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U.S. DEPARTMENT OF ENERGY | Office of Science

FY 2017 Fourth Quarter Performance Metric: Decompose and evaluate the effects of changes to CO_2, climate, and land-use/land-cover on the carbon cycle for the E3SM model

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DISCLAIMER

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1.0 Product Definition

Changes in temperature, precipitation, atmospheric CO_2 concentrations, and land use/land cover have implications for the carbon cycle. Increases in atmospheric CO_2 concentrations lead to more carbon stored in terrestrial ecosystems, while warming tends to reduce terrestrial carbon storage [*P. Friedlingstein et al.*, 2006; *Pierre Friedlingstein et al.*, 2014], although models diverge widely in the strength of these responses. Land-use and land-cover change can result in more or less carbon storage in the land, depending on the change; for example, carbon release to the atmosphere from deforestation accounts for approximately 15% of anthropogenic greenhouse gas emissions on an annual basis [*Le Quere et al.*, 2009], but the regrowth of previously cleared land is a significant carbon sink. Changes in temperature and CO_2 concentrations also influence crop yields [*Rosenzweig et al.*, 2014], which can in turn result in changes in land use and land cover [*Nelson et al.*, 2014]. However, the direction and magnitude of the effect varies across crop and Earth system model. Previous studies have examined the role of changing atmospheric carbon and climate (temperature and precipitation) on the carbon cycle [*P. Friedlingstein et al.*, 2006; *Pierre Friedlingstein et al.*, 2014; *Jones et al.*, 2013], but these studies do not specifically attribute changes to land use/land cover or the feedbacks between changing climate and land use/land cover. To address this problem, we performed a series of experiments, and developed novel analytical metrics, to decompose the effects of carbon, climate, and land use on the carbon cycle for the Energy Exascale Earth System Model (E3SM) project. Higher temperatures tend to reduce carbon storage, while increases in CO_2 concentrations increases carbon storage. Land-use feedbacks increase terrestrial carbon storage, resulting in more carbon stored per unit of temperature change and more carbon stored per unit of CO_2 increase than without feedbacks.

2.0 Product Documentation

The integrated Earth System Model (iESM; [*Collins et al.*, 2015]) couples the energy and land use components of the GCAM integrated assessment (IA) model with the atmosphere, ocean, and land components of an Earth System Model (ESM). Within this modeling framework, carbon, climate, land use, and feedbacks to land use can be isolated and the contribution of each to the global carbon cycle quantified. A new set of simulations and methodology to estimate the contribution of carbon, climate, land, and feedbacks to the carbon cycle is developed for the Energy Exascale Earth System Model (E3SM).

The Integrated Earth System Model (iESM) couples the human economic and energy components of the Global Change Assessment Model (GCAM, www.globalchange.umd.edu/gcam) with the physical, hydrological, and biogeochemical components of the Community Earth System Model (CESM, http://www.cesm.ucar.edu/). The iESM represents a major new model capability that permits the exploration of process-level interactions among human and Earth systems that were previously not represented in the existing suite of computational tools and procedures. The initial version of the iESM focuses on carbon cycle interactions (see Figure 1, [*Collins et al.*, 2015]). Code and input sets are available at: [www.github.com/ACME-Climate/iESM.](http://www.github.com/ACME-Climate/iESM)

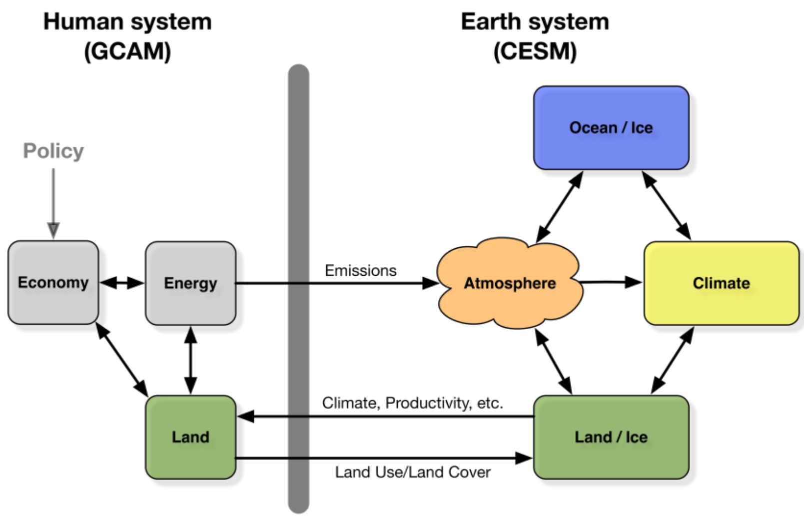

Figure 1. iESM coupling diagram.

