Call for caution regarding the efficacy of large-scale afforestation and its hydrological effects

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["Science becomes dangerous only when it imagines that it has reached its goal" (Shaw, 1906)]

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Abstract

Large-scale afforestation programmes are generally presented as effective ways of increasing the terrestrial carbon sink while preserving water availability and biodiversity. Yet, a meta-analysis of both numerical and observational studies suggests that further research is needed to support this view. The use of inappropriate concepts (e.g., the biotic pump theory), the poor simulation of key processes (e.g., tree mortality, water use efficiency), and the limited model ability to capture recent observed trends (e.g., increasing water vapor deficit, terrestrial carbon uptake) should all draw our attention to the limitations of available theories and Earth System Models. Observations, either based on remote sensing or on early afforestation initiatives, also suggest potential trade-offs between terrestrial carbon uptake and water availability. There is thus a need to better monitor and physically understand the observed fluctuations of the terrestrial water and carbon cycles to promote suitable nature-based mitigation pathways depending on pre-existing vegetation, scale, as well as baseline and future climates.

1. Introduction

According to the sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2022), agriculture, forestry and other land use (AFOLU) currently represent around 15% of the human emissions of greenhouse gases (GHG). Yet, changes in current practices and tree restoration are expected to provide an efficient tool to strengthen the terrestrial carbon sink and, thus, compensate for the residual emissions of carbon dioxide by the mid-century. In modelled socio-economic pathways that reach global net-zero CO_2 emissions, 5–16 $GtCO_2$ are compensated for by net negative emissions and 4 to 20% of these reductions are achieved by CO_2 mitigation options in the AFOLU sector at the point when net zero is reached. This significant contribution however remains very uncertain (by a factor 5) given the lack of quantitative evaluation of on-going afforestation efforts (Friedlingstein et al., 2022).

The 3rd Working Group (WG3) of IPCC claims that AFOLU mitigation options, when sustainably implemented, can deliver large-scale GHG emission reductions and enhanced removals. Yet, the efficiency and sustainability of these land-based carbon dioxide removal (CDR) solutions are still a matter of debate (e.g., Bastin et al., 2019; Lewis et al., 2019; Veldman et al., 2019). Moreover, their potential side-effects on water availability have not been much discussed (Friedlingstein et al., 2019). Last but not least, the growing appropriation of the CDR concepts by the fossil fuel industry, as evidenced by the recent COP28 (https://carbonremovals.org/), may look as a "deadly climate gamble" (https://www.corporateeurope.org/sites/default/files/2022-09/Deadly%20climate%20gamble%20layout_3.pdf) unless carefully legitimized by the scientific community.

In a recent review, Roe et al. (2021a) provided two independent estimates of the land-based mitigation potential in the context of a net-zero emission objective by 2050. According to +1.5°C compatible pathways from integrated assessment models (IAMs), AFOLU and bio-energy with carbon capture and storage (BECCS), can provide 0.9–36.6 (median 13.8) $GtCO_{2e}$/yr of mitigation potential in 2050, which represents 4–40% (median 25%, 16% for AFOLU only) of the total mitigation required for a 1.5 °C pathway (CO_{2e} means the number of metric tons of CO_2 emissions with the same global warming potential as one metric ton of another greenhouse gas). In a parallel supply-side assessment, AFOLU and BECCS actions provide an even larger 2.4–48.1 (median 14.6) $GtCO_{2e}$/yr range of mitigation potential from 2020 to 2050, although the median AFOLU contribution (10.6 $GtCO_{2e}$/yr) is fairly consistent with the top-down estimate (9.1 $GtCO_{2e}$/yr). Yet, IAM results and supply-side analyses differed on types of mitigation measures included and on their relative contributions. Moreover, the feasibility and sustainability of these land-based mitigation options were not considered.

Beyond the technical mitigation potentials, cost-effective estimates have also been assessed (Roe et al., 2021b) and may represent a more realistic target for decision-makers. The global cost-effective potential (i.e., with a cost not exceeding \$100/tCO_{2e}) was found to be approximately 50% from forests and other ecosystems, 35% from agriculture, and 15% from demand-side measures, but shows a strong spatial variability. The forest sector is thus the most attractive land-based CDR solution for some of the world's largest companies which already rely on "carbon offsets" to reach their net-zero emission commitment. A large proportion (about 80%) of the overall afforestation potential is however in Global South countries, where feasibility barriers remain a matter of concern and where a new form of "carbon colonialism" was denounced, consisting of placing the burden of the negative emissions on their shoulders (Navaro, 2022).

Forestry is mentioned as a priority in terms of adaptation and mitigation in achieving the Paris Agreement goals in around 50% of the current Nationally Determined Contributions. The deployment of CDR projects is thus expected to accelerate in the coming years. Large-scale tree planting, along with forest restoration, are being promoted by multiple entities, including non-profit organizations but also commercial initiatives. There are however serious concerns that this is distracting from the need to rapidly phase out use of fossil fuels and that the expansion of forestry framed as a climate change mitigation solution is coming at the cost of carbon rich and biodiverse native ecosystems and local resource rights (Seddon et al., 2021). Besides ethical and justice-related problems, large uncertainties regarding the efficiency, sustainability and collateral hydroclimate effects of these projects must be further scrutinized.

In this review, we first adopt a bottom-up approach and assess both deforestation and afforestation experiments based on state-of-the-art Earth System Models (ESMs) in order to showcase their potentially useful but still uncertain outcomes, as well as their missing or misrepresented processes (Section 2). We then turn to observational studies and existing large-scale afforestation projects to further highlight the actual limitations of afforestation as an efficient CDR method (Section 3). Finally, we conclude that the expected carbon and water benefits of future afforestation programmes need further scientific support and that observations can be increasingly useful to narrow modelling uncertainties in coupled carbon-climate projections (Section 4).

2. Numerical experiments

2.1 Sensitivity of climate to land cover change

a) Deforestation

Several generations of numerical models, ranging from simple IAMs to much more comprehensive ESMs, have been used to explore the consequences of more or less idealized land cover change scenarios.

According to the AR6 WG1, large-scale deforestation has likely decreased evapotranspiration (ET) and precipitation (P), and increased runoff over the deforested regions (Douville et al., 2021a). This assessment is consistent with the model-dependent response of nine ESMs to an idealized global deforestation scenario in which 20 million km^2 of forested areas were replaced with grasslands (Boysen et al., 2020). Yet, the effect on global mean temperature ranged from no significant change to a cooling by 0.55°C and the regional precipitation response was even more uncertain (see also Li et al., 2023a).

At the regional scale, the hydrological impact of deforestation is particularly unclear in the northern mid-latitudes where some models show a precipitation decrease, but others rather show an increase (Fig. 1). In the deforested tropical areas, the decrease in precipitation is generally stronger and more robust although some models show a local increase associated with an horizontal advection of moist air from the Atlantic and west Amazon. These results are broadly consistent with a meta-analysis of previous Amazonian deforestation experiments conducting with global (GCMs) or regional (RCMs) climate models and leading to precipitation changes ranging from –38 to +5 % (Spracklen and Garcia-Carreras, 2015).

Interestingly, it was also suggested that even a limited deforestation of the Amazon rainforest could trigger a dieback of the entire ecosystem (Boers et al., 2017). As recognized by the authors, the physical mechanisms behind such a tipping point are however a matter of debate. Their result was not based on a comprehensive ESM, but on a conceptual model assuming a nonlinear coupling between the Amazon rainforest and the atmospheric moisture transport from the Atlantic to the South American continent. This model is inspired by the Biotic Pump Theory (hereafter BPT, Makarieva and Gorshkov, 2007; Makarieva et al., 2023) which states that low-level air masses move from areas with weak evaporation (E) to areas with more intensive E via condensation-induced mass removal and atmospheric dynamics. The conceptual model leads to a precipitation deficit of up to 40% in non-deforested parts of the western Amazon and regions further downstream. The BTP theory has been however heavily criticized (Meesters et al., 2009; Bouman et al., 2023) and this strong precipitation sensitivityis inconsistent with the hydrological response simulated by most GCMs or ESMs (e.g., Spracklen and Garcia-Carreras, 2015; Ruiz-Vasquez et al., 2020; Boysen et al., 2020).

One of the key uncertainty behind the water cycle response to perturbed land cover is the induced ET change which may depend, regardless of the magnitude and patterns of land-cover change, on the background climate (Willeit et al., 2014), the implemented land management strategy (Kauskal et al., 2017), and the selected ESM (Boysen et al., 2020). Such a response can be compared in off-line land surface model (LSM) simulations driven by prescribed land cover change and atmospheric forcings (Guimberteau et al., 2017). The uncertainty range on ET changes was shown to first depend on the selected GCM forcing, while runoff uncertainty is rather dominated by structural differences among LSMs. Yet, this off-line strategy does not account for land-atmosphere coupling and thus the adjustment of the atmospheric boundary layer to changes in either land cover or LSM (Laguë et al., 2019).

Beyond idealized deforestation experiments, more realistic sensitivity experiments to land cover change or dynamic vegetation have also been conducted and have all suggested a limited vegetation influence on precipitation (e.g., Debortoli et al., 2016; Taylor et al., 2022; Luo et al., 2024). For instance, a multi-model land use change study focusing on the Sahel excludes a major contribution of land use and land cover change to the observed 20th century precipitation variability (e.g., Herman et al., 2023), thereby confirming that land use changes are not large enough to have been the cause of the Sahel drought in the 1980s (Taylor et al., 2002). Another recent hydrologic modelling study focused on the combined effects of forest thinning and global warming on the Beaver Creek watershed (∼1,100- km^2) in central Arizona (Cederstrom et al., 2024). On average, forest thinning was found to increase the annual mean streamflow by +12% through lower plant transpiration by −19%, while also increasing the change in soil water storage by +42%. In contrast with the dominant thinking, forest cover reductions could thus delay the detrimental effects of warming on streamflow until +4°C.

b) Afforestation

Over the last few years, a growing attention has been paid to afforestation/reforestation scenarios rather than deforestation experiments. Beyond the hydroclimate impacts at the regional scale, the main motivation was to assess the expected effect on the global carbon cycle. Planting trees in areas that currently don't have trees – a process called afforestation – is generally considered as a readily available climate change mitigation option, whose efficiency and cost are generally assessed using integrated assessment models (IAMs, Roe et al. 2021a,b) but may depend on location, scale, and both present-day and future climates. Doelman et al. (2020) estimated for instance that large-scale afforestation has a mitigation potential of 4.9 $GtCO_2$/year at 200 US$/$tCO_2$ in 2050 and is thus a suitable albeit relatively minor mitigation option that can only play a limited role in keeping global warming below +2°C under an intermediate (SSP2) emission scenario.

