DOE/SC-CM-19-003

U.S. DEPARTMENT OF ENERGY | Office of Science

FY 2019 First Quarter Performance Metric: Evaluate the Effects of Including Phosphorous Limitations on the Carbon Cycle

July 2019

Contents

1.0 Product Definition 1
2.0 Product Documentation 1
3.0 Results 2
4.0 References 6

Figures

Figure 1. Simulated (left column) GPP (unit: gC/m2/yr) and (right column) NPP (unit: gC/m2/yr) for the Amazon region based on (top row) CLM-CN and (bottom row) CLM-CNP. (Yang et al. 2016). Simulations were performed using the Community Land Model version 4 (CLM4) in its CN and CNP configurations (Yang et al. 2016), with the CNP model as described in earlier published work (Yang et al. 2014).......................................2

Figure 2. Spatial variation of the extent of nutrient limitation on plant growth (regions with a negative value are more limited by N and regions with a positive value are more limited by P) (Yang et al. 2016)... 3

Figure 3. Simulated change in land carbon storage in response to historical increase in [CO_2] (1900–2009): (top) Vegetation carbon, (middle) soil carbon, and (bottom) total ecosystem carbon based on CNP and CN. Unit: Pg C. (Yang et al. 2016)........................3

Figure 4. Land ecosystem carbon response to rising CO_2 concentration. Black lines are for one CNP model configuration, and gray lines are for a second alternative CNP configuration. Solid lines show results based on 100-year smoothing window, while dashed lines use a 75-year smoothing window...4

Figure 5. Land ecosystem carbon response to radiative forcing from rising CO_2 concentration. Black lines are for one CNP model configuration, and gray lines are for a second alternative CNP configuration. Solid lines show results based on 100-year smoothing window, while dashed lines use a 75-year smoothing window. 5

1.0 Product Definition

A paper published in *Nature* in 2000 showed that a climate system model with prognostic atmospheric CO_2 concentration was sensitive to the representation of carbon cycle processes in land and ocean ecosystems (Cox et al. 2000). Since that time a multitude of studies has been performed with increasingly sophisticated climate and Earth system models, examining the interactions or feedbacks, among atmospheric CO_2 concentration, near-surface air temperature, and physical and biological processes on land and in the oceans.

More recently, studies have begun investigating the interactions of the carbon cycle with other biogeochemical cycles. Nitrogen and phosphorous are two of the most important nutrients for plant growth, and the availability of these nutrients plays important roles in the carbon cycle dynamics of land ecosystems. Several modeling studies have examined the interactions of carbon and nitrogen cycles. Those studies reported that the overall effect of land ecosystem nitrogen limitation on the carbon cycle was to reduce the rate of carbon uptake as fertilized by rising atmospheric CO_2 concentration, and to significantly reduce or eliminate the loss of carbon to the atmosphere caused by warming, as compared with earlier modeling studies that ignored nitrogen cycle dynamics. New model development and evaluation have started to produce initial estimates of the influence of phosphorus limitations on global-scale carbon cycle dynamics. Here, the results of those studies are examined and summarized, to reflect the best current understanding of how the additional process-level complexity of phosphorus limitations modifies climate and carbon cycle interactions.

2.0 Product Documentation

Evaluation of the influence of phosphorus limitation on the carbon cycle and carbon-climate feedbacks is presented at two spatial scales. First, the impact of carbon-nitrogen-phosphorus (CNP) coupling is examined relative to coupling of carbon-nitrogen (CN) coupling at the continental scale, focusing on the tropical forests of the Amazon region in South America. Simulation results presented here for the Amazon region are extracted from offline land model simulations using the Community Land Model version 4 (CLM4) in its CN and CNP configurations (Yang et al. 2016).

Second, the influence of CNP coupling is evaluated at the global scale, focusing on quantification of climate-carbon cycle feedbacks over the period 1850-present for simulations carried out within a coupled earth system model. Simulations presented here for the global-scale feedback analysis are extracted from fully coupled atmosphere-ocean-sea ice-land simulations performed with the Energy Exascale Earth System Model (E3SM), version 1.1, in its coupled biogeochemistry configuration (E3SMv1.1-BGC, Burrows et al. in review). The influence of coupled CNP biogeochemistry on carbon-climate feedbacks is evaluated in a quantitative climate-carbon cycle feedbacks framework (Friedlingstein et al. 2001).