Additionally, since iESM is developed within an ESM framework, the model retains all of the capabilities of that ESM. As such, the effect of carbon and climate on the carbon cycle can be isolated, replicating experiments like those described in *P. Friedlingstein et al.* [2006]. Those experiments compare simulations where CO_2 is treated as a nonradiatively active gas (i.e., its effect on climate is excluded) but only affects vegetation growth and exchange with the terrestrial system, with simulations where CO_2 influences climate.

To isolate these factors, a suite of six experiments was developed (see Table 1). Each experiment uses the results of an RCP8.5 simulation (which is based on high-estimated CO_2 emissions) and is run with three different initial conditions, each taken from different points in a long pre-industrial “steady” simulation. In each experiment, some aspects of the experiment were permitted to change, or not, as indicated in Table 1.

Table 1. Experiments and factors that are changed.

Type	CO_2	Climate	Land feedbacks
1	Yes	No	No
2	Yes	No	Yes
3	No	Yes	No
4	No	Yes	Yes
5	Yes	Yes	No
6	Yes	Yes	Yes

Using these simulations, parameters quantifying the contribution of CO_2 (β) and temperature (γ) on the carbon cycle can be calculated following the equations described in *P. Friedlingstein* *et al.* [2006]. These calculations can be expanded to quantify the contribution of land use and land-use feedbacks on the carbon cycle.

3.0 Results

In the RCP8.5, CO_2 concentrations increase over time, exceeding 900 ppm in 2100. These increases, combined with changes in other emissions, result in increases in temperature and precipitation. Land use and land cover also evolve over time as a result of changes in population, income, and agricultural productivity. Population and income result in increases in agricultural demand. Changes in agricultural productivity change the amount of land needed to meet that demand. As a result of these changes, cropland area expands in the RCP8.5 from 15 million km^2 in 2010 to almost 19 million km^2 in 2090 (Figure 2).

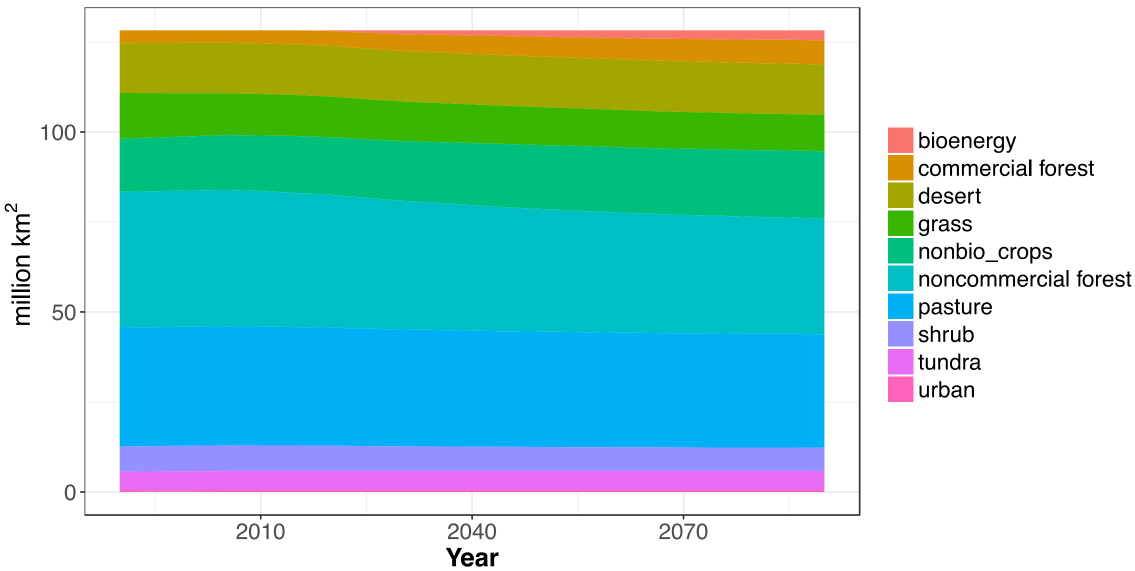

Figure 2. Land use/land cover in the RCP8.5.

