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Changes in the carbon cycle of Amazon ecosystems during the 2010 drought

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Abstract
Satellite remote sensing was combined with the NASA-CASA (Carnegie Ames Stanford Approach) carbon cycle simulation model to evaluate the impact of the 2010 drought (July through September) throughout tropical South America. Results indicated that net primary production in Amazon forest areas declined by an average of 7% in 2010 compared to 2008. This represented a loss of vegetation CO_2 uptake and potential Amazon rainforest growth of nearly 0.5 Pg C in 2010. The largest overall decline in ecosystem carbon gains by land cover type was predicted for closed broadleaf forest areas of the Amazon river basin, including a large fraction of regularly flooded forest areas. Model results support the hypothesis that soil and dead wood carbon decomposition fluxes of CO_2 to the atmosphere were elevated during the drought period of 2010 in periodically flooded forest areas, compared to those for forests outside the main river floodplains.

Keywords: Amazon, drought, forest, NPP, MODIS

S Online supplementary data available from stacks.iop.org/ERL/6/034024/mmedia

The 2009–10 drought in the Amazon region was one of the most severe in recent history. Over 40% of the vegetated Amazon area experienced anomalously low precipitation amounts from July 2010 through September 2010 (Xu *et al* 2011). In rivers across the basin, water levels reached record low levels by October of 2010. According to long-term (100 y) flow records, Rio Negro water level at the Manaus harbor was the lowest on record in 2010 (Lewis *et al* 2011).

The moderate resolution imaging spectroradiometer (MODIS) satellite sensor has provided more than a decade's worth of data for Amazon rainforest studies. MODIS greenness levels, which can be conservatively treated as a measure of light interception capacity of the forest canopies, decreased dramatically in 2010 over an Amazon area more than three and one-half times the size of Texas and did not rapidly recover to previous levels, even after the drought ended in late October 2010 (Xu *et al* 2011). Nearly 50% of the Amazon region that was subject to drought showed significant declines in greenness. These changing MODIS patterns suggested a more widespread and long-lasting impact to Amazonian forests than what could be inferred based solely on rainfall data, leaving the scale and magnitude of this event still to be quantified.

Tropical scientists have hypothesized that warmer temperatures and reduced rainfall could slowly convert some Amazon rainforests into more woody savanna cover (Cox *et al* 2004, Salazar *et al* 2007, Huntingford *et al* 2008, Marengo *et al* 2008, Malhi *et al* 2008). This land cover change could cause carbon stored in the decomposing wood from rainforest dieback to be released into the atmosphere, which would add markedly to current greenhouse gases concentrations of CO_2. Recent MODIS studies of changing greenness in the region have not directly addressed ecosystem carbon emissions (Saleska *et al* 2007, Xu *et al* 2011). The CASA (Carnegie Ames Stanford Approach) simulation model (Potter *et al* 2009a), based also on MODIS enhanced vegetation index

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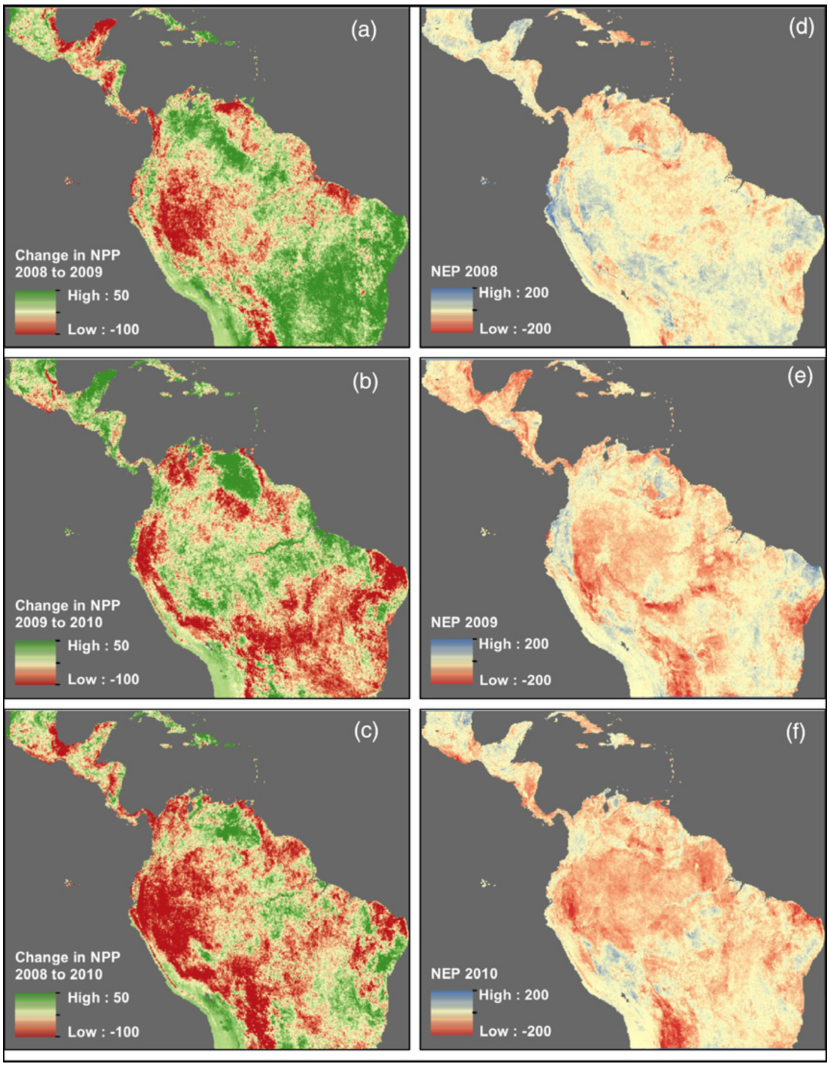

