Variability in Terrestrial Carbon Sinks over Two Decades. Part III: South America, Africa, and Asia

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ABSTRACT: Seventeen years (1982–98) of net carbon flux predictions for Southern Hemisphere continents have been analyzed, based on a simulation model using satellite observations of monthly vegetation cover. The NASA Carnegie Ames Stanford Approach (CASA) model was driven by vegetation-cover properties derived from the Advanced Very High Resolution Radiometer and radiative transfer algorithms that were developed for the Moderate Reso-
lution Imaging Spectroradiometer (MODIS). The terrestrial ecosystem flux for atmospheric CO₂ for the Amazon region of South America has been predicted between a biosphere source of \(-0.17\) Pg C per year (in 1983) and a biosphere sink of \(+0.64\) Pg C per year (in 1989). The areas of highest variability in net ecosystem production (NEP) fluxes across all of South America were detected in the south-central rain forest areas of the Amazon basin and in southeastern Brazil. Similar levels of variability were recorded across central forested portions of Africa and in the southern horn of East Africa, throughout Indonesia, and in eastern Australia. It is hypothesized that periodic droughts and wildfires associated with four major El Niño events during the 1980s and 1990s have held the net ecosystem carbon sink for atmospheric CO₂ in an oscillating pattern of a 4–6-yr cycle, despite observations of increasing net plant carbon fixation over the entire 17-yr time period.

**KEYWORDS:** Carbon; Ecosystems; Remote sensing; Soil

### 1. Introduction

Consistency in methods of carbon accounting across continents is crucial to monitor the worldwide fluctuations in CO₂ levels and to separate the influences of climate variation and land-use change on the net uptake of CO₂ from the atmosphere for persistent storage in plant or soil sinks. Recent studies using satellite remote sensing have indicated that changes in climate have eased several critical constraints to plant growth, such that net primary production (NPP) has increased globally over the past two decades (Nemani et al. 2003; Potter et al. 2003a). The largest increase was observed in tropical ecosystems. Amazon rain forests accounted for over 40% of the global increase in NPP, owing possibly to decreased cloud cover and the resulting increase in solar radiation.

To add spatial details to global estimates, the ecosystem modeling approaches cited above represent the terrestrial biosphere as thousands of georeferenced pixel elements observed continuously from space. Plant and soil microbial physiological processes are simulated for each pixel to transport CO₂ between the simulated land surface and the atmosphere, and to store carbon at the pixel location (Potter 1999; Potter et al. 2003a; Potter et al. 2003b). This type of spatial modeling approach cannot only identify subcontinental carbon sink locations but can also characterize the historical changes in land-cover properties and actual vegetation type at each pixel location using satellite remote sensing. In addition, the effect of simultaneous plant, soil, and climate impacts can be captured in the physiological process description, which is uniquely valuable in a domain where there is still a sparse distribution of long-term field study sites of these effects from which to gather net ecosystem production (NEP) data for continental-scale interpolations.

The National Aeronautics and Space Administration Carnegie Ames Stanford Approach (NASA-CASA) model is designed to estimate monthly patterns in plant carbon fixation, plant biomass, nutrient allocation, litter fall, soil nutrient mineralization, and carbon emissions from soils worldwide (Potter et al. 1993; Potter et al. 1999). This results in spatially discrete predictions of NEP over nearly two decades (Potter et al. 2003b). Direct input of satellite sensor “greenness” data from the Advanced Very High Resolution Radiometer (AVHRR) sensor into the NASA-CASA model are used to estimate spatial variability in monthly NPP,
biomass accumulation, and litter fall inputs to soil carbon pools at a geographic resolution of 0.5° latitude–longitude. Global NPP of vegetation is predicted using the relationship between greenness reflectance properties and the fraction of absorption of photosynthetically active radiation (FPAR), assuming that net conversion efficiencies of PAR to plant carbon can be approximated for different ecosystems or are nearly constant across all ecosystems (Nemani and Running 1989; Sellers et al. 1994; Goetz and Prince 1998; Running and Nemani 1998).

In this study, we analyzed the NPP and NEP results of NASA-CASA model predictions from 1982 to 1998 to compare the variability in continental-scale carbon fluxes for South America to that of southern continental Africa and Asia. Like our earlier reports on variability of carbon sinks in North America and northern Eurasia (Potter et al. 2003b; Potter et al. 2005), this study is intended to improve understanding of global climate controls over terrestrial carbon sinks in the Southern Hemisphere.

