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## Effects of nitrogen limitation on hydrological processes in CLM4-CN

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[1] The role of nitrogen limitation on photosynthesis downregulation and stomatal conductance has a significant influence on evapotranspiration and runoff. In the current Community Land Model with coupled Carbon and Nitrogen cycles (CLM4-CN), however, the carbon and water coupling in stomata is not linked to nitrogen limitation. We modify the incomplete linkages between carbon, nitrogen, and water, and examine how nitrogen limitation affects hydrological processes in CLM4-CN. We then evaluate if the modification can improve the simulation of carbon and water fluxes. Applying the effects of nitrogen limitation on stomatal conductance significantly decreases leaf photosynthesis. It leads to a reduction in canopy transpiration, thereby increasing total runoff, mainly due to increasing subsurface runoff. More available soil water for vegetation from the reduced transpiration helps increase gross primary productivity (GPP) in the relatively moisture-limited regions of grassland/steppe and savanna. However, in the tropics and boreal forest regions, changes in soil water by nitrogen limitation are insignificant, and GPP decreases directly by down-regulated leaf photosynthesis. Decreasing canopy transpiration and increasing runoff from nitrogen limitation improve simulating latent heat flux and runoff by reducing high biases for latent heat flux in the tropics and low biases for runoff in the tropics and northern high latitudes. In addition, the CLM4-CN with leaf-level nitrogen limitation reduces model biases in tropical GPP. Nitrogen limitation on the leaf-level significantly affects hydrological processes in CLM4-CN and improves the simulation of carbon and water fluxes. This process should be included with other recent improvements to reduce model biases as much as possible.

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### 1. Introduction

[2] In order to correctly estimate water demand and supplies, it is important to consider the effects of vegetation on the hydrological cycle. Carbon and water are coupled through the leaf's stomata, which allows CO<sub>2</sub> uptake from the atmosphere through photosynthesis and water to exit through transpiration [Ball *et al.*, 1987; Collatz *et al.*, 1991] as shown in Figure 1. This carbon and water coupling can be explained by the Ball-Berry conductance model [Ball *et al.*, 1987]. In this model, stomatal conductance changes directly with CO<sub>2</sub> assimilation rate scaled by relative humidity, and inversely by the

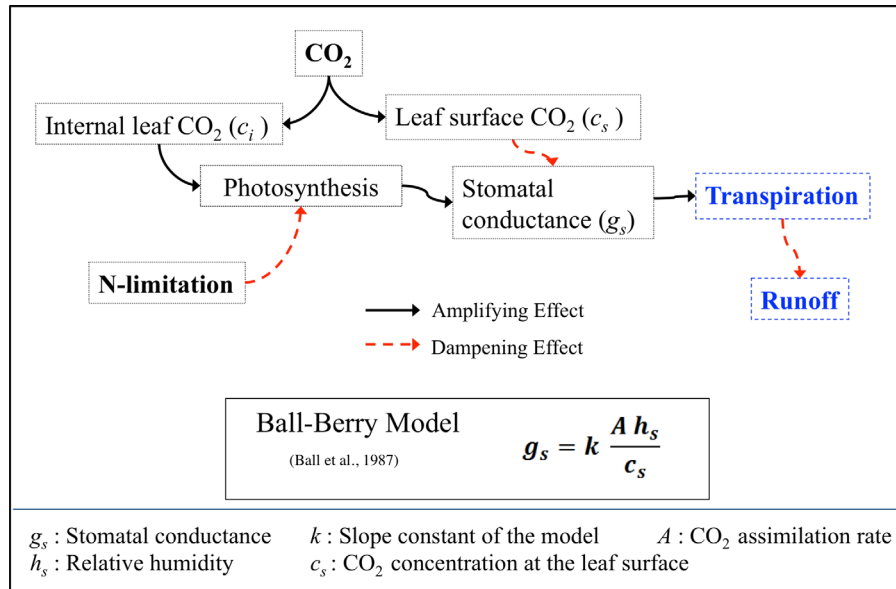
CO<sub>2</sub> concentration at the leaf surface. In this coupling, two different feedbacks are evident. First, elevated CO<sub>2</sub> increases CO<sub>2</sub> concentration at the leaf surface, which is inversely proportional to stomatal conductance (“negative coupling”). On the other hand, elevated CO<sub>2</sub> increases internal leaf CO<sub>2</sub> through CO<sub>2</sub> assimilation, which is proportional to photosynthetic rate and thereby gross primary productivity (GPP) through CO<sub>2</sub> fertilization (“positive coupling”). So stomatal conductance is proportional to atmospheric CO<sub>2</sub> through positive coupling, but it is inversely proportional to atmospheric CO<sub>2</sub> through negative coupling. Elevated CO<sub>2</sub> also increases leaf area index (LAI) [McMurtrie *et al.*, 2008; Ainsworth and Long, 2005], which can help compensate for the reduced stomatal conductance [Kergoat *et al.*, 2002; Leakey *et al.*, 2009]. Photosynthesis and transpiration codepend via stomatal conductance, and it shows the critical importance of ecophysiology and biogeochemistry for surface physics [Bonan *et al.*, 2011].

[3] Nitrogen limitation is another important component in the coupling between carbon and water, and can affect the positive coupling. Nitrogen is the most limiting nutrient to net primary productivity (NPP) in mid-

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**Figure 1.** Carbon-Nitrogen-Water coupling through leaf's stomata.

high latitudes [Vitousek and Howarth, 1991]. Nitrogen limitation diminishes CO<sub>2</sub> fertilization on terrestrial plant productivity in unmanaged ecosystems [Langley and Magonigal, 2010]. For example, NPP in northern and temperate ecosystems is limited by the availability of inorganic nitrogen [e.g., McGuire et al., 1992]. In terrestrial ecosystem simulations, Felzer et al. [2009, 2011] show that accounting for how climate warming and elevated CO<sub>2</sub> affect nitrogen limitation can have a significant effect on runoff through these carbon-water linkages in the eastern and western U.S. Therefore, nitrogen limitation can play an important role in the carbon and water coupling as it can reduce photosynthetic rates [e.g., Sokolov et al., 2008; Thornton et al., 2009; Bonan and Levis, 2010]. By reducing photosynthetic rates, nitrogen limitation can diminish the carbon-water positive coupling and reduce stomatal conductance. This carbon-nitrogen-water coupling leads to a change in canopy transpiration, and thereby runoff. In addition, changing transpiration affects photosynthesis through water stress. Under N-limiting conditions, leaf photosynthesis is more sensitive to reduced stomatal conductance at elevated CO<sub>2</sub> levels, and therefore may respond with an even larger increase in LAI [Ainsworth and Long, 2005; McMurtrie et al., 2008]. We could consider other components such as relative humidity and temperature in this coupling, but in this study, we focus on nitrogen limitation effects in the carbon-nitrogen-water coupling through leaf's stomata.

[4] In order to consider the role of nitrogen cycling in the coupling between carbon and water, we use the Community Land Model with coupled Carbon and Nitrogen cycles (CLM-CN). Carbon-nitrogen cycle coupling in CLM-CN reduces the simulated global terrestrial carbon uptake response to increasing atmospheric CO<sub>2</sub> concentration by 74%, relative to the carbon-only CLM model [Thornton et al., 2007]. How-

ever, the simulated global GPP (~163 PgC/yr) in the latest version of CLM-CN is still higher than observational estimates (~123 PgC/yr) [Beer et al., 2010] due to high bias in the tropics [Lawrence et al., 2011; Bonan et al., 2011, 2012]. More importantly, the carbon and nitrogen coupling is not linked to leaf's stomata, and thus there are missing linkages between leaf-level photosynthesis, canopy transpiration, and hydrological processes in terms of nitrogen limitation in the current CLM-CN. We explain more about these feedbacks in detail in section 2.1.1. In this study, we examine the effects of nitrogen limitation on carbon-nitrogen-water coupling in leaf's stomata and thereby hydrological processes using the version 4 of CLM-CN (CLM4-CN). In addition, we evaluate model outputs from nitrogen limitation experiments using observational data sets for carbon and water fluxes.

