

## **Reviewer Comments #1**

(RC1) This paper investigates the influences of climate, phenology, and disturbance to NEE across various timescales in an evergreen Eastern Amazon forest using a statistical model to represent eddy covariance-derived NEE. What I concerned is the research questions are not clear and lack of storyline through the manuscript. I am curious to know what environmental drivers are responsible for the hourly, seasonal and interannual variability of NEE, respectively, and how many are the relative contributions to the variability of NEE between exogenous changes and endogenous biophysical changes.

**(AC1) We thank the reviewer for the suggestions and we restructured the manuscript to make the narrative clearer and more coherent.**

**We have reframed our motivating research questions in the last paragraph of the introduction, to respectively reflect the exogenous and endogenous influences upon NEE which we discuss throughout the paper (1) meteorology at hourly to interannual timescales (2) phenology at seasonal timescales, and (3) disturbance at interannual timescales, specifically those caused by droughts.**

**We reordered the subsections in our results and discussion to in turn reflect the reframing of our introduction. Specifically, the we re-numbered the subsections of Results Section 3.4, which concerns our empirical modeling of NEE on various timescales, dedicating subsections to quantify the influences upon modeled NEE on hourly timescales (3.4.1) and seasonal timescales (3.4.2), and also discusses the extent to which modeled meteorology and phenology explain NEE on interannual timescales (3.4.3). For each of these sections, we explicitly quantify the relative contribution of each influence upon NEE.**

**Our Discussion section now more closely mirrors the timescale-based structure of the Results section as well, with sections devoted to discussing the influences upon the hourly and seasonal variability (4.1) and the interannual variability (4.2). Importantly, the sections of the Discussion that the reviewer found disconnected, those concerning droughts and disturbances, were moved into subsections of the interannual variability (4.2.1 and 4.2.2, respectively). This gives the discussion of these phenomena a more fitting home: as potential explanations for the patterns seen in annual NEE.**

(RC1) Throughout the abstract, it should be more quantitative in nature. For example, how many are the relative influences of climate, phenology, and disturbance to NEE across various timescales?

**(AC1) We agree that the abstract would benefit from additional quantitative information concerning the relative influences upon NEE. We included information regarding the extent to which phenology influences NEE (1% and 26% on hourly and monthly timescales respectively) in our revised abstract, explaining that the rest of the modeled variability on these timescales is due to meteorology alone. Our abstract discusses and quantifies the extent to which meteorology and disturbance affect annual NEE at this site.**

(RC1) Line 46-49 please cite the references for each driver respectively.

**(AC1) We considered separating references by drivers, but most of the studies we cited examine and quantify the effects of multiple drivers simultaneously.**

(RC1) Line 81-82 did Urbanski et al. (2007) answer this question? Please double check and use the same term: R/RE.

**(AC1) Urbanski et al. answered this question as it applied to the Harvard Forest, a seasonal temperate mid-latitude mixed deciduous forest. Additionally, we corrected this term to RE, consistent with the abbreviation throughout the rest of the manuscript.**

(RC1) Line 80-89 what are relationships among these three questions? Each question looks individual.

**(AC1) We revised them to clarify the connections amongst them. Our three research questions now reflect meteorology, phenology, and drought respectively, and our concluding sentence in this paragraph summarizes them in tandem (see first comment above for details).**

(RC1) Line 94 There was 1918 mm of annual rainfall. Why did it have a 5 month long dry season?

**(AC1) We clarified the dates of the dry season and the definition which we and Hutyra et al. (2007) use: mean monthly precipitation of less than 100 mm.**

(RC1) Line 91-98 Please describe more about the climate condition (temperature), species composition, vegetation/soil type, forest age, water table depth etc.

**(AC1) We have added more site-specific information as requested.**

(RC1) Line 143-145 did you create the correlation and verified each other for these three data sets?

**(AC1) We now clarify that the correlation between the monthly rainfall datasets for the years 2001-2012 was  $R^2=0.88$ . We clarify that additional information about the robustness of the meteorological data sets can be found in Longo (2014).**

(RC1) Line 165-170 did you make any validation for predicted CWD from the box model?

**(AC1) We now clarify that a validation of the model was made against our second and final measurement of CWD in 2012.**

(RC1) Line 172 what is the low-parameter empirical model?

**(AC1) We specify that this refers to the model of Eq. 2.**

(RC1) Line 222-225, these sentences should be placed in Methods, rather than Results.

**(AC1) We removed these sentences from the results and placed them the Methods Section 2.3.**

(RC1) Line 227-230 since Hutyra et al. (2007) has reported these results, what is the sense of your results here? Same problem with line 238-239.

**(AC1) We specify that our slightly different gap-filling methods (Section 2.3) did not create a discrepancy within 95% confidence intervals of random measurement error, between our annually integrated NEE and that of Hutyra et al. (2007), which gives us more confidence that the post-2008 carbon balance results are consistent with previous analyses.**

(RC1) Line 271 Were there any disturbance for 1998-2000?

**(AC1) We did not measure CWD in 1998-2000. However, we added the caveat that we assumed that the disturbance occurred in 1998, because 1999 and 2000 were not characterized by below-average rainfall, to Results Section 3.3, to clarify that we could only infer but did not measure that a disturbance occurred in this year. We provide additional recent evidence that drought events are accompanied by increased mortality and canopy turnover rates, signifying disturbance (Leitold et al., 2018).**

(RC1) Line 762 how about the dry seasonal? Why only 9 days, rather than 90 days?

**(AC1) We chose a small sampling of day from the wet season as an example to highlight the variability between days of different cloudiness. Dry season days tend to be consistently sunny and high-uptake, and therefore an example time series from the dry season would not exemplify variability between days. We specify in the Results Section 3.4.1 “Modeled hourly variability frequently captured the difference in magnitude in NEE between high and low uptake events”. We chose 9 days for our example time series because many more would make the time series figure too crowded and make it hard for the reader to notice the variability between hours and days.**

(RC1) The results section is pretty confusing. Please organize the idea logically. As your title: 'Carbon Exchange in an Amazon Forest: from Hours to Years', what environmental drivers are responsible for the hourly, seasonal and interannual variability of NEE, respectively? How many are the relative contributions to the variability of NEE between exogenous changes and endogenous biophysical changes?

**(AC1) See our response above to the first comment for substantial revisions made to the organization of the Results section.**

(RC1) How did you define the hourly, seasonal and interannual variability of NEE?

**(AC1) Our usage of the term “variability” in NEE reflects the standard within a long history of applied statistical research: deviations of our dependent variable around its mean value. Throughout the paper and for the various timescales examined in our analysis, our use of the term “variability” is consistent with this definition; we therefore did not see the need to define it explicitly within the manuscript.**

(RC1) Line 325 what is the R2 between modeled and observed annual NEE?

**(AC1) We added to this paragraph in Section 3.4.3 that the correlation between modeled and measured yearly NEE was low ( $R^2 = 0.17$ ;  $p = 0.37$ ) owing to the 2002 outlier; if 2002 is excluded, the correlation is high and significant ( $R^2 = 0.81$ ;  $p = 0.014$ ). Much of our discussion section is then devoted to discussing why 2002 was an outlier with respect to other years.**

(RC1) It is also difficult to follow the Discussion section. What are the relationships between these four subtitles? They look pretty individual. Did you discuss the hourly and seasonal variability of NEE? Why don't you focus on explaining your results instead of talking about implications so much? The reader is really curious about your findings.

**(AC1) See our response above to the first comment for substantial revisions made to the organization of the Discussion section.**

## **Reviewer Comments #2**

(RC2) Hayek and others explore the net ecosystem exchange of carbon and its components over multiple years in a forest in the eastern Amazon. The simple model that they propose is interesting and challenges numerous assumptions regarding the seasonality of photosynthesis. That being said, some recent manuscripts by Wu et al. written by many of the authors (see also Kiew et al. doi.org/10.1016/j.agrformet.2017.10.022) indicate a strong vapor pressure deficit limitation to GPP that could (potentially) add quite a bit to the present manuscript given that highly statistical and empirical models are difficult to extrapolate. Investigating relationships between model residuals and VPD (or perhaps soil moisture although the authors are right in noting that its role is often over-simulated, especially given difficulties in measuring soil moisture at depth) would point toward mechanisms that other models could benefit from. Addressing the following minor comments would in my opinion further improve an interesting manuscript.

**(AC2) We agree that VPD can potentially exert a strong influence on NEE at timescales discussed in this manuscript. We actually included this variable in an early version of the analysis and manuscript, but excluded it from the more recent version the reviewer read. We have since incorporated some of these results back into our revised manuscript for reasons explained below.**

**We ran a monthly BIC for model selection on the annual average fit of our model and others on a monthly timescale, including models that had representations of the influence of VPD and diffuse radiation upon LUE, both together and separately. The model selection method accepted these variables for the hourly model fit, but rejected them for the monthly fit, implying that the additional independent variables did not add explanatory power at monthly and longer timescales. We now include this information in the Methods Section 2.6 and present the BIC scores Results Section 3.4.2.**

**These results are consistent with the results of the Wu et al. (2016b) manuscript to which the reviewer refers. Our conclusions were that many of these exogenous variables add explanatory power (in that case, to GEP) at hourly and daily timescales, but on timescales of months or longer, they become increasingly outweighed in effect size and statistical significance endogenous ecosystem changes. We therefore included a reflection on these results in the hourly and seasonal NEE Discussion Section 4.1 of our revised manuscript.**

**Furthermore, regarding interannual variability, VPD and diffuse radiation did not explain the 2002 anomaly, the subject of our discussion regarding legacy effects of the 1998 drought. In the BIC-rejected model containing both VPD and CI, the positive NEE/GEE anomaly remained. The difference between the 2002 model-data annual residual NEE from this VPD-containing model and our model was statistically insignificant. We also examined whether VPD or diffuse radiation were anomalously high or low, respectively, in 2002, causing decreased LUE and leading to lower GEP. Both annual mean VPD and diffuse radiation in 2002 lied within their decadal range.**

**Per the reviewer's suggestion to include a discussion of these variables for additional mechanistic insight, we discuss the anomaly analysis from our higher-parameter VPD and diffuse radiation model in Discussion Section 4.2 of our revised manuscript, and demonstrate that these variables did not significantly change the 2002 positive anomaly in NEE/GEE in our newly added supplemental Fig. S3.**

(RC2) The passages on lines 33-35 in the Abstract are self-contradictory. Please reconcile.