IAMs are however not the most suitable tool for assessing the efficiency of afforestation. They can account for the fact that land ecosystems absorb on average 30% of anthropogenic CO_2 emissions, but the natural fluctuations in the net land surface flux of CO_2 are usually considered as a simple function of global or regional mean surface temperatures and the interactions with the water cycle are not accounted for. In contrast, recent observations suggest that the atmospheric CO_2 growth rate is primarily controlled by changes in terrestrial water storage, with dry years leading to a faster rate of increase (Zhang et al., 2021). While this global relationship was shown to be underestimated in current ESMs (Humphrey et al., 2018), the impacts of water limitations on photosynthesis are simply ignored in most IAMs which typically use low dimensional estimates of the carbon density associated with different land use types to assess the carbon uptake potential.

Apart from sequestering carbon, large-scale afforestation is generally expected to increase regional precipitation levels and to represent a smart, land-based strategy to combat drought (e.g., Ellison et al., 2012; Baker, 2021). Again inspired by the BPT, this possibility has retained the attention of many engineers and organizations interested in forest conservation (e.g., https://hydrologie-regenerative.fr/) or in promoting afforestation as a sustainable mitigation option (e.g., https://forestsnews.cifor.org/10316/ make-it-rain-planting-forests-to-help-drought-stricken-regions). Yet, it has received so far a limited support from the climate modelling community and few numerical studies have been performed so far that validate large-scale afforestation projects as a safe mitigation option.

As an exception, a global hydrological model was recently used to show that a maximum global afforestation scenario would on average increase evaporation by 0.6 mm/day, which could potentially contribue to a subsequent 0.4 mm/day increase of precipitation over land (Tuinenberg et al., 2022). This off-line study is however based on the same unrealistic tree restoration potential as in Bastin et al. (2019) and does not consider the crucial land-atmosphere interactions that may temper the ET response to afforestation in the real world (e.g., Laguë et al., 2019). As another example, van Dijke et al. (2022) explored the hydrological consequences of a 900 Mha tree restoration by using an ensemble of data-driven mechanistic models and found complex changes in water availability ranging from a -38% decrease in some regions to a +6% increase in others.

ESMs are arguably the most comprehensive tool for simulating the water-carbon nexus and, thus, assessing both the mitigation potential and the hydroclimate side effects of afforestation. One such early study (Arora and Montenegro, 2011) focused on the land surface energy budget. Complete (100%) versus partial (50%) afforestation of the land domain currently occupied by crops led to a reduced global warming by around 0.45 and 0.25°C, respectively. The surface warming reduction per unit afforested area was found to be three times higher in the tropics than in the extratropics, suggesting that tropical afforestation is potentially a more effective strategy. Yet, the hydrological response was not explored.

More recently, an emission-driven ESM was used to quantify the potential benefits from pantropical tree restoration through an idealized experiment where all land use in the tropics is stopped and vegetation is allowed to recover under an intermediate (RCP2.6) mitigation scenario (Koch et al., 2021a). Tropical tree restoration of 1529 Mha was found to increase live biomass by 130 Pg C by the end of the century (Fig. 2). Yet, the subsequent reduction in oceanic and extratropical terrestrial carbon uptake implied that carbon in the atmosphere only reduces by 18 Pg C by 2100. The resulting CO_2 benefit (only 9 ppm) thus did not translate to a detectable reduction in global warming and afforestation did not strongly contribute to negative emissions. De Hertog et al. (2022) compared the local and remote responses of three ESMs to four idealized experiments performed under present-day climate conditions, including global afforestation with or without extensive wood harvesting, and a full cropland world with or without extensive irrigation. The surface air temperature response to deforestation was largely consistent with observations, with a cooling in boreal latitudes and a warming in the tropics. Yet, the energy balance components (including latent heat) driving these temperature changes were shown to be model-dependent, thus suggesting an uncertain response of both ET and precipitation at the regional scale.

It has been argued that the global ESMs are flawed because of their relatively coarse horizontal resolution (Branch and Wulfmeyer, 2019) or their misrepresentation of the cooling effect of plant transpiration (Makarieva et al., 2024). The former study however suggests a local heat low effect driven by suppressed rather than increased ET, and thus contradicts the BPT hypothesis. Moreover, afforestation experiments conducted with higher resolution regional climate models do not necessarily show stronger impacts on precipitation (Strandberg and Kjellström, 2019). Several studies also suggest that horizontal resolution may not be the Achille's heel of current ESMs given their lack of structural diversity (e.g., Franks et al., 2017) and limited ability (e.g., Gier et al., 2024) to capture the narrow interactions between the terrestrial water and carbon cycles (cf. Section 2.2).Smaller scale afforestation programmes have arguably even smaller benefits in terms of mitigation, although they may also come with fewer negative side effects. Using a high-resolution LSM, the hydrological impacts of alternative afforestation scenarios across Great Britain have been recently explored (Buechel et al., 2023). Off-line LSM simulations suggested that the proposed scale of afforestation is unlikely to significantly alter regional hydrology (in these relatively wet regions), although it can noticeably decrease minimum flow during dry periods. The afforestation levels only marginally impact hydrological processes compared to prescribed changes in precipitation, temperature, and CO_2. Similarly, a recent pan-African afforestation sensitivity experiment conducted with a high-resolution, atmosphere-only, global numerical weather prediction model did not reveal any significant influence on summer precipitation (Smiatek and Kunstmann, 2023). Finally, a variable-resolution coupled land-atmosphere global climate model was used to investigate the vegetation-induced changes in precipitation over China and found a non-significant increase in precipitation from vegetation greening, though sufficient to cancel out enhanced ET and resulting in weak impact on soil moisture (Li et al., 2018).

2.2 Carbon-water nexus representation in current ESMs

As the next CMIP intercomparison should be based on emissions-driven rather than concentrations-driven ESMs (Sanderson et al., 2023), it becomes even more urgent to assess their ability to simulate the complex interactions between the terrestrial components of the carbon and water cycle, respectively. The LSMs (i.e., land surface components of ESMs) have at their foundation a coupling of evapotranspiration through plant stomata, balanced with carbon uptake for photosynthesis, and the impact of these processes on the land energy and water budget. The representation of these elements is subject to strategies of plant gas exchange (and how these are parameterised) as well as soil properties (depth, texture) and vegetation structure. Coupling of land surface energy partitioning and evapotranspiration with atmospheric processes, as facilitated by ESMs, is also critical for understanding the full implications of both GHG emissions (Döll et al., 2016; D'Odorico et al., 2018) and forest expansion (e.g., Laguë et al., 2019; De Hertog et al., 2022).

The amount of carbon dioxide that plants take from the air depends on how plants respond to water stress. At the same time, plants also control the loss of water from the landscape through transpiration. The ratio of carbon assimilation to ET, referred to as water use efficiency (WUE), has been the focus of many observational and modelling studies and is generally expected to increase as a response to increasing atmospheric CO_2 concentration (e.g., De Kauwe et al., 2013; Zhang et al., 2019; Lavergne et al., 2019; Fatichi et al., 2023). Worldwide *in situ* measurements suggest that water availability and carbon uptake behave quite similarly across many locations and climate conditions (e.g., Short Gianotti and Entekhabi, 2024). Yet, little is known about the interactive effects of rising CO_2 and CO_2-induced climate change on WUE at the scale of ecosystems (Lemordant et al., 2018; Li et al., 2023b). Moreover, water availability is not the only limitation to the observed carbon uptake at the local scale. *In situ* measurements show that enhanced VPD can reduce photosynthesis by the same magnitude as severe soil drying in a deciduous broadleaf forest, and suggest that rising VPD due to global warming may drive drought-like CO_2 flux responses even if soil moisture does not decrease (Sulman et al., 2016).

Models of stomatal conductance implemented in ESMs are typically characterized by a single fitted parameter which may reflect a lack of model diversity and the need of a better and vegetation-trait dependent tuning of this critical parameter (e.g., Franks et al., 2017). Moreover, rising temperature and water vapour pressure deficit (VPD) may play a more important role than declining stomatal conductance in regulating ET and GPP (Fang et al., 2022). Likewise, plant growth can offset the effect of increased WUE on water resources at the regional scale (Singh et al., 2020) and increased WUE may not compensate for carbon loss in European forests (e.g., Montibeller et al., 2022).

The evaluation of state-of-the-art ESMs suggests persistent issues in the representation of the terrestrial carbon and water cycles. Despite an improvement in the simulation of net primary productivity (NPP), unrealistically high correlations are still found with soil carbon stocks and suggest a potential overestimation of the long-term terrestrial carbon sink (Varney et al., 2022). Compared to satellite data and ground observations, most CMIP6 models show an overall bias in land water storage and thus underestimate the maximum annual soil moisture depletion, especially in the Amazon region (Giardina et al., 2024). Simulating the leaf area index (LAI) remains challenging with a large model spread in both CMIP5 and CMIP6 ESMs. Global mean land carbon uptake (NBP) is relatively well reproduced, but hides compensating errors between the northern and southern hemispheres. Overall, a slight improvement in the simulation of land carbon cycle parameters is found in CMIP6 compared to CMIP5, but with many biases remaining (Gier et al., 2024). Most models also fail to capture the present-day tropical forest carbon dynamics (Koch et al., 2021b), as well as historical trends in terrestrial carbon uptake (Peng et al., 2022) or near-surface relative humidity (Douville and Willett, 2022; Simpson et al., 2023; Fig. 3).

Even if the representation of the terrestrial carbon-water nexus has however evolved considerably in recent LSMs (Blyth et al., 2021), persistent atmospheric and land surface biases may thus challenge their on-line performance in coupled simulations. It has been for instance suggested that current ESMs underestimate the response of ET to soil moisture while overestimating its response to vapour pressure deficit (Zhang et al., 2023). Likewise, the most sophisticated LSMs include a nitrogen cycle to better represent the terrestrial carbon cycle (Arora et al., 2020) but most of them overestimate the amount of nitrogen fixation in the tropics and therefore the extent of the latitudinal gradient in the global distribution (Davies-Barnard et al., 2022). Moreover, carbon assimilation following afforestation is a transient process where the uptake rates depend on multiple factors such as the age of the forest. Many modelling groups are presently shifting their vegetation scheme from ‘big leaf’ models to demographic approaches where tree growth evolves as a function of age (Weng et al., 2015; Fisher et al., 2018; Koven et al., 2020; Chen et al., 2022). Regrowth rates are not subject to the lag processes inherent in the real world growth of trees from seeds, and models do not track the disturbance and carbon uptake status of forests of different age.

To sum-up, the increasing complexity of LSMs and the persistent though slightly reduced biases in the other components of the ESMs have not led to a much stronger performance in simulating the present-day climate and the recent trends observed in the terrestrial carbon and water cycles in fully coupled historical simulations. This increased model complexity relies on an enhanced use of Earth observations, yet not available for the simulation of future climate. Model calibration is likely to improve the simulation of present-day climate but may lead to overconfident projections. While ESMs will be increasingly used in emissions-driven mode, their ability to assess the feasibility and hydrological impacts of alternative land-based mitigation strategies remain to be demonstrated.

