U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-CM-19-004

FY 2019 Fourth Quarter Performance Metric: Evaluate the Effects of Including Vegetation Dynamics on Productivity and Surface Energy in the E3SM Model

September 2019

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1.0 Product Definition

Representations of terrestrial ecological processes have been overly simplified in the current generation of models used for climate and ecosystem projections, such as the land surface model (LSM) components of Earth System Models (ESMs). This has implications for the ability of these models to adequately capture climate-ecosystem feedbacks. For example, most LSMs use prescribed, static maps of plant functional types (PFTs), and thus cannot capture shifts in PFT composition. Some LSMs do simulate simplistic PFT shifts, but are constricted to current bioclimatic zones (i.e., zones where the residing vegetation exists depending on temperature gradients, both latitudinal and elevation, and precipitation gradients) instead of emerging from the physiology- and competition-based demographic rates that determine resource competition and plant distributions in real ecosystems. Thus, current ESMs are limited in ecological detail and realism, for example, important factors such as ecosystem structure and demography. Omission of mechanisms, such as mortality and disturbances that influence biomass turnover and carbon allocation response to changing climates, limits the ability of these models to realistically forecast ecosystem responses to anomalous temperature and precipitation conditions.

Therefore, a Vegetation Demographic Model (VDM) called The Functionally Assembled Terrestrial Ecosystem Simulator (FATES) that incorporates dynamic vegetation processes has been implemented within the Department of Energy’s Energy Exascale Earth System Model (E3SM). The benefits of simulating vegetation processes by FATES is that it provides 1) height-structured heterogeneity in light availability, 2) competition for water and nutrient resources that could lead to exclusion or coexistence, 3) ecosystems that assembly mechanistically, 4) representing major disturbances (e.g., extreme drought) and recovery, 5) plant distribution that emerges from trait filtering, and 6) abandons bioclimatic envelopes.

ELM-FATES has been successfully implemented with promising model evaluation and predictive capabilities for carbon cycling, and surface energy and water fluxes. Among multiple advances to ELM-FATES, we have improved a previous high latitude bias in leaf area index and net primary productivity, described in more detail below. Additionally, as a result of dynamic vegetation and ability for plants to assemble in a manner that optimized current conditions, the improved predictions of productive tropical plant functional types increased the evapotranspiration (ET) fluxes from the tropics, a critical water flux for global circulations of water and energy. This analysis showed that improved shifts in global plant distributions lead to large differences in land-atmosphere exchanges.

2.0 Product Documentation

ELM-FATES is a cutting edge VDM coupled within E3SM’s land surface model, ELM, thus representing demography at global scales and is an alternative to the “big-leaf” vegetation processes in ELM. ELM-FATES represents vegetation in a more highly resolved manner through demography. For example, demography provides finer scales of plant heterogeneity, by vegetation being separated into many ‘cohorts’ (i.e. plants of similar height and functional types) across various ‘patches’ (i.e. area of similar time since a disturbance event), therefore allowing for the land surface to be divided into different successional stages. Cohorts of trees are each competing in different growth phases, which can be informed directly by field observations.

For each cohort the dynamic process of recruitment, growth, and mortality are mechanistically represented and emergent properties due to competition. ELM-FATES is a critical addition for representing disturbance-partitioned landscapes in ESMs. For documentation, see https://fates-docs.readthedocs.io/en/latest/index.html.

The underlying model structure and concepts in ELM-FATES are based on the ED model (Moorcroft et al., 2001), introducing individual plants being represented as cohorts, patch 'time-since-disturbance' concept, and trait filtering, but with multiple updates, and coupled to the physical processes inherit to a land surface model scheme (Fisher et al., 2015). A major addition to ELM-FATES is the adoption of the Perfect Plasticity Approximation (PPA) (Purves et. al., 2008) used for the accounting of canopy crown spatial arrangements. Further updates include multi-layer multi-PFT radiation transfer, carbon allocation to storage, and a plant hydrodynamic module (Christoffersen et. al. 2016). The hydrodynamic model simulates different diurnal and seasonal cycles of photosynthetic response to water stress depending on the strategies related to diverse hydraulic traits, which are difficult for traditional ESMs to capture. Plant hydraulics in ELM-FATES enables model-based experiments on how temperature and drought influence plant stress and mortality due to hydraulic failure.

Vegetation demography integrated with plant hydraulics, enhanced representations of plant trait variation, and explicit treatments of resource competition have all been identified as critical areas for advancing current models, and constitute necessary advances for realistically representing future ecosystem states (Choat et. al., 2018, Fisher et. al., 2015, 2018, Scheiter et. al., 2013, Weng et. al., 2015). Demography also provides different sensitivities to rising CO_2 via finer-scale ecological processes, ultimately altering responses of land-atmosphere interactions (Levine et al., 2016; Purves and Pacala, 2008), which cannot be achieved in models with aggregated vegetation.