**(AC2) We removed reference to the 2005 and 2010 droughts specifically, which did not affect this site, and clarify in lines 31-32 that the 1998 drought did affect this site. We discuss the lack of impacts of the 2005 and 2010 droughts upon this site in the Discussion Section 4.2.1.**

(RC2) The intro to line 37 in the paper is a disappointment given the Amazon's central role in global heat and moisture transport and global climate teleconnections. The climate system is about energy, not just carbon. Please re-write.

**(AC2) We agree with the reviewer that energy and matter are both exchanged in large quantities by Amazon forests. We revised the introductory sentence to reflect this.**

(RC2) The Introduction is otherwise well-written and nicely justified.

**(AC2) We thank the reviewer for this assessment. We believe our introduction has been made even stronger by incorporating feedback from RC1.**

(RC2) It would help the reader to justify the following passage using data on line 112-3: However, the interannual variability and trend remained the same regardless of the choice of  $u^*$ Th

**(AC2) We agree that this tendency in the data is important to highlight. We now refer the reader to Saleska et al., (2003), where this tendency for the variability and trend to not be affected by the choice of  $u^*$  filter can be seen for the first three full years of carbon exchange data for our site.**

(RC2) Note inconsistencies in italicizations between equations and text for example in lines 165-6.

**(AC2) We thank the reviewer for highlighting this discrepancy and have corrected it.**

(RC2) 192 and elsewhere: add a space between the number and the unit (in this case mm). See <https://physics.nist.gov/cuu/Units/checklist.html>

**(AC2) We have corrected this mistake.**

(RC2) In paragraph 188, the definition of the dry season was a bit curious with less than 50 mm per 'half-month' of 3 or more 'semi-monthly' periods with low precipitation. Is this a running 'half-month'? Is the dry versus wet season in the Amazon not more consistently defined for people to extend the line of reasoning forwarded by this manuscript to other regions?

**(AC2) Our definition of 50 mm per half-month is consistent with previous work on Amazon forest seasonal variability, which have collectively defined the dry season as 100 mm/month. We selected half-months to get higher resolution for the seasonal onset. Our definition of the wet season onset was unique but still consistent with the common 100 mm month<sup>-1</sup> definition. We selected this definition because it allows for sporadic dry season downpour and ensures that there is not more than one dry season per year. Seasonality in tropical forests is typically defined by the mean seasonal cycle, whereas we were interested in interannual variability in the onset of the wet and dry seasons among various years. We added an additional line in the Methods section to explain that these half-month sums of rainfall were consistent with the common literature definition of full-month sums and provide reference.**

(RC2) Line 204/205 needs a reference. Many modeling assumptions like this could benefit from more references to help the reader understand the decisions that went into model selection.

**(AC2) We added a reference to the Wu et al. GCB manuscript this line and clarified that its inclusion was insignificant after controlling for other variables in the model.**

(RC2) I am very surprised that the nice manuscript by Wu et al. (<https://doi.org/10.1111/gcb.13509>) is not cited in the present manuscript, particularly given their findings regarding diffuse radiation and vapor pressure deficit as important controls over GEP and of course the rather large overlap in authorship between this paper and the present manuscript.

**(AC2) See our response to the first RC2 comment.**

(RC2) I agree on line 218 that GEE ‘represents the lowest-parameter approximation of a direct measurement, but a brief explanation for readers less familiar with eddy covariance (or readers who use the eddy covariance technique but are less familiar with its limitations) would be helpful. Qualifiers like ‘strong’ on line 225 and elsewhere can be avoided (and on that note of course NEE has a strong diurnal cycle). ‘precisely quantified’ on 369 is another example. And ‘surprising’ on 428. It may not have been a surprise to the forest.

**(AC2) Per the reviewer’s suggestions, we changed these lines by omitting these imprecise qualifiers and provide additional quantitative information for the GEE estimate and the reversal of the trend in annual NEE.**

(RC2) On 290 do not use the \* for multiplication as shorthand, this means complex conjugate (see also Fig. 5).

**(AC2) We thank the reviewer for pointing out this mistake. We removed the parameter value from this line and corrected it in the caption of Fig. 5.**

(RC2) The material on line 312 doesn’t belong in a supplement in my opinion as the seasonal patterns of RE and GEE are important to the modeling effort.

**(AC2) We agree that the seasonal patterns of carbon exchange are relevant to modeling efforts. This figure, however, concerns the interannual variability, and we believe that much of the information that it contains is already summarized aptly by figure 7b. We included this figure in the supplement for readers who were additionally curious about how annually averaged model-data residuals compare to the range in annual means for both the data and the model.**

(RC2) ‘best of a statistical model’s ability’ on line 324 is colloquial and probably doesn’t hold for any scientific manuscript of reasonable length.

**(AC2) We removed this phrase from the sentence.**

(RC2) 339 and elsewhere: did 2002 have anomalously high VPD? (see also the paragraph beginning line 436).

**(AC2) For the material in these sections, we now include discussion of VPD in Discussion Section 4.2 per the reviewer’s suggestions in the first RC2 reviewer comment.**

(RC2) Why is ‘Fig. 2b’ bolded on line 356?

**(AC2) We corrected this mistake.**

(RC2) 382: could it be shown that the hypothetical model would not add explanatory power or is this just assumed?

**(AC2) We ran a monthly BIC for model selection on the annual average fit of our model and a spate of others, including a model that had a higher-parameter representation of phenology. The BIC score was in fact higher (less negative) for this model, implying that the additional parameters did not add explanatory power. We left this part of the analysis out of our methods, results, and discussion for the sake of brevity, being extraneous to the more relevant results. We changed this section, simplifying the discussion of phenology so as not to allude to this alternate parameterization, stating “Our single mid-year parameter simplistically up-shifts the trough in a more continuous seasonal oscillation between low and high LUE (Fig. 5) because we lacked independent variables explaining the seasonal oscillation.”**

(RC2) What is Wu et al. 2016a? This is not in the references.

**(AC2) We corrected this inconsistency. Wu et al. 2016a and Wu et al. 2016b are now separate references.**

(RC2) Regarding the 2002, is it possible that disturbance due to tower construction may have impacted NEE? I've seen results from a few towers where there seems to be some initial transient effect on C fluxes, not that the tower wasn't constructed carefully.

**(AC2) We agree with the reviewer that we cannot rule out this or other measurement artifacts, such as those caused by tower construction creating a lower initial flux footprint than that assumed in typical eddy covariance measurement systems. We provide this important caveat in Section 4.2 of the revised manuscript, but qualify it by additionally clarifying that tower construction was completed almost a year before the measurements we used, with preliminary data collection occurring during 2001 (Saleska et al., 2003), potentially allowing time for transient effects to equilibrate.**

(RC2) Table 1: uncertainty estimates should be presented with parameter estimates. (see also Table 2).

**(AC2) We now present 95% confidence intervals alongside mean parameter estimates in Tables 1 and 2.**

(RC2) Figure 1: I can't help but be surprised that a forest can continuously lose C to the atmosphere, but I've seen it in other tropical forests as well when measured using the eddy covariance technique. Per earlier work by the author and team, I wonder if ustar filters are appropriate for tropical forests although trying alternate filters like sigma\_w (see papers by Jocher et al.) don't seem to change things in my experience.

**(AC2) We found that similar filters that are turbulence-based indeed did not change our results, and in fact their use suggested that even more C was lost to the atmosphere when we used that approach. We included results from our alternative nighttime bias correction in Fig S2. We now include a reference to Fig. S2 in the caption of Fig. 1.**

(RC2) Avoid red (or red-ish) and green together in Fig. 7b.

**(AC2) We changed these colors to be monochromatic in black and gray, respectively.**

# 1 Carbon Exchange in an Amazon Forest: from Hours to Years

2 Matthew N. Hayek<sup>1</sup>, Marcos Longo<sup>2</sup>, Jin Wu<sup>3</sup>, Marielle N. Smith<sup>4</sup>, Natalia Restrepo-Coupe<sup>5</sup>, Raphael Tapajós<sup>6</sup>, Rodrigo  
3 da Silva<sup>6</sup>, David R. Fitzjarrald<sup>7</sup>, Plinio B. Camargo<sup>8</sup>, Lucy R. Hutyrá<sup>9</sup>, Luciana F. Alves<sup>10</sup>, Bruce Daube<sup>11</sup>, J William  
4 Munger<sup>11</sup>, Kenia T. Wiedemann<sup>11</sup>, Scott R. Saleska<sup>12</sup>, and Steven C. Wofsy<sup>11</sup>

5 <sup>1</sup> Harvard Law School, Cambridge, MA, United States  
6 <sup>2</sup> NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, United States  
7 <sup>3</sup> Biological, Environmental & Climate Sciences Department, Brookhaven National Lab, Upton, New York, NY, United States  
8 <sup>4</sup> Department of Forestry, Michigan State University, East Lansing, MI, United States  
9 <sup>5</sup> Plant Functional Biology and Climate Change Cluster, University of Technology Sydney, Sydney, NSW, Australia.  
10 <sup>6</sup> Universidade Federal do Oeste do Pará, Santarém, PA, Brazil.  
11 <sup>7</sup> University at Albany SUNY, Albany, NY, United States.  
12 <sup>8</sup> Centro de Energia Nuclear na Agricultura, Universidade de São Paulo, Piracicaba, SP, Brazil.  
13 <sup>9</sup> Department of Earth and Environment, Boston University, Boston, MA.  
14 <sup>10</sup> Center for Tropical Research, Institute of the Environment and Sustainability, UCLA, Los Angeles, CA, United States.  
15 <sup>11</sup> Faculty of Arts and Sciences, Harvard University, Cambridge, MA, United States.  
16 <sup>12</sup> Department of Ecology and Evolutionary Biology, University of Arizona, Tucson, AZ, United States.

