Elevated Wildfire and Ecosystem Carbon Loss Risks Due to Plant Hydraulic Stress Functions: A Global Modeling Perspective

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Abstract: Wildfire risks are increasing due to the atmospheric and vegetation aridity under global warming. Plant hydraulic stress (PHS) functions regulate water transport along the soil–plant–atmosphere continuum under water stress conditions, which probably results in shifts in ecosystem wildfire regimes. Currently, how the PHS functions affect wildfire occurrence and subsequently the ecosystem carbon cycle via carbon loss at a global scale remains unclear. Here, we conducted global simulations during 1850–2010 using Community Land Model version 5 with and without the PHS configuration and quantified the PHS-induced changes. From the global perspective, the PHS functions increased plant transpiration, induced hydraulic redistribution (HR) of soil water by root, and decreased soil moisture; then, the functions increased fire occurrence (count), fire induced carbon loss, and ecosystem net primary productivity by 72%, 49%, and 15%, respectively. Spatially, the PHS functions greatly promoted fire occurrence and the consequent carbon loss in circumboreal forests and tropical savannas; whereas, the fire occurrence was limitedly affected or even decreased in equatorial rainforests. The strong downward HR process in the humid rainforests transported rainwater into deep soil layers, and strict stomatal regulation of the tropical trees restricted transpiration increment under atmospheric aridity, both of which helped to buffer the rainforests against drought and thus decreased fire risk. In contrast, dry savannas showed substantial upward HR, which increased water loss via soil evaporation and transpiration of the grasses with shallow roots. The tree–grass competition for limited soil moisture in the savannas benefited soil evaporation, which could aggravate plant hydraulic failure and increase wildfire risk.

Keywords: wildfire; plant hydraulic stress; ecosystem carbon cycle; transpiration; hydraulic redistribution; soil moisture; net primary productivity; stomatal regulation; community land model

1. Introduction

Wildfire occurrence is increasing rapidly due to the atmospheric and vegetation aridity under global warming [1,2], which has caused substantial economic losses, severe air pollution, human mortality, and environmental damages [2,3]. Wildfire is a climate-sensitive process that can transfer approximately 2 Pg of terrestrial carbon to the atmosphere [4,5], which may reversely serve as a strong, positive feedback to climate change and fire activity [6]. For example, increasing fire frequency and severity may change boreal forests from carbon sinks to carbon sources, which were projected to amplify climate warming [7]. However, the wildfire–climate interactions vary greatly across the globe [8] due to the location-specific sensitivity of vegetation water status to atmospheric aridity [1]. Exploring the underlying mechanisms/processes that regulate wildfire occurrence and the fire-induced ecosystem carbon emissions is essential to account for the importance of wildfire in the ecosystem carbon cycle and wildfire and carbon feedbacks to the global climate system.
As atmospheric aridity increases, plant moisture content usually decreases, which increases the wildfire risk [9]. The degree to which plants dry out under fire weather conditions can vary widely, depending on the diverse plant hydraulic stress functions in regulating water transport along the soil–plant–atmosphere continuum [10], including soil controls on root-zone water availability [11], root water uptake and redistribution [12,13], and plant hydraulic traits that affect transpiration water loss [14]. For example, isohydric plants keep leaf water content steady under atmospheric aridity by constraining transpiration water loss with strict stomatal regulation, whereas the anisohydric plants allow substantial drop-off in leaf water content with minimal stomatal regulation [15]. Root hydraulic redistribution can transport deep soil water to the shallow soil layer during drought periods in ecosystems with an overlapped dry season and growing season [12]. A recent site study [16] also suggested that plant hydraulic traits can cause up to 3-fold variations in vegetation moisture content, and thus affect plant flammability. Currently, how the plant hydraulic stress functions affect wildfire regimes, fire-induced carbon loss, and its contributions to the ecosystem carbon cycle at a global scale has not been explored, and the corresponding differences in the underlying mechanisms among ecosystems are poorly understood.