2. Global data and models

For this analysis, terrestrial NEP fluxes have been computed monthly (over the period 1982–98) at a spatial resolution of 0.5° latitude–longitude using the NASA-CASA biosphere model (Potter 1999; Potter et al. 1999; Potter et al. 2003a). NASA-CASA is a numerical model of monthly fluxes of water, carbon, and nitrogen in terrestrial ecosystems (Figure 1). Our estimates of terrestrial NPP fluxes depend on inputs of global satellite observations for land surface properties and on gridded model drivers from interpolated weather station records (New et al. 2000) distributed across all the continental masses.

Our fundamental approach to estimating NPP is to define optimal metabolic rates for carbon fixation processes, and to adjust these rate values using factors related to limiting effects of time-varying inputs of solar radiation (SOLAR), air temperature (TEMP), precipitation (PREC) (New et al. 2000), predicted soil moisture, and land cover (DeFries and Townshend 1994). Carbon (CO₂) fixed by vegetation as NPP is estimated in the ecosystem model according to the time-varying (monthly mean) fraction of FPAR intercepted by plant canopies and a light utilization efficiency term (emax). This product is modified by stress factors for temperature (Tₐ) and moisture (W) that vary over time and space. The emax term is set uniformly at 0.39 (g C per MJ PAR) (Potter et al. 1993), a value that has been verified globally and for tropical regions by comparing predicted annual NPP to more than 1900 field estimates of NPP (Potter et al. 2003a). Interannual NPP fluxes from the CASA model have been reported (Behrenfeld et al. 2001) and checked for accuracy by comparison to multiyear estimates of NPP from field stations and tree rings (Malmström et al. 1997) and forest inventory reports (Hicke et al. 2002). Our NASA-CASA model has been validated against field-based measurements of NEP fluxes and carbon pool sizes at multiple locations in North America (Potter et al. 2001; Amthor et al. 2001; Potter et al. 2003b).

Our NASA-CASA model is designed to couple seasonal patterns of NPP to soil heterotrophic respiration (Rₛ) of CO₂ from soils worldwide (Potter 1999). 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.

Global soils data for this version of NASA-CASA come from the most recent Food and Agricultural Organization of the United Nations (FAO) Digital Soil Map of the World, 1995 version. Predominant soil type and texture have been determined for each 0.5° grid cell in the model simulations. The major scale discrepancies between these FAO soil polygon data and global satellite datasets used to drive NPP will be in remote desert and high-latitude zones, where the abundance of soil survey information is the weakest, and NPP is the lowest. These FAO soil attributes influence storage potential of carbon in the upper 20–30 cm of the simulated soil profile, with deep clay soils storing more organic matter than lighter sandy soils.

NEP is computed as NPP minus total $R_h$ fluxes, excluding the effects of small-
scale fires and other localized disturbances or vegetation regrowth patterns on carbon fluxes (Schimel et al. 2001). The effects of large-scale (0.5° grid area) disturbances on the continental carbon cycle has been addressed for the NASA-CASA model in Potter et al. (Potter et al. 2003c).

Whereas previous versions of the NASA-CASA model (Potter et al. 1993; Potter et al. 1999) used a normalized difference vegetation index (NDVI) to estimate FPAR, the current model version instead relies upon canopy radiative transfer algorithms (Knyazikhin et al. 1998), which are designed to generate improved spatially varying FPAR products as inputs to carbon flux calculations. These radiative transfer algorithms, developed for the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the NASA Terra platform, account for attenuation of direct and diffuse incident radiation by solving a three-dimensional formulation of the radiative transfer process in vegetation canopies. Monthly gridded composite data from spatially varying channels 1 (visual red) and 2 (near infrared) of the AVHRR have been processed according to the MODIS radiative transfer algorithms and aggregated over the global land surface to 0.5° grid resolution, consistent with the NASA-CASA model driver data for climate variables. To minimize cloud contamination effects, a maximum value composite algorithm was applied spatially for 0.5° pixel values.

