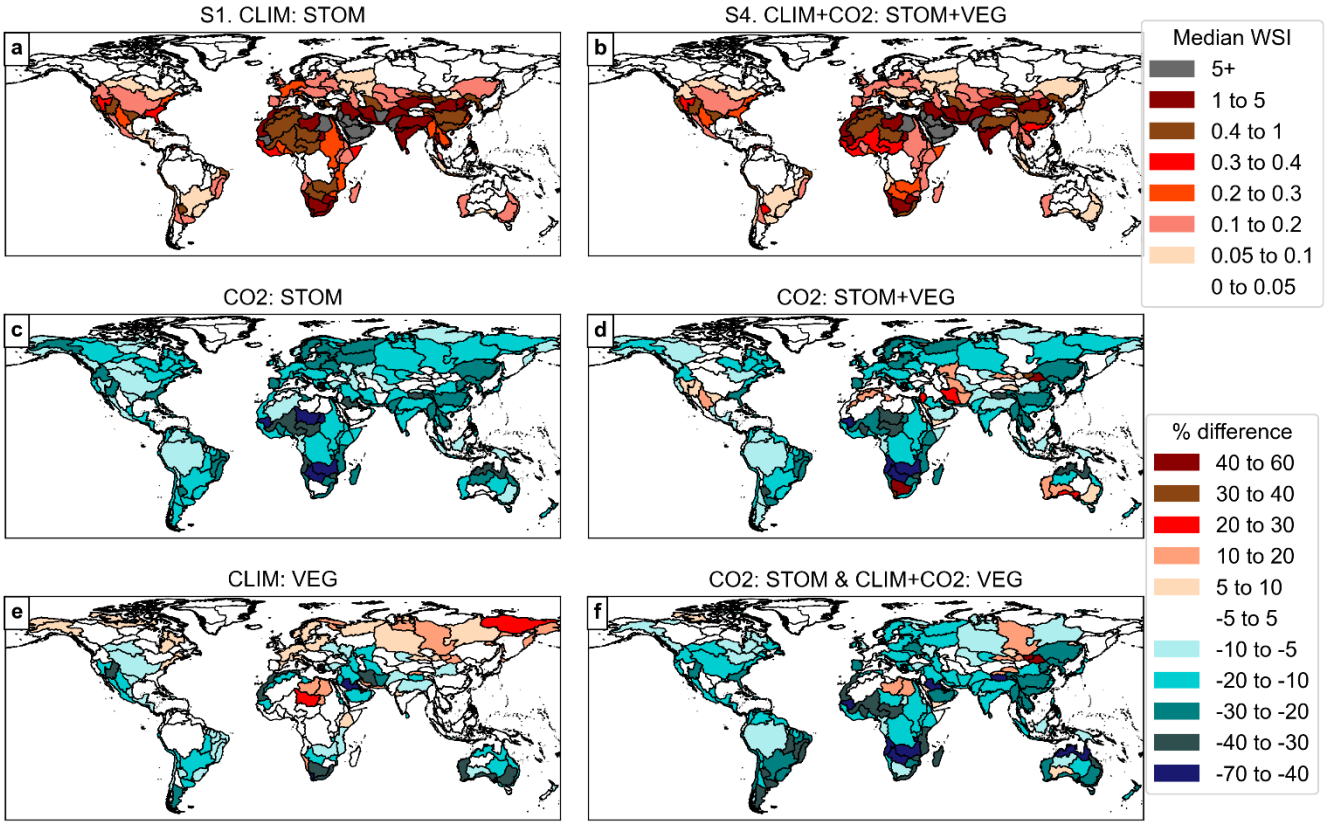

Figure 8: Median WSI in simulations S1 and S4 (top row) and the relative (%) difference in median WSI when including the various isolated factors by river basin for the future period 2076-2095.

Threshold (%)	Factor	Basin count above Threshold	Basin count below -Threshold	Percentage of population above Threshold	Percentage of population below -Threshold
5	CO2: STOM	0	198	0.0	90.1
	CO2: STOM+VEG	26	169	4.4	83.5
	CLIM: VEG	51	76	7.3	33.4
	CO2: STOM & CLIM+CO2: VEG	**17**	**176**	**1.1**	**87.8**
10	CO2: STOM	0	156	0.0	81.4
	CO2: STOM+VEG	18	122	2.7	62.0
	CLIM: VEG	21	43	0.4	9.3
	CO2: STOM & CLIM+CO2: VEG	**11**	**139**	**0.2**	**80.2**
20	CO2: STOM	0	67	0.0	24.7
	CO2: STOM+VEG	7	56	1.0	21.4
	CLIM: VEG	5	15	0.1	2.6
	CO2: STOM & CLIM+CO2: VEG	**4**	**68**	**0.0**	**26.4**
40	CO2: STOM	0	9	0.0	1.6
	CO2: STOM+VEG	2	6	0.3	1.9
	CLIM: VEG	1	2	0.0	0.2
	CO2: STOM & CLIM+CO2: VEG	**3**	**11**	**0.0**	**2.1**

Table 2. Total number of river basins and the percentage of the total projected global population affected by changes in median WSI relative to specific percentage thresholds, driven by various isolated factors for the period 2076–2095.

