

Seeing the Canopy for the Branches: Improved Within Canopy Scaling of Leaf Nitrogen

Key Points:

- We identified a mathematical inconsistency in a submodel scaling nitrogen from leaf to canopy as used in some global land surface models
- Correcting the inconsistency appreciably reduces predicted global gross primary production (GPP)
- We also show that ignoring twigs, branches, stems, and dead leaves in canopy shading schemes introduces errors in global GPP estimates

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Citation:

Butler, E. E., Chen, M., Ricciuto, D., Flores-Moreno, H., Wythers, K. R., Kattge, J., et al. (2020). Seeing the canopy for the branches: Improved within canopy scaling of leaf nitrogen. *Journal of Advances in Modeling Earth Systems*, 12, e2020MS002237. <https://doi.org/10.1029/2020MS002237>

Received 7 JUL 2020

Accepted 20 SEP 2020

Accepted article online 23 SEP 2020

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Abstract Transitioning across biological scales is a central challenge in land surface models. Processes that operate at the scale of individual leaves must be scaled to canopies, and this is done using dedicated submodels. Here, we focus on a submodel that prescribes how light and nitrogen are distributed through plant canopies. We found a mathematical inconsistency in a submodel implemented in the Community and Energy Land Models (CLM and ELM), which incorporates twigs, branches, stems, and dead leaves in nitrogen scaling from leaf to canopy. The inconsistency leads to unrealistic (physically impossible) values of the nitrogen scaling coefficient. The mathematical inconsistency is a general mistake, that is, would occur in any model adopting this particular submodel. We resolve the inconsistency by allowing distinct profiles of stems and branches versus living leaves. We implemented the updated scheme in the ELM and find that the correction reduces global mean gross primary production (GPP) by 3.9 Pg C (3%). Further, when stems and branches are removed from the canopy in the updated model (akin to models that ignore shading from stems), global GPP increases by 4.1 Pg C (3.2%), because of reduced shading. Hence, models that entirely ignore stem shading also introduce errors in the global spatial distribution of GPP estimates, with a strong signal in the tropics, increasing GPP there by over 200 g C m⁻² yr⁻¹. Appropriately incorporating stems and other nonphotosynthesizing material into the light and nitrogen scaling routines of global land models, will improve their biological realism and accuracy.

Plain Language Summary Land surface models that estimate the flow of chemical elements, water, and energy into and out of terrestrial vegetation rely on many submodels. We found a mathematical inconsistency in a widely used submodel that controls how light and nitrogen are distributed through the plant canopy. The inconsistency is centered around how twigs, branches, stems, and dead leaves influence the distribution of nitrogen, and thus photosynthesis, throughout the canopy. When we corrected the inconsistency, we found that the modeled global carbon uptake of terrestrial vegetation decreased by 3%. We further show that completely ignoring twigs, branches, stems, and dead leaves in canopy upscaling inappropriately increases estimated global gross primary production, by failing to account for the shade they cast, with the greatest increases in the tropics.

1. Introduction

There is no universally accepted scheme to describe the complexity of a vegetation canopy. A long-standing approximation is a two-part division of the canopy into sunlit and shaded components (De Pury & Farquhar, 1997; Sinclair et al., 1976; Wang & Leuning, 1998). Other methods include a single big leaf representation of the canopy (Sellers, 1985) or a more computationally intensive multilayer canopy, which is often used to compare with simplified models (De Pury & Farquhar, 1997; Sinclair et al., 1976; Wang & Leuning, 1998). The use of separate sunlit and shaded equations has proved a durable method for scaling leaf values up to the canopy such that several prominent global land surface models have adopted this scheme with a “two-big leaf” model (Dai et al., 2004; Oleson et al., 2013; Thornton & Zimmermann, 2007), while others have applied this division to multilayer models (Clark et al., 2011).