Previous modeling studies have incorporated different representations of plant hydraulic theory (e.g., segmentation into the root, stem, and leaf hydraulic elements) into land surface models (LSMs) to simulate water flow through the soil–plant–atmosphere continuum [12,17,18]. For example, the Community Land Model version 5 (CLM5), a widely used and physically based LSM, includes a plant hydraulic stress (PHS) configuration of vegetation water use, which used leaf and root water potential as the basis for calculating water stress through stomatal conductance and hydraulic root water uptake, respectively [19]. It is worth mentioning that the PHS configuration in CLM5 allows for hydraulic redistribution (HR) and compensatory root water uptake. Previous research has confirmed that the incorporation of PHS configuration into CLM5 improved the estimates of ecosystem water and carbon fluxes [19–21]. Moreover, the PHS-incorporated CLM5 model could well reproduce the global wildfire carbon emission derived from the satellite products [22], and it has advantages against other LSMs, because the CLM5 uniquely considered the seasonality of crop fires and simulated the burning of plant tissue and litter from peat fires and the drought-linked tropical deforestation and degradation fire [23]. The CLM5 model with the PHS configuration offers us an opportunity to investigate how the plant hydraulic stress functions affect global fire regimes and explore the underlying mechanisms.

In the present study, we conducted global simulations during 1850–2010 using CLM5 with and without PHS configuration. The simulation results of plant transpiration, root hydraulic redistribution, soil moisture, ecosystem net primary productivity (NPP), wildfire count, and the fire-induced carbon emissions were extracted, and their differences between the two PHS configurations were quantified. The objectives of this study were to investigate the impacts of plant hydraulic stress functions on predicted wildfire occurrence, fire-induced carbon loss, and its contribution to the ecosystem carbon cycle at a global scale, and to explore the underlying mechanisms. This study would help to better understand the climate–wildfire interactions, and highlight the critical regulating role of plant hydraulic functions.

2. Materials and Methods

2.1. Model Description

CLM5, namely, the land component in Community Earth System Model (CESM) version 2 (http://www.cesm.ucar.edu/, accessed on 7 November 2020), was used in the study [24]. Biogeophysical and biogeochemical processes, including radiation interactions, surface energy fluxes, plant phenology, photosynthesis, respiration, hydrology, and soil carbon and nitrogen cycles, are simulated in CLM5. The global simulations were conducted with the fire module ‘turned on’ and two PHS configurations (without and with PHS) over the industrial era (1850–2010) at a resolution of 0.9° latitude by 1.25° longitude.
The detailed information about the fire module and PHS configuration can be found in the following two sections. The historical CLM5 simulations were forced by Global Soil Wetness Project forcing data set version 1 (GSWP3v1), a 3-hourly 0.5° global forcing product (1901–2014), which is based on the 20th Century Reanalysis version 2 performed with the NCEP (National Centers for Environmental Prediction) model [25], downscaled using the Global Spectral Model using a spectral nudging technique [26], and bias corrected using CRU TS 3.21 (Climate Research Unit Timeseries) [27], GPCC v7 (Global Precipitation Climatology Centre) [28], and Surface Radiation Budget data sets, respectively. The forcing data of the 20-year period, 1901–1920, were cycled and re-used for the period 1850–1900. CLM5 includes land units of vegetated, lake, urban, glacier, and crop, and up to 15 non-crop plant functional types (PFTs) with differences in physiology and structure that may coexist within a single vegetated unit. The vegetation distributions are prescribed in the study, but vegetation state variables (e.g., leaf area index—“LAI”, canopy height) are prognostic. The land cover descriptions in CLM5 come from MODIS products of land cover (MCD12Q1 v5.1), vegetation continuous fields (MOD44B v5.1), LAI (MCD15A2 v5), and albedo (MCD43B3 v5) for the years 2001–2015 (https://lpdaac.usgs.gov/dataset_discovery/modis, accessed on 27 January 2020). More information about the surface datasets used in CLM5 could be found in Lawrence et al. [24].

The standard CLM spin-up protocol was used to achieve carbon, water, and energy equilibrium at the start of the simulations [24]. In detail, CLM5 simulations were initialized from spin-up simulations that consisted of 400 years in accelerated mode, followed by an additional 800 years in “normal mode”. By the end of the spin-up, the total ecosystem carbon (C) was drifting by less than 0.02 Pg C year\(^{-1}\) at global scale, and less than 5% of grid cells were out of carbon balance by drifting more than 1 g C m\(^{-2}\) year\(^{-1}\). In some high-latitude grid cells, however, vegetation could not survive, and soil C turnover rate is slow due to cold climate conditions. In these locations, the high initial soil C stocks do not deplete during the accelerated spin-up phase, which leads to unrealistically high equilibrium soil C stocks in those grid cells. To circumvent this undesirable feature, the C stocks of the slow C pools are set to zero where vegetation C is <0.1 g C m\(^{-2}\) by the end of the accelerated spin-up phase.