The annual cycles of median WSI for the period 2076 to 2095 across several major river basins are illustrated in Fig. 9, along with the relative differences when the isolated factors are included. These basins were selected based on their population and water scarcity levels, ensuring a fair geographic distribution across all continents (excluding the poles).

All basins experience periods of water scarcity during parts of the year. Consistent with previous findings, the inclusion of the CO_2-induced stomatal response mitigates WSI in all basins throughout the year, and especially during water-scarce periods. In some basins, this effect reduces WSI by over 40% during certain times of the year. For instance, in the northwest Africa and Tigris-Euphrates basins (Fig. 9a,c), the WSI is projected to be at least 50% lower during the most water-scarce periods. The basin in southern Africa presents contrasting results to the other basins and to our existing results; when including the CO_2-induced vegetation structural increases in CO2: STOM+VEG, median WSI is 50% higher, which is the case for much of the year. Interestingly, climate-induced vegetation structural changes drive 40-50% reduction in WSI over the year. These two processes appear to be balancing one another out, as the combined effect of all processes results in minimal net change in WSI.

Overall, including all plant responses to CO_2 and climate in S4, consistently mitigates WSI across the year in most basins, with the magnitude of these effects varying across the year. These findings suggest that plant responses to CO_2 have the most substantial impact during periods of water scarcity, highlighting their importance in future water scarcity projections.

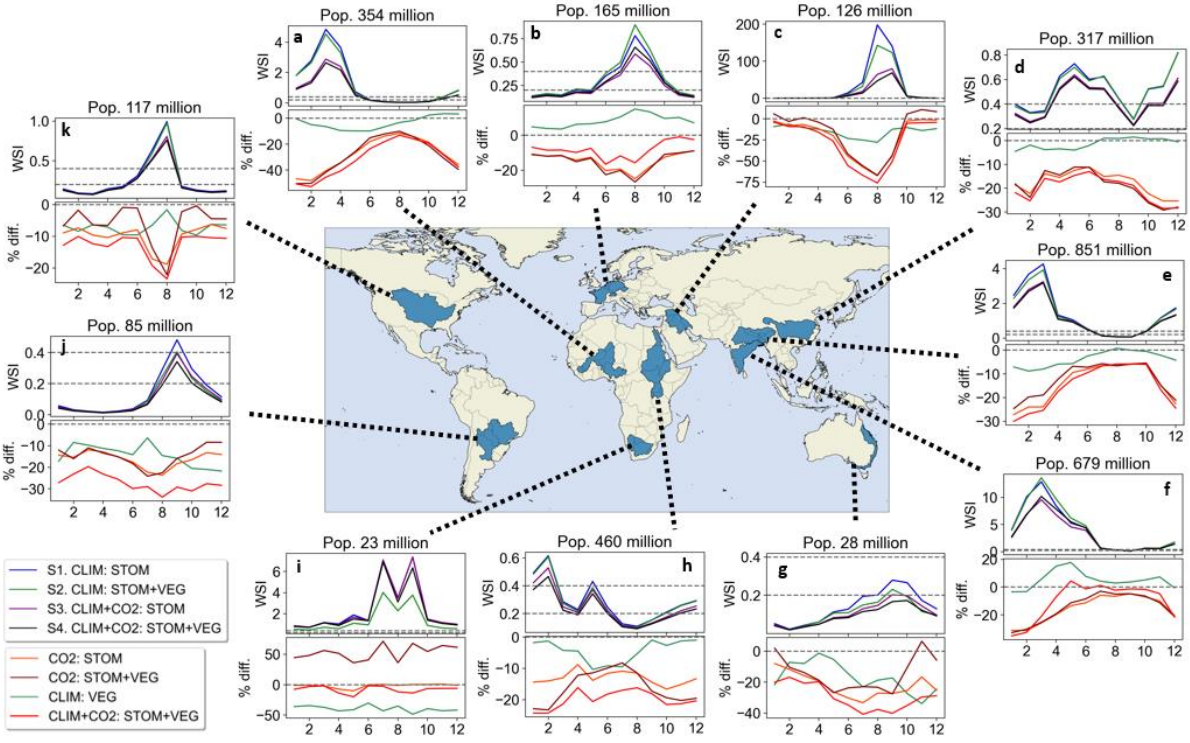

Figure 9: Annual cycles of median WSI, and the relative (%) difference in median WSI when including the various isolated factors for various river basins around the world for the future period 2076-2095. Total population of the basin is noted above each plot.