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A further refinement for the Common Land Model (CoLM) expanded on the two-big leaf model to account in detail for the influence of nongreen elements (i.e., twigs, branches, stems, and dead leaves—stems hereafter) through a stem area index (SAI) (Dai et al., 2004). Initially, SAI was used in the estimation of sensible and latent heat fluxes. These adjustments were later implemented in the Community Land Model (CLM) (Bonan et al., 2011; Oleson et al., 2013) and the use of SAI expanded to influence radiation scaling in an identical manner as leaves. The use of SAI is not as widespread as the two-big leaf scheme and some global models have ignored the effect of SAI on radiation in the canopy (Clark et al., 2011; Haxeltine & Prentice, 1996; Kaplan, 2003; Smith et al., 2001). Beyond the radiative division of the canopy the two-big leaf upscaling scheme also prescribes how photosynthesis scales within the canopy as a function of leaf nitrogen content (per leaf area) and specific leaf area. Previous work has shown canopy photosynthesis to be quite sensitive to upscaling schemes with single-big leaf assimilation errors relative to a multilayer canopy model between 4% and 50% (De Pury & Farquhar, 1997). Here, we describe a mathematical inconsistency that arises in the nitrogen scaling scheme used in the Community Land Model (CLM) and Energy Land Model (ELM). The error occurs under the following conditions: when SAI is large, or when solar zenith angle is high, or when LAI is very small. These conditions are likely to occur under different circumstances. Large SAI is often found in the tropics, high solar zenith angles occur at dawn and dusk, and very small LAI values are common at the beginning and end of the season in deciduous canopies.

The central issue is a mathematical discrepancy that arises in the modification, most thoroughly described in Oleson et al., 2013, to the original two-big leaf scheme when calculating the distribution of nitrogen in the plant canopy. Essentially, there are two systems for calculating depth in the canopy, the “plant area index” that includes both stems and leaves and the leaf area index that counts only leaves. Unfortunately, as we detail below, the distinction between these indices was not maintained consistently. As a result, values of the computed nitrogen scaling coefficient that are erroneous, and under certain conditions nonphysical, occur. The analysis we present here is similar in spirit to recent corrections to the incident solar radiation in the CLM (Zhou et al., 2015).

To summarize, we focus on two key problems in this analysis. First, we demonstrate the inconsistent values that arise in the nitrogen profiles from the current scaling method used in CLM and ELM and show how our solution fixes this issue. Second, we evaluate how the correction influences the land surface carbon cycle. We find that the error has a substantial influence on the carbon assimilated by vegetation: The corrected new model decreases total global gross primary production (GPP) by 3.9 Pg C or nearly 3%.

2. Materials and Methods

Initially, we follow the derivation of Oleson et al., 2013, in our view the most straightforward published example of the canopy scaling equations underpinning CLM and ELM. Radiation is assumed to follow Beer's law within a plant canopy (Monsi, 1953), giving the following estimate of sunlit and shaded fractions for a single vegetated layer at canopy depth v , where v is the sum of overlying LAI and SAI:

$$f_{Sun}(v) = e^{-k_b v}; \quad f_{Sha} = 1 - f_{Sun}, \quad (1)$$

and k_b is the direct beam extinction coefficient, which is a function of canopy leaf (and stem) angle distribution and incident radiation angle:

$$k_b = \frac{G(\mu)}{\mu}, \quad (2)$$

where $G(\mu) = \phi_1 + \phi_2 \mu$ and both ϕ values are empirical estimates (Goudriaan, 1977) with the following values, $\phi_1 = 0.5 - 0.633\chi - 0.33\chi^2$ and $\phi_2 = 0.877(1 - 2\phi_1)$. The χ variable is related to the leaf and stem angle distribution, and μ is the cosine of solar zenith angle. The variables and units used throughout this analysis are summarized in Table 1.

