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Key Points:
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- HR has a very limited effect on the N_2O emission at the Corn Belt site that has strong emissions but with no distinct dry season
- N_2O emissions in ecosystems with a distinct dry season are likely overestimated by CLM or other CENTURY-based Earth system models

Supporting Information:
- Supporting Information S1

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Influences of Root Hydraulic Redistribution on N_2O Emissions at AmeriFlux Sites

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Abstract It has long been suspected that root hydraulic redistribution (HR) affects the carbon and nitrogen cycles. Nitrous oxide (N_2O) is an important greenhouse gas and is the primary stratospheric ozone-depleting substance. To our knowledge, the influences of HR on N_2O emissions have not been investigated. Here we use the HR schemes of Ryel et al. and Amenu and Kumar incorporated into CLM4.5 to examine N_2O emissions at five AmeriFlux sites. The results show that HR reduced N_2O emissions by 28–92% in the four natural ecosystems experiencing a dry season, whereas it had a very limited effect on the Corn Belt site that has strong emissions but with no distinct dry season. We hypothesize that N_2O emissions in ecosystems with a distinct dry season are likely overestimated by CENTURY-based Earth system models.

Plain Language Summary The findings of this study suggest that hydraulic redistribution (HR) may play an important role in N_2O emissions from agricultural regions that have a clearly defined dry season. For example, the expansive corn-growing regions of China are all located in the monsoon area with a distinct dry season. We hypothesize that the HR mechanism acts to significantly reduce N_2O emissions in these regions. HR may also play an important role in limiting N_2O emissions in the Amazonian regions with a tropical monsoon climate, where forests have been converted to agricultural use.

1. Introduction

Nitrous oxide (N_2O) has a lifetime exceeding 100 years (Prather et al., 2012, 2015) and has the third largest radiative forcing among the long-lived greenhouse gases (Hofmann et al., 2006). It is the primary ozone-depleting substance in the stratosphere (Ravishankara et al., 2009). N_2O emissions from terrestrial ecosystems are characterized by high temporal and spatial variability (Groffman et al., 2009; Wagner-Riddle et al., 2007). For example, according to the Emission Database for Global Atmospheric Research (EDGAR), the Southeastern U.S. and the Amazon basin have substantially higher emissions than many other regions (Tian et al., 2010). The heavy use of nitrogen fertilizers in the U.S. Corn Belt makes this region an important anthropogenic N_2O source at the global scale (Miller et al., 2012). In both natural and managed ecosystems, the spatial and temporal variability of N_2O emissions is strongly controlled by soil moisture or water-filled pore space (Grossel et al., 2016; Turner et al., 2016).

In seasonally dry ecosystems, plant roots transfer water from moist soil layers to dry soil layers along the soil water potential gradient. Such hydraulic redistribution (HR) of soil water via plant roots can be upward (hydraulic lift), downward (hydraulic descent), or lateral (Horton & Hart, 1998; Neumann & Cardon, 2012; Prieto et al., 2012; Sardans & Peñuelas, 2014; Yu & D'Odorico, 2017). The effects of HR on the hydrological, carbon, and nitrogen cycles have been demonstrated in numerous field studies (e.g., Cardon et al., 2013; Ryel et al., 2002; Scott et al., 2008). Several recent modeling studies have investigated the effects of HR on the hydrological cycle and carbon dioxide exchange between ecosystems and the atmosphere (Baker et al., 2008; Fu et al., 2016, 2018; Luo et al., 2013; Tang et al., 2015; Wang, 2011). The effect of HR on N_2O emissions, however, has not been investigated.

This study builds on previous research on the effects of HR on ecosystem carbon and water cycles (Fu et al., 2016, 2018). Incorporating HR into the National Center for Atmospheric Research Community Land Model Version 4.5 (CLM4.5; Oleson et al., 2013) improved simulations of soil moisture,

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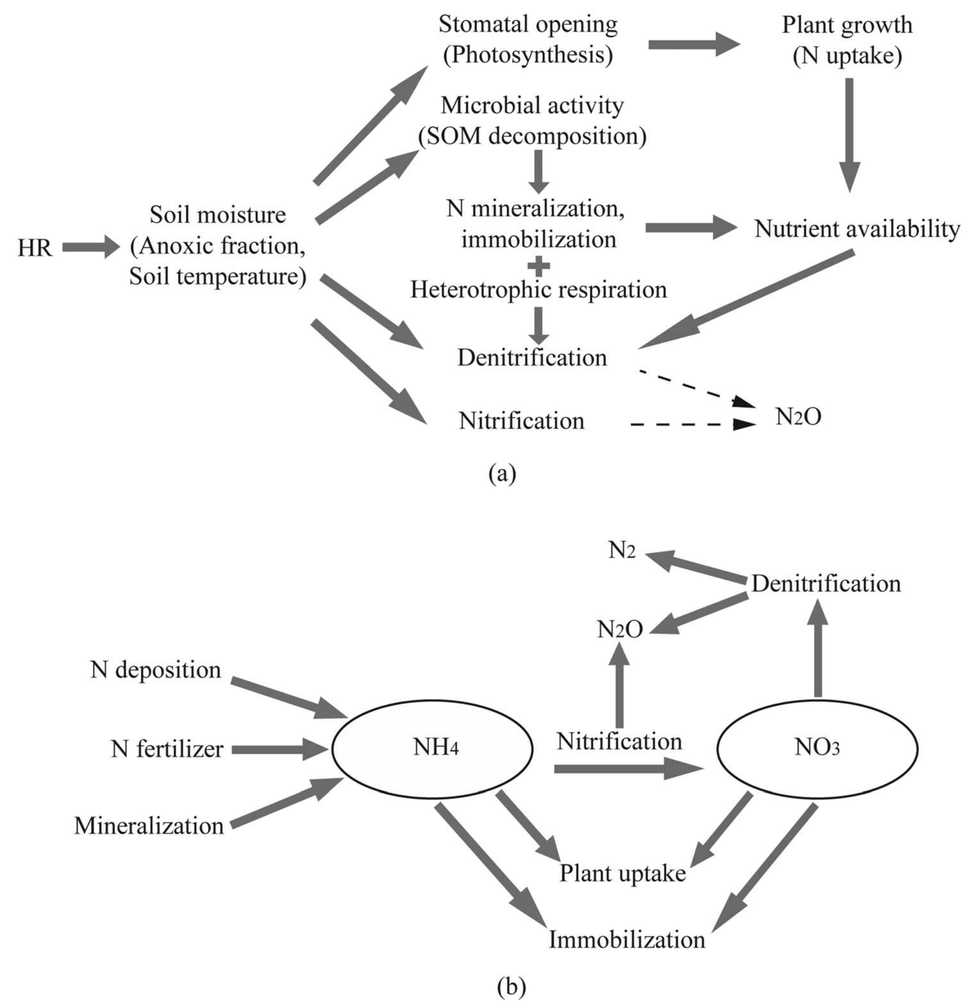