## 2. Methods and Data

### 2.1. Model Description and Experiments

[5] CLM4-CN is the result of merging the biophysical framework of CLM4 [Oleson et al., 2010; Lawrence et al., 2011] with the prognostic carbon and nitrogen dynamics of the terrestrial biogeochemistry model, Biome-BGC version 4.1.2 [Thornton and Rosenbloom, 2005]. CLM4 incorporates several significant scientific advances over CLM3, including revised soil hydrology and snow processes, organic and deep soils, and the ability to model transient land cover change [Oleson et al., 2010]. In addition, improvements are made to the way the offline forcing data (i.e., observed meteorological forcing) are applied across the diurnal cycle and to the partitioning of solar radiation into direct versus diffuse radiation [Lawrence et al., 2011]. One of the major new capabilities in the model, particularly important for this study, is a representation of nitrogen-limiting

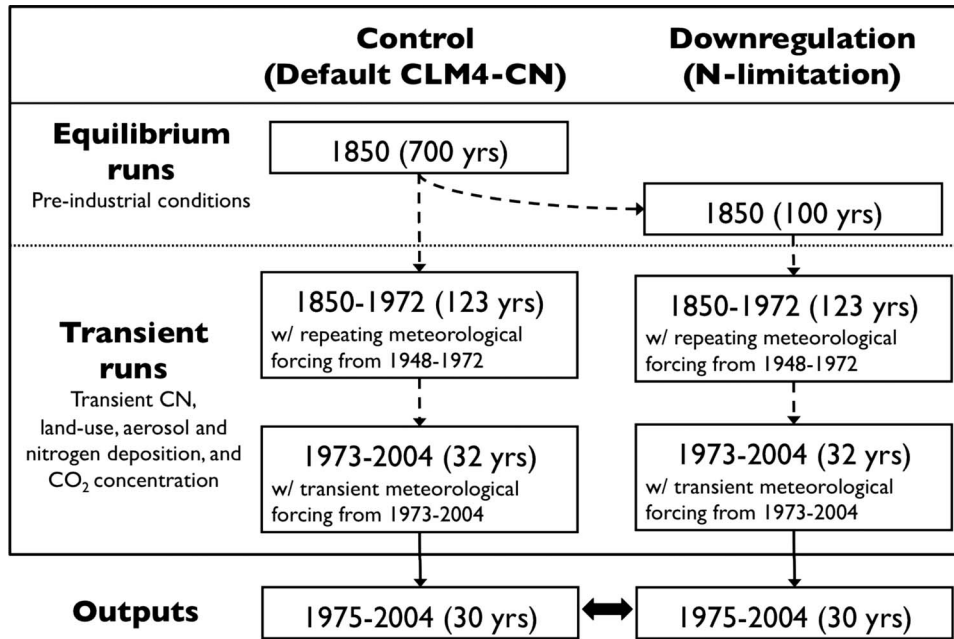


Figure 2. Experimental design for control and downregulation experiments.

effects on the carbon cycle. CLM4-CN is prognostic with respect to all carbon and nitrogen state variables in the vegetation, litter, and soil organic matter, and retains all prognostic quantities for water and energy in the vegetation-snow-soil column from CLM4 [Thornton *et al.*, 2007]. Detailed descriptions for the biogeochemical components of CLM4-CN are in Thornton *et al.* [2007]. CLM4-CN model technical note is in preparation and the document will be available from <http://www.cesm.ucar.edu/models/ccsm4.0/clm/>. However, the nitrogen-limiting effect is not linked to the hydrological processes through stomatal conductance as explained in the following section.

#### 2.1.1. Nitrogen Limitation (Downregulation) Approach

[6] In CLM4-CN, canopy-level photosynthesis (or GPP) is derived by summing the sunlit and shaded leaf-level rates multiplied by the sunlit and shaded leaf area indices, with potential reductions due to limited availability of mineral nitrogen, as described in Oleson *et al.* [2010]. The carbon available for allocation to new growth is calculated at each model time step [Thornton and Zimmermann, 2007]. Total plant nitrogen demand for the time step is calculated from carbon allometry and nitrogen concentration for each tissue type specified by plant functional type (PFT). CLM4-CN uses C/N ratios from the literature [White *et al.*, 2000] for different PFTs to determine the nitrogen concentrations at the tissue level, and therefore is not fully prognostic. Unmet plant nitrogen demand is translated to an excess carbon supply, which is not allocated due to nitrogen limitation [McGuire *et al.*, 1992]. A direct downregulation of canopy-level photosynthetic rate (down-regulated GPP) is scaled by a nitrogen limitation factor, which is calculated by dividing the excess carbon flux

by actual GPP. While the current CLM4-CN has a nitrogen limitation factor to scale GPP, the stomatal resistance (reciprocal of stomatal conductance) is not linked to the down-regulated photosynthesis by nitrogen limitation. For example, the photosynthesis used to control stomatal conductance is calculated from the stomata subroutine within the canopy fluxes module. Then, the leaf-level photosynthesis is used to calculate GPP, and GPP is scaled by the nitrogen limitation factor in the carbon and nitrogen allocation module. Hence, the photosynthesis used to control stomatal conductance is not affected by nitrogen limitation. It could result in missing feedbacks between leaf-level photosynthesis, transpiration, and hydrological processes in terms of nitrogen limitation in CLM4-CN.

[7] In order to fix this deficiency, we scale the photosynthesis in the stomata subroutine by the nitrogen limitation factor for GPP in the carbon and nitrogen allocation module from the previous time step. From the downregulation approach, leaf-level photosynthesis is scaled by the nitrogen limitation factor, and then stomatal conductance is changed by the scaled photosynthesis through the Ball-Berry function. Therefore, nitrogen limitation may affect transpiration in plants and resulting runoff. The fixed version of CLM4-CN for leaf-level nitrogen limitation is available upon request.

#### 2.1.2. Experimental Design

[8] In this simulated study, *control* is a default CLM4-CN and *downregulation* is a fixed CLM4-CN by leaf-level nitrogen limitation (Figure 2). We perform equilibrium runs for initial conditions followed by transient experiments with the Community Earth System Model 1.0.1 (CESM 1.0.1) using CLM4-CN. To get

initial conditions, we run stand-alone CLM4 for 700 simulation years with a repeating 25 year (1948–1972) meteorological forcing and CN, land-use, aerosol and nitrogen deposition, and a CO<sub>2</sub> level for 1850 conditions. From the equilibrium run of the default CLM4-CN (*control*), we save the last restart file and use it as initial conditions for the equilibrium simulations of the nitrogen limitation experiment (*downregulation*) for 100 years. The equilibrium runs for the *control* and *downregulation* provide initial conditions for transient simulations of the *control* and *downregulation*, respectively. Transient simulations for 1850–1972 use transient CN, land-use, aerosol and nitrogen deposition, and CO<sub>2</sub> concentration during 1850–1972, but with a repeating 25 year (1948–1972) meteorological forcing. The simulations for 1850–1972 provide initial conditions for 1973 to the subsequent experiments from 1973 to 2004. The simulations for 1973–2004 use all transient components during 1973–2004 with a transient meteorological forcing. To compare the *downregulation* with the *control* runs, we use 30 year outputs from the 1973–2004 transient experiments, excluding the first 2 years from each simulation. Experimental designs for determining initial conditions and transient simulations are shown in Figure 2.

[9] To compare *downregulation* and *control* runs, we examine the time series of globally (60°S–90°N) averaged annual mean, spatial percentage changes, and spatial differences using 30 year (1975–2004) model outputs. For spatial differences, a student *t* test is conducted to quantify the statistical significance of the difference of means. We use the *t* statistic for unequal population variances, because the *F* tests for the variances of the two samples show significant differences at the 90% in some regions over the globe. Statistically insignificant regions are masked out and significant regions at the 95% level are shown in the map figures.

## 2.2. Observational Data Sets for Evaluation

[10] As newer observations of carbon and water fluxes become available, it is increasingly important to validate biogeochemical models to improve future projections of atmospheric CO<sub>2</sub> concentrations. Improved validation may require changes to existing model parameterizations, which affect model projections of future carbon and water fluxes. As discussed in the previous section, the effects of nitrogen limitation on leaf photosynthesis are not considered in the current version of CLM4-CN when determining transpiration. This incomplete linkage between carbon-nitrogen-water could affect how well the model output agrees with observations. For example, CLM4 simulates high rates of leaf photosynthesis compared with other photosynthesis models [Chen *et al.*, 2011], and the model overestimates carbon uptake due to photosynthesis compared with data-driven estimates and other models, with a particular high bias in the tropics [Beer *et al.*, 2010]. Furthermore, CLM4-CN produces a high bias for evapotranspiration and a low bias for runoff [Lawrence *et al.*, 2011]. In evaluations of model outputs, we address how model biases in carbon and water fluxes

(evapotranspiration, runoff, and GPP) may result from current model assumptions about the effect of nitrogen limitation on transpiration in CLM4-CN.