### 2.2. Fire Module

The fire module includes four components: agricultural fires in cropland, deforestation and degradation fires in the tropical closed forests, non-peat fires outside cropland and tropical closed forests, and peat fires [29]. For fires in cropland, burned-area fraction is determined by fuel availability, socioeconomic factors, and prescribed fire seasonality. The burned-area due to deforestation and degradation fires is determined by human deforestation rate, weather and climate conditions, and fuel load. Non-peat fires outside cropland and tropical closed forests (e.g., savannas, temperate and boreal forests, shrublands and grasslands in the non-peat regions) are calculated by a process-based model of intermediate complexity. It is affected by climate and weather conditions, vegetation composition and structure, and human activities represented by nonlinear functions of population density and economic situations. The burned-area fraction of peat fires depends on climate conditions and the area fraction of peat exposed to the air. After the calculation of burned-area fraction, C emission to the atmosphere during biomass and peat burning is estimated. Estimates of biomass burning and plant-tissue mortality are based on PFT-dependent combustion completeness factors and fire mortality factors. The default conversion factor from dry matter to carbon is 0.5 g C (g dry matter\(^{-1}\)). More detailed information about the fire module in CLM5 can refer to Li et al. [29] and Lawrence et al. [24].

### 2.3. Plant Hydraulic Stress Configuration

Plants face water stresses from both soil moisture drought and the increasing atmospheric water demand, accompanied with intensive water flow dynamics throughout the soil–plant–atmosphere continuum [17]. Previous land surface models, including the earlier
versions of CLM, roughly related a metric of soil moisture to transpiration and neglected the real plant hydraulic functions [18,24]. More mechanistic representations of stresses and vegetation water use dynamics, i.e., the plant hydraulic stress (PHS) configuration, have been incorporated in the CLM5 and been suggested to improve the ecosystem water fluxes estimation [19–21]. Plant hydraulic stress (PHS) configuration is switched on by default and can also be turned off in CLM5. We conducted global simulations without and with the PHS configuration (PHS-off and PHS-on) to investigate the PHS-induced impacts on wildfire regimes and to explore the underlying mechanisms. The two simulations used the default values for CLM5 parameters [24].

In CLM5 simulations without PHS configuration, soil potential is the basis for stomatal conductance water stress (Figure 1); the total transpiration flux is partitioned across soil layers. The root water uptake in a given soil layer $i$ can be expressed as:

$$q_i = \frac{r_i w_i}{\sum_{i=1}^n r_i w_i} T$$  (1)

where $r_i$ is the root fraction of soil layer $i$, $w_i$ is the wilting factor in soil layer $i$, $n$ is the total number of soil layers, and $T$ is plant transpiration.

![Figure 1. Plant water flow and status in CLM5 without (PHS-off) and with (PHS-on) plant hydraulic stress configuration. The PHS configuration simulates water potential ($\psi$) at the leaf, stem, root, and soil levels. HR represent hydraulic redistribution of soil water by roots.](image)

In contrast, the plant hydraulic stress (PHS) configuration introduces vegetation water potential prediction, which is modeled at the root, stem, and leaf levels (Figure 1). Leaf water potential replaces soil potential (i.e., in simulations without PHS) as the basis for stomatal conductance water stress, and root water potential is used to determine hydraulic root water uptake. Thus, the plant water stress in PHS configuration is not only dependent on soil water potential but is also affected by atmospheric water status (e.g., decreasing relative humidity) that is directly applied to stomatal conductance. Transpiration fluxes in PHS configuration are not constrained to be positive, as different soil layers may interact via the root system, supporting plant-mediated hydraulic redistribution (HR; Figure 1).

Root water uptake in a given layer $i$ can be expressed as:

$$q_i = -k_{sr,i}(\psi_{\text{root}} - \psi_{\text{soil},i} + \rho g Z_i)$$  (2)

where $k_{sr,i}$ is hydraulic conductance across the soil and roots in the soil layer $i$; $\psi_{\text{root}}$ and $\psi_{\text{soil},i}$ are water potential in the root collar and soil layer $i$, respectively; and $\rho g Z_i$ accounts for the effects of gravity at the depth of layer $i$.