Figure 1. Schematic representations of the (a) effects of hydraulic redistribution on N_2O emissions and (b) sources and sinks for the soil mineral nitrogen pools.

evapotranspiration (ET), and the Bowen ratio during dry periods at eight seasonally dry AmeriFlux sites (Fu et al., 2016). At four of these AmeriFlux sites, HR was found to affect the model ecosystem-atmosphere CO_2 exchange during dry periods in two ways: (a) enhancing stomatal conductance and photosynthesis and (b) affecting soil microbial activity, heterotrophic respiration, and nutrient availability to plants (Fu et al., 2018).

We hypothesize that HR affects N_2O emissions via its effects on soil moisture and subsequently on the frequency of anoxic conditions, plant growth and uptake of soil N, and microbial mobilization of soil N (Figure 1). The HR effect is likely to be strong in ecosystems that have a distinct dry season and to be weak in ecosystems that are persistently wet or persistently dry throughout the year. At wet sites, a soil water potential gradient sufficient for HR is unlikely to develop. Conversely, dry sites have limited soil moisture for redistribution (Fu et al., 2016; Wang, 2011; Yu & D'Odorico, 2014).

In addition to the HR scheme of Ryel et al. (2002) that was incorporated into CLM4.5 by Fu et al. (2016, 2018), here we added the physically based method of Amenu and Kumar (2008) to CLM4.5 as an alternative HR scheme. The modified CLM4.5 with these two different HR formulations was applied to five AmeriFlux sites with contrasting climates, ecosystem types, and N_2O emission strength. We aimed to (a) evaluate the performance of the widely used CLM model in simulating ecosystem N_2O emissions, (b) investigate the influences of HR on the N_2O emissions of ecosystems with a dry season, and (c) determine whether the HR effect is important for the U. S. Corn Belt, which is a global N_2O emission hot spot that does not have a distinct dry season.

Table 1
Study Site Information

Site	Location	Vegetation	Köppen climate	Annual precipitation (mm)	Study examples
US-Wrc	Washington, USA	Douglas fir, western hemlock	Mediterranean	2,220	(Brooks et al., 2002, 2006)
US-SRM	Arizona, USA	Mesquite trees, bunchgrass, succulents	Cold semi arid	380	(Scott et al., 2008, 2009)
US-SCf	California, USA	Oak/pine forest	Mediterranean	530	(Kitajima et al., 2013)
BR-Sa1	Pará, Brazil	Macaranduba, Jatoba, Taxi	Tropical monsoon	1,910	(Baker et al., 2008)
US-Ro1	Minnesota, USA	Corn; soybean	Humid Continental	879	(Chen et al., 2015)

Note. Information for US-Wrc, US-SRM, US-SCf, and BR-Sa1 sites is from Fu et al. (2018).

2. Material and Methods

2.1. Study Sites and Data

This study focused on five AmeriFlux sites, including the US-Ro1 site in Minnesota (representing the U.S. Corn Belt; Chen et al., 2015), the Douglas fir (US-Wrc) site in Washington State (Brooks et al., 2002, 2006), the Santa Rita Mesquite (US-SRM) site in Arizona (Scott et al., 2008, 2009), the Oak Pine Forest (US-SCf) site in southern California (Kitajima et al., 2013), and the Amazon evergreen forest (BR-Sa1) site in Brazil (Baker et al., 2008). The US-Wrc and US-SCf sites have Mediterranean climates, while the US-SRM site has a cold, semiarid climate. The BR-Sa1 and US-Ro1 sites have tropical monsoon and humid continental climate, respectively. The US-Wrc, US-SRM, US-SCf, and BR-Sa1 sites have a dry season, and HR has been reported at all four sites (Brooks et al., 2006; Kitajima et al., 2013; Oliveira et al., 2005; Scott et al., 2008). In contrast, US-Ro1, which is a corn–soybean rotation agricultural site, lacks a dry season. No studies have examined HR in the Corn Belt region, but experimental greenhouse studies have reported the occurrence of hydraulic lift in maize (4.1–12.6 μl/cm of root per night) using time domain reflectometry (Topp et al., 1996) and isotopic assessment (Wan et al., 2000). Tables 1 and S1 list the detailed site information.

N_2O emissions were measured between 1 January and 11 October 2011 during the corn phase of soybean-corn rotation at US-Ro1. The flux measurements were obtained using six automated chambers (Griffis et al., 2013). Hourly soil-moisture data since 19 July 2011 were obtained from the COsmic-ray Soil Moisture Observing System (COSMOS) project (http://cosmos.hwr.arizona.edu%2FProbes%2FStationDat%2F041%2Findex.php). COSMOS has an effective monitoring depth of 10–25 cm. Annual mean N_2O emission data for the remaining four sites were obtained from the literature or public databases (0.290, 0.080, 0.017, and 0.060 nmol $\cdot$ m^{-2} $\cdot$ s^{-1} at BR-Sa1, US-Wrc, US-SRM, and US-SCf, respectively). ET data for US-Ro1, US-Wrc, US-SRM, and BR-Sa1 sites were obtained from the AmeriFlux databases, while ET data for the SC-SCf site were collected by the Goulden Laboratory (http://www.ess.uci.edu/~california/).