3.0 Results

Global Application of ELM-FATES:

Global application of dynamic vegetation and demography, via ELM-FATES, has been a cutting-edge goal of the E3SM Project. We are happy to report that ELM-FATES has been successfully implemented with promising model evaluation and predictive capabilities particularly for carbon cycling and surface energy and water fluxes. Earlier work demonstrated a very high bias of leaf area index (LAI) and net primary productivity (NPP) in high latitudes globally. Due to ELM-FATES dropping the concept of bioclimatic envelopes and not having prescribed vegetation distribution maps, there were initial unintended consequences of disproportionally over-productive PFTs being able to unrealistically survive in high latitudes. It was identified that an option for plant mortality to occur due to freezing stress, in addition to existing modes of mortality, needed to be implemented in ELM-FATES. Including this important mortality update, as well as increasing the depth of shrub canopies (which were too shallow), and more accurate PFT specific wood density values based on the Global Wood Density Database (Zanne et. al., 2009), corrected the high latitude bias, decreasing LAI (Figure 1). As a result of dynamic vegetation and ability for plants to mechanistically assemble, improved predictions of productive tropical PFTs were contained in tropical locations and increased the evapotranspiration (ET) flux from the tropics, a critical water flux for global circulations of water and energy. This analysis showed that improved shifts in global plant distributions lead to large differences in land-atmosphere exchanges.

Additional global evaluation of the most current version of ELM-FATES still shows an over-prediction of NPP compared to satellite-based MODIS estimates of NPP (Figure 2). This is mainly due to large NPP values in the tropics, and tropical southeast Asia that are higher than observations. There are also known biases in the MODIS NPP product (Zhao et. al., 2006). The globally averaged total aboveground biomass (AGB) is better predicted by ELM-FATES (Figure 3) when compared against AGB reported by FAO and UNECE (Hengeveld et. al., 2015). ELM-FATES very slightly overestimated AGB on average. However large discrepancies of either extreme higher or lower predicted AGB emerged, and the resulting similar estimate of ABG to observations was after regions that were either underestimated or overestimated canceled each other out. ELM-FATES is still considered under testing and evaluation in ELMv2, and is continually being updated for application in ELMv3. For example, to help improve extreme high or low AGB predictions, we suggest the interactions of PFT competition and survival needs to be further evaluated.

Quantifying the Tropical Forest Carbon Sink With ELM-FATES Results:

A recent application of ELM-FATES has been used to evaluate the potential for Amazonian tropical forests to remain a carbon sink as atmospheric CO_2 increases, and specifically using ELM-FATES due to new applications of vegetation structure, competition, and demography (Holm et al. In Review). We simulated an old-growth tropical forest with ELM-FATES and compared to three other terrestrial models differing in scale of vegetation and dynamics, and representation of biogeochemical cycling, all driven with CO_2 forcing from the preindustrial period to 2100. Notably, the two VDMs (ED2 and ELM-FATES) always predicted positive growth in all size classes. In contrast, the field data indicate that a quarter of canopy trees had no detectable growth, and while high interannual variation existed, the biomass change was near-neutral over the 15-year period. With a doubling of CO_2, ELM-FATES predicted an appreciable biomass sink (0.8 Mg ha-1 yr-1). ELM-FATES performance was similar or better than the ELM run in carbon-only mode, suggesting that nutrient competition in VDMs will improve their predictions of response to rising CO_2. We demonstrate that VDMs are comparable to ‘big-leaf’ models, while including finer-scale demography and competition that can be evaluated against field observations.

In a similar second study ELM-FATES was also used in an ensemble of 14 terrestrial ecosystem models was used to simulate the planned free-air CO_2 enrichment experiment AmazonFACE (Fleischer et. al. 2019). Model simulations showed that phosphorus availability reduced the projected CO_2-induced tropical carbon sink by about 50% compared to estimates from models assuming no phosphorus limitation. In this 14-model comparison, ELM-FATES had similar responses to elevated CO_2 as the carbon-nitrogen (CN) models with respect to GPP and NPP (Figure 5). With no influence of nutrient limitation on plant growth or flexible stoichiometry, after 15 years of elevated CO_2 ELM-FATES did not show an increased investment in carbon to leaves and fine roots, which was predicted in most of the CN and CNP models.