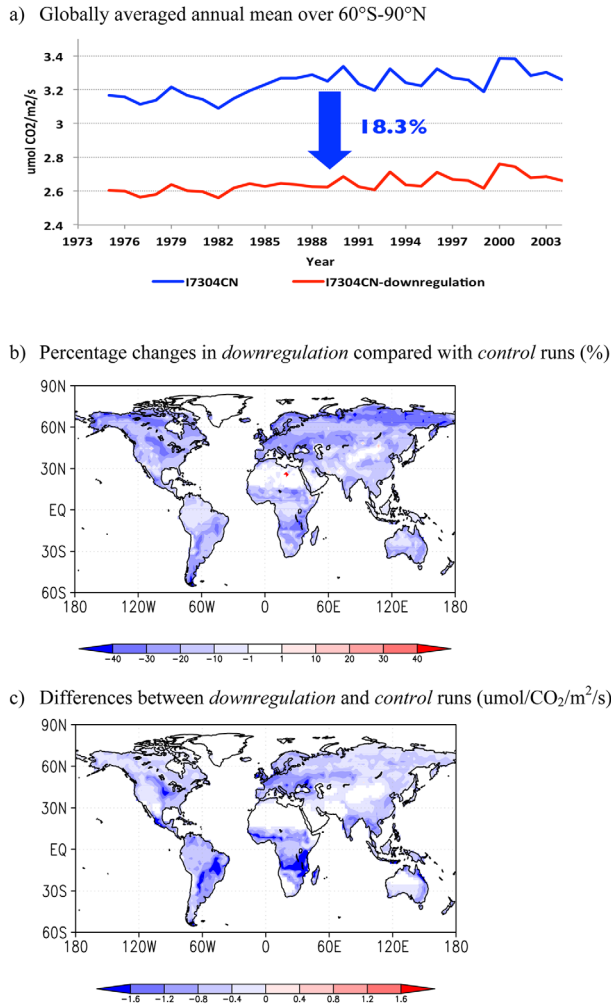
[11] In order to evaluate the CLM4-CN *control* and *downregulation* runs, we use gridded observational carbon and water flux data from FLUXNET-MTE [Jung *et al.*, 2009, 2011]. FLUXNET-MTE is FLUXNET observations of carbon dioxide, water and energy fluxes upscaled to the global scale using the machine learning technique, Model Tree Ensembles (MTE). MTE method is used to predict site-level GPP, terrestrial ecosystem respiration, net ecosystem exchange, latent and sensible heat based on remote sensing data, climate and meteorological data, and information on land use [Jung *et al.*, 2011]. Jung *et al.* [2011] applied the trained MTEs to generate global flux fields at a 0.5° by 0.5° spatial resolution, covering the globe except for Antarctica, with a monthly temporal resolution from 1982 to 2008. In addition, we use surface and subsurface runoff data from the Global Soil Wetness Project 2 (GSWP-2) [Dirmeyer *et al.*, 2006]. GSWP-2 is the multimodel analysis of land surface state variables and fluxes that combines the simulations of more than a dozen different global land surface models. The surface fluxes output data from GSWP-2 have been used as the best estimate of “truth” in numerous global and regional climate-modeling studies [Boone *et al.*, 2010]. The GSWP-2 product is available globally over land on a regular 1° by 1° grid for a 10 year period from January 1986 to December 1995. For the comparisons with CLM4-CN outputs, we upscale FLUXNET-MTE and GSWP-2 data sets spatially to match the 1.9° by 2.5° (longitude by latitude) grid for the model.

## 3. Results and Discussion

### 3.1. Effects of Leaf-Level Nitrogen Limitation on Hydrological Processes

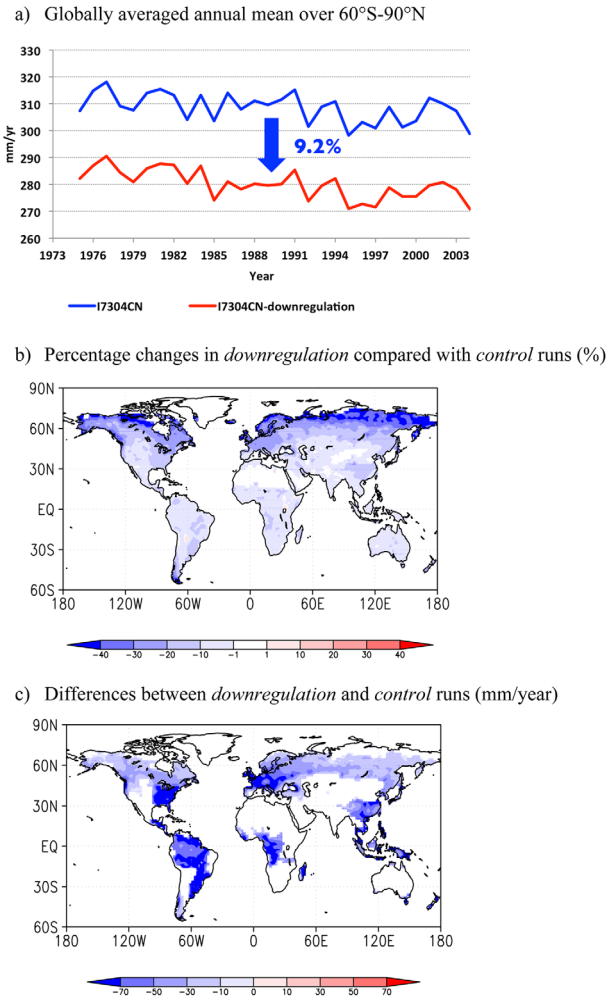
[12] The trend of leaf photosynthesis, which is the sum of sunlit and shaded leaf photosynthesis, is positive in both the *control* and *downregulation* runs, with increasing CO<sub>2</sub> concentration during 1975–2004 (Figure 3a). On the other hand, after scaling leaf photosynthesis by a nitrogen limitation factor, the global annual mean leaf photosynthesis is down-regulated by 18.3%. Leaf photosynthesis decreases by 10% in the tropics, 20% in the midlatitudes, and 30–40% in the northern high latitudes due to nitrogen limitation (Figure 3b). Absolute values of leaf photosynthesis significantly decrease over most vegetated regions of the globe in the *downregulation* run (Figure 3c). Larger reductions in photosynthesis are simulated over Grassland/steppe in Europe and North America and savanna in South America and Africa. In a meta-analysis of the effects of nitrogen addition, LeBauer and Treseder [2008] found an overall nitrogen limitation growth effect of 29%, ranging from 11 to over 100%, including substantial nitrogen limitation in tropical forests.

[13] The use of down-regulated photosynthesis decreases stomatal conductance and then decreases canopy transpiration (Figure 4). During 1975–2004, global



**Figure 3.** Comparisons of leaf photosynthesis between *downregulation* and *control* runs (a) global annual mean (60°S–90°N), (b) percentage changes, and (c) differences (umol/CO<sub>2</sub>/m<sup>2</sup>/s). White areas in Figure 3c represent statistically insignificant changes.

annual mean canopy transpiration decreases by 9.2%, with decreases of 10% in the tropics and midlatitudes and 30–40% in the northern high latitudes (Figures 4a and 4b). Statistically significant differences occur in the tropical regions, northern and eastern North America, Europe, Russia, and South China (Figure 4c). The results suggest that down-regulated photosynthesis decreases transpiration by lowering stomatal conductance. These results are consistent with experiments in which nitrogen fertilization results in increased photosynthesis but reduced stomatal conductance [Cantin *et al.*, 1997; Samuelson, 2000]. Recently, Keenan *et al.* [2013] found that rising levels of atmospheric CO<sub>2</sub> mean plants are able to partly close their leaf pores and still get enough CO<sub>2</sub> for photosynthesis. Furthermore, the closing of stomata especially noticed in their field study of broadleaf trees, reduces leaf transpiration, implying less water uptake from the ground (and potentially increasing runoff).