2.2. Land Surface Model

The CLM4.5 (Oleson et al., 2013), which is part of the Community Earth System Model (CESM) version 1.2.0, was used in this study. The CLM4.5 was implemented using the CENTURY-based soil carbon pool kinetics (CLM45BGC) to simulate plant growth and mortality, carbon, nitrogen, and water cycles of the four natural ecosystems (US-Wrc, US-SRM, US-SCf, and BR-Sa1 sites). At the agricultural US-Ro1 site, CLM45BGC coupled with the crop algorithm (CLM45BGCCROP) was used to simulate these biogeophysical and biogeochemical processes. CLM45BGCCROP can simulate the management (e.g., fertilization) and phenology (e.g., leaf emergence and grain fill) for crops of rainfed and irrigated corn, temperate cereal, winter cereal, and soybean (Oleson et al., 2013). At US-Ro1, we used the model's default fertilizer application rate and timing. The land use at US-Ro1 is corn-soybean rotation, and we simulated the corn phases for 2007, 2009, and 2011 (Chen et al., 2015). The specific data sources and model setup parameters, including land coverage, maximum soil depth, soil texture, and root fraction profile, are shown in Text S1 and Table S2 and reported in Fu et al. (2018).

2.3. HR Schemes

There are two primary approaches to HR modeling: the scheme proposed by Ryel et al. (2002) (e.g., Fu et al., 2016; Li et al., 2012; Wang, 2011) or its variations (e.g., Lee et al., 2005; Yu & D'Odorico, 2015), and the approach proposed by Amenu and Kumar (2008) (e.g., Luo et al., 2013; Quijano & Kumar, 2015; Tang et al., 2015). Ryel et al.'s scheme is an empirical method that describes HR flux based on the soil water potential gradient, while Amenu and Kumar's approach is a physically based method that calculates HR flux using a steady state Richards equation for roots.

The Ryel et al. HR scheme was incorporated into various versions of CLM including CLM3.5 (Wang, 2011; Zheng & Wang, 2007) and CLM4.5 (Fu et al., 2016). In the Ryel et al. scheme, the HR-induced soil water flux $q_{\mathrm{HR}}(i, j)$ (cm/hr) between a receiving soil layer i and a giving soil layer j is quantified as

$$q_{\mathrm{HR}}(i,j) = -C_{\mathrm{RT}} \cdot \Delta\psi_m \cdot c_j \frac{F_{\mathrm{root}}(i) \cdot F_{\mathrm{root}}(j)}{1 - F_{\mathrm{root}}(j)} \cdot D \tag{1}$$

where C_{RT} is the maximum radial soil-root conductance of the entire active root system for water ($\mathrm{cm} \cdot \mathrm{MPa}^{-1} \cdot \mathrm{hr}^{-1}$); $\Delta\psi_m$ is the water potential difference between two soil layers (MPa) simulated using a non–steady state Richards equation in CLM; F_{root} (i) is the root fraction in soil layer i, which is a weighted average of the root fractions of subgrid vegetation types (Zeng, 2001); and D is a switching factor, set to 1.0 during the night and 0.0 during the daytime. The factor that reduces soil-root conductance for water in the giving layer c_j is

$$c_j = \frac{1}{1 + \left(\frac{\psi_j}{\psi_{50}}\right)^b} \tag{2}$$

In equation (2), ψ_j is the soil water potential in layer j (MPa), ψ_{50} is the soil water potential at which soil-root conductance is reduced by 50% (MPa), and b is an empirical constant. The parameters used in Ryel et al.'s scheme are shown in Table S3.

In this study we incorporated the Amenu and Kumar scheme into CLM4.5 as an alternative HR formulation. The Amenua and Kumar approach is based on the non–steady state Richards equation for soil and a steady state Richards equation for roots:

$$\frac{\partial\theta}{\partial t} - \frac{\partial}{\partial z}\left[K_s\left(\frac{\partial\psi_s}{\partial z} - 1\right)\right] = -K_{r,\mathrm{rad}}(\psi_s - \psi_r) \tag{3}$$

$$-\frac{\partial}{\partial z}\left[K_{r,\mathrm{ax}}\left(\frac{\partial\psi_r}{\partial z} - 1\right)\right] = K_{r,\mathrm{rad}}(\psi_s - \psi_r) \tag{4}$$

where θ is volumetric soil water content; K_s, $K_{r,\mathrm{rad}}$, and $K_{r,\mathrm{ax}}$ are soil hydraulic conductivity, and root system hydraulic conductivity in the radial and axial directions, respectively; and ψ_s and ψ_r are the water potentials in soil and roots, respectively. We replaced the default Richards equation in CLM with equation (3), added equation (4), and moved the transpiration term from the Richards equation for soils to the Richards equation for roots. Equations (3) and (4) are discretized into two tridiagonal systems, and the solution is obtained using a method similar to that of Tang et al. (2015). The HR flux in a soil layer at a specific time step is calculated using the right-hand side of equation (4) when ψ_s is smaller than ψ_r. Root system hydraulic conductivity in the radial ($K_{\mathrm{r,rad}}$) and axial ($K_{\mathrm{r,ax}}$) directions are two empirical parameters in the Amenu and Kumar method. Because the root system hydraulic conductivity is directly related to ET, we used observed ET to calibrate these two parameters (Table S3 and Figure S1).

We labeled the CLM4.5 modeling including the Ryel et al.'s HR scheme and the Amenu and Kumar method as "CLM4.5 + HR_Ryle" and "CLM4.5 + HR_AK," respectively, and labeled the default CLM4.5 modeling as "CLM4.5noHR." To obtain a stable vertical soil carbon distribution as initial conditions for these simulations, we performed an accelerated decomposition spin-up run longer than 1,000 years and then a normal spin-up run longer than 200 years (Kluzek, 2013). The decomposition rates of the second and third soil organic matter pools were increased by 14 and 674 times relative to a normal spin-up run, respectively, to achieve an accelerated spin-up time. Spin-up runs were done with the Ryel et al.'s HR scheme included.