4 Discussion

Existing studies on the socioeconomic impacts of water scarcity are typically based on hydrology models that do not include plant physiological or structural responses to CO_2 or climate change (e.g., Dolan et al., 2021; Gosling and Arnell, 2016; Greve et al., 2018; Haddeland et al., 2014; Schewe et al., 2013). By replicating the common approach, i.e., driving a standalone impacts model with climate model output, this study investigates the influence of incorporating these plant responses in such analyses.

Numerous observational and modelling studies have demonstrated the impact of physiological forcing on the water cycle. In line with many of these studies (e.g., Betts et al., 2007; Cao et al., 2010; Gedney et al., 2006), our results suggest that, for the overall global mean, rising CO_2 decreases stomatal conductance and transpiration, leading to higher soil moisture and increased

runoff (Figs. 2 and 3). Projected total runoff increases of 10-12% by the end of the century (Fig. 2e) are analogous with the global mean values suggested in Betts et al. (2007) and Cao et al. (2010). The runoff increases from the stomatal response are most pronounced in the tropics (Fig. 3i), corroborating the findings of several studies (e.g., Davie et al., 2013; Fowler et al., 2019; Lemordant et al., 2018; Yang et al., 2019). Furthermore, also supported by these studies, our results suggest that global mean LAI increases with rising CO_2 (Fig. 2k,n), but, at the global scale, any reductions in runoff due to increased vegetation cover and LAI is outweighed by the increases in runoff due to the CO_2-induced stomatal response, since CO2: STOM+VEG shows relative *increases* for global mean runoff and soil moisture (Fig. 2e-h). However, CO_2- and climate-induced vegetation increases are still projected to drive small decreases in runoff across large areas of the globe, especially semi-arid and arid regions, west USA, parts of mid-latitudes and Australia, supported by several studies (e.g., Piao et al., 2007; Ukkola et al., 2016). Even though these decreases appear negligible in number, water supply is already low in many of these regions and therefore a small decrease can greatly exacerbate water scarcity in these areas.

The increase in global runoff and thus water supply when all the plant responses are included in our simulations translates to reductions in global median WSI. Our results suggest that the wetting effect of the stomatal response to rising CO_2 has the dominating influence over the drying effect of increased vegetation structural response in most places, especially when aggregated by IPCC climate regions and river basins. Under RCP 6.0 and SSP2 "middle-of-the-road" scenarios, global median WSI increases until mid-century and then declines (Fig. 4c), although many places will still experience worsening water scarcity throughout the century (Fig. 6c). Water scarcity projections with and without dynamic plant processes (Figs. 6-8) do not present drastic differences, but the influence of plant responses, particularly the stomatal response to rising CO_2, still have a noticeable effect when the results are collated over larger areas. In most IPCC AR6 regions and river basins, median WSI is *lower* when all plant responses are included in CO2: STOM & CLIM+CO2: VEG (Figs. 7-8; Table 2). Although CO_2-induced stomatal closure substantially increases water supply by ~35% (Fig. 4d), it reduces WSI by only ~20% (Fig. 4e) by 2100. The smaller influence on WSI arises because the largest supply increases are due to the CO_2-induced stomatal response, which has most influence in non-water scarce regions with abundant water supply, such as tropical regions like the Amazon and Southeast Asia (Fig. 6f,g), which contribute less to WSI values.

Notable differences emerge when computing WSI at different spatial scales. At the grid-box level, plant responses often lead to increases in median WSI across many areas (Fig. 6), because local demand, particularly in urban areas, can often substantially exceed local supply, as runoff from surrounding grid-boxes is not accounted for. In contrast, at larger spatial scales, decreases in WSI are more common (Figs. 7 to 9), as aggregating supply and demand across broader areas generally lowers WSI. For river basins, total runoff is assumed to be accessible to all inhabitants within the basin, which smooths out local imbalances. While neither approach fully captures the complexity of water distribution and accessibility, this is not a critical limitation for this study, which is to assess the *relative* influence of vegetation responses on WSI rather than produce precise estimates.