Taken together, these initial regional and global results suggest that while there are certain to be regional differences, especially in tropical forest regions, the global scale implications of phosphorus limitation on carbon cycling may emerge as a second-order modification to the prior estimates associated with the introduction of nitrogen limitation.

3.0 Results

Earlier work has demonstrated the impacts of introducing the nitrogen cycle, compared to carbon-only representations, for offline land and coupled Earth system simulations. Results here examine the further impact of introducing phosphorus limitation on top of the previous carbon-nitrogen coupling. Over the Amazon River basin, dominated by tropical broadleaf evergreen forest, modeled phosphorus limitation tends to restrict gross photosynthetic uptake of carbon (gross primary production, or GPP) in the older and most highly weathered soil regions in the central, southern and eastern parts of the basin, while GPP in the western and northern parts of basin, with younger and less weathered soils, is similar between CN and CNP simulations (Figure 1, left panels). A similar spatial pattern emerges for net primary production (NPP), which also takes into account carbon losses due to plant respiration (Figure 1, right panels).

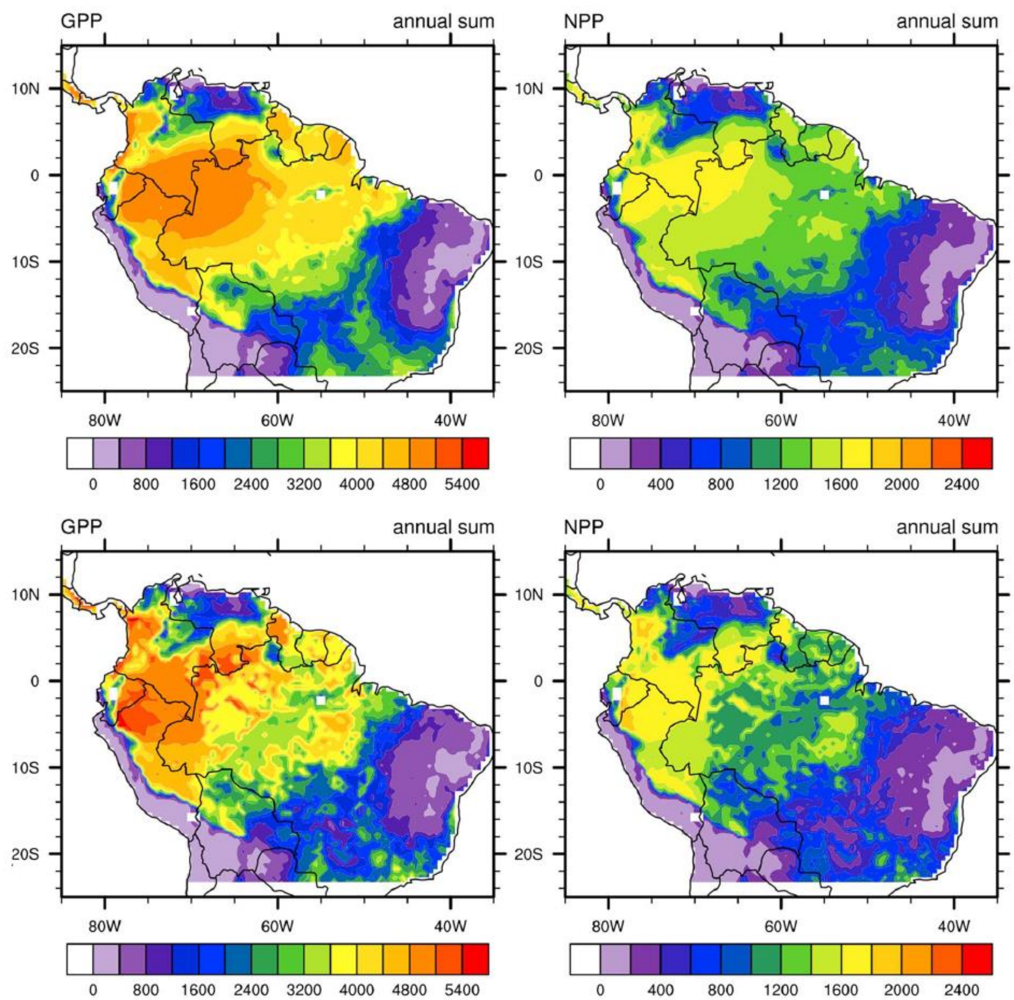

