Supplemental Material for

Changes in the Carbon Cycle of Amazon Ecosystems
During the 2010 Drought

Christopher Potter 1*
Steven Klooster 2, Cyrus Hiatt 2, Vanessa Genovese 2,
Juan Carlos Castilla-Rubio 3

1 NASA Ames Research Center, Moffett Field, CA USA
2 California State University Monterey Bay, Seaside, CA USA
3 Planetary Skin Institute, Silicon Valley, CA, USA
1) **CASA Carbon Flux Algorithms**

As documented in Potter et al. (1993 and 2009a), monthly NPP flux, defined as net fixation of CO₂ by vegetation, is computed in CASA on the basis of light-use efficiency. Maximum conversion efficiencies of photosynthetically active radiation (PAR) to NPP carbon gains can be approximated as being nearly constant across all natural ecosystems (Nemani and Running, 1989; Sellers et al., 1994; Goetz and Prince, 1998; Running and Nemani, 1998). For this study, we used MODIS collection 5 of the Enhanced Vegetation Index (EVI; Huete, et al., 2002 and 2006) as an improvement in the model inputs for PAR interception.

Monthly production of plant biomass is estimated as a product of time-varying surface solar irradiance, Sr, and EVI from the MODIS sensor, plus a constant maximum light utilization efficiency term (emax) that is modified by time-varying stress scalar terms for temperature (T) and moisture (W) effects (Equation 1).

\[
\text{NPP} = \text{Sr} \times \text{EVI} \times e_{\text{max}} \times T \times W
\]

Equation 1

The e_{\text{max}} term is set uniformly at 0.55 g C MJ⁻¹ PAR, a value that derives from calibration of predicted annual NPP to previous field estimates (Potter et al., 2003). This model calibration has been validated globally by comparing predicted annual NPP to more than 1900 field measurements of NPP (see section that follows). Climate drivers for the CASA model were from the National Center for Environmental Prediction (NCEP/DOE II) reanalysis data set (Kistler et al., 2001; Zhao and Running, 2010), and land cover settings were aggregated from the MODIS global 1-km product (Zhao and Running, 2010), by determining the majority 8-km resolution land cover class from the underlying 1-km land cover pixels.

The global 8-km resolution MODIS vegetation index (VI) data sets used as inputs to Equation 1 were generated by aggregating monthly 0.05° (~6 km) data (MOD13C2 version 005) from the USGS LP DAAC. The VI layer was selected from each MOD13C2 spatial composite file and surface water values are converted to “NoData”. To aggregate from a 0.05° cell size to 8-km resolution, the VI values
for each pixel block were interpolated by inverse distance weighting to an average value. Each monthly layer was then multiplied by 0.0001 to scale the data to the standard MODIS VI value range. This aggregation procedure provided the greatest assurance of high-quality, cloud-free VI inputs to the carbon cycle model.

The T stress scalar is computed with reference to derivation of optimal temperatures (Topt) for plant production. The Topt setting will vary by latitude and longitude, ranging from near 0° C in the Arctic to the middle thirties in low latitude deserts. The W stress scalar is estimated from monthly water deficits, based on a comparison of moisture supply (precipitation and stored soil water) to potential evapotranspiration (PET) demand.

Evapotranspiration is connected to water content in the soil profile layers. The soil model design includes three-layer (M1-M3) heat and moisture content computations: surface organic matter, topsoil (0.3 m), and subsoil to rooting depth (1 to 10 m). Maximum rooting depth for cropland and grassland cover types was set at 1 m, whereas non-tropical forest was set at 2 m and tropical forest was set at 10 m (Nepstad et al., 1994; Poulter et al., 2009). These layers can differ in soil texture, moisture holding capacity, and carbon-nitrogen dynamics. Water balance in the soil is modeled as the difference between precipitation or volumetric percolation inputs, monthly estimates of PET, and the drainage output for each layer. Inputs from rainfall can recharge the soil layers to field capacity. Excess water percolates through to lower layers and may eventually leave the system as seepage and runoff.