3. Observations, including remote sensing and on-going afforestation programmes

3.1 Tropics and subtropics

Planting trees require both an important man power and a favourable climate. A growing majority of the world’s population resides in the tropics where the strong rainfall seasonality and variability make the dry season a critical period for vegetation, and adaptation to climate change a particularly difficult challenge (Douville et al., 2021a; Allan, 2023). The key question is not only how the overall water availability will change in a warmer climate, but also the extent to which the projected increase in the number and severity of dry extremes may cause serious and widespread damages (e.g., wildfires, tree mortality) to natural and managed forests and may challenge some if not most of the tree restoration programmes.

Tree ring data emphasise that effective demarcation of water-limited from non-water-limited behaviour of stomata is critical to improving hydrological models and ESMs that operate at regional to global scales (Adams et al., 2021). Multiple forests have already experienced an increased tree mortality since the early 21st century, probably due to increased water limitations and climate variability (e.g., Forzieri et al., 2022). Reported mortality rates appear to be increasing even in moist tropical forests, with significant carbon storage consequences that could be underestimated in current ESMs (McDowell et al., 2018). The majority of the mortality drivers (rising temperature and vapour pressure deficit, drought, wind events, fire, among others) may kill trees in part through carbon starvation and hydraulic failure (Zuidema et al., 2022). Yet, the relative importance of each driver remains unknown (McDowell et al., 2018), as well as the vulnerability of far less studied tropical dry forests (Schröder et al., 2021).

Over Amazonia, the increasing persistence of monthly to seasonal anomalies in remotely sensed vegetation optical depth suggest that more than three quarters of the forest has been losing resilience since the early 2000s, at a faster rate in regions with significant rainfall deficits (Boulton et al., 2022). Observations also show a recent amplification of the precipitation and P-E annual cycles, and an increasing duration of the dry season (Fu et al., 2013; Leite-Filho et al., 2019; Liang et al., 2020; Wainwright et al., 2022; Allan 2023). The perturbed hydrology increases the risk of forest dieback (Brienen et al., 2015), while in return forest loss might intensify regional droughts (Zemp et al., 2017). The risk of self-amplified Amazon forest loss is expected to increase nonlinearly with the dry-season intensification (Bochow and Boers, 2023). Aircraft measurements of low-level carbon dioxide concentrations reveal that southeastern Amazonia already acts as a net carbon source to the atmosphere, partly due to larger warming and moisture stress compared to the western part (Gatti et al., 2021).

In South Asia, climate change, land use and a growing water demand for irrigation all represent major threats for the sustainability of forested areas. India has announced its net-zero target for the year 2070, and measures are being taken to decarbonise many sectors of the economy. Yet, achieving net-zero emissions is here also contingent on carbon capture and storage. In this light, India has pledged to expand its forest cover to absorb an additional three billion tonnes of CO_2 from the atmosphere by 2030. Yet, an increasing year-to-year precipitation variability (Douville et al., 2021a) may challenge this mitigation potential. Indian researchers at the Center for Study of Science, Technology and Policy (CSTEP) suggest that the overall objective cannot be achieved just by reducing deforestation. Restoring the degraded forest land (reforestation) and creating new forests (afforestation) thus appears as an essential strategy. Yet, forestry engineers highlight that insufficient guidance on suitable sites for tree restoration has already led to planting the wrong species or growing trees in unsuitable areas (Ghosh, 2023), thus suggesting a mismatch between the afforestation ambition and the achievable potential.

Central and eastern Sahel are projected to experience stronger monsoon rainfall in a warmer climate, but also an increased precipitation seasonality and variability (Douville et al., 2021a). In this context, the recent pan-African GGW programme for enhancing the resilience of Sahelian landscapes and water resources remains a matter of debate. Over the past fifty years, a large number of local initiatives have resulted in only a limited degree of success (Schucknecht et al., 2016). A visual inspection of very high resolution satellite images indicates that "large-scale tree restoration to prevent the desert expansion has long been promoted but never been really achieved" (Turner et al., 2023).

There are other multiple observational lines of evidence that tree mortality is accelerating in the tropics. As a recent example, Bauman et al. (2022) analyses a 49-year record of tree dynamics from 24 old-growth forest plots encompassing a broad climatic gradient across the Australian moist tropics and found that the tree mortality risk has, on average, doubled across all plots and species over the last 35 years. Associated losses in biomass were not offset by gains from growth and replenishment. Plots in drier climates presented higher average mortality risk, but local mean climate did not predict the pace of the observed increase in mortality risk. A long-term increase in vapour pressure deficit (a decline in relative humidity) was evident across the region and may have been the primary cause of mortality.

In the subtropics, the situation may be even worse. In addition to the projected dryland expansion (e.g., Huang et al., 2015), reliable observations of near-surface water vapour deficit suggest that the land surface drying is generally underestimated by most ESMs over the historical period (Simpson et al., 2023). The implications of this mismatch are substantial (Allan and Douville, 2024). Even drier arid zones can put further pressure on water resources and intensify extreme heat and wildfires. An even drier and thirstier atmosphere can also lead to more rapid onset of drought. The underestimated continental drying is all the more worrying given that the subtropics are among the least densely vegetated regions in the world and could have represented an attractive opportunity to enhance the global terrestrial carbon storage. The observed drying, which has further strengthened since the late 1990s (Xu et al., 2024), may explain the limited success of existing large-scale GGW programmes and warns against the systematic use of afforestation as a suitable mitigation strategy.

3.2 Extratropics

Many satellite observations available since the 1980s have revealed a human-induced "greening" of the northern extratropical land surface, with broad implications for the surface water and carbon budgets (Myneny et al., 1997; Zhou et al., 2001). Using two leaf area index (LAI) products and multiple historical simulations from nineteen ESMs, a formal statistical method was used to attribute such a greening to the human influence on the Earth's climate, including the CO_2 fertilization effect and the associated increase in surface temperature (Mao et al., 2016). Yet, more recent studies suggest that global greening has been overestimated and/or indicate that the greening period has been followed by a significant "browning" (e.g., Cortés et al., 2021; Pan et al., 2018; Chen et al., 2022; Fig. 5). This reversal was largely explained by increasing atmospheric VPD and decreasing in soil moisture north of 45ºN in summer, potentially exacerbated by a possible shift in the vegetation phenology (Lian et al., 2020).

A better understanding of the dominant climatic drivers that control vegetation trends across regions and biomes is essential for assessing ecosystem dynamics and land-climate interactions in a warming world. While temperature has long been considered as dominant control in global vegetation trends, there is growing evidence water availability plays an increasingly important role (Humphrey et al., 2018). In a recent study based on satellite-derived normalized difference vegetation index from 1981 to 2015, Zhang et al. (2021) found that the trends in terrestrial carbon uptake reversed in the early 2000s, mostly due to a recent drying trend and possible changes in water use efficiency (Li et al., 2023b). On the basis of upscaled estimates from machine learning methods and in situ observations, the latter study suggested that, globally speaking, the WUE has not risen as expected since 2001, which may be due to the increased vapour pressure deficit (Allan and Douville, 2024) that can depress photosynthesis while increasing ET.

In Argentina, tree mortality has risen and tree growth has declined since the mid-1970s in the Nothofagus forests, particularly at the lower elevations in the eastern slope of the Andes and as a result of the increasing frequency of drought events (Rodríguez-Catón et al., 2016). Conversely, small-scale afforestation initiatives have been shown to increase water stress as indicated by base flow measurements, namely the proportion of a streamflow not attributable to direct runoff from precipitation or melting snow. Afforestation can reduce base flow by up to 50%, as revealed for instance by a two-year study on seven paired basins. With their deep roots and tall canopies, trees absorb and transpire more water than do grasses, resulting in drier streams. Another study conducted in Uruguay came to similar conclusions: the researchers observed an 18–22% drop in base flow in the afforested watershed compared with the watershed that had been left as grassland (Zhang and Wei, 2021).

Hydrological effects of tree restoration can also vary with time as forests regrow. For instance, Coble et al. (2020) reviewed long-term responses of low flows to logging across 25 catchments in North America. They identified dynamic low-flow responses over three distinct periods associated with the gradual increase in leaf area index and related ET: consistent increase in the first 5 to 10 years, variable responses (increase, no change, or decline) during the next 10 to 20 years, and substantial decline in 16 out of the 25 watersheds decades later. These results highlight the need of long-term monitoring for assessing the hydrological consequences and the sustainability of carbon sequestration as a result of afforestation initiatives. Likewise, the recent dramatic increase in wildfires (Zhao et al., 2021) may also challenge former assessments of the vulnerability of carbon storage in North American boreal forests during the 21st century (Balshi et al., 2009).

In China, most of the tree restoration programmes involve afforestation in areas where annual precipitation is less than 400 millimetres. Drought is thus a major constraint on forest growth and sustainability (Zhao et al., 2023) and a growing number of studies suggest that this strategy has resulted in unintended ecological and water security concerns at the regional scale. A paired plot study of the water balance of afforestation on the Loess Plateau, where water yields have recently dropped by 30 to 50%, has shown that the understorey is the main water consumer in tree plantations (Schwärzel et al., 2019). Yet, annual throughfall under the forest was found to be much weaker compared to grassland areas. Observational regression analyses also support that the water consumed by large-scale afforestation has a considerable impact on water supply and may have contributed to recent droughts (Xiao et al., 2020). Recently, a more comprehensive study based on 72 paired sites across the Loess Plateau confirmed that afforestation led to reduced deep soil moisture (Li et al., 2023c). Overall, the study revealed overlooked hydrological costs and over-optimistic expectations of sustained carbon sequestration under afforestation. Recently, a comprehensive evaluation of recent water constraints and their implications for vegetation growth in China between 1982 and 2015 was conducted by analyzing the spatiotemporal patterns of the relationship between vegetation growth and water availability based on both satellite and in situ observations (Song et al., 2024). The study, also based on an off-line LSM, revealed that water constraints can mediate the climate and atmospheric CO_2 effects on vegetation growth and may thus exacerbate the uncertainty surrounding the vegetation sustainability in a warming climate.

In Europe, Teuling et al. (2019) explored how both changes in climate and land use (mainly deforestation and afforestation) have impacted the amount and distribution of water availability since the 1950s. Using a high resolution Budyko model constrained by lysimeter observations, they showed that increased forest cover, forest stand age, and urbanization have all led to significant changes in runoff. Yet, land use change alone could not explain the main changes in water availability. High-resolution satellite data also suggest that an excess tree mortality in European forests since 1987 can be related to drought events (Senf et al., 2020). The relationship between water availability and tree mortality shows a nonlinear behavior, with excess mortality increasing steeply when the integrated water balance from March to July falls below a given threshold. Overall, drought may already have caused approximately 0.5 Mha of excess forest mortality, albeit not considering the extreme European drought events after 2016.