Figure 1. Simulated (left column) GPP (unit: gC/m2/yr) and (right column) NPP (unit: gC/m2/yr) for the Amazon region based on (top row) CLM-CN and (bottom row) CLM-CNP. (Yang et al. 2016). Simulations were performed using the Community Land Model version 4 (CLM4) in its CN and CNP configurations (Yang et al. 2016), with the CNP model as described in earlier published work (Yang et al. 2014).

Simulations forced with observation-based surface weather drivers were carried out on a 0.5 x 0.5-degree grid, for the period covering years 1850-2009. These results show that nitrogen and phosphorus limitations are both prevalent over the region, with a complex spatial pattern of limitation- and co-limitation-driven by variation in soils and climate, and associated variations in vegetation types (Figure 2).

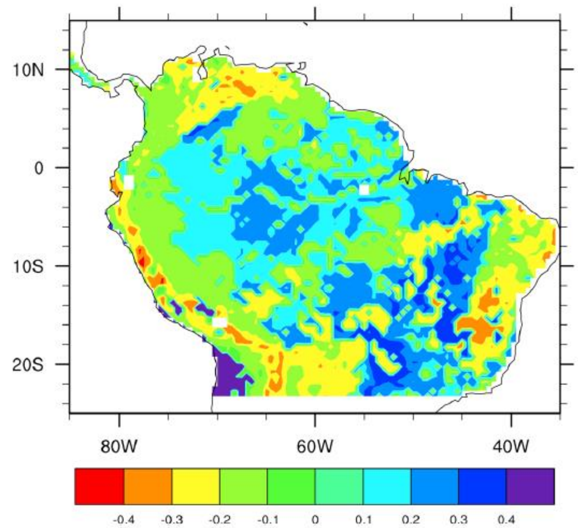

Figure 2. Spatial variation of the extent of nutrient limitation on plant growth (regions with a negative value are more limited by N and regions with a positive value are more limited by P) (Yang et al. 2016).

Modeling results suggest that the carbon uptake response of Amazon basin tropical forest to increased atmospheric CO_2 concentration is about 26% lower when CNP dynamics are considered, than when only CN dynamics are simulated. This influence of phosphorus limitation on land carbon cycle shows up in both vegetation and soil carbon pools (Figure 3).

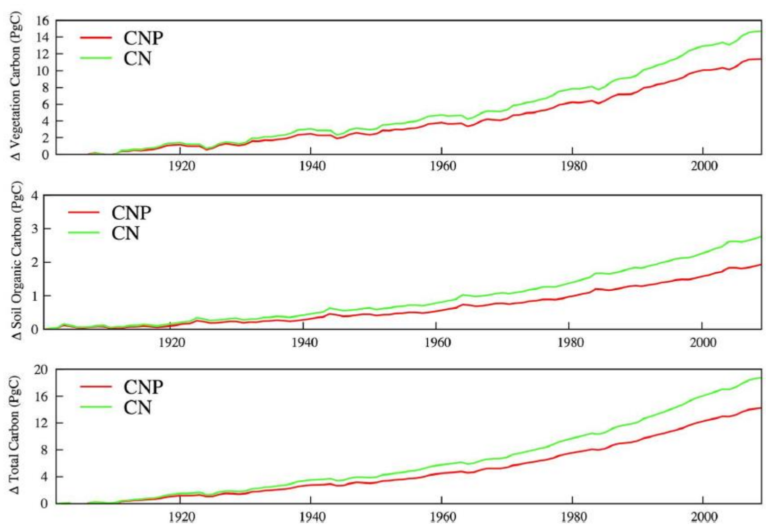

Figure 3. Simulated change in land carbon storage in response to historical increase in [CO_2] (1900–2009): (top) Vegetation carbon, (middle) soil carbon, and (bottom) total ecosystem carbon based on CNP and CN. Unit: Pg C. (Yang et al. 2016).