3. Results and Discussion

3.1. Model Calibration Using Real Emission Fluxes

We calibrated the CLM4.5 + HR_Ryel model using the annual mean N_2O flux values. The average N_2O flux values from the six chambers at US-Ro1 between 1 January and 11 October 2011 were 0.549, 0.114, 0.154, 0.152, 0.150, and 0.240 $\mathrm{nmol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$, with an overall mean value of 0.227 $\mathrm{nmol} \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$. The mean

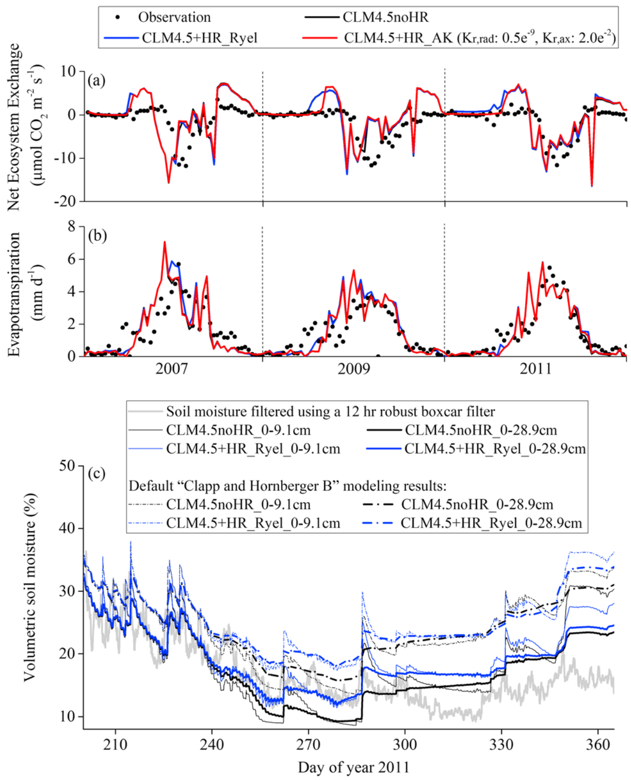

Figure 2. Model validation results for the US-Ro1 site.

N_2O flux observed by Davidson et al. (2004) at the Amazon BR-Sa1 site between 2000 and 2002 was 0.290 nmol · m^{-2} · s^{-1}. No direct field measurements are available for US-Wrc, US-SRM, or US-SCf. For these three sites, we used the fluxes from the Dynamic Land-Ecosystem Model (DLEM; Tian et al., 2010) database. DLEM has a spatial resolution of 32 × 32 km, thereby matching the CLM model in single point mode (~5 × 5 km) in the present study reasonably well. Based on DLEM, the annual mean N_2O fluxes were 0.080, 0.017, and 0.060 nmol · m^{-2} · s^{-1} at US-Wrc, US-SRM, and US-SCf, respectively. For comparison, the flux values based on EDGAR version 2.0 were 0.020, 0.017, and 0.010 nmol · m^{-2} · s^{-1} for the grids where these sites are located. However, the resolution of EDGAR version 2.0 (one degree) is too coarse to be suitable for the present study. Calibrations for the N_2O flux at the five study sites are shown in Text S1.

3.2. Evaluation of Model Accuracy

After implementing the model adjustments for N_2O flux (Text S1 and Figure S2), we evaluated the accuracy of the model in simulating the net ecosystem CO_2 exchange (NEE), latent heat flux, and soil moisture. At US-Ro1, the NEE simulated using the CLM4.5 + HR_Ryel and CLM4.5noHR models roughly captured the observed seasonal dynamics, although an unreasonable minimum value (negative NEE) was obtained during the last time step of harvest (Figure 2a). Here the sign convention for NEE is that a positive NEE indicates CO_2 release to the atmosphere and a negative NEE indicates uptake from the atmosphere. The imperfect phenology scheme in CLM is the main cause of the negative NEE during the harvest time step in the present study (Chen et al., 2015). The R^2 values between the observed and simulated weekly NEE for all three corn years (2007, 2009, and 2011) were 0.25 and 0.27 for CLM4.5 + HR_Ryel and CLM4.5noHR, respectively. The R^2 values for 2011, when the N_2O fluxes were measured, were 0.43 and 0.45 for CLM4.5 + HR_Ryel and CLM4.5noHR, respectively.

At US-Ro1, ET was simulated reasonably well using CLM4.5 (Figure 2b). The R^2 values between the observed and simulated daily ET values were 0.61 and 0.58 for CLM4.5 + HR_Ryel and CLM4.5noHR, respectively. The simulated surface soil moisture was consistent with the observed values (Figure 2c). The R^2 values between the observed and modeled hourly soil moisture levels were 0.48 using CLM4.5 + HR_Ryel and 0.49 using CLM4.5noHR.

The modeled monthly N_2O fluxes agreed well with the observed fluxes for chamber 1 but were significantly higher than the values observed in the other five chambers (Figure 3h). These data indicated the episodic nature of N_2O emissions (Figure 3e) in croplands (Groffman et al., 2009; Wagner-Riddle et al., 2007). However, despite the episodic nature of emissions, the CLM model could generally reproduce the seasonal variability of N_2O emissions for this Corn Belt site.

At US-Wrc, US-SRM, US-SCf, and BR-Sa1, incorporation of the Ryel et al. HR scheme improved the performance of CLM when modeling soil moisture, ET, NEE, and the Bowen ratio (Fu et al., 2016, 2018). The CLM4.5 + HR_AK and CLM4.5 + HR_Ryel models achieved similar accuracies for ET and NEE (Figures 2, S3, and S4). Overall, the CLM4.5 + HR_AK and CLM4.5 + HR_Ryel models captured the broad seasonal dynamics of ET and NEE (Text S1).

3.3. Influences of HR on N_2O Emission

Significant differences in the modeled N_2O fluxes at the four natural ecosystems were found between models that lacked the HR effect (CLM4.5noHR) and those that included it (CLM4.5 + HR_Ryel and CLM4.5 + HR_AK; Figures 3a–3d and 3g). Specifically, the mean annual N_2O fluxes decreased from 0.112 to 0.080 (29%), 0.015 to 0.0012 (92%), 0.279 to 0.055 (80%), and 0.376 to 0.272 (28%) nmol · m^{-2} · s^{-1} following incorporation of the Ryel et al. HR scheme at US-Wrc, US-SRM, US-SCf, and BR-Sa1, respectively. At US-Ro1, the Corn Belt site, the