Of particular concern are other potential drivers of tree mortality associated with the climate-induced water stress, such as wildfires and insect outbreaks. A global assessment suggested that at least some of the world's forested ecosystems may be already responding to climate change and raised concern that forests may become increasingly vulnerable to higher die-off in response to further warming, including in the extratropics (Allen et al., 2010). Recent statistical analyses based on satellite data indicated that global variations of forest cover "generated a mean land surface warming corresponding to about 18% of the global biogeochemical signal due to CO_2 emission from land-use change" from 2003 to 2012 (Alkama et al., 2016). They also revealed "significant increases in fire weather have occurred in most world regions during recent decades due to climate change" (Jones et al., 2022) and a dramatic increase in tree mortality (Hartmann et al., 2022). Advances in high-resolution data, from both field assessments and satellites, are urgently needed for a global stocktake of forest exposure and vulnerability around the world.

4. Discussion and conclusion

Achieving the Paris Agreement requires aggressive mitigation strategies alongside negative emissions of carbon dioxide. According to the latest IPCC report from WG3 (IPCC, 2022), AFOLU currently represents 22% (13 $GtCO_{2e}$) of the total anthropogenic CO_2 emissions but could rapidly become a sink rather than a source of carbon by using well-managed land-based CDR strategies. Yet and so far, it was not possible (i.e., neither in their mandate nor technically feasible) for the other IPCC working groups to express their concerns about the feasibility or potential side-effects of such ambitious tree restoration policies. Carbon removal and sequestration strategies, including AFOLU, are usually represented upstream of ESMs on the basis of much simpler IAMs. The next round of coordinated ESM experiments (i.e., CMIP7) could partly fill this gap (Sanderson et al., 2023). Yet, proper accounting of the coupled Earth system impacts of and feedbacks on such mitigation strategies requires a more explicit process representation to build self-consistent physical and biogeochemical representations of their potential effectiveness and risks under climate change.

Our meta-analysis of existing afforestation initiatives suggests that ill-advised or poorly-managed programmes may be less efficient and beneficial than currently assumed (e.g., Ghosh, 2023). In particular, they can contribute to the depletion of freshwater resources that currently support other human and ecosystem services (e.g., Kaushal et al., 2017). The decrease in water storage may then impact the vegetation capacity to buffer drought events and, ultimately, put at risk the terrestrial carbon storage. Forest restoration strategies thus need to adapt to the ongoing and future climate change, not only in terms of mean state but also considering the projected increase in variability and extremes. In addition, water resources cannot be secured without also considering the rapidly increasing water demand from both a warming atmosphere (Allan et al., 2020) and the growing global population (Abbott et al., 2019).

The resilience of the most aggressive afforestation strategies should be also assessed in the light of current ESM uncertainties in the response of the carbon and water cycles to anthropogenic forcings (Arora et al., 2021; Douville et al., 2021a), especially in terms of extreme dry conditions and their potential impacts on vegetation (Seneviratne et al., 2021). Drought is already considered to be the most widespread factor affecting terrestrial vegetation productivity via direct physiological effects. Drought-related NPP reduction should become prevalent, especially in most arid areas and tropical regions, by the end of 21th century (Xu et al., 2019; Cao et al., 2022). It may thus represent a major obstacle for planning tree restoration in the Global South, as well as in northern subtropical and mid-latitude arid lands where current ESMs may still underestimate the ongoing and future near surface drying (Allan and Douville, 2024).

Beyond the gradual expansion of arid areas, deeper and more reliable assessments of potential tipping points in the water and/or carbon cycle are urgently needed (Lenton et al., 2019; Abrams et al., 2023). Yet, they should not be based on invalid theories or poorly tested elements of ESMs. Symmetrically, over-optimistic assessments of land-based mitigation solutions should be avoided (Arevesen et al., 2010). Projections of both massive forest diebacks (e.g., Cox et al., 2008; Boers et al., 2017) and huge CO2 removals from afforestation (e.g., Bastin et al., 2019; Liang et al., 2024) are frequently featured in "high-profile" publications but may not represent the most plausible outcomes. Worst-case scenarios that cannot be entirely ruled out should however receive a greater attention given their disproportionate implications for both human societies and natural ecosystems (Sutton, 2018). Unravelled model deficiencies leading to unexpected though more plausible (e.g., dry) storylines may also need to reconsider the necessary or feasible mitigation and adaptation policies (e.g., Douville and Willett, 2023). High carbon sequestration potentials should be interpreted with caution, as they often rely on the assumption of large deployement and long-term retention of afforested/reforested lands, and on integrated or Earth system models that may oversimplify forest growth, regrowth, and natural mortality processes (Liang et al., 2024)

The apparent hiatus between the current limitations and expected applications of ESMs in a climate emergency context is all the more perturbing that these models are increasingly used, not only to assess the consequences of different GHG emission scenarios but also the feasibility of more or less ambitious land-based mitigation options (Wallis et al., 2014; Séférian et al., 2018; Bastin et al., 2019; Sanderson et al., 2023; Rocha et al., 2024). Such objectives should however be based on solid assumptions, carefully evaluated ESMs and thoroughly peer-reviewed publications (Friedlingstein et al., 2019). Persistent modelling uncertainties should not be used as a pretext for climate inaction. On the contrary, they must reinforce the sense of urgency and encourage both more ambitious mitigation policies and more cautious adaptation strategies (Douville et al., 2022b).

ESMs are and will remain extremely useful for understanding processes and feedbacks. They are essential to interpret observations and to attribute observed changes in the Earth system, but their increasing complexity may not allow them to narrow the range of climate projections under a given emission scenario. For this purpose, models can be weighted by how well they reproduce interannual variability (Cox et al., 2019), recent trends (Douville and Plazzotta, 2017; Chen et al., 2022) or the full available historical record (Ribes et al., 2021; Douville et al., 2022a). The critical assumptions in statistical methods are that all models are independent and representative of the "truth" while sampling the range of uncertainty. None of these assumptions are strictly valid (Sanderson et al., 2021), but these methods are however increasingly useful and show for instance how the observed historical global warming can be misleading for constraining temperature changes at the regional scale (Ribes et al., 2022) or other changes at the global scale (Douville and Willett, 2023), unless considered together with more directly relevant observations. Such methods can be now applied to other even more policy-relevant variables, regarding both water cycle (e.g., Dutot and Douville, 2023) and carbon cycle (e.g., Keenan et al., 2023).

Our conclusions are broadly consistent with the key findings of another recent synthesis focusing on rangeland afforestation (Briske et al., 2024). According to the study, the presumed benefits of such a land-based mitigation option originate from five major misconceptions: i) conflation between afforestation and reforestation, ii) overestimation of the carbon sequestration potential, iii) insufficient recognition of pre-existing ecosystem services, iv) potential for adverse ecological outcomes, and v) the neocolonial character of afforestation programs. The latter criticism has been echoed by multiple case studies (e.g., Lyons and Westoby, 2014; Richards and Lyons, 2016; Carton and Andersson, 2017) and could become a major obstacle to the implementation of large-scale afforestation programs in the Global South (e.g., Navarro, 2022). Although thousands of people are directly affected and continue to resist these projects around the world, their voices have been so far silenced by those who claim that large-scale afforestation is however needed to compensate for the residual emissions of the Global North. Yet, at the same time, this mitigation option is a lucrative business opportunity which is is rooted in the same structures and interests which led to the privatization of greenhouse gas emissions through carbon trading (Cabello and Gilbertson, 2012). In agreement with Seddon et al. (2020), we thus urge policymakers, researchers and forestry engineers to fully consider the potential trade-offs associated with afforestation, but also to acknowledge that land-based mitigation options are not a substitute for the rapid phase out of fossil fuels and cannot be implemented without the full consent of Indigenous Peoples and local communities.

To sum up, despite the fact that recent modelling studies suggest that afforestation may provide a win-win strategy in the fight against global environmental change (global warming, soil erosion, loss of biodiversity), our meta-analysis leads to more careful conclusions and raises concerns about a possible water for carbon trade-off. The IPCC usually considers multiple lines of evidence, combining a range of fundamental physics, observations and modelling, to provide policy relevant assessments. It is therefore critical that the full range of evidence and impacts – including on local water ressources and populations – are also considered in designing land-based mitigation strategies. It is also urgent to better monitor and physically understand the observed fluctuations of the terrestrial water and carbon cycles and to narrow model uncertainties regarding their projected evolution.

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References

1. Abrams, J.F., Huntingford, C., Williamson, M.S., Armstrong McKay, D.I., Boulton, C.A., Buxton, J.E., et al. (2023) Committed global warming risks triggering multiple climate tipping points. *Earth's Future*, 11, e2022EF003250, https://doi.org/10.1029/2022EF003250

2. Adams, M.A., Buckley, T.N., Binkley, D., Neumann, M., Turnbull, T.L. (2021) CO_2, nitrogen deposition and a discontinuous climate response drive water use efficiency in global forests. *Nature Comm*., 12, 5194, https://doi.org/10.1038/s41467-021-25365-1

3. Alkama, R., & Cescatti, A. (2016). Biophysical climate impacts of recent changes in global forest cover. *Science*, 351, 600–604. https://doi.org/10.1126/science.aac8083

4. Allan, R.P., M. Byrne, A. Cherchi, H. Douville, H. Fowler, T. Ghan, A. Swann, O. Zolina (2020) Advances in understanding large-scale responses of the water cycle to climate change. *Annals of the New York Academy of Sciences*, doi:10.1111/nyas.14337

5. Allan, R.P. (2023) Amplified seasonal range in precipitation minus evaporation, *Environ. Res. Lett*. ,18, 094004

6. Allan, R.P., and Douville, H. (2024) An even drier future for the arid lands. PNAS commentary, 121(2), e2320840121, https://doi.org/10.1073/pnas.2320840121

7. Arora, V.K., Montenegro, A. (2011) Small temperature benefits provided by realistic afforestation efforts. *Nature Geoscience*, 4, 514-518, doi:10.1038/NGEO1182

8. Arora, V.K., et al. (2020) Carbon–concentration and carbon–climate feedbacks in CMIP6 models and their comparison to CMIP5 models. *Biogeosciences*, 17, 4173–4222

9. Badger, A. M. and P. A. Dirmeyer (2016) Diagnosing nonlinearities in the local and remote responses to partial Amazon deforestation, *J. Geophys. Res. Atmos*., 121, 9033–9047, doi:10.1002/2015JD024013

10. Baker, J.C.A. (2021) Planting trees to combat drought. *Nature Geoscience*, 14(7), 458–459. https://doi.org/10.1038/s 41561-021-00787-0

11. Baker, J.C.A., Spracklen, D.V. (2022) Divergent representation of precipitation recycling in the Amazon and the Congo in CMIP6 models. *Geophys. Res. Lett.*, 49(10), e2021GL095136, https://doi.org/10.1029/2021GL095136