The sunlit fraction is scaled up to the canopy through integration, counting both LAI and SAI equally and dividing by their summed total to get an appropriate fraction:

Table 1
Summary of Variables

Variable	Full name (units)
f_{sun}, f_{sha}	Sunlit fraction, shaded fraction in a canopy layer
F_{sun}, F_{sha}	Total canopy sunlit and shaded fraction
LAI	Leaf area index ($m^2 m^{-2}$)
SAI	Stem area index ($m^2 m^{-2}$)
v	Vegetated area index (LAI + SAI) ($m^2 m^{-2}$)
k_b	Direct beam radiation extinction coefficient, leaves
ϕ_1, ϕ_2	Empirical coefficients for calculating k_b
χ	Leaf and stem angle distribution
μ	Cosine of solar zenith angle
n_a	Area-based leaf nitrogen content (g N [leaf] m^{-2} [leaf])
k_n	Canopy depth nitrogen scaling coefficient
k'_b	Direct beam radiation extinction coefficient, stems
$NSCALE_a$	Top of canopy single leaf to average canopy nitrogen scaler
l, s	Leaf and stem area variables for integration ($m^2 m^{-2}$)
$f_{Green}^{Sun}, f_{Green}^{Sha}$	Sunlit and shaded fractions in a canopy layer for photosynthesizing material
$F_{Green}^{Sun}, F_{Green}^{Sha}$	Total canopy sunlit and shaded fractions for photosynthesizing material

Note. If no units are listed the variable is unitless.

$$F_{Sun} = \frac{\int_0^{LAI + SAI} f_{Sun} dv}{LAI + SAI} = \frac{(1 - e^{-k_b(LAI + SAI)})}{k_b(LAI + SAI)}, \quad (3)$$

where the capital letter F indicates the integrated canopy value and the integration is calculated through the full vegetated canopy depth, LAI + SAI. The shaded fraction is straightforwardly calculated in a similar fashion. For brevity, here and throughout most of this analysis, we focus on the sunlit fraction.

A straightforward extension of the sunlit fraction of the canopy is an estimate of the sunlit leaf area:

$$LAI_{Sun} = F_{Sun}LAI. \quad (4)$$

The distribution of nitrogen in the canopy follows a similar procedure, but only leaves are used when calculating canopy depth, prior to division into sun and shade:

$$n_a = e^{-k_n l}, \quad (5)$$

n_a is the area-based leaf nitrogen content, k_n is the nitrogen extinction coefficient, and l is canopy leaf level. In the two-big leaf model n_a is used to estimate a canopy scaling coefficient to evaluate how much lower average canopy nitrogen will be than the topmost leaves of the canopy. The error arises when the nitrogen scaler is applied to the sunlit and shaded fractions of the canopy:

$$NSCALE_a^{Sun} = \frac{\int_0^{LAI} n_{a,leaf}^{Sun} dl}{F_{Sun}LAI} = \frac{1 - e^{-(k_n + k_b)LAI}}{(k_n + k_b)LAI_{Sun}}. \quad (6)$$

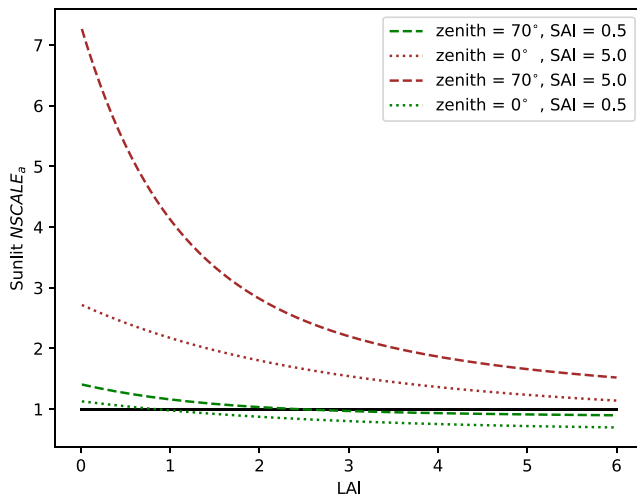


Figure 1. Current estimate of canopy nitrogen scaling in the ELM and CLM models using Equation 6. Brown lines are high SAI, while green lines are modest SAI; the dotted lines have low solar zenith angle, while dashed lines are high. The four lines represent values of the current leaf to canopy nitrogen scaling factor that produce illogical values greater than one, which is indicated by the solid black line. This occurs at high solar zenith angle and modest or low LAI, as indicated by the dashed green line, across all LAI values when SAI is large, and at low LAI even with low solar zenith angle.