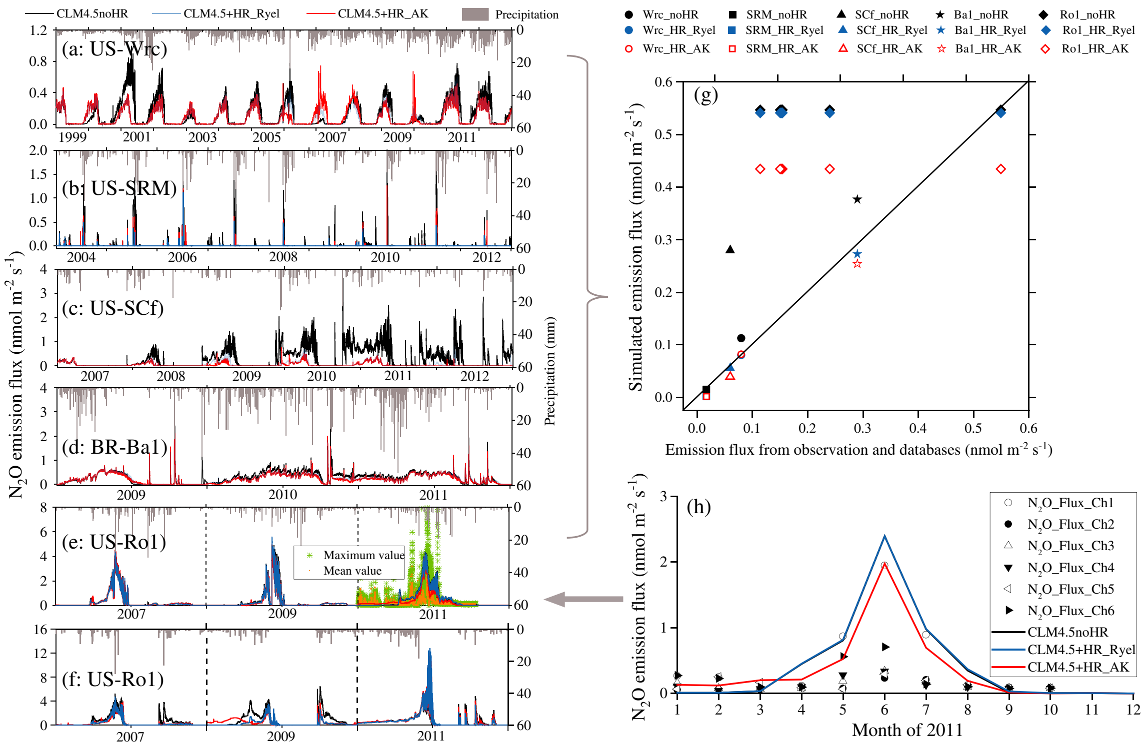

Figure 3. (a–h) N_2O emissions from observations, databases, and simulations. Results in panels (a)–(f), (g), and (h) are on hourly, multiyear, and monthly timescales, respectively. The dots in panel (e) represent chamber observations. Simulation in panel (f) is experimental where the total precipitation amount during June–August was evenly distributed to the rainfall hours in other months. The US-Ro1 AmeriFlux site includes data for 2011 only (data for the other years were unavailable) in panel (g). “Ch1”–“Ch6” in panel (h) represent monitoring chambers 1–6, respectively.

absolute and relative changes were 0.006 $nmol \cdot m^{-2} \cdot s^{-1}$ and 1.1%, respectively. Here the HR mechanism failed to significantly influence N_2O emissions, despite the fact that US-Ro1 was the strongest N_2O source among the sites considered in this analysis. Similar changes were also found when using the Amenu and Kumar HR scheme.

The simulated N_2O fluxes at the five AmeriFlux sites were largely determined by the simulated denitrification rate (Figure S5). The modeled denitrification rate is a function of the anoxic fraction, the heterotrophic respiration rate, and soil nitrate concentration (affected by N mineralization and immobilization, and plant N uptake) in CLM (del Grosso et al., 2000). As shown in Figure 1a, HR directly impacts soil moisture and anoxic fraction. HR influences the heterotrophic respiration rate via changes in soil moisture, and temperature, and subsequently microbial activity and soil organic matter decomposition. HR affects soil nitrate concentration via two ways, (a) affecting stomatal opening and plant growth, and therefore plant N uptake, and (b) affecting microbial activity and soil organic matter decomposition, and therefore N mineralization and immobilization. As an example, the influences of HR on the anoxic fraction-, heterotrophic respiration rate-, and soil nitrate concentration-limited soil denitrification rates at the Ba-Ra1 site are shown in Figure S6. Figure S7 illustrates that HR enhanced N mineralization, immobilization, and plant N uptake, and therefore, affected soil nitrate concentrations at the four natural ecosystem sites during the dry season. Finally, HR affects the ratio of N_2 to N_2O during denitrification and subsequently N_2O emissions by influencing soil moisture, temperature, soil organic matter, heterotrophic respiration, and nitrite concentration (del Grosso et al., 2000).

3.4. Influences of Precipitation Amount on N_2O Emission

The model calculations confirmed that the N_2O emission increased with the annual precipitation amount, whereby increased precipitation caused more frequent anoxic conditions. For example, the simulated annual emissions at the Amazon BR-Sa1 site were 0.181, 0.388, and 0.284 for 2009, 2010, and 2011, respectively, using CLM4.5noHR. Using CLM4.5 + HR_Ryel (CLM4.5 + HR_AK) for the same years generated annual emissions of 0.189 (0.178), 0.289 (0.261), and 0.262 (0.247), respectively (Figure 3d). Notably, 2009 was unusually dry in the Amazon region, with an annual precipitation of only 963 mm at the BR-Sa1 site. In contrast, the annual precipitation amounts in 2010 and 2011 at that site were 1613 and 1627 mm, respectively. The emissions were lowest during the driest year (2009).

Among the five sites, the driest savanna site, US-SRM, had the lowest multiyear average N_2O emission. The influence of precipitation on N_2O emissions was observed in an experimental study of the BR-Sa1 site by Davidson et al. (2004). That study excluded some of the precipitation during the rainy seasons in 2000–2002 and reported that the average N_2O emission decreased from 0.294 (no rainfall exclusion) to 0.170 $nmol \cdot m^{-2} \cdot s^{-1}$ (with rainfall exclusion). Such a reduction is similar to the difference in values between fluxes modeled in wet (2010) versus dry (2009) years in the present study.

The effects of HR on the hydrological cycle (e.g., soil moisture and ET) may be stronger in dry years than in wet years because larger vertical soil water potential gradients can form during these dry periods. For example, the effect of HR on ET at BR-Ba1 was largest during 2009, a dry year (Figure S4). In contrast, the effect of HR on N_2O fluxes was small during dry years because the limited precipitation resulted in a lower frequency of anoxic conditions (e.g., year 2009 at the BR-Ba1 site in Figure 3d).