17 *Corresponding author:* Matthew Hayek (mhayek@law.harvard.edu)

18 **Abstract.** In Amazon forests, the relative contributions of climate, phenology, and disturbance to net ecosystem exchange of  
19 carbon (NEE) are not well understood. To partition influences across various timescales, we use a statistical model to represent  
20 eddy covariance-derived NEE in an evergreen Eastern Amazon forest as a constant response to changing meteorology and  
21 phenology throughout a decade. Our best fit model represented hourly NEE variations as changes due to sunlight, while seasonal  
22 variations arose from phenology influencing photosynthesis and from rainfall influencing ecosystem respiration, where  
23 phenology was asynchronous with dry season onset. We compared annual model residuals with biometric forest surveys to  
24 estimate impacts of drought-disturbance. We found that our simple model represented hourly and monthly variations in NEE  
25 well ( $R^2 = 0.81, 0.59$  respectively). Modeled phenology explained 1% of hourly and 26% of monthly variations in observed  
26 NEE, whereas the remaining modeled variability was due to changes in meteorology. We did not find evidence to support the  
27 common assumption that the forest phenology was seasonally light- or water-triggered. Our model simulated annual NEE well,  
28 with exception to 2002, the first year of our data record, which contained 1.2 MgC ha<sup>-1</sup> of residual net emissions, because  
29 photosynthesis was anomalously low. Because a severe drought occurred in 1998, we hypothesized that this drought caused a  
30 persistent, multi-year depression of photosynthesis. Our results suggest drought can have lasting impacts on photosynthesis,  
31 possibly via partial damage to still-living trees.

## 32 1. Introduction

33 The Amazon's tropical forests are pivotal to global climate, exchanging large, globally important quantities of energy and matter,  
34 including atmospheric carbon (Betts et al., 2004). Amazon forests contain 10-20% of Earth's biomass carbon (Houghton et al.,  
35 2001). Increased emissions of the forest's carbon can therefore accelerate climate change and attention is now focused on how  
36 vulnerable this large reservoir of carbon will be to a potentially drier future climate (de Almeida Castanho et al., 2016; Farrior et  
37 al., 2015; Duffy et al., 2015; Longo et al., 2018; McDowell et al., 2018). Characterizing the response of present-day Amazon rain  
38 forest carbon balance to climate and drought disturbance is a necessary step to improving predictions of future vulnerability.  
39 Eddy covariance CO<sub>2</sub> flux measurements are a powerful tool for quantifying net ecosystem exchange of carbon (NEE)  
40 (Baldocchi, 2003). NEE is the difference between uptake from gross ecosystem productivity (GEP) and emission from

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41 ecosystem respiration (RE). The magnitudes of these gross fluxes are influenced both by exogenous environmental conditions  
42 such as light, moisture, and temperature (Collatz et al., 1991; Bolker et al., 1998; Fatichi et al., 2014; Kiew et al., 2018), as well  
43 as endogenous biophysical properties such as canopy structure, phenology, and community composition (Barford et al., 2001;  
44 Melillo et al., 2002; Dunn et al., 2007; Doughty and Goulden, 2008; Stark et al., 2012; Frey et al., 2013; Morton et al., 2016; Wu  
45 et al., 2016).

46 Partitioning the exogenous and endogenous influences upon eddy covariance NEE is possible using statistical modeling  
47 (Barford et al., 2001, Yadav et al., 2010; Wu et al., 2017). To partition influences upon NEE in a 20-year eddy flux record in a  
48 temperate New England forest, Urbanski et al. (2007) used a statistical modeling approach: by representing hourly NEE merely  
49 as response to exogenous meteorology and annually integrating their results, they concluded that meteorology did not explain the  
50 accelerated uptake seen annually integrated NEE. They hypothesized that residual uptake was due to long-term forest regrowth  
51 and succession, a hypothesis that was corroborated by biometric measurements of increasing canopy foliage and accelerating  
52 mid-successional tree biomass accrual. This novel partitioning framework for NEE has not previously been applied to any  
53 tropical forest, in part because long-term eddy covariance coverage of tropical forests is lacking (Zscheischler et al., 2017). A  
54 simple statistical framework may allow tropical forest CO<sub>2</sub> flux measurements to better inform model development and  
55 improvement.

56 On seasonal timescales, tropical evergreen forests undergo endogenous changes in GEP via the phenology of leaf flush  
57 and abscission (Doughty and Goulden, 2008, Restrepo-Coupe et al., 2013; Wu et al., 2016). The seasonal dependency of  
58 productivity has motivated the development of rooting depth and phenology sub-models in DVGMS (Verbeeck et al., 2011; De  
59 Weirdt et al., 2012; Kim et al., 2012). These sub-models have led to complexity in the modeled mechanisms controlling the GEP  
60 seasonal cycle without necessarily improving accuracy. It is necessary to quantify the magnitude and timing of phenology's  
61 effect on the GEP seasonal cycle after accounting for the integrated hourly response to sunlight.

62 On interannual to decadal timescales, endogenous changes in forest NEE can arise from disturbance and recovery  
63 (Nelson et al., 1994; Moorcroft et al., 2001; Chambers et al., 2013; Espirito-Santo et al., 2014; Anderegg et al., 2015). The km<sup>67</sup>  
64 eddy flux site in the Tapajós National Forest (TNE) presents a unique opportunity to study the potential legacy of disturbance  
65 caused by drought. This Eastern Brazilian Amazon forest lies on the dry end of the rainfall spectrum for tropical evergreen  
66 forests (Saleska et al., 2003; Hutrya et al., 2005). A severe El Niño drought in 1997-1998 was followed by disturbance,  
67 evidenced by a large and heavily respiring CWD pool in 2001. Subsequent NEE measurements showed a 4-year transition from a  
68 net carbon source in 2002 to nearly carbon-neutral in 2004 and 2005 (Hutrya et al., 2007). The observed disequilibrium state led  
69 researchers to the hypothesis that RE was high but dissipating, and that the forest will continue to transition into equilibrium,  
70 becoming a sink throughout the decade (Pyle et al., 2008). Conversely, this hypothesis implies that any new disturbance should  
71 drive the forest back into disequilibrium, becoming a source again. We test these predictions using meteorological records, forest  
72 inventories of aboveground biomass (AGB) and CWD, and an additional 3.5 years of eddy flux data, resumed after a 2.5-year  
73 interruption, collected since prior studies.

74 In this study, we test hypotheses related to controls of NEE on multiple timescales at an Eastern Amazon rain forest.  
75 Specifically, we sought to answer the following questions: (1) what were the effects of exogenous meteorology upon NEE across  
76 hourly to yearly timescales? (2) What is the seasonal effect of canopy phenology upon NEE? Is phenology synchronized with  
77 wet/dry seasonality? (3) Major basin-wide droughts occurred in 1998 before eddy flux measurements began, and were reported  
78 again in 2005 and 2010 (Zeng et al., 2008; Phillips et al., 2009; Lewis et al., 2011; Doughty et al., 2015) during the span of  
79 measurements. Did any of these basin-wide droughts affect the TNF in particular? What was the impact of drought upon  
80 interannual variability and the decadal trend in NEE? Furthermore, which NEE component, GEP or RE, was perturbed most by

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81 | drought? Overall, we statistically partitioned the multiple influences on NEE across timescales from hours to an entire decade of  
82 | eddy flux and forest inventory measurements.

## 83 | 2 Methods

### 84 | 2.1 Site Description

85 | The Tapajós National Forest (TNF) is located to the southeast of the convergence of the Tapajós and Amazon Rivers in  
86 | Pará, Brazil. The forest site is on the dry end of the spectrum of evergreen tropical forests, receiving 1918 mm of annual rainfall  
87 | and experiencing a 5 month long dry season from July 15 to December 14, defined by average monthly precipitation of less than  
88 | 100 mm (Hutyra et al., 2007). Temperature and humidity average 25 °C and 85% respectively (Rice et al., 2004). The forest has  
89 | a closed canopy with a height of roughly 40 m (Stark et al., 2012), emergent trees up to 55 m (Rice et al., 2004). The forest has  
90 | fast turnover rates with much of the population consisting of small-diameter trees (Pyle et al., 2008), but many larger trunks, an  
91 | uneven age distribution, many epiphytes, and emergent trees; the forest may be considered primary or “old growth” (Goulden et  
92 | al., 2004). Soils are predominantly nutrient-poor clay oxisols with some sandy utisols (Rice et al., 2004), both of which have low  
93 | organic content and cation exchange capacity. The forest terrain is 75 m upland on a plateau adjacent to the nearby Tapajós  
94 | River, and a deep water table accessed by roots sometimes more than 12 meters deep (Hutyra et al., 2007). The flux tower that  
95 | provided flux and meteorological data is located near km 67 of the Santarém-Cuiabá highway. The tower and site are designated  
96 | by site ID “BR-Sa1” in the FLUXNET data system, but are herein referred to simply as “km67”.