The error in Equation 6 arises due to the disconnect between the f_{leaf}^{Sun} index and LAI_{Sun} . In Equation 6 f_{leaf}^{Sun} , the fraction of sunlit leaves is only integrated through the leaf area. Then, the integral is normalized by LAI_{Sun} , which integrates through the sum of LAI and SAI (Equation 3). Thus, Equation 6 uses two different integral limits in the numerator and denominator and this is the source of the error. The results of four example values are shown in Figure 1. That the equation results in an error is immediately apparent as the scaling coefficient ($NSCALE_a$), by definition, reduces canopy nitrogen from a maximum value and thus should never be greater than one; yet in all four examples, the coefficient exceeds one at some LAI values, and at high SAI, at all LAI values.

We propose a solution that preserves differential nitrogen between sunlit and shaded portions of the canopy by amending the model to integrate through separate SAI and LAI indices. The new sunlit and shaded fractions are only used for the calculations of nitrogen scaling; the old scheme is still used when calculating radiation interception. This produces a new sunlit and shaded canopy fraction that allows green leaves to be cleanly separated from nonphotosynthesizing canopy material:

$$f_{Green}^{Sun} = e^{-(k_b l + k'_b s)}, \quad (7)$$

where k'_b is the extinction coefficient for stems, l is the canopy leaf area index, and s is the canopy SAI. This separation may be understood as a

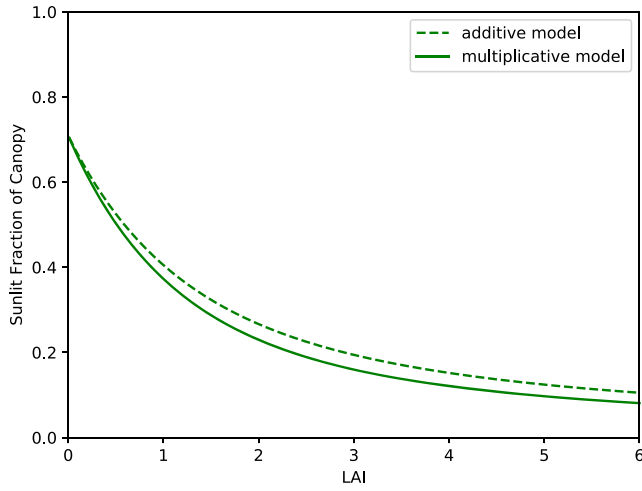


Figure 2. Fraction of sunlit leaves in the canopy. The updated multiplicative model maintains a different, but comparable sunlit fraction to the current model across a wide range of LAI values. The solar zenith angle is fixed at 70° , SAI is 0.5, and χ is 0 for these calculations.

separation of the canopy components in that we no longer expect stem and leaf elements to accumulate in the canopy at identical rates, but they may vary as appropriate. This formulation leads directly to a whole canopy estimate as follows:

$$F_{Green}^{Sun} = \frac{\int_0^{LAI} e^{-k_b l} dl \int_0^{SAI} e^{-k'_b s} ds}{LAI SAI} \quad (8)$$

$$= \frac{(1 - e^{-k_b LAI})(1 - e^{-k'_b SAI})}{k_b LAI k'_b SAI}$$

The green sunlit fraction for the multiplicative scheme described in Equation 8 is different from, but close to the old fraction, as shown in Figure 2. In order to properly normalize the sunlit fraction it must be divided by both LAI and SAI independently, rather than their sum. Thus, this formula (Equation 8) is “multiplicative” in relation to the “additive” formula, Equation 3, which produces an inconsistent nitrogen scaler. This disconnects the sunlit and shaded fractions of the photosynthesizing material (Equation 8, multiplicative) from the radiation scaling (Equation 3, additive). The multiplicative scheme always produces a lower sunlit fraction of the canopy than the additive scheme, which is consistent with it focusing only on the photosynthesizing components of the canopy.