Increases in CO_2 concentrations and changes in temperature and precipitation (i.e., climate) affect agricultural productivity. CO_2 concentrations result in global increases in productivity, while changes in climate lead to more regionally differentiated effects (Figure 3). Regional differences depend on magnitude of temperature increase in the climate cases, as well as the direction and magnitude of changes in precipitation. These changes result in further effects that propagate to the models' land-use/land-cover projections. Increases in productivity tend to result in declines in cropland area, as more food, feed, and fiber can be produced on less land. CO_2 changes lead to a decline in global cropland area of ~1.5 million km^2. Changes in climate result in a decline in global cropland area of ~1 million km^2.

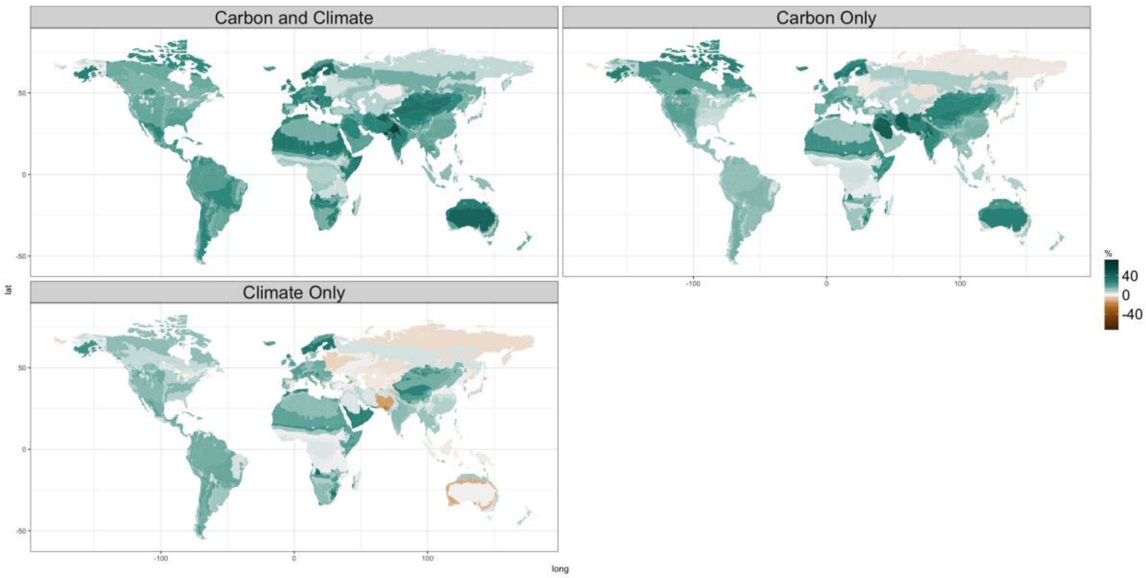

Figure 3. Change in wheat yield due to carbon and climate (top left), climate only (bottom left), carbon only (top right).

Changes in climate and atmospheric carbon result in changes in terrestrial carbon over time (Figure 4, solid lines), with increases in atmospheric carbon leading to increases in carbon storage. Running the model with climate changes only results in a decline in total terrestrial carbon. The inclusion of land-use feedbacks (changes in land cover due to changes in productivity, as described above) increases the terrestrial carbon storage (Figure 4, circled lines). These increases are due to change in land cover, specifically reductions in cropland and increases in forest cover, that are implemented by GCAM as it attempts to clear regional and global markets, and meet the demands of a rising and richer global population, throughout the 21st century.