3. Variability in terrestrial carbon sinks

For global comparison purposes, the Southern Hemisphere tropical (SHT) zone is defined as the latitudes between the equator and 30°S across the entire globe. In terms of predicted annual NPP, the SHT zone was estimated to vary between 16.6 and 18.4 Pg C (1 Pg = 10^{15} g) per year (Potter et al. 2003b). The NASA-CASA model predicts a general increase in NPP toward the high end of this range for the SHT region over this 17-yr time period of 1982–98 (Figure 2a). NPP for the Amazon region alone (between the northwestern corner of 6°N, 77°W and the southeastern corner of 20°S, 45°W) was predicted to vary between 8.7 (in 1983) and 9.8 Pg C (in 1997) per year (Potter et al. 2004).

Predicted NEP fluxes for the SHT zones were estimated between an annual source (to the atmosphere) of −0.29 Pg C per year (in 1983), to a sink (from the atmosphere) of +0.87 Pg C per year (in 1989) over the period 1982–98 (Potter et al. 2003b). Unlike the predicted NPP for this period, predicted NEP does not increase notably. NEP oscillates on a 4–6-yr cycle, with low points in 1983, 1987, 1991, and 1997 (Figure 2b). Since the predicted global NEP flux for CO₂ varied similarly over time between an annual source of −0.9 Pg C per year to a sink of +2.1 Pg C per year, the SHT zone could have had a major influence over the biosphere–atmosphere exchange of carbon during the period. Predicted NEP for the Amazon region alone varied between −0.17 Pg C per year (in 1983) to +0.64 Pg C per year (in 1989), with a seasonal anomaly range of up to ±0.1 Pg C per month (Potter et al. 2004).

It should be noted that the NASA-CASA model does not explicitly estimate sources of terrestrial carbon emitted to the atmosphere from small-scale ecosystem disturbances, such as from wildfires’ source fluxes of CO₂, nor from other major land-use changes over decades. Nevertheless, we have demonstrated that the
Figure 2. NASA-CASA results from interannual simulations for the Southern Hemisphere tropical (SHT) zone. (a) NPP monthly anomalies (light line) and 12-month running mean (heavy line). (b) NEP monthly anomalies (light line) and 12-month running mean (heavy line).
FPAR time series can capture sources of terrestrial carbon emitted to the atmosphere from large-scale ecosystem disturbances (Potter et al. 2003c).

The remainder of our analysis involves data transformations to detect anomalies in NEP fluxes at a subregional level. The first step in this analysis of interannual variability was the conversion of all time series to monthly Z-score values, which can be used to specify the relative statistical location of each monthly value within the 17-yr population distribution (e.g., all Januarys are adjusted with respect to the long-term mean January value). The numerical Z score indicates the distance from the long-term monthly mean as the number of standard deviations above or below the mean. The main difference between the t statistic and the Z score is that the Z score uses a monthly sample standard deviation, whereas the t score uses population standard deviation, which is usually unknown.

While our NASA-CASA model results show several consecutive multiyear periods during which the magnitudes of continental sinks for CO2 in the southern regions were fairly constant, the predicted spatial pattern of these sink fluxes was actually quite variable from one year to the next. Areas showing the highest interannual variability on NEP fluxes were defined according to the number of anomalously low (LO) or anomalously high (HI) monthly events detected in the 17-yr time series. We used an anomalous event threshold value of 1.7 standard deviations (SDs) LO or HI relative to the long-term (1982–98) NEP monthly mean value. In the use of a one-tailed (LO or HI) statistical test, rejection of the null hypothesis means that every observation in the sample belongs to the same population of all other observations in the same sample (i.e., is not an outlier). In separate one-tailed tests for LO and HI events, an SD > 1.7 represents the 95% confidence level for outliers in the population (Stockburger 1998). Additionally, a threshold value of greater than three anomalous NEP-LO or NEP-HI monthly events, representing anomaly sums just inside the 99th percentile, was used to identify the areas of high interest for interannual variability, which also ensures that at all locations identified there would have, on average, at least one anomalous monthly event detected every 5 yr in the time series.