12. Balshi, M.S., et al. (2009) Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st century. *Glob. Change Biol.*, https://doi.org/10.1111/j.1365-2486.2009.01877.x

13. Bastin, J-F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., Zohner, C.M., Crowther, T.W. (2019) The global tree restoration potential. *Science*, 365, 76–79, doi:10.1126/science.aax0848

14. Bauman, D. et al. (2022) Tropical tree mortality has increased with rising atmospheric water stress. *Nature*, 608, 528-533, https://doi.org/10.1038/s41586-022-04737-7

15. Blyth, E.M., Arora, V.K., Clark, D.B., Dadson, S.J., De Kauwe, M.G., Lawrence, D.M., Melton, J.R., Pongratz, J., Turton, R.H., Yoshimura, K. and Yuan, H. (2021) Advances in land surface modelling. *Current Climate Change Reports*, 7(2), 45-71

16. Bochow, N., Boers, N. (2023) The South American monsoon approaches a critical transition in response to deforestation. *Sc. Adv.*, 9, eadd9973

17. Boers, N., Marwan, N., Barbosa, H.M.J., & Kurths, J. (2017) A deforestation-induced tipping point for the South American monsoon system. *Sc. Rep.*, 7, 41489, doi:10.1038/srep41489

18. Bonan, G.B., Williams, M., Fisher, R.A. and Oleson, K.W., 2014. Modeling stomatal conductance in the earth system: linking leaf water-use efficiency and water transport along the soil–plant–atmosphere continuum. *Geosci. Model Dev.*, 7(5), 2193-2222

19. Boulton, C.A., Lenton, T.M., Boers, N. (2022) Pronounced loss of Amazon rainforest resilience since the early 2000s. *Nature Climate Change*, 12, 271–278, https://doi.org/10.1038/s41558-022-01287-8

20. Bouman, M. (2023) Investigating the biotic pump theory - A study on condensation-induced atmospheric dynamics, *MSc thesis*, Wageningen University, https://edepot.wur.nl/634471

21. Boysen, L., et al. (2020) Global climate response to idealized deforestation in CMIP6 models. *Biogeosc. Disc*., https://doi.org/10.5194/bg-2020-229

22. Branch, O., and Wulfmeyer, V. (2019) Deliberate enhancement of rainfall using desert plantations. *P. Natl. Acad. Sci. USA*, 116(38), 18841–18847

23. Brienen, R. J. W. et al. (2015) Long-term decline of the Amazon carbon sink. *Nature*, 519, 344–348

24. Briske, D.D., Vetter, S., Coetsee, C. and Turner, M.D. (2024) Rangeland afforestation is not a natural climate solution. Front. Ecol. Environ., 22(5), e2727, doi:10.1002/fee.2727

25. Brovkin, V. et al. (2013) Effect of Anthropogenic Land-Use and Land-Cover Changes on Climate and Land Carbon Storage in CMIP5 Projections for the Twenty-First Century. *J. Clim.*, 26, 6859-6881

26. Buechel, M., Slater, L., Dadson, S. (2023) Afforestation impacts on terrestrial hydrology insignificant compared to climate change in Great Britain. *Hydrol. Earth Syst. Sci*., https://doi.org/10.5194/hess-2023-138

27. Cao, S., Wang, G. & Chen, L. (2010) Questionable value of planting thirsty trees in dry regions. *Nature,* 465, 31, https://doi-org.insu.bib.cnrs.fr/10.1038/465031d

28. Cao, D. et al. (2022) Projected increases in global terrestrial net primary productivity loss caused by drought under climate change. *Earth's Future,* doi: 10.1029/2022EF002681

29. Carton, W. & Andersson, E. (2017) Where Forest Carbon Meets Its Maker: Forestry-Based Offsetting as the Subsumption of Nature. Society & Natural Resources, 30(7), 829-843

30. Cederstrom, C.J., Vivoni, E.R., Mascaro, G., & Svoma, B. (2024) Forest treatment effects on watershed responses under warming. Water Resources Research, 60, e2023WR035627. https://doi.org/10.1029/2023WR035627

31. Chai, Y., Martins, G., Nobre, C., von Randow, C., Hen, T., Dolman, H. (2021) Constraining Amazonian land surface temperature sensitivity to precipitation and the probability of forest dieback. *npj Clim. and Atmos. Sc*., 6, https://www.nature.com/ar-ticles/s41612-021-00162-1

32. Chen, Z., Zhou, T., Chen, X., Zhang, W., Zhang, L., et al. (2022) Observationally constrained projection of Afro-Asian monsoon precipitation. *Nature Comm*., 13, 2552, https://doi.org/10.1038/s41467-022-30106-z

33. Chen, Y.-Y., Huang, W., Cheng, C.-T., Hong, J.-S., Yeh, F.-L., & Luyssaert, S. (2022) Simulation of the impact of environmental disturbances on forest biomass in Taiwan. *J. of Geophys. Res.: Biogeosciences*, 127, e2021JG006519, https://doi.org/10.1029/2021JG006519

34. Chitra-Tarak, R., Xu, C., Aguilar, S., Anderson-Teixeira, K.J., Chambers, J., Detto, M., Faybishenko, B., Fisher, R.A., Knox, R.G., Koven, C.D., Kueppers, L.M., Kunert, N., Kupers, S.J., McDowell, N.G., Newman, B.D., Paton, S.R., Pérez, R., Ruiz, L., Sack, L., Warren, J.M., Wolfe, B.T., Wright, C., Wright, S.J., Zailaa, J. and McMahon, S.M. (2021) Hydraulically-vulnerable trees survive on deep-water access during droughts in a tropical forest. *New Phytol.*, 231, 1798-1813, https://doi.org/10.1111/nph.17464

35. Clark, M.P., Y. Fan, D.M. Lawrence, J.C. Adam, D. Bolster, D.J. Gochis, R.P. Hooper, M. Kumar, L.R. Leung, D.S. Mackay, R.M. Maxwell, C. Shen, S.C. Swenson, and X. Zeng (2015) Improving the representation of hydrologic processes in Earth System Models, *Water Resour. Res*., 51, 5929–5956, doi:10.1002/2015WR017096

36. Coble, A.A., et al., (2020) Long-term hydrological response to forest harvest during seasonal low flow: Potential implications for current forest practices. *Sci. Total Environ.*, 730, 138926

37. Cortés, J., Mahecha, M. D., Reichstein, M., Myneni, R. B., Chen, C., & Brenning, A. (2021) Where are global vegetation greening and browning trends significant? *Geophys. Res. Lett.*, 48, e2020GL091496. https://doi.org/10.1029/2020GL091496

38. Costantini, M., Colin, J., & Decharme, B. (2023) Projected climate-driven changes of water table depth in the world's major groundwater basins. *Earth's Future*, 11, e2022EF003068. https://doi.org/10.1029/2022EF003068

39. Cox, P.M (2019) Emergent Constraints on Climate-Carbon Cycle Feedbacks. *Current Climate Change Reports*, https://doi.org/10.1007/s40641-019-00141-y

40. Davies-Barnard, T., Zaehle, S., Friedlingstein, P. (2022) Assessment of the impacts of biological nitrogen fixation structural uncertainty in CMIP6 Earth System Models. *Biogeosciences*, 19, 3491-3503, https://doi.org/10.5194/bg-19-3491-2022

41. Debortoli, N.S., Dubreuil, V., Hirota, M., Filho, S.R., Lindoso, D.P., Nabucet, J. (2016) Detecting deforestation impacts in Southern Amazonia rainfall using rain gauges. *Int. J. Climatol.*, 37, 2889–2900, https://doi.org/10.1002/joc.4886

42. De Hertog, S.J., Havermann, F., Vanderkelen, I., Guo, S., Luo, F., Manola, I., Coumou, D., Davin, E.L., Duveiller, G., Lejeune, Q. and Pongratz, J. (2022) The biogeophysical effects of idealized land cover and land management changes in Earth system models. *Earth System Dyn. Discussions*, 1-53

43. De Kauwe, M.G., Medlyn, B.E., Zaehle, S., et al. (2013). Forest water use and water use efficiency at elevated CO2: a model-data intercomparison at two contrasting temperate forest FACE sites. *Glob. Change Biol.*, 19, 1759-1779

44. De Kauwe, M.G., Medlyn, B.E., Ukkola, A.M., Mu, M., Sabot, M.E., Pitman, A.J., Meir, P., Cernusak, L.A., Rifai, S.W., Choat, B. and Tissue, D.T., 2020. Identifying areas at risk of drought-induced tree mortality across South-Eastern Australia. *Glob. Change Biol.*, 26(10), 5716-5733

45. Delire, C., Foley, J.A., Thompson, S. (2004) Long-Term Variability in a Coupled Atmosphere–Biosphere Model. *J. Climate*, 17, 3947-3059

46. D’Odorico, P., Davis, K.F., Rosa, L., Carr, J.A., Chiarelli, D., Dell’Angelo, J., et al. (2018) The global food-energy-water nexus. *Reviews of Geophysics*, 56, 456–531 https://doi.org/10.1029/2017RG000591

47. Doelman, J., et al. (2020) Afforestation for climate change mitigation: Potentials, risks and trade-offs. *Glob. Change Biol.*, https://doi.org/10.1111/gcb.14887

48. Döll P., H. Douville, A. Güntner, H. Müller Schmied, Y. Wada (2016) Modelling freshwater systems at the global scale: Challenges and prospects. *Surv. Geophys*., 37, 195-221, doi:10.1007/s10712-015-9343-1

49. Dong, B. and R. Sutton (2015) Dominant role of greenhouse-gas forcing in the recovery of Sahel rainfall. *Nature Climate Change*, 5, 757–760, doi:10.1038/nclimate2664

50. Doughty, C. E. et al. (2015) Drought impact on forest carbon dynamics and fluxes in Amazonia. *Nature*, 519, 78–82 (2015).