Now, the sunlit canopy nitrogen scaling scheme is updated using the updated f_{Green}^{Sun} values. Here we have already combined the nitrogen and sunlit fraction terms in the LAI integral:

$$NSCALE_a^{Sun} = \frac{\int_0^{LAI} e^{-(k_b + k_n)l} dl \int_0^{SAI} e^{-k'_b s} ds}{F_{Green}^{Sun} LAI SAI} \quad (9)$$

$$= \frac{(1 - e^{-(k_b + k_n) LAI})(1 - e^{-k'_b SAI})}{(k_b + k_n) k'_b F_{Green}^{Sun} LAI SAI}$$

$$= \frac{k_b (1 - e^{-(k_b + k_n) LAI})}{(k_b + k_n)(1 - e^{-k_b LAI})}$$

Note that in the calculation of $NSCALE_a^{Sun}$ the stem component is algebraically eliminated. As this is the core of our correction, we also show the updated nitrogen scalar for shade:

$$NSCALE_a^{Sha} = \frac{\iint n_a (1 - f_{Green}^{Sun}) dl ds}{(1 - F_{Green}^{Sun}) LAI SAI} = \frac{SAI(1 - e^{-k_n LAI})}{k_n (1 - F_{Green}^{Sun}) LAI SAI} - NSCALE_a^{Sun} \quad (10)$$

As further confirmation that the multiplicative solution is consistent, the whole canopy nitrogen scaling is the weighted average of the sunlit and shaded scalings (Figure 3) with weights equal to their respective fractions in the canopy as described in Equations 9 and 10. The old, incorrect equations and their updated analogues are summarized in Table 2.

3. Land Surface Model Protocol

To evaluate the influence of the scaling error we implemented the corrected scheme in the land model affiliated with the Energy Exascale

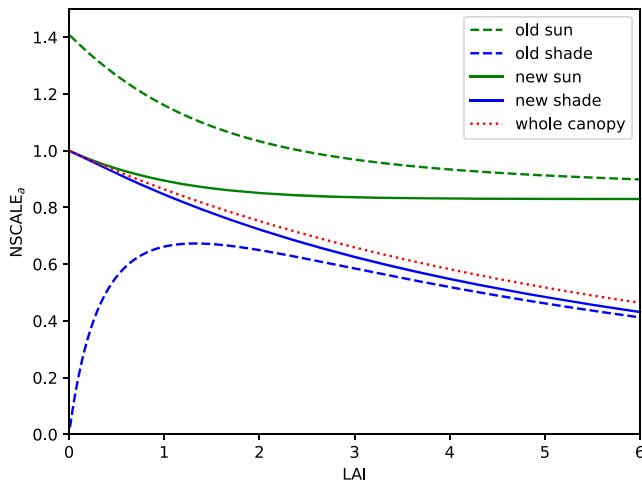


Figure 3. Comparison of nitrogen scaling factors. Here we show the full suite of nitrogen scaling models. Sunlit leaves are represented in green, shaded leaves are in blue, and the undivided whole canopy is in red. The additive model is represented by dashed lines and the multiplicative model by solid lines and the whole canopy independent of model is a dotted line. The solar zenith angle is fixed at 70° , SAI is 0.5, and χ is 0. Note the divergence in the old additive model when LAI is small and that the whole canopy is the weighted average of the updated multiplicative model.

Table 2
Comparison of Old Incorrect Equations and Their Updated Equivalents

Old equation	Corrected equation
1	7
3	8
6	9

Earth System Model (E3SM), the ELM. We used a 600-yr final spin-up following a 250-yr accelerated decomposition spin-up (Koven et al., 2013; Thornton & Rosenbloom, 2005) to stabilize the carbon and nutrient (both nitrogen and phosphorus) pools and then evaluated the output of a transient run from 1850–2009. For ease of comparison, we focus on the end of the transient run and present annual averages from 1980–2009.