An example NEP time series for a tropical forest site (DeFries and Townshend 1994) in the eastern Amazon (Figure 3) illustrates a location where several anomalously LO versus HI monthly events have occurred in cycles. Anomalous LO NEP events in tropical forest areas of Brazil, such as those seen in 1987, can be associated with major wildfires that can burn millions of hectares in one year (Nepstad et al. 1999; Potter et al. 2003c). Predicted NEP over practically the entire Amazon region east of 60°W was highly correlated with the Southern Oscillation index (SOI), indicating that cycles in rainfall have been the principal determinant of model estimates for NPP and NEP in this region. SOI is computed as the standardized difference between sea level pressure (SLP) measured in Tahiti (17°S, 149°W) and Darwin, Australia (13°S, 131°E), and is considered to be an indicator of atmospheric impacts of El Niño (Trenberth and Hurrell 1994). A regional map of maximum correlations between SOI and NEP Z scores has been published previously in Potter et al. (Potter et al. 2004).

To assess the possibility of random occurrence of NEP monthly events in the dataset, it was found that drawing random SD values from a sample of size of 204 months 10 000 times gives an expectation of about 22 anomalies (SD > 1.7) per site over the time of the simulation. If we expect equal distribution of NEP events
between high and low anomalies, the expected number of NEP-LO and NEP-HI events due to random chance would be 11, with the confidence intervals around them influenced by the autocorrelation in NEP between months (and their spatial distribution influenced by the spatial autocorrelation of the model inputs). Therefore, only locations showing greater than 11 anomalies in either the NEP-LO and the NEP-HI time series are considered to fall outside the range of potential random occurrence.

High interannual variability in NEP fluxes can be readily identified at locations across the South American continent at levels that approach the maximum of 20 cumulative NEP-LO or NEP-HI monthly events in the time series (Figure 4). According to the distribution of NEP-LO events (Figure 4a), the areas of highest variability in South America were detected in the south-central rain forest areas of the Amazon basin. Similar levels of variability were recorded across central forested portions of Africa and Southeast Asia, especially in Indonesia. According to the distribution of NEP-HI events (Figure 4b), the areas of highest variability are detected in southeastern Brazil, the southern horn of East Africa, and in eastern

Figure 3. Time series example (1982–98) of NEP monthly Z scores (units = standard deviation (SD)) line plot for a humid forest ecosystem location in central Amazon (5°S, 50°W). Original units of NEP were g C m⁻² month⁻¹. SOI is plotted with its correlation coefficient to monthly NEP anomalies at a 3-month lag time.
Australia. There is minimal overlap between the areas of highest cumulative NEP-LO versus NEP-HI monthly events in these two figures.

4. Associations with climate events

Association analysis can offer further insights into the types of dependencies that exist among variables within a large dataset (Agrawal and Srikant 1994). Anomalously LO or anomalously HI monthly events for the main NASA-CASA model

![Images of maps showing NEP monthly anomalies in 17-yr time series (1982-98)](http://example.com/image)

**Figure 4.** Location of NEP monthly anomalies in the 17-yr time series (1982–98) for (a) NEP-LO anomalies and (b) NEP-HI anomalies. Color bar shows number of LO or HI anomalous events at each pixel location.
time series inputs of TEMP, PREC, SOLAR, and FPAR can be mapped in association with LO or HI monthly events for predicted NEP. As in the case of NEP, we used an anomalous event threshold value of 1.7 SD or greater from the long-term (1982–98) climatic monthly mean value.

It is important to note that, because the NASA-CASA model has numerous nonlinear functions that are used to transform the input variables of TEMP, PREC, SOLAR, and FPAR into predicted ecosystem NEP fluxes, a large fraction of anomalously LO or HI monthly events for NEP detected in Figure 4 may have no consistent associations with the four inputs variables at the threshold value selected. This is not to imply that one input variable or another is not a dominant control over NEP fluxes, simply because we do not report it as such in the association counts below. To the contrary, many nonlinear dependencies between model inputs and NEP predictions may fall below our threshold values of 1.7 SD, and hence we can compare the association counts among the four input variables with NEP anomalies only in a relative sense, rather than in an effort to explain all or most of the continent-wide NEP-LO and NEP-HI monthly events depicted in Figure 4. Association counts presented below should be considered representative samples of the strongest dependencies between NEP and at least one of the four input variables, rather than an exhaustive analysis of controls on NEP at every land location in Figure 4.