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### 97 | 2.2 Eddy Covariance Measurements

98 | Hourly fluxes of NEE were calculated using the sum of hourly turbulent eddy fluxes plus the hourly change in height-  
99 | weighted average CO<sub>2</sub> concentration in the canopy air column. Our measurements covered two contiguous periods: one from  
100 | January 2002 to January 2006 (period 1) and another from July 2008 to December 2011 (period 2). The tower fell in January  
101 | 2006 when a tree snapped a supporting guy-wire. Measurements resumed in July of 2008 when the tower was rebuilt and  
102 | equipment repaired. Measurements ceased again in 2012 when electrical failures damaged measurement and calibration systems.  
103 | Some data collection has resumed since 2015, although gaps in this data were much larger than those in periods 1 and 2,  
104 | precluding calculating annual carbon balance after 2011.

### 105 | 2.3 Flux Data Processing, Quality Control, and Gap Filling

106 | Nighttime NEE measurements were filtered for low turbulence. We used a turbulence threshold filter of  $u_*^{Th} = 0.22$  to  
107 | ensure consistency with previous studies (Saleska et al., 2003; Hutyra et al., 2008). The absolute magnitude of nighttime  
108 | respiration and resulting carbon balance was highly sensitive to the selection of  $u_*^{Th}$ , (Saleska et al., 2003; Miller et al., 2004).  
109 | However, the interannual variability and trend remained the same regardless of the choice of  $u_*^{Th}$  (Saleska et al., 2003). Errors in  
110 | total annual NEE therefore do not reflect potentially large  $u_*^{Th}$  error, and should be interpreted as errors in the differences  
111 | between years, not errors in the annual magnitude of the carbon source/sink. Coverage of hourly NEE was substantial for both  
112 | periods in the total eddy covariance record. After quality control and outlier detection, period 1 (2002-2006) had 80% and period  
113 | 2 (mid 2008-2011) had 75% data coverage for all hours. Filtering for  $u_*$  below the threshold of 0.22 m/s left 48% and 42%  
114 | coverage of period 1 and 2 respectively.

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115 We used established gap-filling models to obtain annual NEE totals. Gross ecosystem productivity (GEP) was gap-filled  
116 using a hyperbolic fit curve between GEP and PAR (Waring et al., 1995). For ecosystem respiration (RE), we adapted the  
117 method by Hutyrá et al. (2007), who calculated missing, filtered, and daytime hours using 50 *u*-filtered nighttime hour bins,  
118 instead using a running average of 50 *u*-filtered nighttime hours, allowing us to capture the onset of semiannual seasonal  
119 transitions in RE. Consistent with other tropical forest sites, temperature was not used in our gap-filling, because temperature  
120 variability at tropical forests is low, which results in weak and insignificant correlations with RE (Carswell et al., 2002). We  
121 calculated annual errors as 95% bootstrap confidence intervals by resampling like-hours with replacement (NEE conditions for  
122 the same month, time of day, and similar PAR conditions), instead of resampling all hourly NEE, so that resampling did not  
123 capture diurnal and long-term nonstationary.

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## 124 2.4 Meteorological Measurements

125 Meteorological variables measured at km67 included photosynthetically active radiation (PAR), temperature, and  
126 specific humidity. Downward drifts in PAR data due to a degrading sensor were corrected by de-trending a time series of mid-  
127 day PAR observations in the top 95th percentile of each month (Longo, 2014). This threshold included substantial information  
128 about the sunniest hours, throughout which intensity should remain constant between years for any given month. We scaled the  
129 radiation time series using the proportion between the fitted trend and the initial fitted value. Simultaneous total incoming  
130 shortwave radiation measurements allowed us to partially fill missing periods of PAR data using a relationship derived from  
131 linear regression in simultaneously measured hours ( $R^2 = 0.98$ ).

132 Rainfall measurements were greatly underestimated at this site because of a faulty tipping bucket rain gauge. We  
133 discarded site-based data and calculated a distance-weighted synthetic hourly rainfall time series from a network of nearby  
134 meteorological stations, with locations ranging from 10 km to 110 km away from km67. More information on the meteorological  
135 network is available in Fitzjarrald et al. (2008). Detailed information about the subsequent calculations of the synthetic  
136 precipitation data set and PAR drift correction are available in Longo (2014).

137 Additionally, the Brazil National Institute of Meteorology (INMET) has a station at Belterra, located 25 km away from  
138 km67, with daily precipitation totals dating back to 1971, which were used to corroborate the seasonal and long-term trends at  
139 km67. Correlation between these two monthly datasets for the years 2001-2012 was  $R^2=0.88$ . Altogether there were three data  
140 sets: the local tower-based meteorology, the mesoscale network meteorology data interpolated to km67, and the INMET  
141 meteorology. Further information regarding the robustness of these three datasets, and correlations amongst them, can be found  
142 in Longo (2014). The three datasets provided us with at least two redundant estimates for all meteorological variables at km67.

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## 143 2.5 Coarse Woody Debris and Mortality

144 To assess how disturbance coincided with changes in NEE, we conducted surveys of coarse woody debris (CWD).  
145 These surveys capture the magnitude and dynamics of the respiring pool of dead tree biomass. Transect subplots were surveyed  
146 in 2001 for pieces greater than 10 cm in diameter (Rice et al., 2004). Bootstrapped confidence intervals were quantified by  
147 resampling subplots totals (n=321) with replacement. Additionally, in 2006, pieces only greater than 30 cm in diameter were  
148 surveyed. Lastly, we conducted an additional CWD survey in 2012 using the line-intercept method (Van Wagner, 1968)  
149 throughout all transects for a total length of 4 km to minimize sampling uncertainty. Bootstrap confidence intervals were  
150 quantified by resampling line segment totals (n=40) with replacement. These two different methodologies have previously

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151 produced consistent simultaneous results within measurement uncertainties, which were 20% larger for line-intercept sampling  
152 than plot-based sampling (Rice et al., 2004).

153 Because CWD surveys were conducted infrequently, we inferred mortality from aboveground biometry surveys in  
154 1999, 2001, 2005, 2008, 2009, 2010, and 2011. Trees larger than 10 cm diameter at breast height (DBH) were surveyed and were  
155 converted to biomass using non-species specific equations (Chambers et al., 2001a) based on sampling previously established  
156 protocols for this site (Rice et al., 2004; Pyle et al., 2008). Mortality biomass was inferred by tallying biomass of dead trees that  
157 were alive in the prior survey. Sometimes, trees were missed by the census surveyors before they could be confirmed dead or  
158 were found again. In 2012 we assigned missing trees that were not later found alive an equal probability of dying in all surveyed  
159 years they had been missing (Longo, 2014). We used tree mortality to model CWD over time using a simple box model with a  
160 first-order rate equation:

161 
$$\frac{dCWD}{dt} = -k \cdot CWD + M \quad (1)$$

162 where M is the mortality rate input to the CWD pool ( $MgC\ ha^{-1}yr^{-1}$ ) and  $k$  is the decay loss rate of  $0.124\ yr^{-1}$ . The loss rate is  
163 derived from measurements of respiring CWD in Manaus, Amazonas (Chambers et al, 2001b) and snag density measurements  
164 taken at km67 (Rice et al., 2004). The box model initial condition was the 2001 survey of total CWD. This model allowed us to  
165 assess whether disturbances after 2001 were sufficient to cause an increase in CWD or whether disturbances after 2001 were  
166 minimal and the CWD pool respired and depleted gradually. The final timestep of the model was validated against the second  
167 and final full measurement of CWD made in 2012.

## 168 2.6 Empirical NEE Model

169 Our low-parameter empirical model represents the mean response of NEE to hourly and seasonal changes in exogenous  
170 meteorology and seasonal changes in phenology throughout the decade. We used our model to diagnose interannual  
171 nonstationarity in model residuals, which correspond to endogenous ecosystem changes in photosynthesis and respiration rates  
172 between years, give or take random measurement error and unaccounted for model terms. We fit the model to the entire 7.5-year  
173 interrupted eddy covariance record of raw,  $u$ -filtered hourly NEE ( $NEE_{obs}$ ):

174 
$$NEE_{Model} = a_0 + a_1 s_R + \frac{a_2 PAR}{a_3 + PAR} \cdot (1 - k_{pheno} s_{pheno}) \quad (2)$$

175 where  $NEE_{Model}$  is the modeled hourly NEE. The models were fit in two steps: first, the two model parameters that represent RE,  
176  $a_0$  and  $a_1$ , were fit to nighttime data, then the remaining three GEP parameters were fit to daytime data. Parameter  $a_0$  is the wet  
177 season intercept for RE. Parameter  $a_1$  is an adjustment of the ecosystem respiration during the rainfall-defined dry season (factor  
178 variable  $s_R$ , defined in detail below). Parameters  $a_2$  and  $a_3$  are the Michaelis-Menten light response parameters. We also include a  
179 simple scaling factor for endogenous changes in phenology: a time-varying binary factor variable  $s_{pheno}$  represents timing in  
180 changes to the intrinsic light use efficiency ( $LUE \equiv 1 - k_{pheno}$ ) within an average seasonal cycle. The purpose of this simplistic  
181 scaling factor was to determine when the timing of endogenous seasonal shifts in LUE that were not explained by light and  
182 moisture were most pronounced.