To evaluate the global-scale influence of phosphorus limitation on carbon-climate feedbacks, multiple coupled simulations were compared. Coupled simulations used a spatial resolution of approximately 1.0 x 1.0 degrees for land and atmosphere, and a mesh for ocean and sea ice simulation varying in resolution from 60 km at mid-latitudes, to 30 km at the equator and the poles. By comparing simulations with and without the influence of rising CO_2 concentration on photosynthesis and vegetation physiology, the global land ecosystem response to rising CO_2 was estimated (Figure 4). The set of simulations presently available is only complete through the end of the historical period (2006), and so a direct comparison with prior results looking out to feedback effects at the end of the 21st century is not yet possible. The historical results demonstrate an overall declining trend in the CO_2 fertilization response, and comparison to prior work suggests that the values by the end of the 21st century may be close to prior feedback effects seen for models with CN coupling. Two different model representations of the CNP dynamics are used in these results, both of which give similar results.

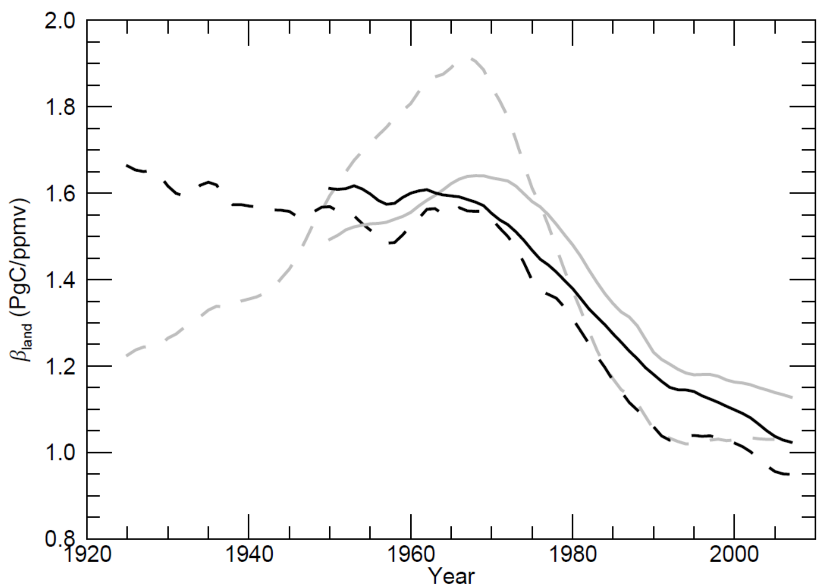

Figure 4. Land ecosystem carbon response to rising CO_2 concentration. Black lines are for one CNP model configuration, and gray lines are for a second alternative CNP configuration. Solid lines show results based on 100-year smoothing window, while dashed lines use a 75-year smoothing window.

Comparison of additional simulation results with and without the influence of rising CO_2 concentration on radiative forcing in the atmosphere shows that both CNP model configurations predict a loss of carbon due to climate warming during the historical period, although with considerable temporal variability and with little consistency between model configurations (Figure 5). Comparing to prior C-only results suggests that these two model configurations are much less sensitive to warming than are models which lack nutrient dynamics, and the current results are quantitatively similar to models that include CN coupling.