Obviously, the incorporation of PHS configuration in CLM5 would affect water transports through the soil–plant–atmosphere continuum, change vegetation water status (Figure 1), and possibly change the risk of wildfire occurrence and the fire-induced carbon emissions. Thus, we examined plant transpiration, hydraulic redistribution (HR) of soil water by roots, soil moisture, ecosystem net primary productivity (NPP), fire counts, and
fire-induced carbon emissions from CLM5 global simulations with and without PHS configurations (PHS-on and PHS-off); the differences between these two PHS configurations were calculated to determine the effects of plant hydraulic stress functions on global wildfire occurrence, the fire-induced carbon loss and its offset to the ecosystem carbon gain (i.e., NPP), and to explore the contrasting underlying mechanisms across ecosystems. Finally, we summarized the simulation results (i.e., transpiration, HR, soil moisture, NPP, fire count and fire-induced carbon loss) across the globe for both PHS-on and PHS simulations, and quantified the PHS-induced impacts (i.e., \[\frac{(PHS-on)-(PHS-off)}{(PHS-off)} \times 100\%\]) on wildfire regimes, ecosystem water, and carbon fluxes from the global perspective.

3. Results

3.1. Changes in Ecosystem Water Transports

Plant transpiration was simulated by CLM5 with and without PHS configurations (PHS-on and PHS-off), and the PHS-induced (PHS-on minus PHS-off) plant transpiration from the global simulation was temporally averaged (1850–2010) at each pixel. As shown in Figure 2a, the incorporation of PHS configuration in CLM5 increased (positive PHS induced values) the simulated plant transpiration globally, except for some declines in tropical (woody) savannas that were distributed around the rainforest in South America and Africa. High PHS-induced transpiration increases appeared mainly in the Northern Hemisphere, especially in forests in eastern China and United States and in the circumboreal forests in Canada, Europe, and Russia, along with the southern part of South America (Figure 2a,b). The PHS configuration also resulted in the root hydraulic redistribution (HR) processes, which were neglected in the CLM5 simulations without PHS configuration. The upward HR can transport deep soil water to the shallow soil layer during drought; whereas, the downward HR tends to happen after intensive rainfall and transport excess surface soil water to the deeper soil layer [12]. Strong hydraulic redistribution (HR) processes mostly appeared in regions between 30° N and 40° S, and moderate HR could be found in northeastern China, western Europe, and eastern United States (Figure 2c–f). The rainforests around the equator (e.g., in Amazon and Congo basins and southeastern Asia) had strong downward HR, and the tropical savannas distributed around the rainforests showed strong upward HR (Figure 2c,e). The PHS-induced plant transpiration increases enhanced the total water loss from soil, while the two types of HR (upward and downward HR) complicated the PHS-induced soil moisture changes in different soil layers.

As expected, the incorporation of PHS configuration into the CLM5 generally decreased simulated soil moisture in north of 30° N for both shallow (0–30 cm) and deep (30–86 cm) soil layers (Figure 3a–d), which could be attributed to the PHS-induced increase in transpiration water loss in those regions (Figure 2a). The HR processes caused varying PHS-induced soil moisture changes in different PFTs and regions between 30° N and 40° S. For example, the incorporation of PHS configuration brought about substantial simulated upward HR in the tropical savannas, which resulted in PHS-induced increases and decreases in soil moisture in the shallow (0–30 cm) and deep (30–80 cm) layers, respectively (Figure 3). In contrast, remarkable simulated downward HR in the Amazon and Congo basins caused PHS-induced decreases and increases in soil moisture in the shallow and deep layers, respectively (Figure 3).
Figure 2. Spatial distributions of the PHS-induced (Delta) plant transpiration change and hydraulic redistribution (HR) of soil water by roots. The pixels in the left panels (a,c,e) represent temporally averaged values during 1850–2010 and the vertical thick lines in (b,d,f) represent the latitudinal mean of values in corresponding left panels.
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Figure 3. Spatial distributions of the PHS-induced (Delta) changes in soil moisture in the shallow (0–30 cm) and deep layers (30–80 cm). The pixels in the left panels (a,c) represent temporally averaged values during 1850–2010 and the vertical thick lines in (b,d) represent the latitudinal mean in corresponding left panels.