183 Atmospheric moisture and diffuse radiation, in addition to radiation, are also known to affect photosynthesis at tropical  
184 sites on short timescales (Kiew et al., 2018), by affecting stomatal closure hence controlling the degree to which photosynthetic  
185 uptake saturates at high PAR. We tested a higher-parameter model based on light and moisture model representing exogenous

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186 [changes to LUE from Wu et al. \(2017\)](#) to examine whether these meteorological variables added explanatory power to our model  
187 [at monthly and longer timescales. This model adjusts LUE by multiplying terms that account for effects of vapor pressure deficit](#)  
188 [\(VPD:  \$1-k\_{VPD}\$ \) and cloudiness index \(CI:  \$1-1-k\_C\$ \) a statistical proxy for diffuse radiation. To determine whether this model was](#)  
189 [parsimonious, we evaluated the Bayesian Information Criteria \(BIC\) of the data-model mean monthly residuals for the model in](#)  
190 [Eq. 2 and the higher-parameter light and moisture model. We found that the higher-parameter model was not parsimonious](#)  
191 [because the additional parameters did not improve the goodness of fit at monthly timescales. We explain these results further in](#)  
192 [Section 3.4.2 and discuss their implications further in Sections 4.1 and 4.2.](#)

193 This forest site has coincident deficits in rainfall and ecosystem RE during the dry season (Saleska et al., 2003; Goulden  
194 et al., 2004) due to desiccation of dead wood, leaf litter, and other substrates for heterotrophic respiration (Hutyra et al., 2008).

195 To depict this reduced dry season [RE](#), we set dry season  $s_R=1$  and wet season  $s_R=0$ , fitting  $a_I$  to the mean dry season [RE](#). We  
196 defined the dry season onset as the period during which rainfall is below 50 mm per half-month, [consistent with previous](#)  
197 [definitions of tropical forest dry season as 100 mm month<sup>-1</sup> \(e.g. Saleska et al., 2016\).](#) We defined the wet season onset as the  
198 first in a series of 3 or more semi-monthly periods with rainfall greater than 50mm; [this definition allows](#) for sporadic dry season  
199 downpour [whilst](#) ensuring that there is not more than one dry season per year. Although  $a_I$  does not vary across years, our  
200 meteorologically-defined  $s_R$  permits the duration of the dry season to vary interannually. A longer dry season in a given year  
201 would therefore result in less RE (more net uptake) when  $NEE_{Exo}$  is integrated over that full year.

202 We tested three different seasonal timings for the phenology factor variable: (1)  $s_{pheno}=0$  year-round (no phenology), (2)  
203  $s_{pheno}=1$  during the dry season and  $s_{pheno}=0$  during the wet season, and (3)  $s_{pheno}=1$  during the peak of leaf flush (June 15 to Sept  
204 14) (Hutyra et al., 2007) and  $s_{pheno}=0$  all other times of the year. In scenario 2, the timing of phenology varies interannually, but  
205 in scenarios 1 and 3, modeled phenology does not differ between years and therefore does not influence interannual variability in  
206 modeled GEP or NEE.

207 After subtracting hourly  $NEE_{Model}$  from  $NEE_{obs}$ , the annually integrated residuals reflect changes in the ecosystem's  
208 efficiency irrespective of the aggregate response to meteorology, plus or minus random error and unaccounted for meteorological  
209 controls. Upper-level soil moisture, for instance, [exerts seasonal controls upon NEE at various tropical sites differently](#)  
210 [depending on terrain \(Hayek et al., 2018; Kiew et al., 2018\)](#) but is not included in the model because it was insignificantly  
211 associated with GEP (Wu et al., 2017) or RE at this site [after we controlled for other variables, including wet and dry season](#)  
212 [onset, in our model](#). Examples of a change in intrinsic ecosystem efficiency may occur in the aftermath of a drought, during  
213 which leaf stomates close, causing the ecosystem to sequester less CO<sub>2</sub> per unit incident PAR than average, or a storm inducing  
214 widespread mortality and a pulse of CWD during which RE would be higher than average for a given season or year. In both  
215 scenarios, we would expect residuals to be positive during or after the event, because the ecosystem would sequester less and  
216 emit more CO<sub>2</sub> relative to other years. To assess which aggregated annual residuals were significantly different from zero, we  
217 quantified 95% confidence intervals in annual NEE residuals due to random error using bootstrapping (Section 2.3).

218 We partitioned both  $NEE_{obs}$  and  $NEE_{Model}$  into RE and GEE (GEE = -GEP, to keep the same sign convention as eddy  
219 flux NEE) to determine which of the two components were more adequately represented by our model. For observations of NEE,  
220 [RE](#), and GEE, we used hours during which a direct  $u^*$  filtered measurement of NEE occurred. Observations of RE were  
221 nighttime hours during which NEE was measured; observations of GEE are daytime hours during which the 50-hour running  
222 average RE was subtracted from measured NEE. Partitioned GEE is not a direct observation, but represents the lowest-parameter  
223 approximation of a direct measurement (GEE = NEE - RE see Wu et al., 2017). Our GEE/RE results are limited by not  
224 accounting for partitioning bias.

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226 **3.1 Eddy Covariance Measurements of CO<sub>2</sub> Fluxes**

227 NEE has a **large** diurnal cycle **relative to its mean seasonal cycle**, with a mean diel range of 25.05  $\mu\text{mol m}^{-2} \text{s}^{-1}$ . The  
 228 range of the mean seasonal cycle is 2.46  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , or 10% of the mean diel range. Annual totals of NEE are presented in Fig.  
 229 1. For period 1, the first four years, annual NEE is similar to that reported previously by Hutyyra et al. (2007) **despite using**  
 230 **slightly modified gap-filling procedures here (Section 2.3)**. The previously reported trend remains: a moderate source in 2002 of  
 231 2.7  $\text{MgC ha}^{-1} \text{yr}^{-1}$  ( $\pm 0.5$  95% bootstrap confidence intervals) tapering off to nearly carbon neutral totals in the following years,  
 232 within confidence limits, of 0.5 ( $\pm 0.6$ )  $\text{MgC ha}^{-1} \text{yr}^{-1}$  in 2004 and 0.2 ( $\pm 0.6$ )  $\text{MgC ha}^{-1} \text{yr}^{-1}$  in 2005. During the three subsequent  
 233 years that comprise period 2, 2009-2011, the forest returned to a moderate source of carbon, with a range of  $1.8 \pm 0.6 \text{ MgC ha}^{-1}$   
 234  $\text{yr}^{-1}$  in 2010 to  $2.5 \pm 0.5 \text{ MgC ha}^{-1} \text{yr}^{-1}$  in 2009. We examined measurements of rainfall, coarse woody debris (CWD), and  
 235 aboveground biomass (AGB) for indications of drought or other disturbance during 2002-2011 to explain these patterns seen in  
 236 annual NEE totals.

237 **3.2 Meteorological Measurements and Drought**

238 We examined our distance-weighted interpolated estimate of km67 rainfall for trends and droughts. Our precipitation  
 239 estimate was consistent with previous estimates of precipitation for this site and region, with a minimum of 1595 mm in 2005  
 240 and maximum of 2137 mm in 2011 (Saleska et al., 2003; Nepstad et al., 2007). While 2005 annual precipitation was a minimum,  
 241 no previous groundwater deficits in carbon exchange, latent heat flux, or sensible heat fluxes were observed during this year  
 242 (Hutyyra et al, 2007). Our measurements did not indicate that any drought occurred during or immediately preceding period 2 of  
 243 NEE measurements. In fact, period 2 annual rainfall totals increased on average by 20% relative to period 1. The dry season in  
 244 2009 was longer than average, lasting 6 months (Fig. 2a). Mean annual radiation was expectedly anti-correlated with annual  
 245 rainfall. Accordingly, period 2 experienced 4% less mean annual PAR than period 1.

246 Our synthetic decade-long rainfall record corresponded closely with the nearby INMET Belterra measurements,  
 247 although INMET Belterra had on average 220 mm of rainfall more per year, likely due to differences in circulation and  
 248 convection between the km67 forest and Belterra pasture land surface (Fitzjarrald et al., 2008). Annual rainfall totals throughout  
 249 the decade of eddy flux measurements 2002-2011 lay well within the historical variability of annual rainfall since 1972, which  
 250 experienced a range of 974 to 3057 mm of annual precipitation (Fig. 2b). The second and third lowest annual precipitation totals  
 251 occurred during 1997-1998, which were 1391 and 1218 mm respectively, during a major El Niño event, which persisted from  
 252 June of 1997 to June of 1998 (Ross et al., 1998) and corresponded with a 9 month long dry season, the longest in the historical  
 253 record.

254 **3.3 Coarse woody debris and mortality**

255 We examined measurements of CWD over time to assess whether a disturbance might have impacted the period 2  
 256 carbon balance. Compared to CWD stocks in 2001 of 48.6 ( $\pm 5.9$ )  $\text{MgC ha}^{-1}$ , CWD stocks in 2012 were significantly lower at  
 257 30.5  $\text{MgC ha}^{-1}$  ( $\pm 7.4$ ) (Fig. 3). Errors in the 2012 pool were 25% larger. The larger magnitude of error is consistent with higher  
 258 uncertainty for line-intercept sampling relative to area-based sampling at the TNF (Rice et al., 2004). Because CWD  
 259 measurements were sparse in time, we included an additional measurement in 2006 of large CWD, with diameter greater than or  
 260 equal to 30 cm, totaling  $20.8 \pm 12.8 \text{ MgC ha}^{-1}$ . We compared this measurement with similarly sized CWD from other surveys

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261 (Fig. 3). Total large CWD was  $25.7 \pm 11.4 \text{ MgC ha}^{-1}$  in 2001, and  $19.8 \pm 11.9 \text{ MgC ha}^{-1}$  in 2012. Differences in large CWD  
262 between 2001 and 2006 and between 2006 and 2012 are small relative to their uncertainties, but they still show a qualitative  
263 downward trend over time.