4. Results

The multiplicative leaf and stem shading eliminates the mathematical inconsistency and, in contrast to the additive model, provides plausible values of $NSCALE_a$ under all conditions. Figure 3 displays an example of the old and updated estimates together including sunlit, shaded and the undivided whole canopy values for nitrogen scaling which is unchanged with our update (Equation 5). Though separately calculated, the whole canopy estimate is the average of the multiplicative model weighted by the updated sunlit and shaded fractions. Note that as LAI grows the whole canopy estimate is closest to the shaded fraction as a larger and larger fraction of the canopy is shaded. At the same time the sunlit scaling remains relatively steady, which can be visualized as a “shell” of sunlit leaves on the periphery of the canopy. This suggests that the new formulation is both mathematically consistent and biologically realistic. By contrast, the additive model approaches a nonphysical scaling value of 0 in the shaded portion of the canopy as well as a nonphysical value greater than 1 in the sunlit portion when LAI is small (less than ≈ 2).

The influence on the global carbon cycle is surprisingly substantial. In total, global annual average GPP from 1980–2009 is reduced by 3.0% from the inconsistent model, or by $3.9 \text{ Pg C m}^{-2} \text{ yr}^{-1}$. GPP is especially reduced in the tropics with scattered increases and decreases across other regions (Figure 4). In aggregate, as shown in the right panel of Figure 4, latitudinal averages are always negative, with largest differences in the tropics, a region of high LAI and SAI. Note that this version of default ELM has a somewhat high annual average GPP (1980–2009) of 131.6 Pg C , and the reduction brought about by the updated canopy scaling scheme brings it into the uncertainty range of empirically estimated global GPP (Beer et al., 2010).

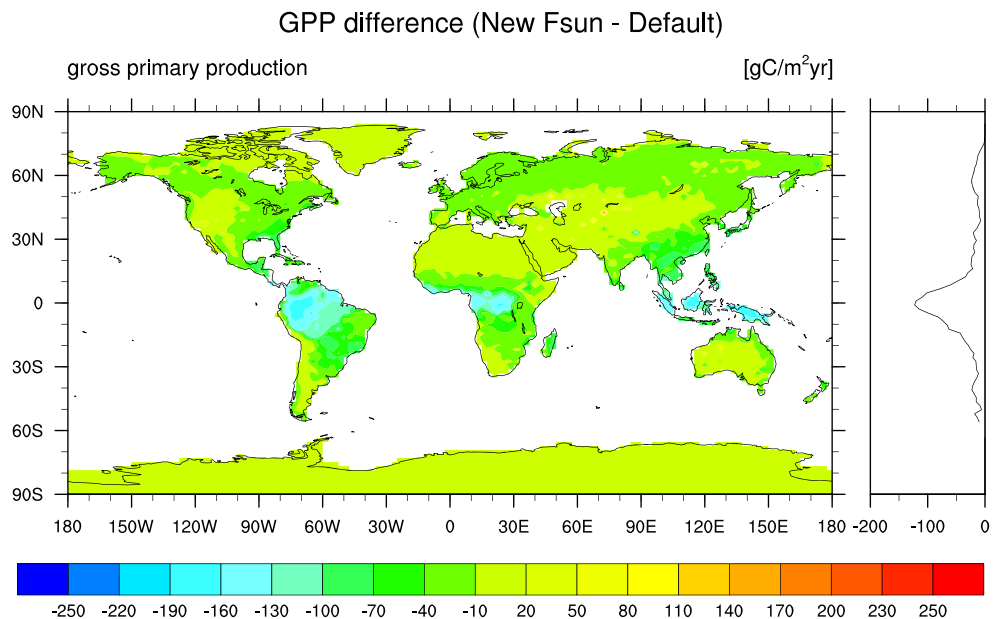


Figure 4. The difference in GPP between the updated multiplicative and default additive models. The right panel is the latitudinal average of the primary map. The multiplicative model produces a substantial decline in GPP across the tropics. A portion of these GPP shifts are also correlated with changes in temperature, see Figure 5.