3.5. Effects of Dry Season on N_2O Emissions

The direction of HR was mainly upward (hydraulic lift) at US-Ro1, and it occurred primarily during June to August, July to September, and August to October in 2007, 2009, and 2011, respectively (Figure S8). The average hydraulic lift during these three periods was 0.56 mm/day, comparable to those at US-Wrc (0.60 mm/day) and US-SCf (0.71 mm/day) sites during the dry season (Fu et al., 2016). The hydraulic lift increased surface-soil moisture during the dry periods (Figure 2c). However, the effects of HR on ET (Figure 2b), NEE (Figure 2a), and the soil nitrogen cycle (Figure S7) were limited. Figure 3 shows that the influence of HR on the N_2O flux at US-Ro1 was limited compared to the other four sites. US-Ro1 has a humid continental climate that has no defined dry season, and precipitation is distributed evenly throughout the year. In contrast, the other four natural ecosystem sites where HR occurs have distinct seasonal dry periods of longer than two months. Thus, the lack of a defined dry season at US-Ro1 explains why HR-induced soil moisture changes failed to influence ET, NEE, and N_2O emissions.

To verify the influences of the dry season on N_2O emission, we performed one modeling experiment for the US-Ro1 site. In this experiment, simulations of CLM4.5noHR, CLM4.5 + HR_Ryel, and CLM4.5 + HR_AK were driven using a revised precipitation temporal distribution. Specifically, precipitation during June–August was moved to other months evenly when rainfall occurred. Using the unrevised precipitation, HR did not clearly affect the soil N cycles (Figure S7). After revising the precipitation distribution, HR increased the modeled N mineralization, immobilization, and plant N uptake and decreased soil nitrate concentration (Figure S9), nitrification, and denitrification rates at the US-Ro1 site, similar to HR's influences on the nitrogen cycle during dry seasons at other sites (Figure S7). Using the revised precipitation, the simulated emissions with CLM4.5 + HR_Ryel and CLM4.5 + HR_AK were 36% and 26% smaller than the modeling results with CLM4.5noHR, respectively (Figure 3f), confirming the importance of a dry season on the N_2O emissions. These findings add further support that HR influences multiple biogeophysical and biogeochemical processes in ecosystems that have a defined dry season (Fu et al., 2016; Neumann & Cardon, 2012).

Our findings suggest that HR may play an important role in N_2O emissions from agricultural regions that have a clearly defined dry season. For example, the expansive corn-growing regions of China are all located in the monsoon area with a distinct dry season. We hypothesize that the HR mechanism may act to significantly reduce N_2O emissions in these regions. HR may also play an important role in limiting N_2O emissions in the Amazonian regions with a tropical monsoon climate, where forests have been converted into agricultural use. The influence of HR on N_2O emissions is expected to increase in many parts of the dry tropics, where the rainfall seasonality has been increasing over the past century (Feng et al., 2013).

4. Conclusions

In this study, utilizing two HR formulations (of Ryel et al., 2002, and Amenu and Kumar, 2008) incorporated into CLM4.5, we investigated the impact of HR on N_2O emission at four natural ecosystem sites that have a distinct dry season and one Corn Belt site that does not experience a dry season. Our modeling results demonstrated that HR reduced the N_2O emissions from the four natural ecosystems that have a distinct dry season but had very little impact at the Corn Belt site. The results for the Amazon site indicated that both N_2O emissions and the effect of HR on the emissions were reduced during dry years. To improve regional N_2O budget estimates, we recommend field studies designed to examine the effects of HR on N_2O emissions in cropping systems subject to climates that have a distinct dry season. We hypothesize that these emissions are likely overestimated by CLM or other CENTURY-based Earth system models.

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References

Amenu, G. G., & Kumar, P. (2008). A model for hydraulic redistribution incorporating coupled soil-root moisture transport. *Hydrology and Earth System Sciences*, *12*(1), 55–74. https://doi.org/10.5194/hess-12-55-2008

Anderson, R. G., & Goulden, M. L. (2011). Relationships between climate, vegetation, and energy exchange across a montane gradient. *Journal of Geophysical Research*, *116*, G01026. https://doi.org/10.1029/2010JG001476

Baker, I. T., Prihodko, L., Denning, A. S., Goulden, M. L., Miller, S., & da Rocha, H. R. (2008). Seasonal drought stress in the Amazon: Reconciling models and observations. *Journal of Geophysical Research*, *113*, G00B01. https://doi.org/10.1029/2007JG000644

Brooks, J. R., Meinzer, F. C., Coulombe, R., & Gregg, J. (2002). Hydraulic redistribution of soil water during summer drought in two contrasting Pacific Northwest coniferous forests. *Tree Physiology*, *22*(15-16), 1107–1117. https://doi.org/10.1093/treephys/22.15-16.1107

Brooks, J. R., Meinzer, F. C., Warren, J. M., Domec, J., & Coulombe, R. (2006). Hydraulic redistribution in a Douglas-fir forest: Lessons from system manipulations. *Plant, Cell & Environment*, *29*, 138–150. https://doi.org/10.1111/j.1365-3040.2005.01409.x

Cardon, Z. G., Stark, J. M., Herron, P. M., & Rasmussen, J. A. (2013). Sagebrush carrying out hydraulic lift enhances surface soil nitrogen cycling and nitrogen uptake into inflorescences. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(47), 18,988–18,993. https://doi.org/10.1073/pnas.1311314110

Chen, M., Griffis, T. J., Baker, J., Wood, J. D., & Xiao, K. (2015). Simulating crop phenology in the Community Land Model and its impact on energy and carbon fluxes. *Journal of Geophysical Research: Biogeosciences*, *120*, 310–325. https://doi.org/10.1002/2014JG002780

Davidson, E. A., Ishida, F. Y., & Nepstad, D. C. (2004). Effects of an experimental drought on soil emissions of carbon dioxide, methane, nitrous oxide, and nitric oxide in a moist tropical forest. *Global Change Biology*, *10*(5), 718–730. https://doi.org/10.1111/j.1365-2486.2004.00762.x

Feng, X., Porporato, A., & Rodriguez-Iturbe, I. (2013). Changes in rainfall seasonality in the tropics. *Nature Climate Change*, *3*(9), 811–815. https://doi.org/10.1038/nclimate1907