264 A box model of CWD (Eq. 2) allowed us to estimate the transient behavior of the CWD pool throughout years in which  
265 it was not directly measured (Fig. 3). The CWD mortality input rates  $M$  were derived from forest inventory surveys. The box  
266 model shows no large spikes from mortality events outweighing the respiration rate, and its derivative is negative throughout  
267 time, predicting a continuously depleting CWD pool. The box model estimate for 2012 CWD is  $26.2 \text{ MgC ha}^{-1}$ , and lies well  
268 within the uncertainty of the concurrent 2012 measurement. We see no evidence via increased CWD that disturbance has  
269 occurred since the start of measurements.

270 Assuming that the large initial CWD pool arose from a past disturbance, hypothetically following the 1997-1998 El  
271 Niño drought, we ran the CWD box model (Eq. 2) backward in time to estimate the magnitude of such a disturbance. We  
272 assumed that the disturbance occurred in 1998 because 1999 and 2000 were not characterized by below-average rainfall. Severe  
273 drought events have been accompanied by increased mortality and canopy turnover rates in intact Amazon forests (Leitold et al.,  
274 2018). Because the CWD measurement was made in July of 2001, we calculated the box model CWD value to the end of the El  
275 Niño drought in June 1998 using the same respiration rate,  $k$ , and the mean mortality,  $M$ , for all surveys, and applied this rate to  
276 the mean and 95% bootstrapped confidence intervals of the 2001 measurement ( $48.6 \pm 5.9 \text{ MgC ha}^{-1}$ ). Our estimate of the CWD  
277 pool immediately following the drought was thus  $63.7 \pm 8.1 \text{ MgC ha}^{-1}$ . Subtracting the 2012 measurement of  $30.2 \pm 7.3 \text{ MgC ha}^{-1}$   
278 <sup>1</sup> from this number, which is our best estimate of equilibrium CWD that may have existed before the 1997-1998 El Niño drought,  
279 we estimate drought-induced mortality to be  $33.5 \pm 15.4 \text{ MgC ha}^{-1}$ , or 12-31% of present AGB.

## 280 3.4 Empirical NEE Model

### 281 3.4.1 Hourly variability in NEE

282 Optimized parameter values for our model are included in Table 1. Our model predicted 81% of the variance in  
283 observed hourly NEE, and captured 94% of the amplitude of the diurnal cycle. The only hourly independent variable in the  
284 model was PAR; hourly NEE in our model was therefore predominantly driven by changes in sunlight. Modeled hourly  
285 variability frequently captured the difference in magnitude in NEE between high and low uptake events (example time series  
286 shown in Fig. 4).

### 287 3.4.2 Seasonal variability in NEE

288 In our best-fitting model parameterization, phenology was asynchronous with the dry season (Table 2). Over the mean  
289 seasonal cycle, removing this seasonal phenology parameterization resulted in positive residual NEE from June 15 to September  
290 14, hence over-predicting uptake during this time (Fig. 5a). Our final model, however, simplistically corrects for this positive  
291 anomaly, adjusting NEE by 16% (Fig. 5b, Table 2). Although this seasonal transition appears to be more gradual over the season,  
292 our simplistic, low-parameter phenology representation was chosen for parsimony. While the seasonal timing of respiration,  $s_r$ ,  
293 varied by meteorological inputs (semi-monthly total rainfall <50 mm), we could not identify a similar seasonal meteorological  
294 trigger for phenology and therefore used set calendar dates.

295 Our model predicted monthly mean NEE well ( $R^2=0.59$  across all months). Hourly changes in PAR integrated over  
296 monthly and seasonal time periods. Therefore, seasonal variability in our model was controlled by precipitation, sunlight, and a  
297 simplistic parametric representation of phenology (Eq. 2; Table 1).

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**Deleted:** and by downscaling the hourly PAR response

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298 Part of the remaining seasonal variability was explained by random measurement error: bootstrap 95% confidence  
299 intervals representing hourly measurement errors in monthly mean NEE had an average range of  $1.07 \mu\text{mol m}^{-2}\text{s}^{-1}$ , 47% of the  
300 mean NEE seasonal cycle's range. The model slightly over-predicted the mean seasonal cycle's magnitude, although well within  
301 the model and measurement interannual variability (Fig. 6). The model attributed the greatest sink to October, because (1)  
302 October rainfall was low enough each year to be classified as part of the dry season, (2) PAR was consistently high due to sunny  
303 conditions after the dry season onset, and (3) the phenology scaling factor ( $1 - k_{\text{pheno}} * s_{\text{pheno}}$ ) returned to 1 after Sept 14, increasing  
304 the October LUE and pushing the carbon balance further towards a sink.

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305 A higher-parameter model with VPD and diffuse radiation from Wu et al. (2017) explained additional variance in  
306 hourly NEE but not in monthly NEE (Table S1). The BIC score for this model (-31.4) was greater than (more negative) than that  
307 from our main model (-35.6; Eq. 2), because it did not improve the goodness of fit but contained additional parameters. The BIC  
308 results imply that VPD and diffuse radiation do not explain significant additional variance relative to our model (Eq. 2) at  
309 monthly and greater timescales.

### 310 3.4.3 Interannual Variability in NEE

311 Hourly changes in PAR and seasonal changes in precipitation integrated annually to determine yearly sums of modeled  
312 NEE. Therefore, interannual variability was controlled by precipitation and sunlight. Phenology did not vary interannually,  
313 therefore it did not affect interannual variability in modeled NEE.

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314 We disaggregated the meteorological influence on NEE, represented by our model (Eq. 2), from long-term changes in  
315 forest's ecological efficiency by examining the annually integrated hourly model residuals. In 2002, there were a total of 1.2  
316  $\text{MgC ha}^{-1}\text{yr}^{-1}$  of excess emissions unaccounted for by the modeled mean response to meteorology (Fig. 7a). The correlation  
317 between modeled and measured yearly NEE was low and insignificant ( $R^2 = 0.17$ ;  $p = 0.37$ ) owing to the 2002 anomaly: if 2002  
318 is excluded as an outlier, the correlation is high and significant ( $R^2 = 0.81$ ;  $p = 0.014$ ). All other years were not significantly  
319 different from zero within random measurement error, represented by 95% bootstrap confidence intervals, indicating that these  
320 years are well predicted by meteorological variability, including the relatively higher emission/lower uptake in period 2 (Fig. 1).

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of NEE allowed us to  
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321 On average, period 2 saw a 20% increase in annual precipitation relative to period 1. Abbreviated dry season lengths  
322 and lack of radiation from increased cloudiness in period 2 resulted in less modeled net uptake relative to period 1.

323 We partitioned observed and modeled NEE into RE and GEE. Interannual variations in RE were accurately represented  
324 as changes in wet and dry season length (Fig. S1). The range in annual residual RE is therefore small compared to that of annual  
325 residual GEE (Fig. 7b). In 2002, mean model GEE had  $0.85 \mu\text{mol m}^{-2}\text{s}^{-1}$  more uptake than observations. Therefore, the  $1.2 \text{ MgC}$   
326  $\text{ha}^{-1}\text{yr}^{-1}$  residual emissions in 2002 were more likely due to anomalously low photosynthesis rather than high RE.

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## 327 4 Discussion

### 328 4.1 Hourly and Seasonal Changes in NEE and Implications for Modeling Phenology

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329 Hourly changes in NEE were due predominantly to changes in sunlight (Fig. 4). Phenology only played a small role in  
330 modeled hourly variability, improving the fit of our model by only 1% relative to a model that only used meteorology and lacked  
331 a phenology parameterization (Table 2).

332 Seasonal changes, on the other hand, were due to a combination of sunlight, rainfall inputs, and phenology (Fig. 6). The  
333 model parameterization contained a seasonal decrease in respiration ( $a_r$ ) that was synchronous with the dry season, a timing that



334 was consistent with other tropical forest sites, but can exert the opposite influence depending on terrain, drainage, and inundation  
335 (Kiew et al., 2018). A phenological LUE decrease in GEP ( $1-k_{pheno}$ ) was asynchronous with the dry season (Eq. 5; Table 2).  
336 Modeled phenology explained 26% of the variability in observed monthly NEE (Table 2).  
337 VPD and diffuse radiation do not explain significant additional variance in NEE relative to our model (Eq. 2) at  
338 monthly timescales (Table 1; Table S1). The relative importance of phenology at monthly timescales, compared to that of VPD  
339 and diffuse radiation, is consistent with other findings regarding GEP at our research site: moving from finer to coarser temporal  
340 resolution, the influence of exogenous meteorology becomes outweighed by that of exogenous ecosystem changes such as those  
341 in phenology (Wu et al. 2017).

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342 Seasonal changes in LUE are well explained by canopy leaf age and demography both at this site and at a comparatively  
343 wetter forest site in Manaus, showing good agreement with a model informed by camera and trap-based observations of leaf  
344 flushing and shedding (Wu et al., 2016). Our single mid-year parameter simplistically up-shifts the trough in a more continuous  
345 seasonal oscillation between low and high LUE (Fig. 5) because we lacked independent variables explaining the seasonal  
346 oscillation.