In the association counts of NEP with anomalous FPAR or SOLAR monthly events, we considered only two possible cases, LO with LO and HI with HI, since these two model inputs operate solely in NPP model calculations in a near-linear fashion to alter NEP estimates. The near-linear form of this relationship derives from the empirical calibration in our original CASA model for NPP (Potter et al. 1993). This means that FPAR-LO or SOLAR-LO can decrease NPP (but not soil $R_h$) and hence potentially result in a NEP-LO monthly event (but not in a NEP-HI monthly event). The reverse effect on NPP-HI events (but not on soil $R_h$) can result from FPAR-HI or SOLAR-HI monthly events. In the association counts of NEP with anomalous TEMP or PREC monthly events, we instead considered all four possible cases, LO with LO, LO with HI, HI with LO, and HI with HI, since these two model inputs operate in both NPP and soil $R_h$ model calculations to alter NEP estimates.

The most readily detectable association between model input events and NEP monthly events for South America was with anomalous FPAR (LO and HI combined) monthly events (Table 1), followed in decreasing order by PREC, SOLAR, and TEMP monthly events. The same general association patterns were observed for sub-Saharan Africa (Table 2) and southern Asia and Australia (Table 3) regions. Associations of NEP-LO monthly events with FPAR-LO monthly events occurred at a frequency twice that of NEP-HI monthly events with FPAR-HI events in both South America and in sub-Saharan Africa.

FPAR-LO monthly anomalies were detected to co-occur with NEP-LO monthly anomalies mainly in the northern Andes Mountains, the central and southern Amazon basin, throughout western and central Africa, and Southeast Asia, whereas FPAR-HI monthly anomalies were detected to co-occur with NEP-HI monthly anomalies mainly in southeastern Brazil, the horn of East Africa and southern Africa, and in eastern Australia (Figure 5). These spatial patterns suggest FPAR-LO anomalies occur most frequently in areas of the Southern Hemisphere
that are susceptible to periodic droughts and associated wildfires. Tropical deforestation by cutting, burning, and logging have been contributing factors to land-cover degradation in the central and southern Amazon basin over the past decade (Nepstad et al. 1999). Similar deforestation impacts on FPAR-LO and NEP-LO event frequency may explain the predicted NASA-CASA results throughout the Southeast Asia region, where drought, fire, and forest logging interactions have been documented (Siegert et al. 2001; Page et al. 2002). Mason and Goddard (Mason and Goddard 2001) also showed correlations between ENSO and precipitation anomalies in parts of Southeast Asia, Australia, and southern Africa that correspond to areas of highest NEP anomalies detected in Figure 4a.

### 5. Discussion

Our NASA-CASA model results reveal important patterns of geographic variability in carbon sinks within major continental areas of the Southern Hemisphere. Consistent with the results of Nemani et al. (Nemani et al. 2003), AVHRR satellite-derived observations and NASA-CASA model predictions imply that net primary productivity of tropical terrestrial ecosystems has increased markedly over the last two decades of the twentieth century. Amazon rainforest areas accounted for 42% of the global NPP increase, benefiting from what Nemani et al. (Nemani

<table>
<thead>
<tr>
<th>Model inputs</th>
<th>NEP-LO total</th>
<th>NEP-HI total</th>
<th>NEP-LO percent 100</th>
<th>NEP-HI percent 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMP-LO</td>
<td>69</td>
<td>8</td>
<td>0.74</td>
<td>0.14</td>
</tr>
<tr>
<td>TEMP-HI</td>
<td>99</td>
<td>27</td>
<td>1.85</td>
<td>1.00</td>
</tr>
<tr>
<td>PREC-LO</td>
<td>132</td>
<td>94</td>
<td>0.19</td>
<td>0.07</td>
</tr>
<tr>
<td>PREC-HI</td>
<td>314</td>
<td>491</td>
<td>2.17</td>
<td>1.31</td>
</tr>
<tr>
<td>SOLAR-LO</td>
<td>713</td>
<td>—</td>
<td>12.29</td>
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</tr>
<tr>
<td>SOLAR-HI</td>
<td>—</td>
<td>50</td>
<td>0.00</td>
<td>6.23</td>
</tr>
<tr>
<td>FPAR-LO</td>
<td>2472</td>
<td>—</td>
<td>14.76</td>
<td>0.00</td>
</tr>
<tr>
<td>FPAR-HI</td>
<td>—</td>
<td>1091</td>
<td>0.00</td>
<td>8.13</td>
</tr>
</tbody>
</table>

Table 2. Counts of 0.5° pixels in sub-Saharan Africa for co-occurrence of model input events with NEP monthly anomalous events.