51. Douville, H., K. Raghavan, J. Renwick, R.P. Allan, P.A. Arias, M. Barlow, R. Cerezo-Mota, A. Cherchi, T.Y. Gan, J. Gergis, D. Jiang, A. Khan, W. Pokam Mba, D. Rosenfeld, J. Tierney, and O. Zolina, 2021: Water Cycle Changes. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panelon Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press,

Cambridge, United Kingdom and New York, NY, USA, pp. 1055-1210, doi:10.1017/9781009157896.010

52. Douville, H., S. Qasmi, A. Ribes, O. Bock (2022a) Global warming at near-constant tropospheric relative humidity is supported by observations. *Communications Earth & Environment*, 3, 237, https://doi.org/10.1038/s43247-022-00561-z

53. Douville, H., R.P. Allan, P.A. Arias, R.A. Betts, MA.Caretta, A. Cherchi, A. Mukherji, K. Raghavan, J. Renwick (2022b) Water remains a blind spot in climate change policies. *PLOS Water*, 1(12), e0000058, https://doi.org/10.1371/journal.pwat.0000058

54. Douville, H., R. Chadwick, M. Saint-Lu, B. Medeiros (2023) Drivers of dry day sensitivity to increased CO_2. *Geophys. Res. Lett*., 50, e2023GL103200, https://dx.doi.org/10.1029/2023GL103200

55. Dutot, E., Douville, H. (2023) Revisiting the potential to narrow uncertainty in annual runoff projections of Arctic rivers. *Geophys. Res. Lett*., 50, e2023GL104039, https://dx.doi.org/10.1029/2023GL104039

56. Douville, H., Willett, K. (2023) A drier than expected future, supported by near-surface relative humidity observations. *Sc. Adv*., 9, ade6253, https://doi.org/10.1126/sciadv.ade6253

57. Eller, C.B., Rowland, L., Mencuccini, M., Rosas, T., Williams, K., et al. (2020) Stomatal optimization based on xylem hydraulics (SOX) improves land surface model simulation of vegetation responses to climate. New Phytol, 226, 1622-1637, https://doi.org/10.1111/nph.16419

58. Ellison, D. N., Futter, M., Bishop, K. (2012) On the forest cover–water yield debate: From demand-to supply-side thinking. *Glob. Change Biol.*, 18(3), 806–820

59. Fang, Y., Leung, L.R., Koven, C.D., Bisht, G., Detto, M., Cheng, Y., McDowell, N., Muller-Landau, H., Wright, S.J. and Chambers, J.Q. (2022) Modeling the topographic influence on

aboveground biomass using a coupled model of hillslope hydrology and ecosystem dynamics. *Geosci. Model Dev.*, 15(20), 7879-7901

60. Fatichi. S., Paschalis, A., Bonetti, S., Manoli, G., Pappas, C. (2023) Water Use Efficiency: A review of spatial and temporal variability. *Chapter in the Encyclopedia of Soils in the Environment*, Second Edition, 5, 527-542, https:// doi.org/10.1016/B978-0-12-822974-3.00166-X

61. Fisher, R.A., et al. (2017) Vegetation demographics in Earth System Models: A review of progress and priorities. *Glob. Change Biol.*, doi:10.1111/gcb.13910

62. Franks, P.J., Berry, J.A., Lombardozzi, D.L., Bonan, G.B. (2017) Stomatal Function across Temporal and Spatial Scales: Deep-Time Trends, Land-Atmosphere Coupling and Global Models. *Plant Physiol.*, 174, 583-602

63. Friedlingstein, P. (2015) Carbon cycle feedbacks and future climate change. *Philosophical Trans. R. Soc. A*, https://doi.org/10.1098/rsta.2014.0421

64. Friedlingstein, P., M. Allen, J.G. Canadell, G.P. Peters, S.I. Seneviratne. Comment on “The global tree restoration potential”. *Science*, 10.1126/science.aay8060 (2019)

65. Friedlingstein, P., et al. (2022) Global Carbon Budget 2022, *Earth Syst. Sci. Data*, 14, 4811–4900, https://doi.org/10.5194/essd-14-4811-2022

66. Fu, R., Yin, L., Li, W., Myneni, R.B. (2013) Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. *P. Natl. Acad. Sci. USA*, 110 (45), 18110-18115, https://doi.org/10.1073/pnas.1302584110

67. Gatti, L.V., et al. (2021) Amazonia as a carbon source linked to deforestation and climate change. *Nature*, 595, 388–393

68. Ghosh, S. (2023) Planting trees alone won’t solve the climate crisis. *Nature*, https://www.nature.com/articles/d44151-023-00166-1

69. Giardina, F., Padrón, R.S., Stocker, B.D., Schumacher, D.L., Seneviratne, S.I. (2024) Dry biases in land water storage and excessive soil moisture limitation in CMIP6 models. *Research Square Preprint*, https://doi.org/10.21203/rs.3.rs-4086740/v1

70. Gier, B.K., Schlund, M., Friedlingstein, P., Jones, C.D., Jones, C., Zaehle, S., Eyring, V. (2024) Representation of the Terrestrial Carbon Cycle in CMIP6. a*rXiv Preprint*, https://arxiv.org/abs/2402.05671

71. Guilbert, M., Terray, P., Mignot, J. (2023) Intermodel spread of historical Indian monsoon rainfall change in CMIP6: The role of the tropical Pacific mean-state. *J. Climate*, doi:10.1175/JCLI-D-22-0585.1

72. Guimberteau, et al. (2017) Impacts of future deforestation and climate change on the hydrology of the Amazon Basin: a multi-model analysis with a new set of land-cover change scenarios. *Hydrol. Earth Syst. Sci*., 21, 1455–1475, doi:10.5194/hess-21-1455-2017

73. Hartmann, H., et al. (2022) Climate Change Risks to Global Forest Health: Emergence of Unexpected Events of Elevated Tree Mortality Worldwide. *Annu. Rev. Plant Biol*., 73, 673–702, https://doi.org/10.1146/annurev-arplant-102820-012804

74. Herman, R.J., Biasutti, M., Kushnir, Y. (2023) Drivers of low-frequency Sahel precipitation variability: comparing CMIP5 and CMIP6 ensemble means with observations. *Climate Dynamics*, 61, 4449–4470, https://doi.org/10.1007/s00382-023-06755-1

75. Hoek van Dijke, A.J. et al. (2022) Shifts in regional water availability due to global tree restoration. Nature Geoscience, 15, 363–368, https://doi.org/10.1038/s41561-022-00935-0

76. Huang, J., Yu, H., Guan, X., Wang, G., Guo, R. (2015) Accelerated dryland expansion under climate change. *Nature Climate Change*, doi:10.1038/NCLIMATE2837

77. Humphrey, V., Zscheischler, J., Ciais, P., Gudmundsson, L., Sitch, S. & Seneviratne, S.I. (2018) Sensitivity of atmospheric CO2 growth rate to observed changes in terrestrial water storage. Nature, 560, 628-631, https://doi.org/10.1038/s41586-018-0424-4.

78. IPCC, 2022: Summary for Policymakers [P.R. Shukla, J. Skea, A. Reisinger, R. Slade, R. Fradera, M. Pathak, A. Al Khourdajie, M. Belkacemi, R. van Diemen, A. Hasija, G. Lisboa, S. Luz, J. Malley, D. McCollum, S. Some, P. Vyas, (eds.)]. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. *Cambridge University Press*, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001

79. Jackson, L.S., et al. (2020) The effect of explicit convection on couplings between rainfall, humidity and ascent over Africa under climate change. *J. Climate*, doi:10.1175/JCLI-D-19-0322.1

80. Joetzjer E., H. Douville, C. Delire (2013) Present-day and future Amazonian precipitation in global climate models: CMIP5 versus CMIP3. *Clim. Dyn*., doi:10.1007/s00382-012-1644-1

81. Jones, M.W., Abatzoglou, J.T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M., et al. (2022) Global and regional trends and drivers of fire under climate change. *Reviews of Geophysics*, 60, e2020RG000726. https://doi.org/10.1029/2020RG000726

82. Kaushal, S.S., Gold, A.J., Mayer, P.M. (2017) Land Use, Climate, and Water Resources — Global Stages of Interaction. *Water*, 9, 815; doi:10.3390/w9100815

83. Kennedy, D., Swenson, S., Oleson, K.W., Lawrence, D.M., Fisher, R., Lola da Costa, A.C. and Gentine, P. (2019) Implementing plant hydraulics in the community land model, version 5. Journal of Advances in Modeling Earth Systems, 11(2), 485-513

84. Knutti, R., Sedláček, J., Sanderson, B.M., Lorenz, R., Fischer, E.M. and Eyring, V. (2017) A climate model projection weighting scheme accounting for performance and interdependence. *Geophys. Res. Lett.*, 44, 1909–1918.

85. Koch, A., Brierley, C. and Lewis, S.L. (2021a) Effects of Earth system feedbacks on the potential mitigation of large-scale tropical forest restoration. *Biogeosciences*, 18(8), 2627-2647

86. Koch, A., Hubau, W., & Lewis, S. L. (2021b) Earth System Models are not capturing present-day tropical forest carbon dynamics. *Earth's Future*, 9, e2020EF001874. https://doi.org/10.1029/2020EF001874

87.

88. Laguë, M.M., Bonan, G.B., Swann, A.L.S. (2019) Separating the Impact of Individual Land Surface Properties on the Terrestrial Surface Energy Budget in both the Coupled and Uncoupled Land–Atmosphere System. *J. Climate*, 32, 5725–5744, https://doi.org/10.1175/JCLI-D-18-0812.1

89. Lavergne, A, Graven, H, De Kauwe, MG, et al. (2019) Observed and modelled historical trends in the water-use efficiency of plants and ecosystems. *Glob. Change Biol.*, 25, 2242-2257

90.

91. Leite-Filho, A.T., de Sousa Pontes, V.Y., Costa, M.H. (2019). Effects of deforestation on the onset of the rainy season and the duration of dry spells in southern Amazonia. *J. Geophys. Res.: Atmospheres*, 124, 5268–5281, https://doi.org/10.1029/2018JD02953

92. Lemordant, L., P. Gentine, A.S. Swann, B.I. Cook, and J. Scheff (2018) Critical impact of vegetation physiology on the continental hydrologic cycle in response to increasing CO2. *Proc. Nat. Acad. Sciences*, 115(16), 4093–4098, doi:10.1073/pnas.1720712115

93. Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., & Schellnhuber, H. J. (2019). Climate tipping points — Too risky to bet against. *Nature*, 575(7784), 592–595, https://doi.org/10.1038/d41586-019-03595-0

94. Lewis, S.L., Mitchard, E.T.A., Prentice, C., Maslin, M., Poulter, B. (2019) Comment on "The global tree restoration potential". *Science*, doi:10.1126/science.aaz0388

95. Li, J., Duan, Q., Wang, Y-P., Gong, W., Gan, Y., Wang, C. (2018) Parameter optimization for carbon and water fluxes in two global land surface models based on surrogate modelling. *Int. J. Climatol.*, 38, e1016–e1031

96. Li., Y., Piao, S., Li, L.Z.X., Chen, A., Wang, X., et al. (2018) Divergent hydrological response to large-scale afforestation and vegetation greening in China. *Sc. Adv*., 4, eaar4182

97. Li, Y., Baker, J.C.A., Brando, P.M., Hoffman, F.M., Lawrence, D.M., et al. (2023a) Future increases in Amazonia water stress from CO_2 physiology and deforestation. *Nature Water*, 1, 769-777, https://doi.org/10.1038/s44221-023-00128-y

98. Li, F., Xiao, J., Chen, J., Ballantyne, A., Jin, K., et al. (2023b) Global water use efficiency saturation due to increased vapor pressure deficit. *Science*, 381, 672-677

99. Li, H. et al. (2023c) Afforestation triggers water mining and a single pulse of water for carbon trade-off in deep soil. *Agriculture, Ecosystems and Environment*, 356, 108655