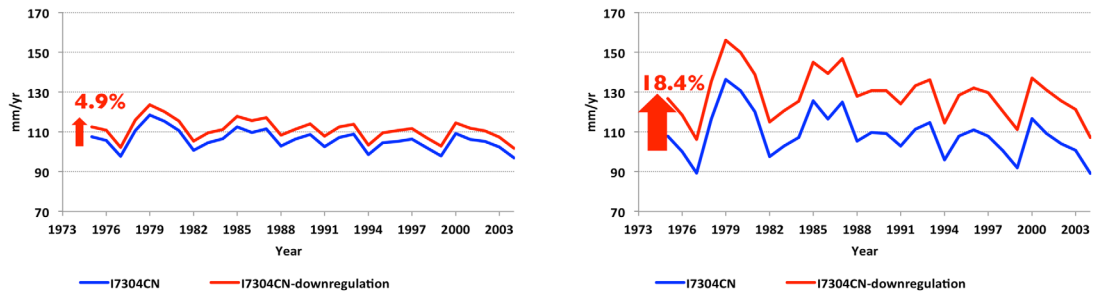


**Figure 4.** Comparisons of canopy transpiration between *downregulation* and *control* runs (a) global annual mean (60°S–90°N), (b) percentage changes, and (c) differences (mm/yr). White areas in Figure 4c represent statistically insignificant changes.

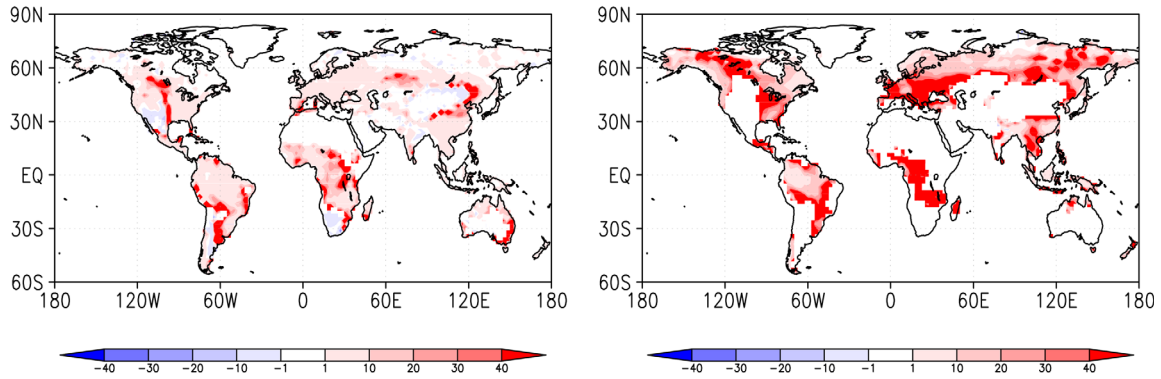
[14] Spatial patterns of decreasing total evapotranspiration, which is the sum of canopy transpiration, canopy evaporation, and ground evaporation, are consistent with those of decreasing canopy transpiration in the *downregulation* experiment (not shown here). PFT-dependent differences in latent heat fluxes (LE) between *downregulation* and *control* runs support the decreased total evapotranspiration as showing the reduced LE in all PFTs (Figure 9a). LE is the total evapotranspiration in CLM4-CN converted to energy units (W/m<sup>2</sup>).

[15] Reducing canopy transpiration can lead to increasing runoff over vegetated regions. There is an increase in both surface and subsurface runoff in the *downregulation* run (Figure 5a). However, surface runoff increases (4.9%; left) are not as large as increases in subsurface runoff (18.4%; right). Spatial differences of subsurface runoff significantly increase in tropical savanna and midlatitude grassland/steppes by more than 40% (Figures 5b and 5c, right). Therefore, increasing

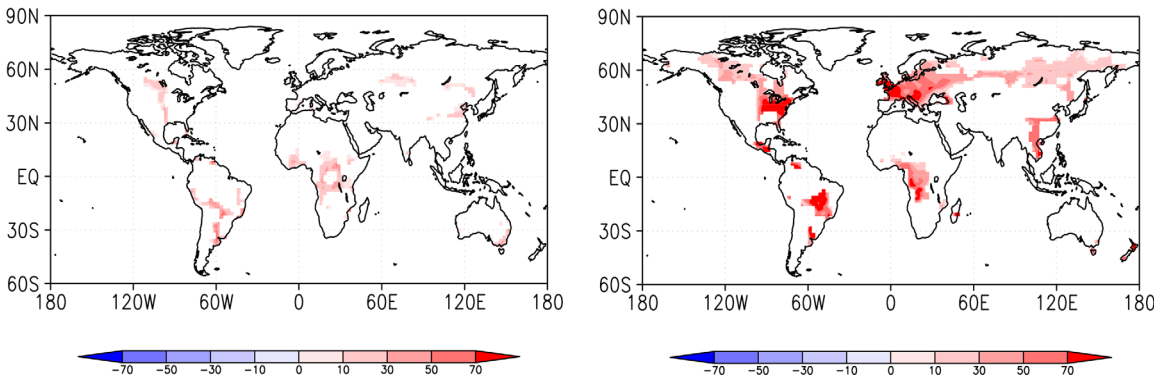
a) Globally averaged annual mean over 60°S–90°N



b) Percentage changes in *downregulation* compared with *control* runs (%)



c) Differences between *downregulation* and *control* runs (mm/year)



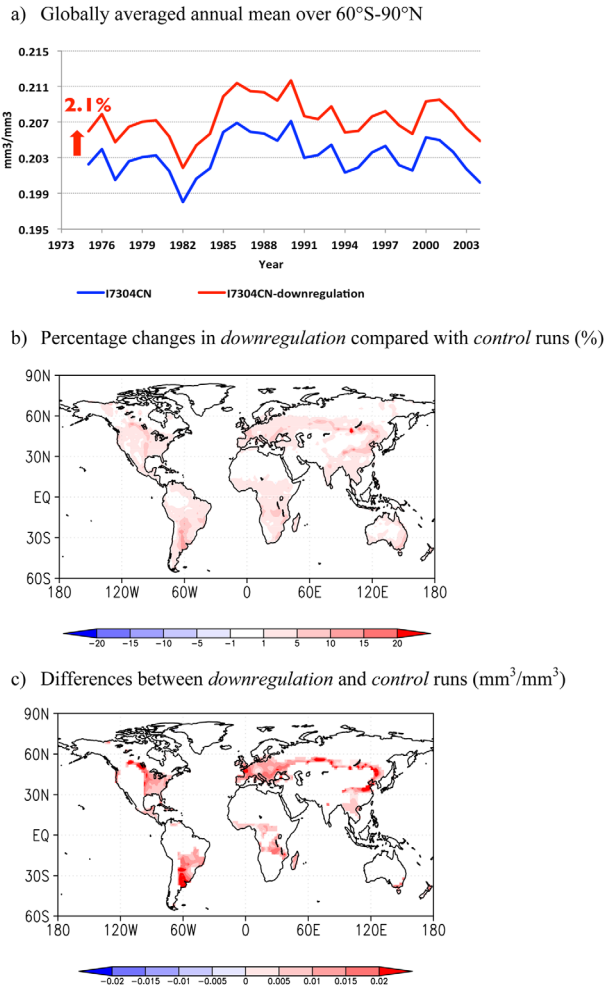
**Figure 5.** Comparisons of surface runoff (left) and subsurface runoff (right) between *downregulation* and *control* runs (a) global annual mean (60°S–90°N), (b) percentage changes, and (c) differences (mm/yr). White areas in Figure 5c represent statistically insignificant changes.

runoff is mainly due to increasing subsurface runoff by lower canopy transpiration in the *downregulation* run, which means lower transpiration requires less water from the deeper rooting depths.