<table>
<thead>
<tr>
<th>Model inputs</th>
<th>NEP-LO total</th>
<th>NEP-HI total</th>
<th>NEP-LO percent 100</th>
<th>NEP-HI percent 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMP-LO</td>
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<td>2</td>
<td>0.74</td>
<td>0.14</td>
</tr>
<tr>
<td>TEMP-HI</td>
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<td>2</td>
<td>1.85</td>
<td>1.00</td>
</tr>
<tr>
<td>PREC-LO</td>
<td>25</td>
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<td>PREC-HI</td>
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<td>1.31</td>
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<td>SOLAR-LO</td>
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<td>12.29</td>
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</tr>
<tr>
<td>SOLAR-HI</td>
<td>—</td>
<td>19</td>
<td>0.00</td>
<td>6.23</td>
</tr>
<tr>
<td>FPAR-LO</td>
<td>3755</td>
<td>—</td>
<td>14.76</td>
<td>0.00</td>
</tr>
<tr>
<td>FPAR-HI</td>
<td>—</td>
<td>2359</td>
<td>0.00</td>
<td>8.13</td>
</tr>
</tbody>
</table>
et al. 2003) hypothesize to be decreased cloud cover and resulting increased radiation.

Nonetheless, using the NASA-CASA model that addresses both plant CO₂ uptake (NPP) and soil microbial decomposition, we cannot infer that net storage of carbon (NEP) in tropical regions increased in a pattern consistent with NPP trends (Figure 2). Instead, we hypothesize that periodic droughts and wildfires associated with four major El Niño events during the 1980s and 1990s (Figure 3) have held the NEP carbon sink for atmospheric CO₂ in an oscillating pattern with little increase in the long-term annual mean NEP. Although climate observations and terrestrial modeling may suggest increasing plant carbon fixation over the past two decades in tropical ecosystems, there is scarce evidence upon which to conclude that a substantial increment in NPP carbon has remained in tropical vegeta-

![Figure 5. Collocation of NEP monthly anomalies in the 17-yr time series (1982–98) with FPAR monthly anomalies. Each colored pixel meets a threshold value of greater than three co-occurring events during the entire time series. Blue pixels are LO-LO event associations, green pixels are HI-HI event associations, and red pixels are both LO-LO and HI-HI event associations.](image)

<table>
<thead>
<tr>
<th>Model inputs</th>
<th>NEP-LO total</th>
<th>NEP-HI total</th>
<th>NEP-LO percent</th>
<th>NEP-HI percent</th>
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</thead>
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<td>15</td>
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<td>1.00</td>
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<tr>
<td>FPAR-LO</td>
<td>1623</td>
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<td>0.00</td>
</tr>
<tr>
<td>FPAR-HI</td>
<td>—</td>
<td>1196</td>
<td>0.00</td>
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</tr>
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tion and soil pools for more than a decade. Rather, drought-induced disturbance and rapid decomposition of dead plant biomass may return the majority of incremental NPP carbon to the atmosphere in the years between El Niño events.

While additional years of data collection and analysis are required, a unique advantage of combining ecosystem modeling with global satellite sensor drivers for vegetation-cover properties is to enhance the spatial resolution of sink patterns for CO₂ in the terrestrial biosphere. On the temporal scale, this AVHRR dataset used to generate FPAR input to the NASA-CASA model now extends for 20 yr of global monthly imagery at 8-km spatial resolution, which permits model evaluations within the context of other global long-term datasets for climate and atmospheric CO₂ levels. Through the addition of even higher-resolution (1 km) FPAR estimates beginning in 2000 from the MODIS sensor, we can identify numerous relatively small-scale patterns throughout the world where terrestrial carbon fluxes may vary between net annual sources and sinks from one year to the next. Predictions of NEP for these areas of high interannual variability will require further validation of carbon model estimates, with focus on both flux algorithm mechanisms and potential scaling errors to the regional level.

Although there is still a need to accurately quantify the absolute size of the NEP variability over the Amazon region, this objective is not necessarily more relevant to the global carbon cycle than quantifying the number of anomalies in NEP over the past several decades. This is because locations that are constantly varying from one season to the next or one year to the next, regardless of their absolute NEP flux, are the most poorly understood in terms of process-level controls on carbon fluxes in plant and soils. These locations should be identified and studied further in LBA and subsequent Amazon regional campaigns.

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