Net ecosystem production (NEP) can be computed as NPP minus soil microbial respiration (Rh) fluxes, excluding the effects of small-scale fires and other localized disturbances or vegetation regrowth patterns on carbon fluxes. The CASA soil model Potter et al. (2009a) uses a set of compartmentalized difference equations for Rh fluxes. First-order decay equations simulate exchanges of decomposing plant residue (metabolic and structural fractions) at the soil surface. The model also simulates surface soil organic matter (SOM) fractions that presumably vary in age and chemical composition. Turnover of active (microbial biomass and labile substrates), slow (chemically protected), and passive (physically protected) fractions of the SOM are represented.
2) **CASA Model Validation**

Interannual NPP fluxes from the CASA model have been reported previously (Behrenfeld et al., 2001) and validated against multi-year estimates of NPP from field stations and tree rings (Malmström et al., 1997). Net ecosystem fluxes of carbon from CASA have been validated against atmospheric inverse model estimates over two decades (Potter et al., 2003). For this latest application, a comparison of observed NPP \( (n = 1927) \) from field based measurements to predicted annual values from the CASA model was made to provide validation of terrestrial NPP predictions across all ecosystem types. Observed NPP values were compiled for the Ecosystem Model-Data Intercomparison (EMDI) activity by the Global Primary Productivity Data Initiative (GPPDI) working groups of the International Geosphere Biosphere Program Data and Information System (IGBP-DIS; Olson et al., 1997). Monthly MODIS EVI inputs resulted in a highly significant correlation \( (R^2 = 0.91) \) and a close 1:1 match of observed to CASA predicted NPP values, with the year 2001 selected as an example (Fig. S1).

In this comparison to observed NPP, the CASA model was also tested for sensitivity to the vegetation index monthly time series as well by driving the NPP algorithm separately with either MODIS-EVI or MODIS-FPAR monthly inputs, holding climate inputs constant. A lower level of saturation in the low-to-medium range of plant production estimated from CASA modeling with EVI inputs compared to FPAR inputs was discovered by comparison of the two scatter plots over the range of annual NPP from 100-300 g C m\(^{-2}\) yr\(^{-1}\) (Fig. S1). Not only did EVI result in less overall scatter in the predicted versus observed plot (i.e., \( R^2 = 0.81 \) using MODIS FPAR inputs), the match to observed NPP in the high global range (of greater than 1000 g C m\(^{-2}\) yr\(^{-1}\)) was markedly more consistent with EVI compared to MODIS FPAR inputs.

By way of additional model validation in South American ecosystems, comparison of CASA seasonal NPP against measured monthly NEP fluxes from the Large-scale Biosphere-Atmosphere Experiment in Amazonia (LBA) showed close agreement at the Tapajos (Pará) forest experimental site (Potter et al., 2009a). At the ZF2 Manaus forest site, Chambers et al. (2004) directly measured respiration rates from live leaf, live wood, and forest soil surfaces to derive an indirect NPP flux estimate of 900 g C m\(^{-2}\) yr\(^{-1}\). Annual NPP from CASA for this general area (2.5° S lat, 60° W lon)
around Manaus varied between 782 – 871 g C m\(^{-2}\) yr\(^{-1}\) from 2000 and 2004. These CASA model predictions are further validated by the estimated NPP range of 864 ± 96 g C m\(^{-2}\) yr\(^{-1}\) from a review of 29 carbon study sites in humid tropical forest areas (Luyssaert et al., 2007).

3) Flooded Forest Area Examples of Drought Impacts

Three areas in the Amazon region were selected to illustrate of the impact of drought in 2010 on the carbon balance of floodplain forest ecosystems: A) Rio Urituyacu floodplain near Santa Rosa, Peru; B) the Rio Itui headwaters, north of Foz do Riozinho, Brazil; and C) the Rio Paru floodplain near Ramos, Brazil. Figures S2A-S2C show the river courses, the nearby cities, and the areas of flooded forest cover, all over a background of CASA predicted NEP fluxes for 2010 with dark red shades indicating the highest levels of carbon loss to the atmosphere.
Supplemental Figures and Captions

Figure S1. Comparison of observed NPP ($n = 1927$; Olson et al., 1997) to predicted annual values from the CASA model, driven separately by (a) MODIS-EVI and (b) MODIS-FPAR monthly inputs for the year 2001. The 1:1 regression line on each graph is shown, along with the linear correlation coefficient for the best fit to that 1:1 line.
Figure S2.

A) Rio Urituyacu floodplain near Santa Rosa, Peru
B) Rio Itui headwaters, north of Foz do Riozinho, Brazil
C) Rio Paru floodplain near Ramos, Brazil

References

Behrenfeld, M. J., J. T. Randerson, C. R. McClain, G. C. Feldma, S. Q. Los, C. I. Tucker, P. G. Falkowski, C. B. Field, R. Frouin, W. E. Esaias, D. D. Kolber, and N. H. Pollack, 2001. Biospheric primary production during an ENSO transition. Science 291, 2594-2597.