Fu, C., Wang, G., Bible, K., Goulden, M. L., Saleska, S. R., Scott, R. L., & Cardon, Z. G. (2018). Hydraulic redistribution affects carbon cycling via soil microbial activity and suppressed fire. *Global Change Biology*. https://doi.org/10.1111/gcb.14164

Fu, C., Wang, G., Goulden, M. L., Scott, R. L., Bible, K., & Cardon, Z. G. (2016). Combined measurement and modeling of the hydrological impact of hydraulic redistribution using CLM4.5 at eight AmeriFlux sites. *Hydrology and Earth System Sciences*, *20*(5), 2001–2018. https://doi.org/10.5194/hess-20-2001-2016

Grant, R., Hutyra, L., de Oliveira, R. C. Jr., Munger, J., Saleska, S., & Wofsy, S. (2009). Modeling the carbon balance of Amazonian rain forests: Resolving ecological controls on net ecosystem productivity. *Ecological Monographs*, *79*(3), 445–463. https://doi.org/10.1890/08-0074.1

Griffis, T. J., Lee, X., Baker, J. M., Russelle, M. P., Zhang, X., Venterea, R., & Millet, D. B. (2013). Reconciling the differences between top-down and bottom-up estimates of nitrous oxide emissions for the U.S. Corn Belt. *Global Biogeochemical Cycles*, *27*, 746–754. https://doi.org/10.1002/gbc.20066

Groffman, P. M., Butterbach-Bahl, K., Fulweiler, R. W., Gold, A. J., Morse, J. L., Stander, E. K., et al. (2009). Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models. *Biogeochemistry*, *93*(1–2), 49–77. https://doi.org/10.1007/s10533-008-9277-5

Grossel, A., Nicoullaud, B., Bourennane, H., Lacoste, M., Guimbaud, C., Robert, C., et al. (2016). The effect of tile-drainage on nitrous oxide emissions from soils and drainage streams in a cropped landscape in Central France. *Agriculture, Ecosystems & Environment*, *230*, 251–260.

Hofmann, D. J., Butler, J. H., Dlugokencky, E. J., Elkins, J. W., Masarie, K., Montzka, S. A., & 912 Tans, P. (2006). The role of carbon dioxide in climate forcing from 1979 – 2004: Introduction 913 of the annual greenhouse gas index. *Tellus Series B: Chemical and Physical Meteorology*, *58*(5), 614–619. https://doi.org/10.1111/j.1600-0889.2006.00201.x

Horton, J. L., & Hart, S. C. (1998). Hydraulic lift: A potentially important ecosystem process. *Trends in Ecology & Evolution*, *13*(6), 232–235. https://doi.org/10.1016/S0169-5347(98)01328-7

Idso, S. B. (1981). A set of equations for full spectrum and 8- to 14-μm and 10.5- to 12.5-μm thermal radiation from cloudless skies. *Water Resources Research*, *17*(2), 295–304. https://doi.org/10.1029/WR017i002p00295

Jackson, R. B., Canadell, J., Ehleringer, J. R., Mooney, H. A., Sala, O. E., & Schulze, E. D. (1996). A global analysis of root distributions for terrestrial biomes. *Oecologia*, *108*(3), 389–411. https://doi.org/10.1007/BF00333714

Kitajima, K., Allen, M. F., & Goulden, M. L. (2013). Contribution of hydraulically lifted deep moisture to the water budget in a Southern California mixed forest. *Journal of Geophysical Research: Biogeosciences*, *118*, 1561–1572. https://doi.org/10.1002/2012JG002255

Kluzek, E. (2013). *CESM research tools: CLM4.5 in CESM1.2.0 user's guide documentation*. Boulder: National Centers for Atmospheric Research.

del Grosso, S. J., Parton, W. J., Mosier, A. R., Ojima, D. S., Kulmala, A. E., & Phongpan, S. (2000). General model for N_2O and N_2 gas emissions from soils due to denitrification. *Global Biogeochemical Cycles*, *14*(4), 1045–1060. https://doi.org/10.1029/1999GB001225

Lee, J. E., Oliveira, R. S., Dawson, T. E., & Fung, I. (2005). Root functioning modifies seasonal climate. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(49), 17,576–17,581. https://doi.org/10.1073/pnas.0508785102

Li, L., Wang, Y., Yu, Q., Pak, B., Eamus, D., Yan, J., et al. (2012). Improving the responses of the Australian community land surface model (CABLE) to seasonal drought. *Journal of Geophysical Research*, *117*, G04002. https://doi.org/10.1029/2012JG002038

Luo, X., Liang, X., & McCarthy, H. R. (2013). VIC+ for water-limited conditions: A study of biological and hydrological processes and their interactions in soil-plant-atmosphere continuum. *Water Resources Research*, *49*, 7711–7732. https://doi.org/10.1002/2012WR012851

Miller, S. M., Kort, E. A., Hirsch, A. I., Dlugokencky, E. J., Andrews, A. E., Xu, X., et al. (2012). Regional sources of nitrous oxide over the United States: Seasonal variation and spatial distribution. *Journal of Geophysical Research*, *117*, D06310. https://doi.org/10.1029/2011JD016951

Neumann, R. B., & Cardon, Z. G. (2012). The magnitude of hydraulic redistribution by plant roots: A review and synthesis of empirical and modeling studies. *The New Phytologist*, *194*(2), 337–352. https://doi.org/10.1111/j.1469-8137.2012.04088.x

Oleson, K., Lawrence, D. M., Bonan, G. B., Drewniak, B., Huang, M., Koven, C. D., et al. (2013). Technical description of version 4.5 of the Community Land Model (CLM), NCAR Technical Note NCAR/TN-503CSTR (420 pp.). https://doi.org/10.5065/D6RR1W7M

Oliveira, R. S., Dawson, T. E., Burgess, S. S. O., & Nepstad, D. C. (2005). Hydraulic redistribution in three Amazonian trees. *Oecologia*, *145*, 354–363. https://doi.org/10.1007/s00442-005-0108-2

Parton, W., Mosier, A. R., Ojima, D. S., Valentine, D. W., Schimel, D. S., Weier, K., & Kulmala, A. E. (1996). Generalized model for N_2 and N_2O production from nitrification and denitrification. *Global Biogeochemical Cycles*, *10*(3), 401–412. https://doi.org/10.1029/96GB01455