100. Lozano-Baez, S.E et al. (2019) Land restoration by tree planting in the tropics and subtropics improves soil infiltration, but some critical gaps still hinder conclusive results. *Forest Ecology and Management*, 444, 89-95

101. Lu, C., Zhao, T., Shi, X. Cao, S. (2018) Ecological restoration by afforestation may increase groundwater depth and create potentially large ecological and water opportunity costs in arid and semiarid China. *J. Cleaner Prod.*, 176, 1213-1222, https://doi.org/10.1016/j.jclepro.2016.03.046

102. Lu, Z., Miller, P. A., Zhang, Q., Zhang, Q.,Wårlind, D., Nieradzik, L., et al. (2018) Dynamic vegetation simulations of the mid-Holocene Green Sahara. *Geophys. Res. Lett*., 45, 8294-8303, https://doi.org/10.1029/2018GL07919

103. Luo, X., Ge, J., Cao, Y., Liu, Y., Yang, L., Wang, S., & Guo, W. (2024). Local and nonlocal biophysical effects of historical land use and land cover changes in CMIP6 models and the intermodel uncertainty. Earth's Future, 12, e2023EF004220, https://doi.org/10.1029/2023EF004220Lyons, K. & Westoby, P. (2014) Carbon colonialism and the new land grab: Plantation forestry in Uganda and its livelihood impacts. Journal of Rural Studies, 36, 13-21

104. McDowell, N., et al. (2018) Drivers and mechanisms of tree mortality in moist tropical forests. *New Phytol*., 219, 851–869

105. Makarieva, A.M. & Gorshkov, V.G. (2007) Biotic pump of atmospheric moisture as driver of the hydrological cycle on land. *Hydrol. Earth Syst. Sci*., 11, 1013–1033

106. Makarieva, A.M, Nefiodov, A.V., Nobre, A.D., Baudena, M., Bardi, U., Sheil, D., Saleska, S.R., Molina, R.D., Rammig, A. (2023) The role of ecosystem transpiration in creating alternate moisture regimes by influencing atmospheric moisture convergence. *Glob. Change Biol*., 29, 2536–2556

107. Makarieva, A.M. , Nefiodov, A.V., Rammig, A., Nobre, A.D. (2024) Re-appraisal of the global climatic role of natural forests for improved climate projections and policies. https://arxiv.org/abs/2301.09998 (submitted)

108. Malhi, Y., Aragão, L.E.O.C., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., Sitch, S., McSweeney, C., and Meir, P. (2009) Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest, *P. Natl. Acad. Sci. USA*, 106, 20610–20615, https://doi.org/10.1073/pnas.0804619106

109. Marthews, T. R., Dadson, S. J., Clark, D. B., Blyth, E. M., Hayman, G. D., Yamazaki, D., Becher, O. R. E., Martínez-de la Torre, A., Prigent, C., and Jiménez, C. (2022) Inundation prediction in tropical wetlands from JULES-CaMa-Flood global land surface simulations, *Hydrol. Earth Syst. Sci*., 26, 3151-3175, https://doi.org/10.5194/hess-26-3151-2022

110. Meesters, A.G.C.A., Dolman, A.J., and Bruijnzeel, L.A. (2009) Comment on "Biotic pump of atmospheric moisture as driver of the hydrological cycle on land" by A. M. Makarieva and V. G. Gorshkov, *Hydrol. Earth Syst. Sci*., 13, 1299–1305, https://doi.org/10.5194/hess-13-1299-2009

111. Molina, R.D., Salazar, J.F.,Martínez, J.A., Villegas, J.C., & Arias, P.A. (2019). Forest-induced exponential growth of precipitation along climatological wind streamlines over the Amazon. *J. Geophys. Res.:Atmos.*, 124, 2589–2599, https://doi.org/10.1029/2018JD029534

112. Monerie, P.-A., C.M. Wainwright, M. Sidibe, and A.A. Akinsanola (2020) Model uncertainties in climate change impacts on Sahel precipitation in ensembles of CMIP5 and CMIP6 simulations. *Climate Dynamics*, 55, 1385–1401, doi:10.1007/s00382-020-05332-0

113. Montibeller, B., Marshall., M., Mander, U., Uuemaa, E. (2022) Increased carbon assimilation and efficient water usage may not compensate for carbon loss in European forests, *Comm. Earth Env*., 3, 194, https://doi.org/10.1038/s43247-022-00535-1

114.

115. Navarro, R. (2022) Climate Finance and Neo-colonialism: Exposing Hidden Dynamics. In: Cash, C., Swatuk, L.A. (eds) The Political Economy of Climate Finance: Lessons from International Development. International Political Economy Series. Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-031-12619-2-8

116. Pan, N., Feng, X., Fu, B., Wang, S. Ji, F., Pan, S. (2018) Increasing global vegetation browning hidden in overall vegetation greening: Insights from time-varying trends. Remote Sensing of Environment, 214, 59-72

117. Parry, I.M., P.D.L. Ritchie, and P.M. Cox (2022) Evidence of localised Amazon rainforest dieback in CMIP6 models. *Earth Syst. Dynam*., 13, 1667–1675, https://doi.org/10.5194/esd-13-1667-2022

118. Peng, J., Dan, L., Yang, F., Tang, X., & Wang, D. (2021). Global and regional estimation of carbon uptake using CMIP6 ESM compared with TRENDY ensembles at the centennial scale. Journal of Geophys. Res. Atmos., 126, e2021JD035135, https://doi.org/10.1029/2021JD03513

119. Polcher, J., Schrapffer, A., Dupont, E., Rinchiuso, L., Zhou, X., Boucher, O., Mouche, E., Ottlé, C., and Servonnat, J. (2023) Hydrological modelling on atmospheric grids: using graphs of sub-grid elements to transport energy and water, *Geosci. Model Dev*., 16, 2583–2606, https://doi.org/10.5194/gmd-16-2583-2023

120. Qiu, H., Bisht, G., Li, L., Hao, D., and Xu, D. (2024) Development of inter-grid-cell lateral unsaturated and saturated flow model in the E3SM Land Model (v2.0), *Geosci. Model Dev*., 17, 143-167, https://doi.org/10.5194/gmd-17-143-2024

121. Ribes, A., Qasmi, S., Gillett, N. (2021) Making climate projections conditional on historical observations. *Science Advances*, 7, eabc0671

122. Richards, C. & Lyons, K. (2016) The new corporate enclosures: Plantation forestry, carbon markets and the limits of financialised solutions to the climate crisis. Land Use Policy, 56, 209-216

123. Robock, A. (2016) Albedo enhancement by stratospheric sulfur injections: More research needed. *Earth’s Future*, 4, doi:10.1002/2016EF000407

124. Rocha, M. et al. (2024) From Earth System Models to Integrated Assessment Models: Bridging the gap in climate modelling. ESM 2024 Research highlights, https://www.esm2025.eu/esm-iam-framework/

125. Rodríguez-Catón, M., Villalba, R., Morales, M. and Srur A. (2016) Influence of droughts on Nothofagus pumilio forest decline across northern Patagonia. *Ecosphere*, 7(7), e01390

126. Roe, S., et al. (2021a) Contribution of the land sector to a 1.5 °C world. *Nature Climate Change*, https://doi.org/10.1038/s41558-019-0591-9

127. Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J., Emmet-Booth, J., Engelmann, J. and Fricko, O. (2021b) Land-based measures to mitigate climate change: Potential and feasibility by country. *Glob. Change Biol.*, 27(23), 6025-6058.

128. Ruiz-Vasquez, M., Arias, P.A., Martínez, J.A., Espinoza, J.C (2020) Effects of Amazon basin deforestation on regional atmospheric circulation and water vapor transport towards tropical South America. *Climate Dynamics,* 54, 4169–4189

129. Sanderson, B.M. et al. (2021) The potential for structural errors in emergent constraints. *Earth Syst. Dynam.*, 12, 899–918

130. Sanderson, B.M. et al. (2023) The need for carbon emissions-driven climate projections in CMIP7. *EGU Preprint Discusion*, https://doi.org/10.5194/egusphere-2023-2127

131. Schrapffer, A., Sörensson, A., Polcher, J. et al. (2020) Benefits of representing floodplains in a Land Surface Model: Pantanal simulated with ORCHIDEE CMIP6 version. *Clim. Dyn*., 55, 1303–1323, https://doi.org/10.1007/s00382-020-05324-0

132. Schröder, J.M., Ávila Rodríguez, L.P., Günter, S. (2021) Research trends: Tropical dry forests: The neglected research agenda? *For. Policy Econ*., 122, 102333

133. Schucknecht, A., Meroni, M., Rembold, F. (2016) Monitoring project impact on biomass increase in the context of the Great Green Wall for the Sahara and Sahel Initiative in Senegal, *EUR 28020,* doi:10.2788/639268

134. Schurer, A.P., Ballinger, A.P., Friedman, A.R., Hegerl, G.C., (2020) Human influence strengthens the contrast between tropical wet and dry regions. *Environ. Res. Lett*., 15, 104026

135. Schwärzel, K.; Zhang, L., Montanarella, L., Wang, Y., Sun, G. (2020) How afforestation affects the water cycle in drylands: A process-based comparative analysis. *Glob. Change Biol.*, 26, 944-959, doi:10.1111/gcb.14875

136. Seddon N, Smith A, Smith P, et al. 2021. Getting the message right on nature-based solutions to climate change. *Glob. Change Biol.*, 27, 1518–1546.

137. Séférian, R., Rocher, M., Guivarch, C., Colin, J. (2018) Constraints on biomass energy deployment in mitigation pathways: the case of water scarcity. *Environ. Res. Lett*., 13, 054011, https://doi.org/10.1088/1748-9326/aabcd7

138. Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., et al. (2010) Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99, 125-161

139. Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A. Di Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou, 2021: Weather and Climate Extreme Events in a Changing Climate. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. *Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766, doi:10.1017/9781009157896.013.

140. Simpson, I.R. , McKinnon, K.A., Kennedya, D., Lawrence, D.M., Lehner, F., Seager, R. (2023) Observed humidity trends in dry regions contradict climate models. *P. Natl. Acad. Sci. USA*, in press

141. Singh, A., Kumar, S., Akula, S., Lawrence, D. M., & Lombardozzi, D. L. (2020) Plant growth nullifies the effect of increased water-use efficiency on streamflow under elevated CO2 in the Southeastern United States. *Geophys. Res. Lett.*, 47, e2019GL086940. https://doi.org/10.1029/2019GL086940

142. Smiatek, G., Kuntsmann, H. (2023) Potential Impact of the Pan-African Great Green Wall on Sahelian Summer Precipitation: A Global Modeling Approach with MPAS. *Earth Interactions*, 2, e220013, doi:10.1175/EI-D-22-0013.1

143.