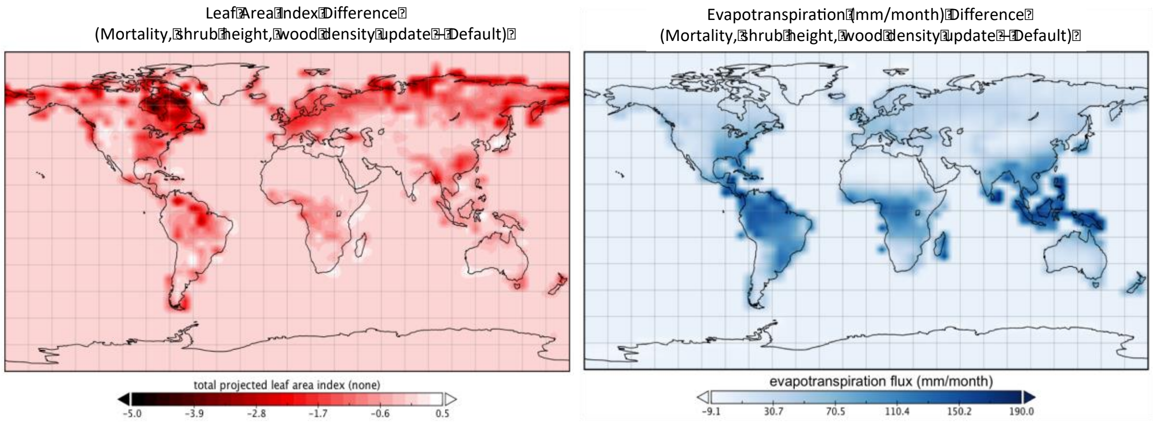

Figure 1. Decrease in leaf area index (LAI) and resulting increase in evapotranspiration (ET; mm month^{-1}) as a result of updating ELM-FATES (from the default version) by including a freezing-stress mortality, increasing shrub crown depth, and improving wood density parameterization.

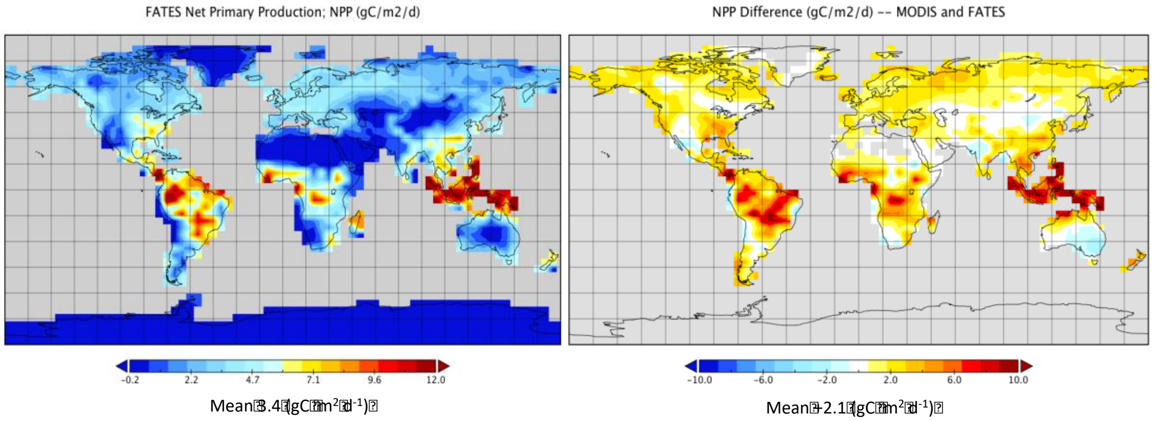

Figure 2. Estimated net primary productivity (NPP; gC m^{2} d^{-1}) by ELM-FATES, and difference as compared to MODIS derived NPP. ELM-FATES has a higher NPP bias of +2.1 gC m^{2} d^{-1} compared to MODIS.

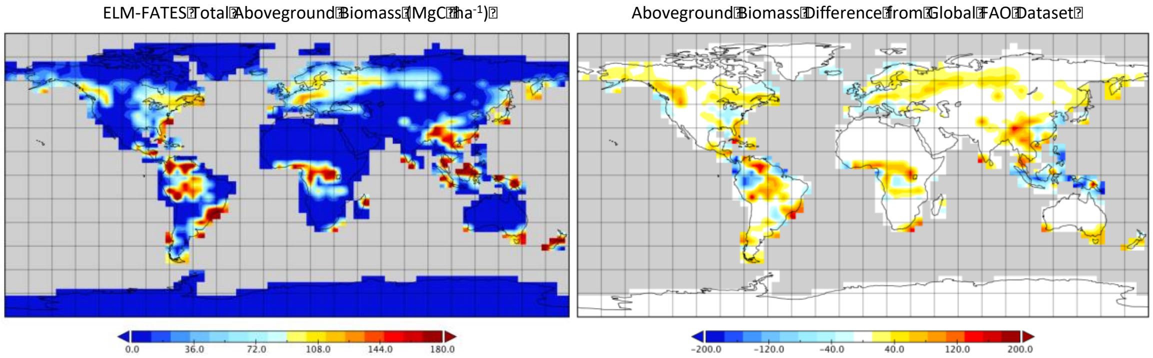

Figure 3. Estimated aboveground biomass (AGB; MgC ha^{-1}) by ELM-FATES, and difference as compared to global AGB reported by FAO and UNECE (Hengeveld et al. 2015). The majority of AGB discrepancies are either extreme higher or lower AGB predictions, and overall has a slightly higher AGB bias of +5.2 MgC ha^{-1} compared to observations.