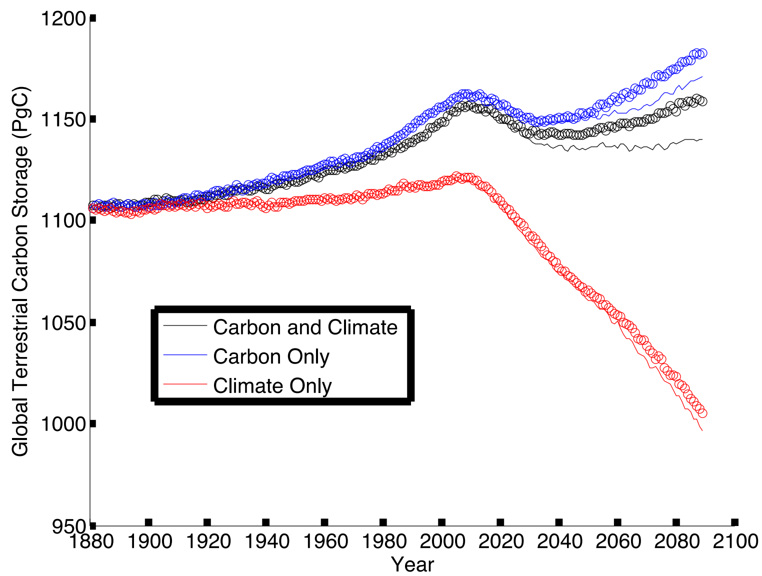

Figure 4. Evolution of terrestrial carbon storage with (circles) and without (solid lines) land-use feedbacks for simulations with carbon only (blue), climate only (red), and carbon and climate (black).

Finally, these simulations can be used to calculate carbon cycle parameters, quantifying the effect of increase in temperature (γ) and increase in CO_2 concentrations (β) on carbon storage. As noted above, temperature tends to reduce carbon storage, resulting in negative γ parameters (Figure 5). Increases in CO_2 concentrations increase carbon storage, resulting in positive β parameters (Figure 5). These parameters change when land-use feedbacks are included. Since these feedbacks increase terrestrial carbon storage, they increase both carbon cycle parameters. Such an effect has not previously been quantified.

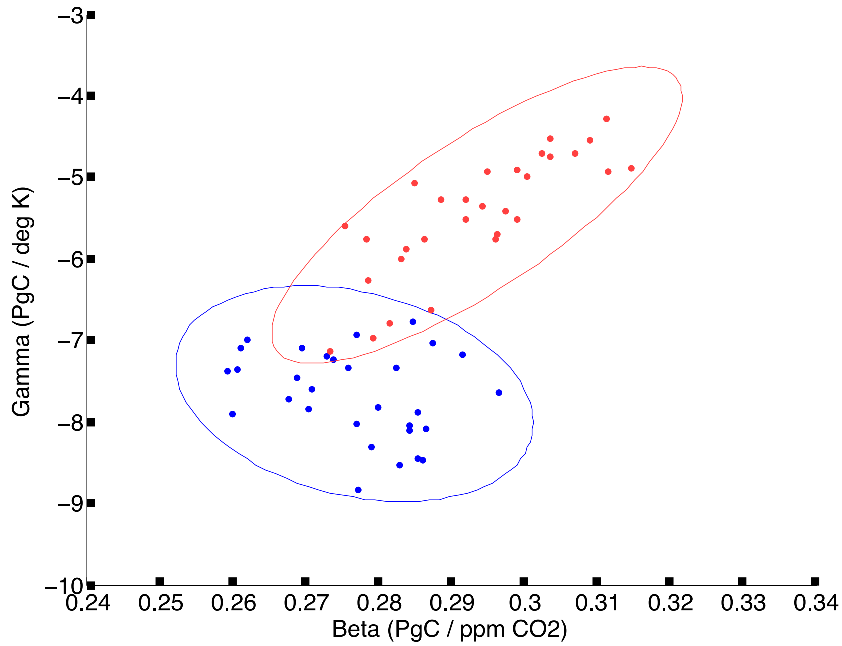

Figure 5. Carbon (β) and climate (γ) feedback parameters with (red) and without (blue) land-use feedbacks. Ellipses indicate the 95% confidence interval surrounding the joint distribution of the two parameters.

4.0 References

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