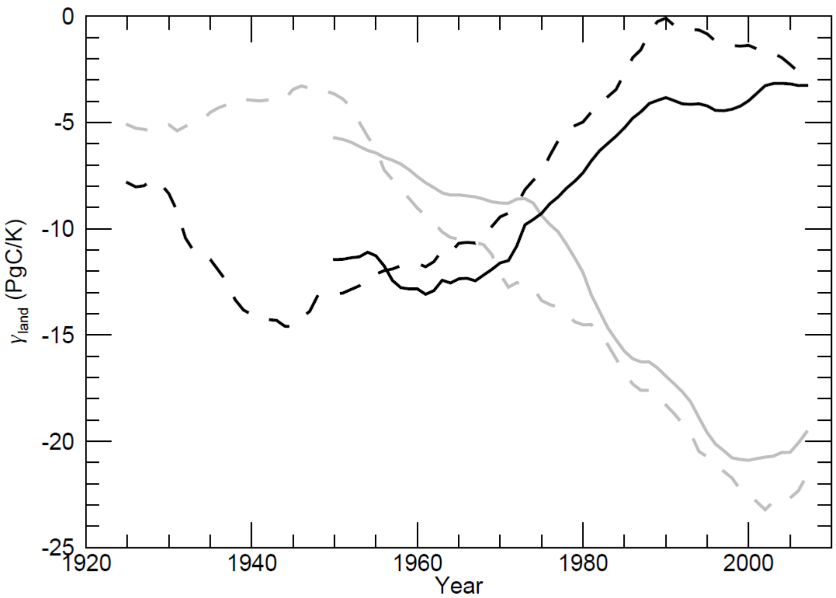

Figure 5. Land ecosystem carbon response to radiative forcing from rising CO_2 concentration. Black lines are for one CNP model configuration, and gray lines are for a second alternative CNP configuration. Solid lines show results based on 100-year smoothing window, while dashed lines use a 75-year smoothing window.

Taken together, these regional and global results suggest that the CNP coupled models will be more similar to the CN coupled models than either of those configurations are to the earlier C-only simulations. There are certain to be regional differences from CNP coupling, especially in the tropical forest regions with old, weathered soils. The global scale implications of phosphorus limitation on carbon cycling may emerge as a second-order modification to the prior estimates associated with the introduction of nitrogen limitation. Further analysis will need to be carried out once global coupled CNP simulations have been extended to the end of the 21st century. That work is currently underway.

4.0 References

Burrows, S.M., et al. (in review). “The DOE E3SM coupled model v1.1 biogeochemistry configuration: overview and evaluation of coupled carbon-climate experiments.” *Journal of Advances in Modeling the Earth System* (in review).

Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFires, J. Galloway, M. Heimann, C. Jones, C. Le Quéré, R. B. Myneni, S. Piao and P. Thornton (2013). “Carbon and Other Biogeochemical Cycles.” Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T. F. Stocker, D. Qin, G.-K. Plattneret al. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Cox, P. M., R. A. Betts, C. D. Jones, S. A. Spall and I. J. Totterdell 2000. “Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model.” *Nature* 408: 184-187

Denman, K. L., G. Brasseur, A. Chidthaisong, P. Ciais, P. M. Cox, R. E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P. L. da Silva Dias, S. C. Wofsy and X. Zhang (2007). “Couplings between changes in the climate system and biogeochemistry.” Climate Change 2007: The Physical Science Basis. S. Solomon, D. Qin, M. Manninget al. Cambridge, United Kingdon and New York, NY, USA, Cambridge University Press: 499-588.

Friedlingstein, P., J.-L. Dufresne, P. M. Cox and P. Rayner 2003. “How positive is the feedback between climate change and the carbon cycle?” Tellus 55B: 692-700.

Prentice, I. C., Farquhar, G. D., Fasham, M. J. R., Goulden, M. L., Heimann, M., Jaramillo, V. J., Kheshgi, H. S., Le Quéré, C., Scholes, R. J., and Wallace, D. W. R. L.: 2001, “The carbon cycle and atmospheric carbon dioxide,” in J. T. Houghton et al. (eds.), Climate Change 2001: The Scientific Basis, Cambridge University Press, New York, pp. 185–237.

Yang, X., P. E. Thornton, D. M. Ricciuto and W. M. Post 2014. “The role of phosphorus dynamics in tropical forests - a modeling study using CLM-CNP.” *Biogeosciences* 11: 1667-1681, 10.5194/bg-11-1667-2014.

Yang, X., P. E. Thornton, D. M. Ricciuto and F. M. Hoffman 2016. “Phosphorus feedbacks constraining tropical ecosystem responses to changes in atmospheric CO_2 and climate.” *Geophysical Research Letters* 43(13): 7205-7214, 10.1002/2016GL069241.

U.S. DEPARTMENT OF
ENERGY

Office of Science