[16] More available soil water due to decreasing plant transpiration is simulated in the *downregulation* run, with a global increase of 2.1% (Figure 6a). Statistically significant increases of more than 5% are shown in grassland/steppes and savanna in the *downregulation*

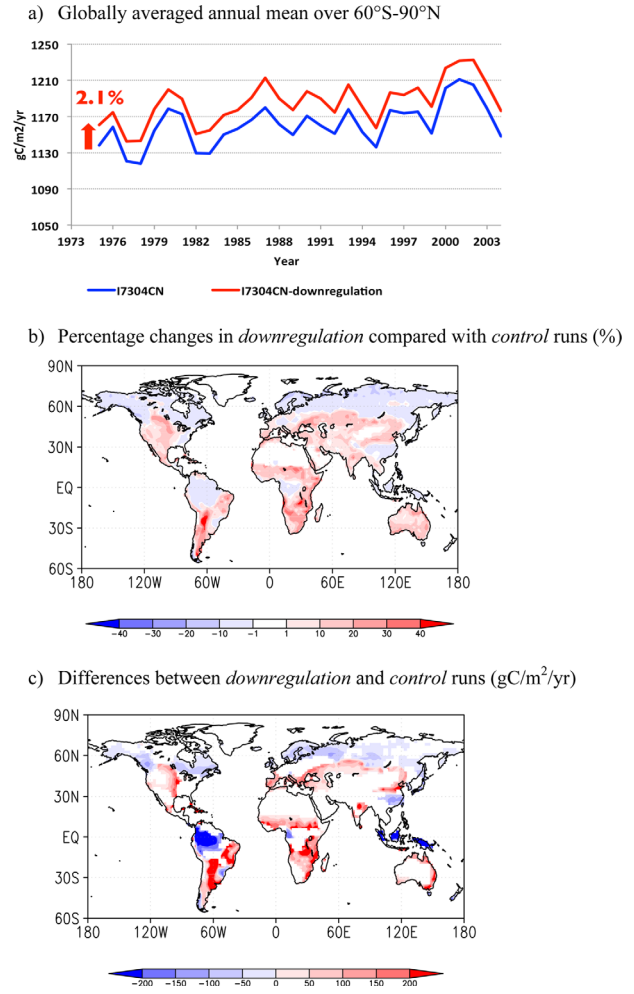
run (Figures 6b and 6c). More soil water reduces water stress and can lead to more favorable conditions for terrestrial plant productivity.

[17] Global annual mean GPP is increasing from 1975 to 2004, which is consistent with increasing leaf photosynthesis during the same period (Figure 7a). However, GPP in the *downregulation* run is greater than in the control run by 2.1% globally, which is opposite from leaf photosynthesis. In addition, the spatial



**Figure 6.** Comparisons of volumetric soil water between *downregulation* and *control* runs (a) global annual mean (60°S–90°N), (b) percentage changes, and (c) differences ( $\text{mm}^3/\text{mm}^3$ ). White areas in Figure 6c represent statistically insignificant changes.

distributions of GPP differences between the *downregulation* and *control* runs are not consistent with those of leaf photosynthesis (Figures 7b and 7c). For example, GPP significantly decreases in tropical and boreal forests, but it significantly increases in grassland/steppe and savanna regions (Figure 7c). In the PFT-dependent differences in GPP, the GPPs of the plants in tropical and boreal regions decrease except for tropical deciduous trees, while the GPPs of crop, grass, and shrub in tropical and temperate regions increase (Figure 9b). Increasing GPP over grassland/steppe and savanna regions leads to increasing GPP in the global annual mean difference (Figure 7a). Changes in soil water (Figure 6c) could explain the spatial distribution of GPP differences. In the *downregulation* run, soil water significantly increases over grassland/steppe and savanna regions. Consequently, increasing soil water in the relatively moisture-limited regions decreases water stress and results in an increase in GPP, consistent with data from African savannas [Weber *et al.*, 2009]. In addition,

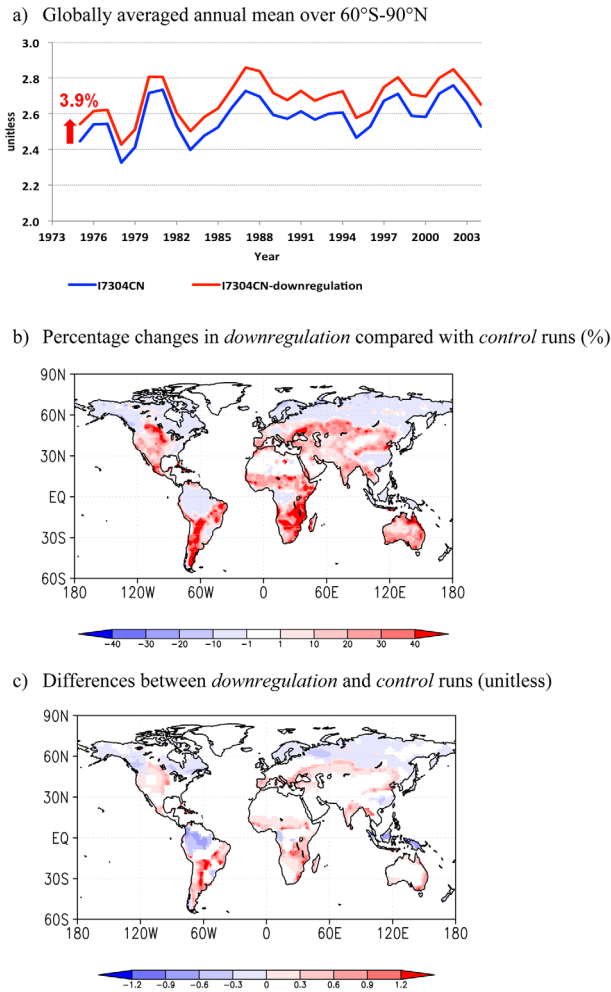


**Figure 7.** Comparisons of gross primary productivity (GPP) between *downregulation* and *control* runs (a) global annual mean (60°S–90°N), (b) percentage changes, and (c) differences ( $\text{gC}/\text{m}^2/\text{yr}$ ). White areas in Figure 7c represent statistically insignificant changes.

more soil water from reducing evapotranspiration increases nitrogen mineralization and reduces nitrogen limitation [Felzer *et al.*, 2011]. On the other hand, changes in soil water in tropical rainforest and boreal forest regions are insignificant (Figure 6c), and thus decreasing leaf photosynthesis from nitrogen limitation directly decreases GPP in the relatively moist regions (Figures 7c and 9b).

[18] In CLM4-CN, GPP is derived by multiplying leaf-level photosynthesis by LAI. Changes in total projected LAI in the *downregulation* run are consistent with changes in GPP, with significant increases in grassland/steppe and savanna and decreases in tropical rainforest and boreal forest regions (Figure 8). The effect of nitrogen limitation reduces leaf area in the relatively moist regions directly by reducing leaf photosynthesis, while LAI significantly increases in the relatively moisture-limited regions by reducing water stress through the carbon-nitrogen-water coupling. In water-limited ecosystems, increasing LAI by





**Figure 8.** Comparisons of leaf area index (LAI) between *downregulation* and *control* runs (a) global annual mean ( $60^{\circ}\text{S}$ – $90^{\circ}\text{N}$ ), (b) percentage changes, and (c) differences. White areas in Figure 8c represent statistically insignificant changes.

reducing water stress with N-induced reduction in stomatal conductance compensates for decreasing leaf-level photosynthesis by nitrogen limitation. In addition, if there is more water available in N-limited regions, that will allow for more decomposition, which results in great net N-mineralization, available inorganic nitrogen, and plant nitrogen uptake, thus helping to alleviate the N-limiting conditions and thus increasing LAI. Total projected LAI in the moisture-limited regions increases by more than 40% and leads to a global increase of 3.9%. These global and regional LAI changes explain GPP changes in the *downregulation* run. The simulated results of GPP are consistent with recent findings based on observational analysis and terrestrial ecosystem modeling that the effect of water availability on GPP is large in savannas, shrublands, grasslands, and agricultural areas, but relatively less in tropical and boreal forests [Beer *et al.*, 2010; Felzer *et al.*, 2011].