3.2. Fire Count Changes

From CLM5 simulations without PHS configuration (PHS-off), the temporally averaged fire count during 1850–2010 was low in arid regions of the Northern Hemisphere (e.g., in the western United States, northern Africa, and central Eurasia) and in humid rainforests (e.g., in Amazon and Congo basins and southeastern Asia); high fire count was found in tropical savannas, southwestern Asia (e.g., in India), and northern Australia (Figure 4a). The incorporation of PHS configuration in CLM5 caused more transpiration water loss and soil moisture decline across the globe (Figures 2 and 3), which might increase wildfire risks. As expected, compared with the PHS-off simulation, the CLM5 simulation with PHS configuration (PHS-on) showed more fire occurrence across the globe, and the high fire count extended to the high latitudes of the Northern Hemisphere (Figure 4c). The PHS-induced (PHS-on minus PHS-off) increase in fire count was distributed widely across the Eurasia, Australia, and southern Africa and dispersed in western North America and southern South America (Figure 4e).
Figure 4. Spatial distributions of the temporally averaged (1850–2010) fire count from CLM5 simulations without (PHS-off, (a,b)) and with PHS (PHS-on, (c,d)) configurations and their differences (PHS-on minus PHS-off, (e,f)). The pixels in the left panels represent fire count per unit area (Counts km$^{-2}$ yr$^{-1}$) and the vertical thick lines in (b,d,f) represent the latitudinal amount with area multiplied in corresponding left panels.
The annual global fire count from PHS-off and PHS-on simulations showed a significant increasing trend of 912 yr\(^{-1}\) and 534 yr\(^{-1}\) (\(p < 0.001\)) from 1950 to 2010 based on the Mann–Kendall trend test. For the PHS-induced (Delta) annual global fire count, a changepoint with low value could be identified in the early 1960s for the long-term trend; significant decreasing and increasing trends of \(-697\text{ yr}^{-1}\) and 2170 yr\(^{-1}\) were detected before and after the changepoint, respectively (Figure 5a). The annual global fire count averaged from 1950 to 2010 was \(7.5 \times 10^5\), \(1.3 \times 10^6\), and \(5.4 \times 10^5\) for the PHS-off and PHS-on simulations and their difference (Delta), respectively (Figure 5b). The interannual variation in global fire count was closely relevant to the climate dynamics. For example, the extreme high fire count in the late 1920s (Figure 5a) was caused by the synchronous large-scale severe drought that happened in south of 30° N [30] where plants are peculiarly prone to fire (Figure 4); the low PHS-induced fire count in the early 1960s could be attributed to the decreasing global land surface temperature over those years [31].

![Figure 5. Annual global fire count during 1850–2010 from CLM5 simulations without (PHS-off) and with PHS (PHS-on) configurations and their difference (Delta). The fluctuations of annual global fire count during 1850–2010 were shown in (a). Boxes in (b) represent the interquartile ranges of the annual global fire count distributions, solid lines (circles) in the boxes represent median (averaged) values, and whiskers extend to one interquartile range.](image)

### 3.3. Fire Induced Carbon Emissions and Ecosystem Net Primary Productivity

The spatial distribution of temporally averaged ecosystem net primary productivity (NPP) was similar from the CLM5 simulations without (PHS-off) and with PHS (PHS-on) configurations. Large simulated NPP values were in forest ecosystems, especially for the rainforests around the equator, and comparatively small values were in savannas, shrublands, grasslands, and desert regions (Figure 6a–d), consistent with people’s common knowledge. Compared with PHS-off simulations, the incorporation of PHS configuration decreased the simulated NPP in the tropical rainforests and some boreal forests in the Russian Far East, and increased it in the rest of the global regions, especially for the forest ecosystems in the North Hemisphere (Figure 6e).
Figure 6. Spatial distributions of ecosystem net primary productivity (NPP) and fire-induced carbon (C) loss from CLM5 simulations without (PHS-off) and with PHS (PHS-on) configurations and their difference (Delta). The pixels in (a,c,e,g,i,k) represent temporally averaged values during 1850–2010 and the vertical thick lines in (b,d,f,h,j,l) represent the latitudinal mean in corresponding left panels.

Consistent with the fire count distributions shown in Figure 6, high fire-induced carbon (C) loss was mainly found in tropical savannas and southern Asia from both PHS-off and PHS-on simulations (Figure 6g,i). Compared with PHS-off simulations, the incorporation of PHS configuration greatly increased the simulated fire-induced C loss in tropical savannas and circumboreal forest ecosystems, whereas limited changes or even decreases were found in the tropical rainforests (Figure 6k).