Figure 1. (a)–(c) Regional maps of annual NPP anomalies derived from subtraction of the 2009 and 2010 from 2008 total NPP values, and ((d) and (f)) annual NEP fluxes for 2008, 2009, and 2010 from the CASA model. All carbon fluxes shown are in units of g C m^{-2} yr^{-1}.

(EVI) data, indicated consistently high carbon sink fluxes prior to the drought of 2005 (Marengo *et al* 2008), particularly in forests of the western portions of the Brazilian states of Acre and Rondônia and the northern portions of the state of Pará. In other areas of the basin over the years 2000–4, CASA showed consistently elevated CO_2 source fluxes from terrestrial ecosystems to the atmosphere, particularly in deforested zones throughout the state of Maranhâo and in the southern portions of Amazonas (Potter *et al* 2009a, 2009b).

Below we present new CASA model results for Amazon carbon fluxes from 2008–10 MODIS monthly EVI inputs (Huete *et al* 2006) to assess regional CO_2 emission impacts of the recent drought. The model has been designed to estimate monthly patterns in carbon fixation, plant biomass increments, nutrient allocation, litter fall, soil carbon pools and CO_2 emissions (Potter *et al* 1993, 2003, 2009a and supplemental material-1 available at stacks.iop.org/ERL/6/034024/mmedia). Deforestation fire emissions were not considered in this modeling study of the years 2008–10. CASA was previously validated using tower flux estimates of net ecosystem production (NEP) in Amazon forests (Potter *et al* 2009a and supplemental material-2 available at stacks.iop.org/ERL/6/034024/mmedia). Gridded monthly climate inputs for these CASA runs were from National Center for Environmental Prediction (NCEP) reanalysis products (version NCEP/DOE II; Kistler *et al* 2001).

Net primary production (NPP) in Amazon forest areas declined by an average of 7% in 2010 compared to 2008 (figures 1(a)–(c)). This represents a loss of vegetation CO_2 uptake and potential Amazon rainforest growth of nearly 0.5 Pg C (1 Pg $= 10^{15}$ g) in 2010, relative to total Amazon basin NPP of 7.6 Pg C in 2008. CASA predicted a major decline in annual NPP from 2008 to 2009 in the western Amazon states of Brazil and in much of the forested areas of Peru. The decline in annual NPP expanded westward into Columbia, Ecuador, and Peru and into the northeastern Amazon states of Brazil from 2009 to 2010. NPP in much the savanna-dominated areas of Brazil also declined between 2009 and 2010.

Across the Amazon river basin, the CASA model predicted that annual NEP changed from a relatively neutral

Table 1. CASA model predictions of NEP and NPP carbon fluxes in land cover classes of the Amazon region from 2008 to 2010. Negative NEP values represent the net ecosystem source fluxes of CO_2 to the atmosphere, where positive NEP values represent the net sink fluxes CO_2 from the atmosphere to the ecosystems.

Land cover class code	Area cover (km^2)	Mean NEP flux, 2008 ($g\,C\,m^{-2}\,yr^{-1}$)	Mean NEP Flux, 2009 ($g\,C\,m^{-2}\,yr^{-1}$)	Mean NEP Flux, 2010 ($g\,C\,m^{-2}\,yr^{-1}$)	Per cent change in NPP, 2008–9 (%)	Per cent change in NPP, 2009–10 (%)	Per cent change in NPP, 2008–10 (%)
14[a]	663 944	13.95	−15.89	−26.58	4.13	−8.54	−4.98
20[b]	1 312 977	4.31	−21.94	−32.72	1.94	−6.70	−5.17
30[c]	1 367 472	−0.26	−23.76	−28.97	1.28	−4.93	−4.16
40[d]	7 700 672	−5.13	−38.94	−44.68	−2.83	−2.88	−5.82
50[e]	501 389	6.70	−42.39	−57.81	−0.12	−6.62	−7.06
60[f]	44 446	4.47	−2.13	−53.29	4.32	−11.92	−8.27
70[g]	146 433	14.33	−26.11	4.11	−1.03	−0.50	−1.78
100[h]	17 209	4.59	−33.93	−9.21	0.19	−2.15	−2.10
110[i]	255 845	5.07	−11.87	−15.86	0.20	−2.44	−2.91
120[j]	135 403	0.94	−18.01	−9.78	−0.89	−0.17	−1.42
130[k]	1 254 880	9.27	−9.69	−24.56	2.00	−6.72	−5.21
140[l]	558 898	−5.93	−24.98	−16.91	−2.74	0.33	−2.97
150[m]	127 574	6.06	6.07	−4.10	4.50	−2.28	2.07
160[n]	266 860	−5.79	−47.73	−54.16	−4.31	−1.78	−6.20
170[o]	15 191	−6.73	−33.97	−21.67	−4.22	0.44	−4.12
180[p]	164 330	0.62	−34.23	−22.82	−0.59	−3.64	−4.54