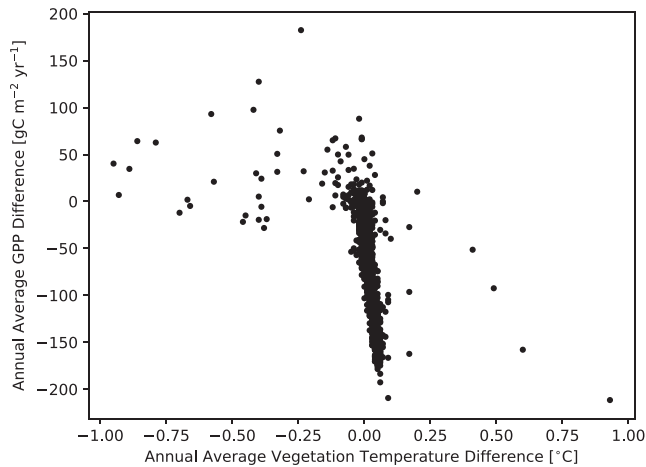


Figure 5. The correlation between annual average temperature difference and GPP. The Pearson's correlation is -0.35 , and this provides some insight into how GPP increased in a small subset of pixels.

Beyond the decrease in GPP from the removal of improperly large sunlit nitrogen scaling, we show that a portion of the change in GPP is correlated with changes in vegetation temperature, likely due to changes in LAI and canopy temperature (Figure 5). The Pearson's correlation coefficient is -0.35 between annual average temperature and GPP, and this provides some insight into why a small number of pixels (3.1%) see an increase in GPP. The changes in temperature are likely a result of changes in LAI and transpiration and the increases in GPP may be due to cooling in hot locations.

The updated scaling scheme results in a lower global GPP estimate due to the corrected conservation of canopy nitrogen. As indicated in Figures 1 and 3 the inconsistent scaling scheme resulted in nitrogen scalars with values sometimes larger than one. As the maximum carboxylation rate in ELM is linearly related to nitrogen content these scaling values produce elevated photosynthesis estimates due to erroneously increased leaf nitrogen concentrations. While the conditions under which this mathematical inconsistency is most dramatic are not optimal for photosynthesis (high solar zenith angle and large SAI values), the error occurs frequently

enough to produce an increase in global annual average GPP that is nearly 40% of global carbon emissions from burning fossil fuels in recent years, for example, in 2017 when emissions were approximately 10 Pg C (Le Quéré et al., 2018).

To further compare our results to models that do not use SAI at all, we conducted an ELM simulation in which SAI was removed from all calculations. Under the eliminated SAI scenario we found that global annual average GPP increased by 4.1 Pg C relative to the version of ELM with the corrected f_{Green}^{Sun} , with a notable increase in the tropics of over $200 \text{ g C m}^{-2} \text{ yr}^{-1}$ (Figure 6). This suggests that models that have ignored the influence of stems are likely to be compensating elsewhere for the decrease in photosynthesis due to stem induced reductions in incident radiation.