The simulated annual global NPP induced by the incorporation of PHS configuration (PHS-on minus PHS-off) fluctuated from 1850 to 1930, then continuously increased till 2010 with a significant trend of 22.6 Tg C yr$^{-1}$ ($p < 0.001$) based on the Mann–Kendall trend test (Figure 7). Similarly, the PHS-induced annual global fire carbon loss showed a significant increasing trend of 2.9 Tg C yr$^{-1}$ ($p < 0.001$) from 1930 to 2010 (Figure 7). The PHS-induced annual global fire C loss averaged during 1850–2010 could offset approximately 8% of the PHS-induced ecosystem C gain (i.e., NPP) (Figure 7).
3.4. Plant Hydraulic Stress Function Impacts from the Global Perspective

The plant hydraulic stress functions increased the globally averaged water loss via plant transpiration by 49.6% from 1850 to 2010, which could induce soil moisture decreases. Moreover, the downward HR (37 mm yr\(^{-1}\)) was weaker than the upward HR (53 mm yr\(^{-1}\)), resulting in a greater decline in soil moisture for the shallow soil layers (0–30 cm; −4.2%) compared with the deep layers (30–80 cm; −3.7%). The resultant drier environment increased wildfire risk; the fire count and fire-induced carbon (C) loss increased by 72% and 49%, respectively. The plant hydraulic stress functions increased the ecosystem NPP by 15% (Figure 8).

![Figure 7. PHS-induced (Delta) fire carbon loss versus ecosystem carbon gain (i.e., net primary productivity, NPP).](image)

![Figure 8. Quantifying the effect of plant hydraulic stress (PHS) function on wildfire regimes, and ecosystem water and carbon fluxes from the global perspective. Each index in the figure were firstly summarized across the globe for simulations with and without PHS configuration (PHS-on and PHS-off), and their increase rates from PHS-off to PHS-on simulations (i.e., \(\frac{(PHS\text{-on}) - (PHS\text{-off})}{(PHS\text{-off})} \times 100\%\)) were calculated.](image)
4. Discussion

The annual global fire count derived from satellite (i.e., Terra/MODIS) observations (2001–2002) was $1.24 \times 10^6$ [32], which is close to that ($1.39 \times 10^6$) simulated by the CLM5 with plant hydraulic stress (PHS) configuration, whereas the simulations without PHS configuration ($8.23 \times 10^5$) seriously underestimated the global fire occurrence (Figure 5). The present study further showed that the global fire count increment induced by PHS functions could be attributed to the elevated ecosystem water loss via plant transpiration and the resultant drier environment from the global perspective (Figure 8). Consistent with our results, the PHS configuration has been proven to increase plant transpiration at 81 FLUXNET sites across the globe [20] and over four different climatic subregions of China [21]. The PHS configuration uses water stress on leaf water potential to restrict transpiration; stress on transpiration can be induced by decreasing atmospheric moisture (e.g., increasing vapor pressure deficit) and soil water supply, and the latter was also regulated by root hydraulic redistribution (HR) processes [19]. The HR processes include the hydraulic lift of water from moist deep soils to dry shallow soils during drought periods [33], the hydraulic descent of soil water, usually following a precipitation event [34], and lateral water transport [35], which have been documented in a wide range of experimental and numerical studies for different ecosystems and plant species [12,13,36,37]. It can be seen that the HR processes with different directions accelerate the uniform distribution of soil moisture, which helps the plant roots absorb soil water more efficiently. This is a meaningful water-holding mechanism of plants, as excessive rainwater could be transported via downward HR to the deep soil layer and then transported back to the shallow soil layer during drought conditions [12]. From the global perspective, stronger downward HR than the upward HR benefited the transpiration of deep-rooted plants, and the ecosystem carbon gain (i.e., NPP) also increased via the coupling between photosynthesis and transpiration through the stomata [38]. The increasing rate of fire and corresponding carbon loss (49%) induced by plant hydraulic function was much higher than that of ecosystem C gain (i.e., NPP; 15%), which might have negative effects on ecosystem carbon sequestration and its feedback on global change; more attention should be given to the impact of plant hydraulic function on wildfire regimes, as more fire weather conditions (e.g., drought and warming) were predicted in the future [39].