Furthermore, our findings may overestimate WSI in places, as our proxy for water supply is total runoff estimated using JULES, which does not include some sources which can supplement water supply, such as groundwater extraction. Another consideration which could mean our WSI estimates are too high, is because water demand for irrigation is estimated by hydrology model 'H08', which, like many other hydrology models, does not account for physiological forcing. Additional atmospheric CO_2 generally makes crops more water-efficient, lowering water required for irrigation, and thus potentially alleviating water scarcity.

The HadGEM2-ES climate data driving JULES in this study has been bias corrected following the ISIMIP2b protocol, although some residual biases remain in the JULES version used (Mathison et al., 2023). For 1980–2006, their evaluation indicates negligible runoff biases for most river basins. However, slight runoff underestimations in China and the northern high latitudes translate to overestimations in WSI in our study. Conversely, slight runoff overestimations in eastern USA translate to underestimations in WSI in our study. To assess the influence of plant responses, we take the difference between two simulations that share similar biases, and thus this minimises overall biases. Non-linear biases may persist when comparing simulations with differing plant responses, but these are expected to be relatively small compared with other uncertainties inherent in such modelling studies.

JULES uses parameterisation schemes to represent hydrological and biophysical processes. For example, the stomatal conductance scheme (see Appendix B) simplifies a complex process which varies across species, ecosystems, and climates (Norby and Zak, 2011). Evaluating the accuracy of such parameterisation schemes on a global scale is a major challenge, primarily due to limited observational data. Experiments such as Free Air CO_2 Enrichment (FACE) have provided valuable insights into plant physiological responses to elevated CO_2, which are crucial for land surface model developments, but are currently at a small number of point locations. Model-data comparison studies suggest mixed performance at simulating CO_2 effects on water-use efficiency, with models performing well for some sites and species but poorly for others (De Kauwe et al., 2013; Walker et al., 2014). Although JULES has not yet been comprehensively assessed in these studies, its behaviour is expected to be broadly comparable to the models evaluated. Furthermore, some studies suggest that the magnitude of the CO_2-effect on river runoff records in JULES is reasonable within uncertainty bounds (Gedney et al., 2006, 2014).

Since only one land surface model was assessed in this study, further work could test additional models to examine the sensitivity of the results. We would anticipate broadly consistent outcomes across LSMs when testing the stomatal response, as many LSMs employ stomatal conductance parameterisation schemes derived from similar formulations. However, we would expect a wider spread of responses in LSMs when testing vegetation structural responses, given that different Dynamic Global Vegetation Models apply alternative approaches to dynamic vegetation compared with the TRIFFID scheme used in JULES (Sitch et al., 2008).

Finally, we recognise that, to mimic typical hydrology impact studies, JULES was run standalone driven by climate model output, without feedbacks to the driving climate model. For example, disabling the stomatal response to rising CO_2 in JULES typically increases transpiration (Fig. 2), which typically enhances atmospheric moisture affecting humidity, temperature, and precipitation. Such feedbacks could amplify differences in water scarcity projections between simulations with and without vegetation responses. Assessing the importance of these missing interactions could highlight the value of using hydrology models coupled to the atmosphere for water scarcity assessments.

5 Conclusions

Our results suggest that including plant physiological and structural responses to rising CO_2 and associated climate change in JULES partially moderates water scarcity in many regions throughout this century. Enhanced water-use efficiency driven by CO_2-induced stomatal closure contributes to increased water availability, particularly the tropics. The supply increase translates to decreases in WSI in many regions, although the largest increases in water supply occur in regions that already experience abundant rainfall, such as the tropics, which are typically areas that do not suffer from water scarcity. Thus, when averaged globally, the CO_2-induced stomatal response drives relatively smaller reductions in WSI than increases in water supply. Our projections also indicate potential increases in WSI in certain semi-arid and arid regions, attributed to CO_2- and climate-induced expansions in vegetation cover and leaf area, reducing water availability in already water-limited areas. When WSI is calculated across IPCC climate regions and river basins, the incorporation of all dynamic plant responses partially moderates projected WSI for most of the global population. Our findings highlight the need to incorporate vegetation dynamics, primarily physiological forcing, into hydrology models to improve the robustness of water scarcity assessments.

We note that there are limitations inherent in modelling the complex interactions between the biosphere and hydrosphere under changing climate conditions. The results presented here are based on assumptions and parameterisations within the JULES land surface model. Further research is needed to refine these findings, particularly through the use of more advanced representations of plant responses to elevated CO_2 and climate change, supported by observational data. Such efforts will enhance the accuracy and reliability of future water scarcity projections, improving their utility for policymakers and water resource managers.