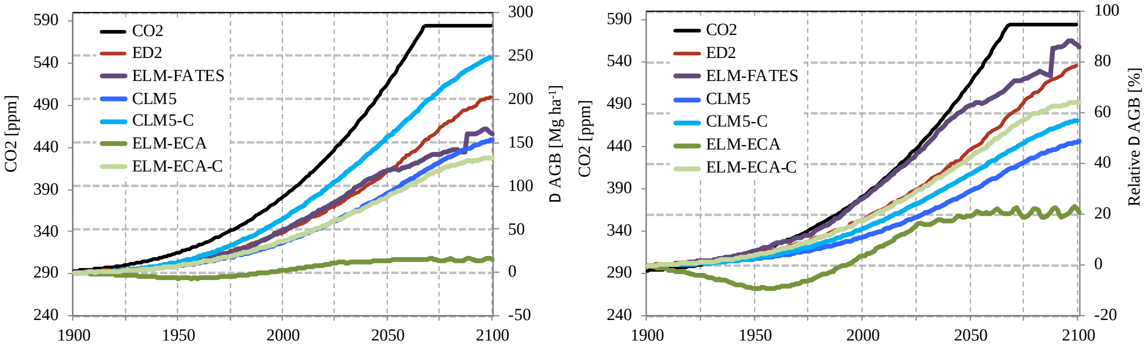

Figure 4. Projected biomass estimates to 2100 (right y-axis) relative to pre-industrial values (year 1900), at the Central Amazon ZF2 site from four terrestrial biosphere models, with two baseline simulations of the big-leaf models as unconstrained carbon-only model versions (CLM5-C and ELMv1-ECA-C). DAGB reported as (a) absolute change in AGB (Mg ha^{-1}) from 1900 values, with increasing modeled annual biomass increment (Mg ha^{-1} yr^{-1}), and (b) relative change in AGB (%) from 1900 values. Left y-axis on both panels (referencing the black line): Atmospheric CO$_2$ concentration driving the model simulations. Holm et. al., In Review.

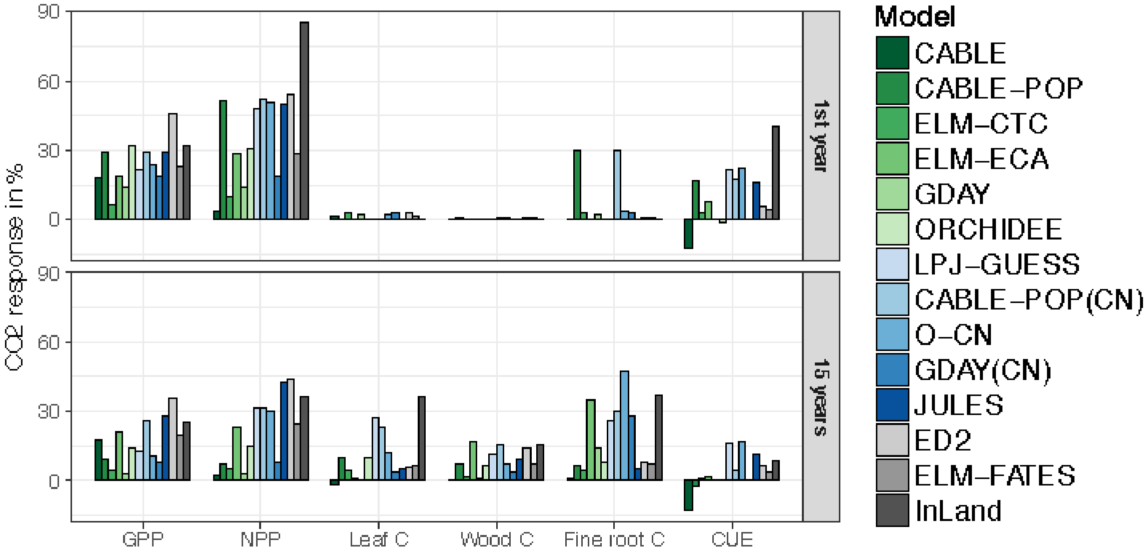

Figure 5. Relative effect of eCO$_2$ on GPP, NPP, leaf C, wood C, fine root C and plant CUE. Shown are initial effects (1st year) on top and final effects after 15 years of eCO$_2$ (mean of 13th to 17th year), both in %. C-only models are in shades of grey including ELM-FATES, CN models are depicted in shades of blue, and CNP models are depicted in shades of green. From Fleischer et. al., 2019.

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