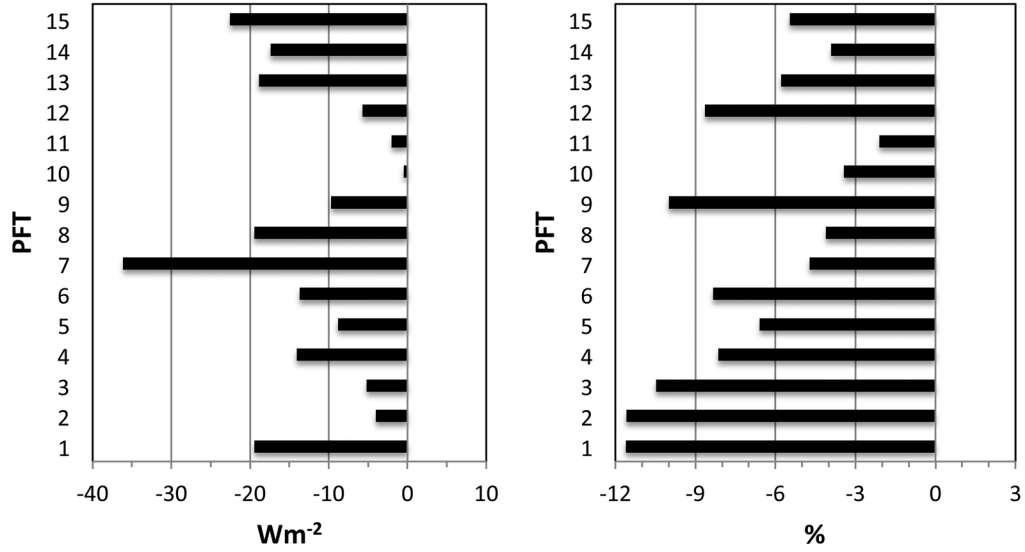
### 3.2. Evaluating Model Outputs

[19] We examine if there is an improvement in simulating carbon and water fluxes in the *downregulation* run relative to the *control* run. We base the evaluation on LE and GPP from FLUXNET-MTE for 1982–2004 and surface and subsurface runoff from GSWP-2 for 1986–1995. The global spatial distribution of annual mean LE for 1982–2004 from the CLM4-CN *control* is generally consistent with that from FLUXNET-MTE (Figures 10a and 10b). LE is largest in tropical climates followed by midlatitude humid climates in East Asia, eastern North America, and western and central Europe. However, the magnitude of LE from CLM4-CN is different from FLUXNET-MTE, with high biases in the tropics and midlatitudes by  $30$ – $40$   $\text{W}/\text{m}^2$  (Figure 10c). In the *downregulation* run, LE decreases from the *control* case (Figure 10d), which is due to a significant reduction in canopy transpiration (Figure 4). Decreasing LE in the *downregulation* run reduces high biases in the tropics and midlatitudes. Decreasing LE in the northern high latitudes may increase low biases of LE over those regions, but the biases are relatively less than tropical biases. Zonally averaged LE (Figure 10e) from the CLM4-CN *control* shows high biases, so decreasing LE in the *downregulation* run reduces the biases by  $5$ – $10$   $\text{W}/\text{m}^2$  in the tropics.

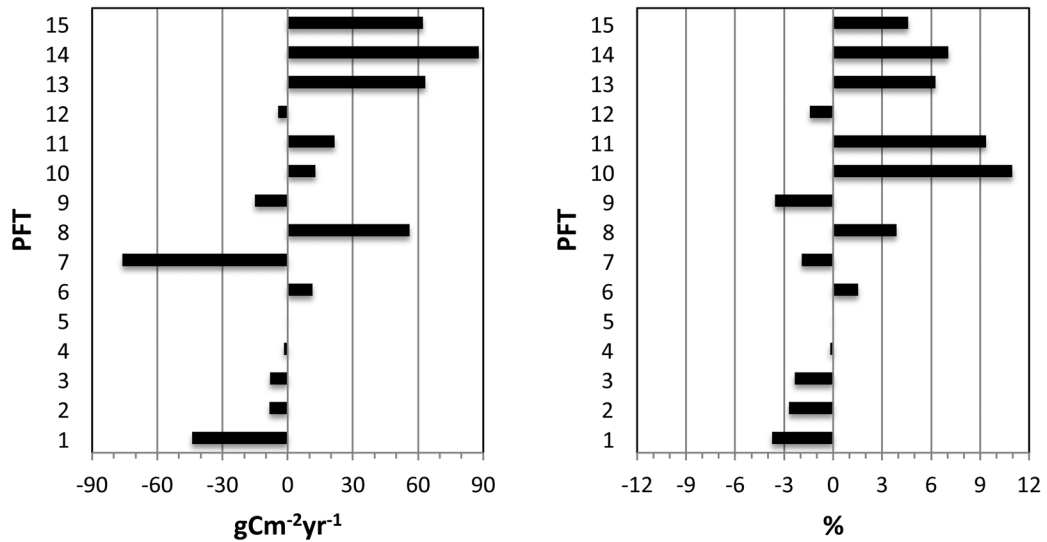
[20] Decreasing canopy transpiration results in a significant increase in total runoff in the *downregulation* run, mainly due to changes in subsurface runoff (Figure 5). We evaluate total runoff (sum of surface and subsurface runoff) from CLM4-CN using the GSWP-2 data from 1986 to 1995. The global spatial distributions of annual mean runoff from the CLM4-CN *control* show large runoff in the western Amazon, Southeast Asia, Ganges River in South Asia, coastal regions of the Gulf of Alaska, and western Scandinavia, which are consistent with those from GSWP-2 (Figures 11a and 11b). The spatial differences between the CLM4-CN *control* and GSWP-2 show that CLM4-CN runoff is lower than GSWP-2 across the globe, with significant low biases in the tropics and northern high latitudes by  $300$   $\text{mm}/\text{yr}$  (Figure 11c). In the *downregulation* run, runoff increases across the globe from the *control* case (Figure 11d). Zonally averaged annual mean of runoff from CLM4-CN is generally well captured, with two peaks in the equatorial and northern high latitude regions, even though there are low biases in the highest runoff regions (Figure 11e). Therefore, the increasing runoff reduces low runoff biases in the current CLM4-CN, especially in the tropics, by  $50$ – $100$   $\text{mm}/\text{yr}$  (Figure 11f) and the northern high latitudes by  $20$   $\text{mm}/\text{yr}$  (Figure 11g).

[21] Lastly, we evaluate GPP from the CLM4-CN *control* and *downregulation* runs using GPP from FLUXNET-MTE for 1982–2004. The global spatial distributions of GPP from the CLM4-CN *control* generally capture those from the observations, but CLM4-CN simulates GPP too high in the tropical regions (Figures 12a and 12b). In other regions, there are high model biases in boreal forests, but low biases in savanna in Africa and South America (Figure 12c). On the other