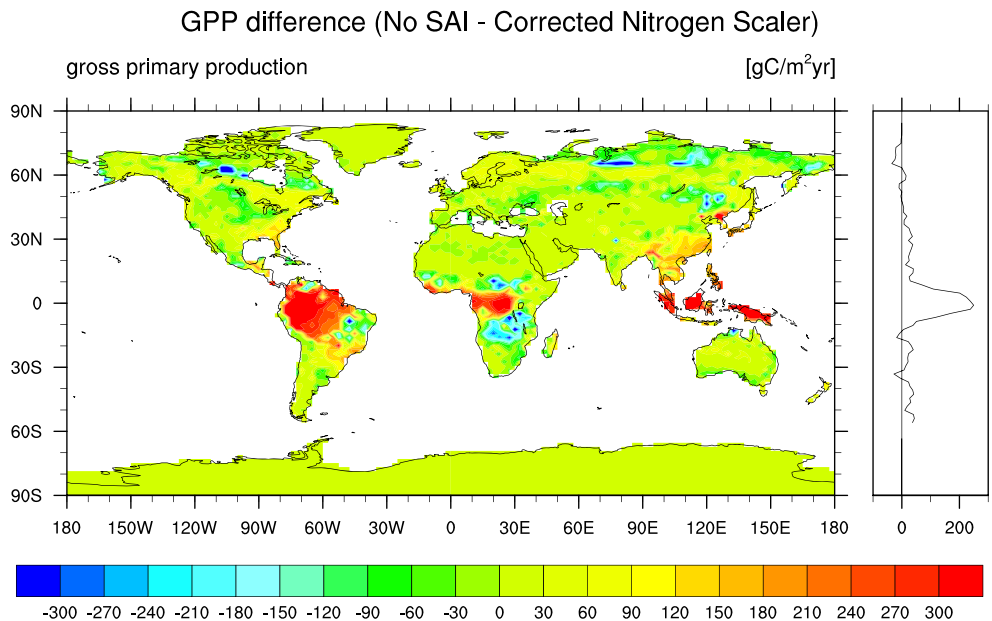


Figure 6. The difference in GPP between a model with SAI removed and the model with updated model with corrected nitrogen scaling. The right panel is the latitudinal average of the primary map. There is a significant jump in GPP across the tropics that declines toward the poles.

5. Conclusions

Our new multiplicative scheme, with consistently separated LAI and SAI, corrects the mathematical error in nitrogen scaling in the additive scheme (Oleson et al., 2013), which fulfills the primary purpose for its development. In the multiplicative scheme the nitrogen scalar will not exceed one under any conditions, at any times of day and year, and across all levels of LAI and SAI. The sunlit fraction is close to, but systematically smaller than the additive model across all LAI values >0 (Figure 2). As the mathematical inconsistency will have repercussions for the nitrogen scalar in any land surface model that uses the Dai separation of sunlit and shaded leaves (Dai et al., 2004), there are other models that will benefit from this correction (at least the CoLM). This suite of adjustments suggest that the multiplicative submodel should be incorporated into existing models that make use of SAI when calculating nitrogen distribution (such as CLM and ELM). Last, land models that do not currently incorporate SAI are likely to be overestimating the sunlit fraction of their canopy, as eliminating stems from the corrected ELM raised global GPP by 4.1 Pg C and tropical GPP by over 200 g C m⁻² yr⁻¹. Thus, while this analysis has focused on ELM, the incorporation of the Dai SAI model with the canopy scaling equations developed here should improve the accuracy of many existing land models.

Land surface models incorporate a diverse array of biochemical and biophysical processes. Not all processes for these submodels are vetted to the same degree. Occasional inconsistencies are likely inevitable as the complexity of these models continue to increase. However, when clear mathematical errors arise and solutions are at hand the corrected submodels should be incorporated into the full land surface models. Each improvement in mathematical, biological and physical fidelity should provide us with greater confidence in the predictions we increasingly rely on from the most detailed representations of the Earth System we have developed to date.

Data Availability Statement

The model output and code used to generate the figures for this manuscript may be found at Zenodo (<https://zenodo.org/record/3934661>) (<https://doi.org/10.5281/zenodo.3934661>).

Conflict of Interest

The authors declare no affiliations or financial conflicts of interest.

Acknowledgments

They thank Nick Smith and an anonymous reviewer for their comments that improved the manuscript. This research was supported as part of the Energy Exascale Earth System Model (E3SM) project, funded by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research (including Grant DE-SC0012677 to P. B. R.) and Biological Integration Institutes Grant NSF-DBI-2021898 (to P. B. R.).

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