Chambers, J. Q., E. S. Tribuzy, L. C. Toledo, B. F. Crispim, N. Higuchi, J. dos Santos, A. C. Araujo, B. Kruijt, A. D. Nobre, and S. E. Trumbore. 2004, Respiration from a tropical forest ecosystem: Partitioning of sources and low carbon use efficiency. Ecological Applications 14: S72-S88.

Goetz, S. J, and S. D. Prince, 1998, Variability in light utilization and net primary production in boreal forest stands. Canadian Journal of Forest Research. 28: 375-389.

Huete, A., Didan, K., Miura, T., and Rodriguez, E., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens. Environ., 83, 195 – 213.
Huete, A. R., K. Didan, Y. E. Shimabukuro, P. Ratana, S. R. Saleska, L. R. Hutyra, W. Yang, R. R. Nemani, and R. Myneni, 2006, Amazon rainforests green-up with sunlight in dry season, *Geophys. Res. Lett.*, 33, L06405, doi:10.1029/ 2005GL025583.

Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woollen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van den Dool, H., Jenne, R., and Fiorino, M. 2001, The NCEP-NCAR 50-Year Reanalysis: Monthly Means CD-ROM and Documentation, *B. Am. Meteorol. Soc.*, 82, 247–268.

Luyssaert, S., I. Inglima, M. Jung, A. D. Richardson, M. Reichstein, D. Papale, and more than 20 other authors, 2007, CO₂ balance of boreal, temperate, and tropical forests derived from a global database, *Global Change Biology*, 13:12, 2509-2537.

Malmström, C. M., M. V. Thompson, G. P. Juday, S. O. Los, J. T. Randerson, and C. B. Field, 1997. Interannual variation in global scale net primary production: Testing model estimates. *Global Biogeochem. Cycles*. 11, 367-392.

Nemani, R. R. and S. W. Running, 1989, Testing a theoretical climate-soil-leaf area hydrologic equilibrium of forests using satellite data and ecosystem simulation, *Agric. For. Met.*, 44, 245-260.

Nemani, R. R., C. D. Keeling, H. Hashimoto, W. M. Jolly, S. C. Piper, C. J. Tucker, R. B. Myneni, and S. W. Running, 2003, Climate driven increases in global terrestrial net primary production from 1982 to 1999. *Science*. 300, 1560-1563.

Nepstad, D. C., et al., 1994, The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures, *Nature*, 372, 666 – 669.

Olson, R. J., J. M. O. Scurlock, W. Cramer, W. J. Parton, and S. D. Prince, 1997, From Sparse Field Observations to a Consistent Global Dataset on Net Primary Production. IGBPDIS Working Paper No. 16, IGBP-DIS, Toulouse, France, 1997.

Potter, C. S., J. T. Randerson, C. B. Field, P. A. Matson, P. M. Vitousek, H. A. Mooney, and S. A. Klooster, 1993, Terrestrial ecosystem production: A process model based on global satellite and surface data, *Global Biogeochem. Cycles*, 7, 811-841.

Potter, C., S. Klooster, A. Huete, V. Genovese, M. Bustamante, L. Guimaraes Ferreira, R. Cosme de Oliveira Junior, and R. Zepp, 2009a, Terrestrial carbon sinks in the Brazilian Amazon and Cerrado region predicted from MODIS satellite data and ecosystem modeling, *Biogeosciences*, 6, 1-9.

Potter, C., S. Klooster, R. Myneni, V. Genovese, P. Tan, V. Kumar, 2003, Continental scale comparisons of terrestrial carbon sinks estimated from satellite data and ecosystem modeling 1982-98. *Global and Planetary Change*, 39, 201-213.

Poulter, B., U. Heyder, and W. Cramer, 2009, Modelling the sensitivity of the seasonal cycle of GPP to dynamic LAI and soil depths in tropical rainforests, *Ecosystems*, 12(4), 517-533.

Running, S. W., and R. R. Nemani, 1998, Relating seasonal patterns of the AVHRR vegetation index to simulated photosynthesis and transpiration of forests in different climates. *Remote Sensing of
Sellers, P. J., C. J. Tucker, G. J. Collatz, S. O. Los, C. O. Justice, D. A. Dazlich, and D. A. Randall, 1994, A global 1x1 NDVI data set for climate studies. Part 2: the generation of global fields of terrestrial biophysical parameters from the NDVI. *International Journal of Remote Sensing*. 15, 3519-3545.

Zhao, M. and S. W. Running, 2010, Drought-induced reduction in global terrestrial net primary production from 2000 through 2009, *Science*, 329, 940-943.