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347 The seasonally asynchronous nature of phenology-mediated LUE establishes a middle ground in debates over whether  
348 the Eastern Amazon canopy is enhanced or “greens up” during the dry season (Huete et al., 2006; Myneni et al, 2007; Samanta et  
349 al., 2012; Morton et al., 2014; Bi et al., 2015; Guan et al., 2015; Saleska et al., 2016). Changes to the canopy’s LUE do indeed  
350 occur, but not synchronously with the dry season at our site (Fig. 5). Evidence from previous studies at the TNF suggests that  
351 changes in phenological LUE result from carbon allocation shifting from stem allocation to the turnover and production of new  
352 leaves (Goulden et al., 2004) supporting the prevailing hypothesis that tropical trees have been selected to coordinate new leaf  
353 production ahead of dry seasonal peaks of irradiance (Wright and van Schaik, 1994). The GEP seasonal cycles at additional  
354 evergreen Amazon forest sites are not well described by sunlight alone (Restrepo-Coupe et al., 2013). Averaging over seasonal  
355 windows is therefore likely to miss a potential inter-seasonal depletion and enhancement of canopy LUE if additional regions of  
356 evergreen Amazon forest similarly exhibit seasonally asynchronous phenology.

357 Interannual variation in phenology is represented mechanistically in phenology and LUE sub-models, which have been  
358 optimized using km67 eddy flux data, but nonetheless fail to reproduce the observed mid-year GEP decrease at this site. Kim et  
359 al. (2012) present a light-triggered phenology scheme, which assumes higher modeled leaf turnover rates and higher maximum  
360 leaf photosynthesis during the dry season, and hence produced higher dry season GEP. Their model produced leaf flushing rates  
361 that lagged behind observations, and contradicted observations that light-controlled GEP decreases mid-year at km67 (Fig. 5).  
362 Another phenology scheme has been developed by De Weirtd et al. (2012), which attributes excess leaf allocation to the turnover  
363 of new, more efficient leaves, but nevertheless over-predicted mid-year GEP at km67 relative to their prior model. Wu et al.  
364 (2016), on the other hand, successfully represent the GEP seasonal cycle using their model of leaf age and demography, but  
365 relied on observations of canopy leaf fluxes. Their model, however, does not provide a meteorologically-triggered mechanism  
366 for seasonal leaf shedding and flushing. Therefore, until such a trigger can be identified, models that mechanistically represent  
367 phenology are primed to make erroneous predictions about the interannual and long-term consequences of changing seasonal  
368 lengths for the Amazon carbon balance.

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#### 369 4.2 Interannual variability in NEE

370 Annual totals of measured NEE exhibited an unpredicted trend: despite previous hypotheses that the years after period 1  
371 would continue to trend downward towards more uptake (Hutyra et al., 2007; Pyle et al., 2008), the ecosystem returned to a  
372 moderate carbon source in all three years of period 2 (Fig. 1). We examined whether the reversal of the period 1 trend throughout

373 period 2 could be explained by exogenous changes in climate or an endogenous biophysical change. We developed the model  
374 selection framework to partition these two sources of variability.

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375 Our model represented NEE well across a variety of timescales (Figs. 4, 5, 7). On yearly timescales, interannual  
376 differences in  $NEE_{Model}$  were due to exogenous meteorology, as phenology did not vary interannually. The model predicted  
377 annual NEE accurately within 95% confidence limits of random measurement error for 6 out of 7 years (Fig. 7a), including  
378 period 2, during which the forest returned to a carbon source (Fig. 1). The model representation of the period 2 source was due to  
379 lower radiation and higher rainfall relative to period 1, consistent with findings of light-limitation in Amazon forests derived  
380 from satellite observations of climate and vegetation activity (Nemani et al., 2003).

381 The overall magnitude of the carbon source/sink, however, was highly sensitive to the choice of  $u_*$  filter, consistent with  
382 previous findings (Saleska et al., 2003; Miller et al., 2004; Hayek et al., 2018). We therefore applied a novel correction to the  
383 long-term magnitude of NEE that is independent of the  $u_*$  filter (Hayek et al., 2018), which indicated that the ecosystem may in  
384 fact be a slight sink, but that the interannual variability, which our model represents, remained the same (Fig. S2). The overall  
385 magnitude of the carbon source/sink therefore does not affect or results concerning the variability between years. The least net  
386 uptake still occurred in 2002, from which NEE remained insignificantly different in 2009 and 2011.

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387 We examined the possibility that a systematic high bias in 2002 PAR could result in an over-prediction of 2002 GEP  
388 and erroneously cause a positive 2002 residual. We found that PAR was appropriately drift-corrected by corroboration with  $R_{net}$ ,  
389 which was not affected by drifts. Additionally, we note that rainfall was not atypical in 2002 relative to 2003-2005 (Fig. 2).

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390 Additional meteorological variables such as the vapor pressure deficit (VPD) and diffuse radiation did not appear to  
391 explain residual NEE in 2002. A model including these variables did not explain the positive NEE/GEE anomaly in 2002 (Fig.  
392 S3). The annual means of both VPD and CI in 2002 lied within their decadal range, making high VPD or low diffuse radiation  
393 unlikely explanations for low photosynthetic uptake. These meteorological factors did not appear to significantly impact  
394 interannual changes in NEE, consistent with previous findings regarding GEP at this site (Wu et al., 2017).

395 We cannot rule out that the 2002 source may be a measurement artifact, caused for example by disturbance following  
396 tower construction. We note, however, that tower construction was completed almost a year before the measurements we used,  
397 with preliminary data collection occurring during 2001 (Saleska et al., 2003). We examine the possibility that 1998 drought-  
398 based disturbance impacted forest GEP through 2002 in section 4.2.2.

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#### 399 4.2.1 Temporal and spatial heterogeneity of droughts

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400 Our multiple records of meteorology adjacent to our research site (Fig. 2), which we used to inform our simple model of  
401 NEE, can also shed light on the larger discussion of recent droughts in the Amazon. Previous reports of 21<sup>st</sup> century droughts in  
402 this region are inconsistent. For the 2010 Amazon drought, Lewis et al. (2011) show that water deficits during were minimal in  
403 the Eastern Amazon region, consistent with our findings. However, Doughty et al. (2015) report ubiquitous detrimental effects of  
404 the 2010 drought basin-wide, including a -3 MgC ha<sup>-1</sup> GEP anomaly overlying the TNE. Our results contradict these findings: we  
405 did not find anomalously low water inputs, nor a concurrent GEP or NEE anomaly (Fig. 7b), in 2010. For the 2005 Amazon  
406 drought, Zeng et al. (2008) claim that North Tropical Atlantic warming in the dry Jul-Oct quarter led to rainfall reductions  
407 everywhere in the Amazon, a result not borne out by our precipitation analysis. The two supposedly basin-wide droughts in 2005  
408 and 2010 did not appear to affect the region in which this particular site lies. Measurements and empirical modeling of CWD  
409 over time support this finding because no interim disturbances were detected between 2001 and 2011 (Fig. 3). The spatial extent  
410 and severity with which a more recent 2015-2016 El Niño drought impacted Amazon forests, however, remains to be quantified.

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#### 4.2.2 Legacy impacts of drought on ecosystem function

Our model over-predicted photosynthetic uptake in 2002, but predicted RE well (Fig. 7b; Fig. S1), suggesting that a drought-disturbance in 1998 persistently affected forest GEP, not RE, through 2002. These findings contradict a previously established hypothesis that legacy effects of a prior drought disturbance increased RE in 2002 via increased CWD respiration ( $R_{CWD}$ ) and related pathways of decomposition (Saleska et al., 2003; Rice et al., 2004; Hutrya et al., 2007; Pyle et al., 2008). CWD measurements from the km67 site suggest that there was major disturbance before measurements of  $CO_2$  eddy fluxes began. Three years after the 1998 drought, there was a large pool of CWD ( $48.6 \text{ MgC ha}^{-1}$  in 2001), implying that a drought-based disturbance had occurred in the past. By 2012, the CWD pool respired faster than it could accrue additional necromass from mortality (Fig. 3), implying that no additional impactful disturbance occurred at this site between 2002 and 2012. Although  $R_{CWD}$  was in fact higher in 2002 than 2005, this difference accounted for only  $0.2 \mu\text{mol m}^{-2} \text{ s}^{-1}$  (Fig. 3) of respiration. Changes in  $R_{CWD}$  therefore explain the small differences in annual RE (Fig. S1), but inadequately account for the full  $1.3 \mu\text{mol m}^{-2} \text{ s}^{-1}$  ( $2.4 \text{ MgC ha}^{-1} \text{ yr}^{-1}$ ) difference in NEE between these years (Fig. 1; Fig. 7).

Identifying the cause of the reduced 2002 GEP is beyond the scope of this statistical modeling study. It is possible that the 1997-1998 El Niño drought not only killed entire trees, but also damaged living trees through hydraulic failure and partial limb death, affecting canopy photosynthesis for subsequent years. An analysis of over 1000 temperate forest census sites suggests that recovery of live tree biomass accumulation may be delayed by up to four years after drought (Anderegg et al., 2015). Following the 2005 and 2010 western droughts, findings from forest inventories (Brienen et al., 2015) and remote sensing (Saatchi et al., 2013), suggested that legacy effects from tropical forest droughts can also persist for four years or more. Drought cavitation due to xylem embolisms reduces hydraulic conductivity leading to whole tree mortality (Choat et al., 2012), initiating a classic disturbance-recovery scenario in which felled trees generate canopy gaps for early successional seedlings and saplings to immediately capitalize on newly available light, causing  $CO_2$  sources to approximately balance sinks (Chambers et al., 2004). However, cavitation is also known to cause branch dieback in still living trees (Koch et al., 2004), reducing canopy foliage partially but not completely forfeiting light resources to the understory. Drought-induced limb diebacks therefore potentially prolong forest recovery relative to immediate disturbances such as windfall. We hypothesize that partial drought damage to surviving trees can persistently affect whole-forest photosynthesis. Our findings, that a 1997-1998 drought-disturbance was followed by reduced photosynthesis in 2002, emphasize the need to better mechanistically understand multi-year legacy impacts following droughts in evergreen Amazon forests.