Key to land cover class names from ESA, GLOBCOVER 2009 (Bicheron *et al* 2008).
[a] Rainfed croplands. [b] Mosaic cropland (50–70%)/vegetation (grassland/shrubland/forest) (20–50%).
[c] Mosaic vegetation (grassland/shrubland/forest) (50–70%)/cropland (20–50%).
[d] Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5 m).
[e] Closed (>40%) broadleaved deciduous forest (>5 m).
[f] Open (15–40%) broadleaved deciduous forest/woodland (>5 m).
[g] Closed (>40%) needleleaved evergreen forest (>5 m).
[h] Closed to open (>15%) mixed broadleaved and needleleaved forest (>5 m).
[i] Mosaic forest or shrubland (50–70%)/grassland (20–50%).
[j] Mosaic grassland (50–70%)/forest or shrubland (20–50%).
[k] Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5 m).
[l] Closed to open (>15%) herbaceous vegetation. [m] Sparse (<15%) vegetation.
[n] Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily).
[o] Closed (>40%) broadleaved forest or shrubland permanently flooded.
[p] Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil.

year of zero regional net flux in 2008, to large regional source fluxes of −0.29 Pg C and −0.42 Pg C in 2009 and 2010, respectively (table 1). This drought effect was roughly equivalent to the combined effects of anthropogenic deforestation and forest fires in undisturbed Amazonian forests, estimated at between 0.3 and 0.6 Pg C emitted annually (Aragão and Shimabukuro 2010). NEP is the CASA model net flux estimate of CO_2 between the ecosystems and the atmosphere that accounts fully for changes in soil respiration rates and CO_2 sources from decomposition of down woody material in forests and savannas. On an area (m^2) basis, Amazon rainforest NEP fluxes shifted from a near-zero annual sum in 2008 to a net source flux of CO_2 to the atmosphere in excess of $-40\ g\,C\,m^{-2}\,yr^{-1}$ in 2009 and in 2010. Predicted annual NEP flux changed from positive (ecosystem carbon sink) to negative (ecosystem carbon source) from 2008 to 2009 over most rainforests of the western Amazon states of Brazil and in Peru (figures 1(d)–(f)). Annual NEP flux became more strongly negative in 2010 over rainforest areas of Columbia, Ecuador, and the eastern Amazon states of Brazil.

The largest overall decline in NEP (in both 2009 and 2010) by land cover type was predicted for closed broadleaf forest areas of the Amazon river basin, at mean net loss range of −53 to $-57\ g\,C\,m^{-2}\,yr^{-1}$ (table 1). Closed broadleaf cover in the Amazon includes a large fraction (35%) of regularly flooded forest areas (Bicheron *et al* 2008). Since annual NPP losses between 2009 and 2010 were no greater on average for flooded forests than the CASA model predicted for other (upland) forest cover types in the Amazon, we can hypothesize that soil and dead wood carbon decomposition fluxes of CO_2 to the atmosphere were elevated during the drought period of 2010 in what are regularly flooded forest areas, compared to forests outside the main river floodplains. CASA modeling identified the following floodplain forests of the region as prime study areas to test this hypothesis further: Rio Urituyacu floodplain near Santa Rosa, Peru; the Rio Itui headwaters, north of Foz do Riozinho, Brazil; and the Rio Paru floodplain near Ramos, Brazil. (supplemental material-3 available at stacks.iop.org/ERL/6/034024/mmedia).

Perhaps the most important climate–ecological hypothesis yet to be tested for the Amazon region is whether declines in rainforest productivity, such as those predicted during the years 2009 and 2010, were accompanied by widespread mortality of trees and opening of previously closed forest canopy cover. Questions remain as to whether deep rooting can entirely buffer the forest from future dry conditions. Observational data of such water and temperature stress conditions, together with high resolution (1 m or less) remote sensing of tree dieback patterns and canopy gap formation, will be important methods to monitor these vulnerable ecosystems.

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