The impacts of plant hydraulic stress functions on ecosystem fire occurrence show clear heterogeneity across the globe. The circumboreal forests across Canada, Europe, and Russia are suffering from wildfires due to recent climate warming and precipitation anomaly [40], which is consistent with the simulation results in the study (Figure 4c). The present study further shows that the plant hydraulic stress functions played a critical role in the high fire risk of the northern forests (Figures 4e and 6k), via increasing plant transpiration (Figure 2a) and the resultant drier environment (Figure 3). In contrast to the boreal forests, the fire occurrence in the humid rainforests (e.g., in the Amazon and Congo basins and southeastern Asia) was comparatively limited (Figure 4c). Compared with the boreal forests, the plant hydraulic stress functions restricted the transpiration increment in the rainforests (Figure 2a), even though they experience much higher atmospheric water demand (e.g., higher air temperature). Moreover, stronger downward HR than upward HR (Figure 2c,e) helps the rainforests reserve rainwater in deep soil layers, which can buffer drought events and thus decrease the fire risk. Consistent with our simulation results, evergreen broadleaf forests in the tropics were suggested to have very strict stomatal regulation under high water stress [41] and downward HR has previously been observed in the Amazonian trees [42]. The plant hydraulic stress functions in those two ways can be critical water-holding mechanisms for the humid rainforests, which avoid hydraulic failure, ensure plant physiological activity during water stress, and avoid fire hazards and fire-induced carbon emissions, although at the cost of declined carbon gain (i.e., NPP; Figure 6e) due to the strict stomatal regulation. In contrast to the strong downward HR in the humid rainforests, upward HR dominated in the dry environment [33], e.g., the simulated strong upward HR process in the tropical (woody) savannas over South America.
and Africa (Figure 2c). In (woody) savannas, grasses are indeed formidable competitors for soil moisture against trees [43]. Moreover, the competition can be “unfair” for trees due to their plant hydraulic stress functions because deep-rooted trees in the savannas tend to decrease transpiration via stomatal regulation during water stress and transport deep soil water to the upper dry soil layers (i.e., upward HR; Figure 2c), which supported water use for grasses with shallow roots and increased water loss via soil evaporation. This is especially significant for the woody savannas distributed around the Congo basin, which showed substantial PHS-induced increases (decreases) in soil moisture of the upper (deep) layers (Figure 3) and decreases in the plant transpiration (Figure 2a). The tree–grass competition for limited soil moisture in the (woody) savannas benefited soil evaporation, resulting in increased plant mortality and wildfire risk.

5. Conclusions

In the present study, we conducted global simulations during 1850–2010 using CLM5 with and without plant hydraulic stress (PHS) configurations. The simulation results of plant transpiration, root hydraulic redistribution, soil moisture, ecosystem net primary productivity (NPP), fire counts, and the fire-induced carbon emission were extracted, and corresponding differences between the two PHS configurations were quantified. The key findings of this study include:

- From the global perspective, the PHS functions increased plant transpiration via hydraulic redistribution (HR) of soil water by roots, and increased fire occurrence (count), fire-induced carbon loss, and ecosystem carbon gain (i.e., net primary productivity) by 72%, 49%, and 15%, respectively.
- Spatially, the PHS functions greatly promoted fire occurrence and fire-induced carbon emissions in circumboreal forests and tropical savannas, while limited changes or even decreases occurred in equatorial rainforests.
- The downward HR process in the humid rainforests transported rainwater into deep soil layers, and strict stomatal regulation of the tropical trees restricted transpiration increase under atmospheric aridity, both of which helped to buffer the rainforests against drought and thus decreased fire risk.
- The upward HR process in the dry (woody) savannas increased water loss via soil evaporation and transpiration of the shallow-rooted grasses. The tree–grass competition for limited soil water in the savannas benefited soil evaporation, which might increase plant mortality and fire risk.

Our study demonstrated the critical role of plant hydraulic stress functions in affecting wildfire regimes and corresponding carbon emissions. The conclusions in the study can be partly supported by previous studies, including fire estimations derived from satellite products and limited field observations of the plant hydraulic traits (e.g., hydraulic redistribution and stomatal regulation behaviors). The internal relations between plant hydraulic stress functions and wildfire regimes require further verifications through field monitoring, especially considering the possible substantial impacts of wildfire on ecosystem functions in a warmer climate.

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