a) LE differences between downregulation and control by PFTs



b) GPP differences between downregulation and control by PFTs

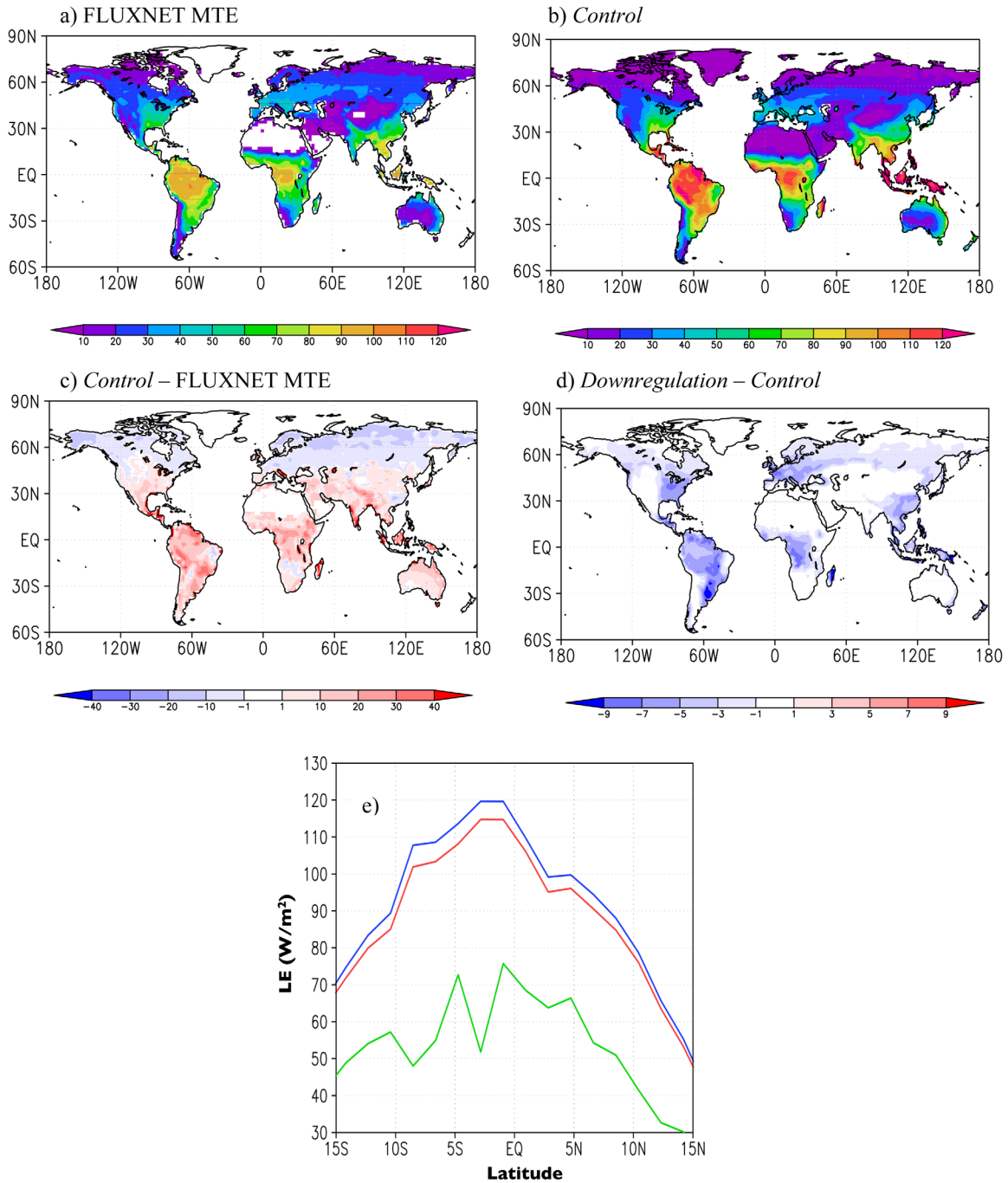


Plant Functional Type (PFT) in Y-axis

- |   |  |                          |
|---|--|--------------------------|
| 1- Needleleaf evergreen tree, boreal    | 7- Broadleaf evergreen tree, tropical    | 12- C3 grass, arctic     |
| 2- Needleleaf deciduous tree, boreal    | 8- Broadleaf deciduous tree, tropical    | 13- C3 grass, non-arctic |
| 3- Broadleaf deciduous tree, boreal     | 9- Broadleaf deciduous shrub, boreal     | 14- C4 grass             |
| 4- Needleleaf evergreen tree, temperate | 10- Broadleaf evergreen shrub, temperate | 15- C3 crop              |
| 5- Broadleaf evergreen tree, temperate  | 11- Broadleaf deciduous shrub, temperate |                          |
| 6- Broadleaf deciduous tree, temperate  |  |                          |

**Figure 9.** PFT-dependent differences in (a) LE and (b) GPP between *downregulation* and *control* runs. (left) absolute differences ( $W/m^2$  for LE and  $gCm^{-2} yr^{-1}$  for GPP) and (right) percentage differences (%).

hand, GPP from the *downregulation* run is less in the tropical and boreal forest regions, but more in grassland/steppe and savanna regions, relative to GPP from the *control* run (Figure 12d). The spatially different changes in GPP can reduce GPP biases in the current CLM4-CN. For example, annual mean GPP in the



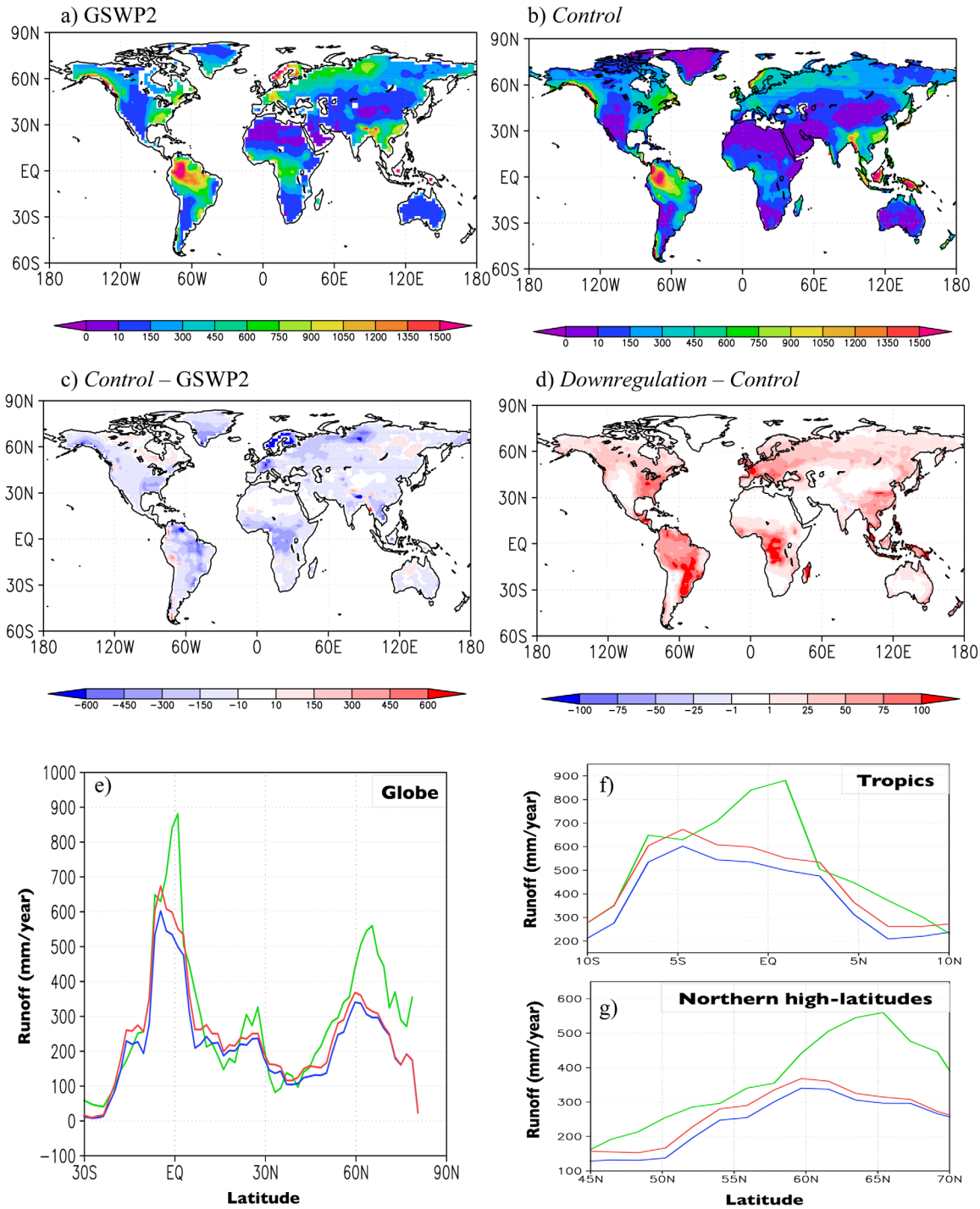
**Figure 10.** Evaluations of CLM4-CN control and downregulation with FLUXNET MTE for latent heat flux ( $W/m^2$ ), (a) FLUXNET MTE, (b) Control, (c) Control–FLUXNET MTE, (d) Downregulation–Control, and (e) zonal mean, with FLUXNET MTE (green), control (blue), and downregulation (red).

tropical Amazon in the downregulation run reduces high model biases over the tropical regions as a whole (Figure 12e), but by a very small amount.