Prather, M. J., Holmes, C. D., & Hsu, J. (2012). Reactive greenhouse gas scenarios: Systematic exploration of uncertainties and the role of atmospheric chemistry. *Geophysical Research Letters*, *39*, L09803. https://doi.org/10.1029/2012GL051440

Prather, M. J., Hsu, J., DeLuca, N. M., Jackman, C. H., Oman, L. D., Douglass, A. R., et al. (2015). Measuring and modeling the lifetime of nitrous oxide including its variability. *Journal of Geophysical Research: Atmospheres*, *120*, 5693–5705. https://doi.org/10.1002/2015JD023267

Prieto, I., Armas, C., & Pugnaire, F. I. (2012). Water release through plant roots: New insights into its consequences at the plant and ecosystem level. *The New Phytologist*, *193*(4), 830–841. https://doi.org/10.1111/j.1469-8137.2011.04039.x

Quijano, J. C., & Kumar, P. (2015). Numerical simulations of hydraulic redistribution across climates: The role of the root hydraulic conductivities. *Water Resources Research*, *51*, 8529–8550. https://doi.org/10.1002/2014WR016509

Ravishankara, A. R., Daniel, J. S., & Portmann, R. W. (2009). Nitrous oxide: The dominant ozone-depleting substance emitted in the 21st century. *Science*, *326*(5949), 123–125. https://doi.org/10.1126/science.1176985

Ryel, R. J., Caldwell, M. M., Yoder, C. K., Or, D., & Leffler, A. J. (2002). Hydraulic redistribution in a stand of Atemisia tridentata: Evaluation of benefits to transpiration assessed with a simulation model. *Oecologia*, *130*(2), 173–184. https://doi.org/10.1007/s004420100794

Sardans, J., & Peñuelas, J. (2014). Hydraulic redistribution by plants and nutrient stoichiometry: Shifts under global change. *Ecohydrology*, *7*(1), 1–20. https://doi.org/10.1002/eco.1459

Scott, R. L., Cable, W. L., & Hultine, K. R. (2008). The ecohydrologic significance of hydraulic redistribution in a semiarid savanna. *Water Resources Research*, *44*, W02440. https://doi.org/10.1029/2007WR006149

Scott, R. L., Jenerette, G. D., Potts, D. L., & Huxman, T. E. (2009). Effects of seasonal drought on net carbon dioxide exchange from a woody-plant-encroached semiarid grassland. *Journal of Geophysical Research*, *114*, G04004. https://doi.org/10.1029/2008JG000900

Tang, J., Riley, W. J., & Niu, J. (2015). Incorporating root hydraulic redistribution in CLM4.5: Effects on predicted site and global evapotranspiration, soil moisture, and water storage. *Journal of Advances in Modeling Earth Systems*, *7*, 1828–1848. https://doi.org/10.1002/2015MS000484

Tian, H., Xu, X., Liu, M., Ren, W., Zhang, C., Chen, G., & Lu, C. (2010). Spatial and temporal patterns of CH4 and N2O fluxes in terrestrial ecosystems of North America during 1979–2008: Application of a global biogeochemistry model. *Biogeosciences*, *7*(9), 2673–2694. https://doi.org/10.5194/bg-7-2673-2010

Topp, G. C., Watt, M., & Hayhoe, H. N. (1996). Point specific measurement and monitoring of soil water content with an emphasis on TDR. *Canadian Journal of Soil Science*, *76*(3), 307–316. https://doi.org/10.4141/cjss96-037

Turner, P. A., Griffis, T. J., Mulla, D. J., Baker, J. M., & Venterea, R. T. (2016). A geostatistical approach to identify and mitigate agricultural nitrous oxide emission hotspots. *Science of the Total Environment*, *572*, 442–449. https://doi.org/10.1016/j.scitotenv.2016.08.094

Wagner-Riddle, C., Furon, A., Mclaughlin, N. L., Lee, I., Barbeau, J., Jayasundara, S., et al. (2007). Intensive measurement of nitrous oxide emissions from a corn-soybeanwheat rotation under two contrasting management systems over 5 years. *Global Change Biology*, *13*(8), 1722–1736. https://doi.org/10.1111/j.1365-2486.2007.01388.x

Wan, C., Xu, W., Sosebee, R. E., Machado, S., & Archer, T. (2000). Hydraulic lift in drought-tolerant and -susceptible maize hybrids. *Plant and Soil*, *219*(1/2), 117–126. https://doi.org/10.1023/A:1004740511326

Wang, G. (2011). Assessing the potential hydrological impacts of hydraulic redistribution in Amazonia using a numerical modeling approach. *Water Resources Research*, *47*, W02528. https://doi.org/10.1029/2010WR009601

Warren, J. M., Hanson, P. J., Iversen, C. M., Kumar, J., Walker, A. P., & Wullschleger, S. D. (2015). Root structural and functional dynamics in terrestrial biosphere models – Evaluation and recommendations. *New Phytologist*, *205*(1), 59–78. https://doi.org/10.1111/nph.13034

Yu, K., & D'Odorico, P. (2014). Climate, vegetation, and soil controls on hydraulic redistribution in shallow tree roots. *Advances in Water Resources*, *66*, 70–80. https://doi.org/10.1016/j.advwatres.2014.02.003

Yu, K., & D'Odorico, P. (2015). Hydraulic lift as a determinant of tree–grass coexistence on savannas. *The New Phytologist*, *207*(4), 1038–1051. https://doi.org/10.1111/nph.13431

Yu, K., & D'Odorico, P. (2017). From facilitative to competitive interactions between woody plants and plants with crassulacean acid metabolism (CAM): The role of hydraulic descent. *Ecohydrology*, *10*(3), e1799. https://doi.org/10.1002/eco.1799

Zeng, X. (2001). Global vegetation root distribution for land modeling. *Journal of Hydrometeorology*, *2*, 525–530. https://doi.org/10.1175/1525-7541(2001)002<0525:GVRDFL>2.0.CO;2

Zheng, Z., & Wang, G. (2007). Modeling the dynamic root water uptake and its hydrological impact at the Reserva Jaru site in Amazonia. *Journal of Geophysical Research*, *112*, G04012. https://doi.org/10.1029/2007JG000413