Appendices

Appendix A

The four JULES simulations and calculations for the “isolated factors”

		Vegetation structure (includes coverage, LAI and canopy height)		Calculations for isolated factor(s):
		Dynamic vegetation off (fixed at preindustrial)	**Dynamic vegetation on**	
Plant physiology CO_2 levels in JULES	**277 ppm** (fixed at preindustrial)	S1. CLIM: STOM	S2. CLIM: STOM+VEG	**S2 - S1. CLIM: VEG**
	RCP 6.0	S3. CLIM+CO2: STOM	S4. CLIM+CO2: STOM+VEG	*Not used*
Calculations for isolated factor(s):		**S3 - S1. CO2: STOM**	**S4 - S2. CO2: STOM+VEG**	**S4 - S1. CO2: STOM & CLIM+CO2: VEG**

Table A1: The four JULES simulations driven by identical climate model output, and a combination of fixing plant CO_2 and structural vegetation responses.

Appendix B

Stomatal Conductance Scheme used in JULES

The version of JULES used in this study uses a coupled canopy conductance and photosynthesis model (Cox et al., 1998) where stomatal conductance to water vapour g_s (m s^{-1}) is based on:

$$g_s = -1.6A\frac{RT^*}{c_i - c_a} \quad (1)$$

where *A is* the net photosynthetic rate (mol CO_2 m^{-2} s^{-1}), *R* is the universal gas constant (J K^{-1} mol^{-1}), *T** is the leaf surface temperature (K), c_i the internal CO_2 partial pressure (Pa), c_c the leaf surface CO_2 partial pressure (Pa) and factor of 1.6 accounting for molecular diffusivity differences between water and CO_2. Vapour deficit at the leaf surface (D, kg kg^{-1}) affects stomatal conductance through the gradient between c_a and c_i is based on the equation by Jacobs (1994):

$$\frac{c_i - \Gamma^*}{c_a - \Gamma^*} = f_0\left(1 - \frac{D}{D_{crit}}\right) \quad (2)$$

where Γ^* is the photorespiration compensation point (Pa) and D_{crit} and f_0 are PFT-specific calibration parameters, which are directly related to the parameters from the Leuning (1995) model (for details see Cox et al., 1998). Potential non-stressed leaf level photosynthesis is calculated in JULES using the C3 and C4 photosynthesis models of Collatz et al. (1991) and Collatz et al. (1992) respectively.

The Jacobs formulation is a simplified version of the Leuning (1995) model, which in turn is based on the (Ball et al., 1987) model but depends on humidity deficit at the leaf surface instead of relative humidity.

Runoff processes in JULES

In this version of JULES, soil is divided into 4 layers, each with its own water content, which is determined by considering the inputs, such as precipitation, and outputs such as evapotranspiration and infiltration. The moisture content of each soil layer influences water movement, affecting how much percolates downward to deeper layers or moves horizontally as lateral flow. Additionally, in this version of JULES a TOPMODEL-type scheme is included, based on Clark and Gedney (2008) and Gedney and Cox (2003). This accounts for the influence of topography on soil moisture and runoff, enhancing JULES's ability to simulate the sub-grid spatial variability. Surface runoff is generated when precipitation exceeds the soil's infiltration capacity, when the soil becomes fully saturated, or when sub-grid scale inundation occurs. In TOPMODEL-based schemes, sub-surface runoff, or "baseflow", occurs with lateral flow below the water table, and its magnitude is influenced by soil moisture and soil type.

Code availability

Python has been used to conduct our analysis. Code is available on GitHub at https://github.com/jessica-stacey/water-scarcity-plants-jules.

Data availability

Output from JULES simulations can be made available upon request. Water demand data is available from the ISIMIP database (e.g., https://data.isimip.org/search/query/amanww/tree/ISIMIP2b/OutputData/water_global/h08/hadgem2-es/). Population data is also available from the ISIMIP database (https://data.isimip.org/datasets/6eee7c61-4baa-4b1d-aa81-d854f217f07e/).

Author contributions

JS: Conceptualisation, investigation, methodology, formal analysis, visualisation, writing draft
RAB: Conceptualisation, methodology, supervision, writing (review and editing)
AH: Supervision, methodology, validation, writing (review and editing)
LM: Supervision, writing (review and editing)
NG: Writing (review and editing)

Competing interests

The authors declare that they have no conflict of interest.

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