#### 4. Conclusions and Remarks

[22] Nitrogen limitation at the leaf-level significantly affects hydrological processes in CLM4-CN. In the downregulation simulations in which nitrogen limitation

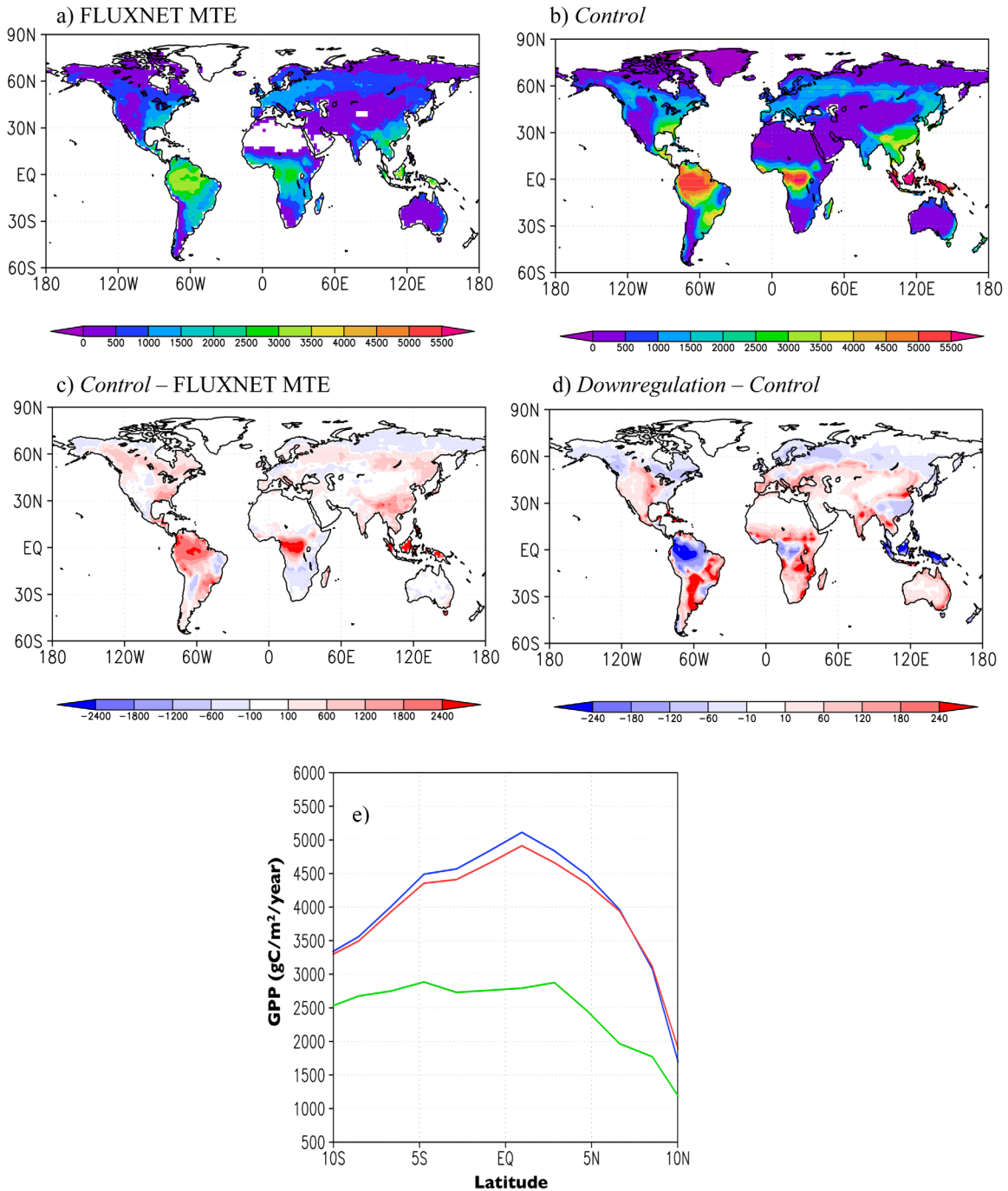
is applied to stomata, nitrogen limitation reduces leaf photosynthesis, which leads to a reduction in canopy transpiration by decreasing stomatal conductance, and results in increasing total runoff. Globally averaged leaf photosynthesis is down-regulated by 18.3%, with significant decreases over most vegetated regions of the globe. Therefore, the photosynthesis used to determine stomatal conductance is lower, and thereby global annual canopy transpiration decreases by 9.2%.



**Figure 11.** Evaluations of CLM4-CN *control* and *downregulation* with GSWP2 for total runoff (mm/yr), (a) FLUXNET MTE, (b) *Control*, (c) *Control*–FLUXNET MTE, (d) *Downregulation*–*Control*, and zonal mean for (e) globe, (f) tropics, and (g) northern high latitudes, with GSWP2 (green), *control* (blue), and *downregulation* (red).

Significant increases in runoff by reducing transpiration occur in tropical savanna and midlatitude grassland/steppes, where subsurface runoff increases by more than 40%. In addition, more available soil water results from decreasing canopy transpiration, which reduces water stress and provides more favorable conditions for plant productivity in moisture-limited regions. Thus,

changes in the hydrological cycle by nitrogen limitation affect changes in GPP through two different processes. In the tropical and boreal forested regions, reduced leaf photosynthesis by nitrogen limitation directly decreases GPP. On the other hand, in the grassland/steppe and savanna regions, the down-regulated photosynthesis indirectly affects GPP by the photosynthesis-stomatal



**Figure 12.** Evaluations of CLM4-CN control and downregulation with FLUXNET MTE for GPP ( $\text{gCm}^{-2} \text{yr}^{-1}$ ), (a) FLUXNET MTE, (b) Control, (c) Control–FLUXNET MTE, (d) Downregulation–Control, and (e) zonal mean, with FLUXNET MTE (green), control (blue), and downregulation (red). Figure 12d is the same as Figure 8b (30 year mean from 1975 to 2004) but in the different time period of 1982–2004.

conductance feedback: less leaf photosynthesis leads to less transpiration, more soil water, less water stress, and higher GPP. Thus, GPP in the downregulation run decreases in the relatively moist regions, but increases in the relatively moisture-limited regions, relative to the control.

[23] Significant changes in canopy transpiration and runoff due to nitrogen limitation on the leaf-level

reduce the biases of LE and runoff in CLM4-CN, relative to those from observational and multimodel ensemble data. High biases of LE in the tropics and midlatitudes are reduced by decreasing LE in the downregulation run. Low biases of total runoff in the tropics and northern high latitudes are also reduced by increasing runoff, mainly due to increasing subsurface runoff. In addition, CLM4-CN with leaf-level nitrogen

limitation reduces high GPP biases in tropical forests and low GPP biases in savanna regions, even though there are still high biases of GPP in the tropics. Recently, there were other efforts to reduce the GPP and LE biases in CLM4. The revised model of the photosynthesis-stomatal conductance parameterization from Bonan *et al.* [2011] greatly improved the GPP and evapotranspiration. More recently, Bonan *et al.* [2012] further improved the simulated GPP by using the photosynthetic parameter ( $V_{cmax}$ ) from observed global leaf trait syntheses. The revised model using the plant nitrogen storage pool in CLM4-CN [Thornton *et al.*, 2011] could improve the seasonality of nitrogen availability, which would contribute to a smaller GPP bias. After the dry bias in permafrost soils in CLM4 is reduced, the vegetation productivity simulated by the model is also improved [Swenson *et al.*, 2012]. The next logical step should be to combine all of these improvements, including those from this study.

[24] There are two different feedbacks in carbon and water coupling in stomata. Atmospheric  $CO_2$  is positively coupled with stomatal conductance by internal leaf  $CO_2$  levels, but is negatively coupled with stomatal conductance by leaf surface  $CO_2$  concentration. Increases in future atmospheric  $CO_2$  concentration will have counteracting effects on hydrological processes through these positive and negative couplings. Another interesting issue is whether changes in hydrological processes due to leaf-level nitrogen limitation could be large enough to alter near-surface and possibly large-scale climate conditions through changes in surface heat and moisture budgets. Furthermore, it may be important to explore how changes in runoff from nitrogen limitation in the northern high latitudes affect the freshwater flow into the Arctic and the resulting ocean conveyor belt circulation (i.e., meridional overturning in the Atlantic). To address these issues, CESM simulations with the fully coupled atmosphere, land, and ocean, using the advances from this study and also recent model improvements in CLM, are needed.

[25] The finding of this study provides useful information to the land/ecosystem-modeling community, as the current CLM-CN may be underestimating vegetation productivity and LAI in dry regions as a result of elevated  $CO_2$ , whereas it may be overestimating vegetation productivity and LAI in moist regions of the world. Most of the terrestrial biosphere models used in climate change assessments, including the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment, do not consider nitrogen limitations on net carbon storage [Sokolov *et al.*, 2008]. If the effects of nitrogen limitation on hydrological processes are applied to downscaled and climate impact models, then there might be substantial differences in runoff or crop yield that would have large human consequences.

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