144. Song, Y., Penuelas, J., Ciais, P., Wang, S., Zhang, Y., Gentine, P., et al. (2024). Recent water constraints mediate the dominance of climate and atmospheric CO_2 on vegetation growth across China. Earth's Future, 12, e2023EF004395, https://doi.org/10.1029/2023EF004395

145. Spracklen, D. and Garcia-Carreras, L. (2015) The impact of Amazonian deforestation on Amazon basin rainfall. *Geophys. Res. Lett.*, 42, 9546–9552, doi:10.1002/2015gl066063

146. Staal, A., Theeuwen, J.J.E., Wang-Erlandsson, L., Wunderling, N., Dekker, S.C. (2023) Targeted rainfall enhancement as an objective of forestation. *Glob. Change Biol.*, 30:e17096, https://doi.org/10.1111/gcb.17096

147. Strandberg, G., Kjellström, E. (2019) Climate impacts from afforestation and deforestation. *Earth Interactions*, 23, 1-27, doi: 10.1175/EI-D-17-0033.1

148. Sulman, B.N., Roman, D.T., Yi, K., Wang, L., Phillips, R.P., and Novick, K.A. (2016) High atmospheric demand for water can limit forest carbon uptake and transpiration as severely as dry soil, Geophys. Res. Lett., 43, 9686–9695, doi:10.1002/2016GL069416.

149. Sutton, R.T. (2018) Ideas: a simple proposal to improve the contribution of IPCC WG1 to the assessment and communication of climate change risks. *Earth Syst. Dynam. Discuss.*, https://doi.org/10.5194/esd-2018-36

150. Swenson, S.C., Clark, M., Fan, Y., Lawrence, D.M. and Perket, J. (2019) Representing intrahillslope lateral subsurface flow in the community land model. *Journal of Advances in Modeling Earth Systems*, 11(12), 4044-4065

151. Taylor, C.M., Lambin, E.F., Stephenne, N., Harding, R.J., Essery, R.L.H. (2002) The Influence of Land Use Change on Climate in the Sahel. *J. Climate*, 15, 3615-3629

152. Taylor, C.M., Klein, C., Parker, D.J., Harris, B.L. (2022) “Late-stage” deforestation enhances storm trends in coastal West Africa. *P. Natl. Acad. Sci. USA*, 119 (2) e2109285119, https://doi.org/10.1073/pnas.2109285119

153. Taylor, S.D., Marconi, S. (2020) Rethinking global carbon storage potential of trees. A comment on Bastin et al. (2019). *Annals of Forest Science*, 77, 23, https://doi.org/10.1007/s13595-020-0922-z

154. Teuling, A.J., et al. (2019) Climate change, reforestation/afforestation, and urbanization impacts on evapotranspiration and streamflow in Europe. *Hydrol. Earth Syst. Sci*., 23, 3631–3652, https://doi.org/10.5194/hess-23-3631-2019

155. Tuinenberg, O.A., Bosmans, J.H.C., Staal A. (2022) The global potential of forest restoration for drought mitigation. *Environ. Res. Lett.*, 17, 034045, https://doi.org/10.1088/1748-9326/ac55b

156. Turner, M.D. et al. (2023) Great Green Walls: Hype, Myth, and Science. *Annu. Rev. Environ. Resour*., 48, 263–287, https://doi.org/10.1146/annurev-environ-112321-111102

157. Varney, R.M., Chadburn, S.E., Burke, E.J., Cox, P.M. (2022) Evaluation of soil carbon simulation in CMIP6 Earth system models. *Biogeosciences*, 19, 4671–4704, https://doi.org/10.5194/bg-19-4671-2022

158. Veldman, J.W., et al. (2019) Comment on “The global tree restoration potential”. *Science*, doi:10.1126/science.aay7976

159. Wainwright, C.M., Allan, R.P., & Black, E. (2022). Consistent trends in dry spell length in recent observations and future projections. *Geophys. Res. Lett.*, 49, e2021GL097231. https://doi.org/10.1029/2021GL097231

160. Wallis, P.J., et al. (2014) The water impacts of climate change mitigation measures. *Climatic Change*, 125, 209–220, doi:10.1007/s10584-014-1156-6

161. Weng, E.S., Malyshev, S., Lichstein, J.W., Farrior, C.E., Dybzinski, R., Zhang, T., Shevliakova, E. and Pacala, S.W. (2015) Scaling from individual trees to forests in an Earth system modeling framework using a mathematically tractable model of height-structured competition. *Biogeosciences*, 12(9), 2655-2694

162. Willeit, M., Ganopolski, A., Feulner G. (2014) Asymmetry and uncertainties in biogeophysical climate–vegetation feedback over a range of CO_2 forcings. *Biogeosciences*, 11, 17–32, doi:10.5194/bg-11-17-2014

163. Xu, T., Valocchi, A.J., Ye, M., Liang, F., Lin, Y.-F. (2017), Bayesian calibration of groundwater models with input data uncertainty, Water Resour. Res., 53, 3224-3245, doi:10.1002/2016WR019512.

164. Xu, C., McDowell, N.G., Fisher, R.A., Wei, L., Sevanto, S., Christoffersen, B.O., Weng, E. and Middleton, R.S. (2019) Increasing impacts of extreme droughts on vegetation productivity under climate change. *Nature Climate Change*, 9(12), 948-953

165. Xu, C., Christoffersen, B., Robbins, Z., Knox, R., Fisher, R. A., Chitra-Tarak, R., Slot, M., Solander, K., Kueppers, L., Koven, C., and McDowell, N. (2023) Quantification of hydraulic trait control on plant hydrodynamics and risk of hydraulic failure within a demographic structured vegetation model in a tropical forest (FATES–HYDRO V1.0), *Geosci. Model Dev.*, 16, 6267–6283, https://doi.org/10.5194/gmd-16-6267-2023

166. Xu, W., Xia, X., Piao, S., Wu, D., Li, W., Yang, S., & Yuan, W. (2024) Weakened increase in global near-surface water vapor pressure during the last 20 years. *Geophys. Res. Lett.*, 51, e2023GL107909, https://doi.org/10.1029/2023GL107909

167. Yao Y, Wang X, Zeng Z, Liu Y, Peng S, Zhu Z, et al. (2016) The Effect of Afforestation on Soil Moisture Content in Northeastern China. *PLoS ONE* 11(8): e0160776. https://doi.org/10.1371/journal.pone.0160776

168. Yao, Y., Joetzjer, E., Ciais, P., Viovy, N., Cresto Aleina, F., Chave, J., Sack, L., Bartlett, M., Meir, P., Fisher, R. and Luyssaert, S. (2022) Forest fluxes and mortality response to drought: model description and evaluation at the Caxiuanã drought experiment. *Geosci. Model Dev*., 15(20), 7809-7833

169. Yin, Z., Wang, X.H., Ottlé, C., Zhou, F., Guimberteau, M., Polcher, J., Peng, S.S., Piao, S.L., Li, L., Bo, Y. and Chen, X.L. (2020) Improvement of the irrigation scheme in the ORCHIDEE land surface model and impacts of irrigation on regional water budgets over China. *Journal of Advances in Modeling Earth Systems*, 12(4), p.e2019MS001770

170. Zhang, Q., Ficklin, D., Manzoni, S., Wang, L., Way, D., Phillips, R.P., Novick, K.A. (2019) Response of ecosystem intrinsic water use efficiency and gross primary productivity to rising vapor pressure deficit. *Env. Res. Letters*, 14, 074023

171. Zhang, A., et al. (2021) Water availability surpasses warmth in controlling global vegetation trends in recent decades revealed by satellite time series. *Environ. Res. Lett*., 16, 074028

172. Zhang, M., Wei, X. (2021) Deforestation, forestation, and water supply. A systematic approach helps to illuminate the complex forest-water nexus, Science, 371, 990-991, doi:10.1126/science.abe7821

173. Zhang, W., Koch, J., Wei, F., Zeng, Z., Fang, Z., & Fensholt, R. (2023) Soil moisture and atmospheric aridity impact spatio-temporal changes in evapotranspiration at a global scale. *J. Geophys. Res.: Atmosphere*, 128, e2022JD038046, https://doi.org/10.1029/2022JD038046

174. Zhao, B., Zhuang, Q., Shurpali, N., Köster, K., Berninger, F., and Pumpanenet, J. (2021) North American boreal forests are a large carbon source due to wildfires from 1986 to 2016. *Scientific Reports*, 11, 7723, https://doi.org/10.1038/s41598-021-87343-3

175. Zhao, D., Zhang, Z., & Zhang, Y. (2023) Soil moisture dominates the forest productivity decline during the 2022 China compound drought-heatwave event. *Geophys. Res. Lett* ., 50, e2023GL104539. https://doi.org/10.1029/2023GL104539

176. Zuidema, P.A., Babst, F., Groenendijk, P. et al. (2022) Tropical tree growth driven by dry-season climate variability. *Nat. Geosci*., 15, 269–276, https://doi.org/10.1038/s41561-022-00911-8

List of figures:

Figure 1: Spatial patterns of annual precipitation responses (mm/year) to an idealized global deforestation scenario across nine CMIP6 Earth System Models. Only statistically significant changes are shown. Contours depict the model-dependent although broadly similar areas of deforestation (Source: Boysen et al., 2020).

Figure 2: Effect of tropical land-use stop and secondary succession on cumulative global carbon fluxes (2006–2100 CE) in (a) control, (b) restoration, and (c) cumulative difference between restoration and control simulation for land–atmosphere flux (F_{LA}, green), ocean-atmosphere flux (F_{OCN}, blue), deforestation emissions (E_{LUC}, brown), atmospheric carbon (F_{A}, orange), and fossil fuel emissions (E_{FF}, grey). The difference in fossil fuel emissions is zero and not plotted. Dashed line indicates zero; fluxes below zero indicate a carbon benefit in the restoration simulation with respect to the control simulation. Note the different vertical scales (Source: Koch et al., 2021a).

Figure 3: Area weighted average of 12 month running-mean near surface relative humidity anomalies (%) relative to the 1980-1990 climatology over global arid and semi-arid regions. Black shows ERA5, purple shows the CMIP6 ensemble mean, the pink range shows the 2.5th to 97.5th percentile range across all the members from all models for CMIP6, maroon dashed shows the LENS2 ensemble mean, blue solid shows the AMIP6 ensemble mean, the light blue shading shows the 2.5th to 97.5th percentile range across all AMIP members from all models and blue dashing shows another ensemble mean based on a single model ensemble driven by observed sea surface temperatures (Source: Simpson et al., 2023).

Figure 4: Schematic on approaches to explicitly characterize and reduce the myriad uncertainties in assessments of the hydrologic impacts of climate change and the development of representative quantitative hydrologic storylines for specific applications (Source: Clark et al., 2016).

Figure 5: Break-off and decline of the global mean growing season integrated LAI from around 2001, as diagnosed after averaging across three remote sensing data sets (AVHRR, GIMMS3g and GLASS) for the period 1982–2018 (Source: Chen et al., 2022).