#### 5 Conclusions

The decade-long record of eddy flux at km67 in the TNF demonstrated unpredictable trends in 7.5 years of measured NEE. Our simple, low-parameter empirical model could represent interannual differences in NEE as integrated continuous responses to changes in meteorology, with exception to the first year, suggesting that increased moisture and decreased sunlight, not an interim disturbance, were responsible for the elevated period 2 carbon source. Although overall magnitude of the carbon source/sink was highly sensitive to the specific choice of  $u^*$  filter, the interannual variability, which was predicted by the model, remained the same. Contrary to some reports, no major drought was apparent in concurrent rainfall records, nor was a major concurrent disturbance apparent in biometry surveys of this site from 2001 through 2011.

Our model represented a seasonal mid-year decline in GEP. Our representation of phenology follows set calendar dates, and cannot distinguish between various hypotheses concerning the environmental trigger for seasonal leaf shedding and flushing.

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448 DVGMs and other numerical simulation ecosystem models that represent phenology as a response to light-triggered leaf flushing  
449 or root water constraints do not tend to represent the seasonal cycle of GEP accurately and are therefore in danger of over-  
450 predicting the future response of photosynthesis to longer dry seasons resulting from climate change.

451 Our finding that reduced photosynthesis, not increased respiration, contributed to the high NEE source in 2002 modifies  
452 the previous hypothesis that the 1997-1998 El Niño drought disturbance affected NEE via respiration. Our findings support a  
453 corollary hypothesis that partial drought-induced damage to still-living trees can impact whole-ecosystem photosynthesis  
454 adversely for multiple years, which is consistent with findings from regional and global-scale forest biometric studies (Anderegg  
455 et al., 2015; Brienen et al., 2015). In order to understand how drought-disturbance uniquely impacts forest recovery,  
456 observational studies and plot-based manipulation experiments are needed in conjunction with models. Such future research is  
457 needed to determine the return times for droughts at which persistent forest biomass loss and collapse may occur.

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#### 458 Acknowledgments and Data

459 This work was supported by funding from a National Science Foundation PIRE fellowship (OISE 0730305) and a U.S.  
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461 Berkeley Laboratories (LBL) Ameriflux network database at <http://ameriflux.lbl.gov/sites/siteinfo/BR-Sa1>.

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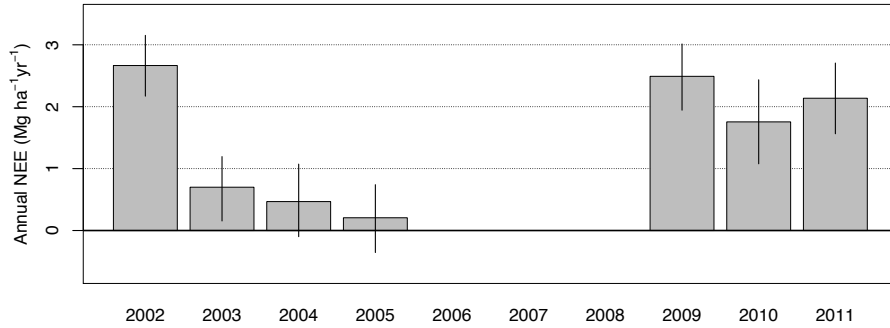
692 **Tables and Figures**

Model Parameters					hourly R <sup>2</sup>	monthly R <sup>2</sup>
$a_0$	$a_1$	$a_2$	$a_3$	$k_{pheno}$		
9.43	-1.32	-39.2	760.9	0.164	0.81	0.59
(9.30, 9.56)	(-1.49, -1.15)	(-39.8, -38.6)	(733.2, 788.6)	(0.156, 0.171)		

693 **Table 1.** Model parameter values (95% confidence intervals in parentheses) and R<sup>2</sup> fit. Parameters have the following units:  $a_0$ ,  $a_1$ , and  
694  $a_2$ :  $\mu\text{mol-CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ;  $a_3$ :  $\mu\text{mol-photon} \text{ m}^{-2} \text{ s}^{-1}$ ;  $k_{pheno}$ : unitless.

$s_{pheno}$ timing	$k_{pheno}$	hourly R <sup>2</sup>	monthly R <sup>2</sup>
None	-	0.80	0.33
Dry Season	0.117 (0.109, 0.125)	0.80	0.32
June 15 to Sept 14*	0.164 (0.156, 0.171)	0.81	0.59

695 **Table 2.**  $k_{pheno}$  parameter values (95% confidence intervals in parentheses) and hourly and monthly model fit associated with various  
696 seasonal timings of the phenology factor variable  $s_{pheno}$ . \*Final model parameterization.



697 **Figure 1.** Annual sums of NEE in kg/ha/year. Error bars are 95% confidence intervals. Positive values indicate a source of CO<sub>2</sub> to the  
698 atmosphere. Net emission of carbon to the atmosphere during every year in the time series was possibly due to choice of  $u_c^{Th}$  (Fig. S2  
699 for annual NEE time series derived from an alternative choice of flux bias correction).  
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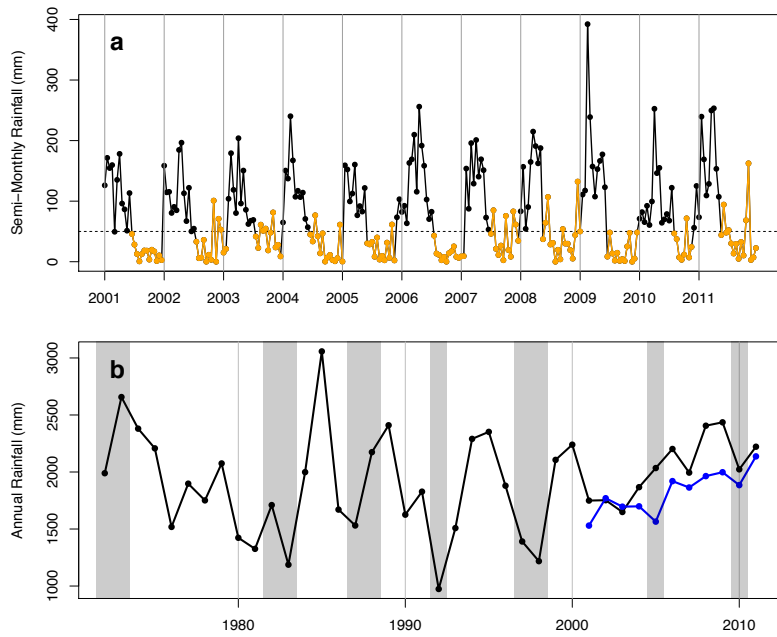
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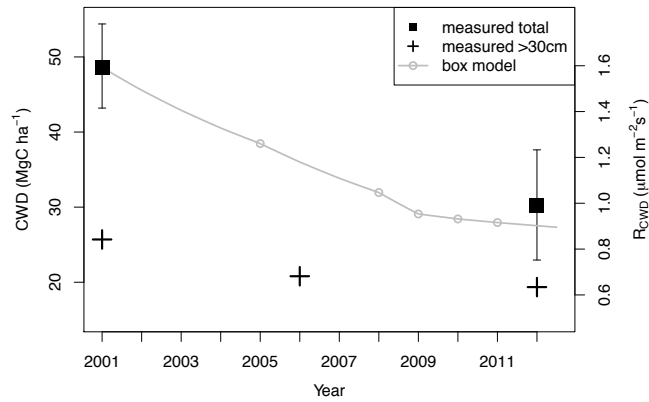
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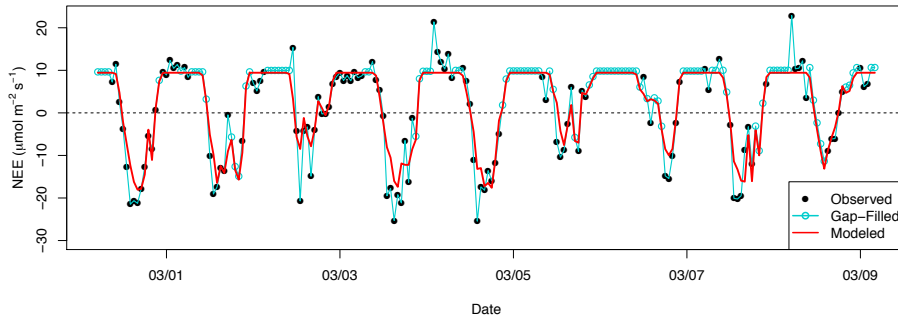
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702 **Figure 2.** (a) Semi-monthly dry season rainfall totals for wet season (black) and dry season (orange). Hourly rainfall was estimated by  
 703 objective analysis (Eq. 1) from meteorology stations nearby km67. The horizontal dashed line shows the dry season threshold of 50 mm  
 704 per half-month. (b) Yearly totals of rainfall from Belterra INMET station (black), 25 km away from km67, and km67 rainfall  
 705 estimated by objective analysis (blue). Recent El Niño anomalies (grey shaded areas) coincide with droughts in the 1990s but not in the  
 706 2000s (blue points) at this site, when annual rainfall was within the long-term historical variability.



707

708 **Figure 3.** Measurements of total CWD (black squares with 95% bootstrapped CI error bars) and subsets of CWD  $\geq 30$  cm diameter  
 709 (black crosses) show a decrease over time. CWD box model (grey line) also shows a gradual decrease in CWD over time. The initial  
 710 condition is the 2001 measurement of CWD; source is input from mortality inferred by biometry census (census times represented by  
 711 grey circles); sink is an empirical respiration rate of  $0.124 \text{ yr}^{-1}$  [Pyle et al., 2008]. Left axis shows the CWD respiration flux ( $R_{\text{CWD}}$ )  
 712 corresponding to the equivalent amount of CWD on the right axis.



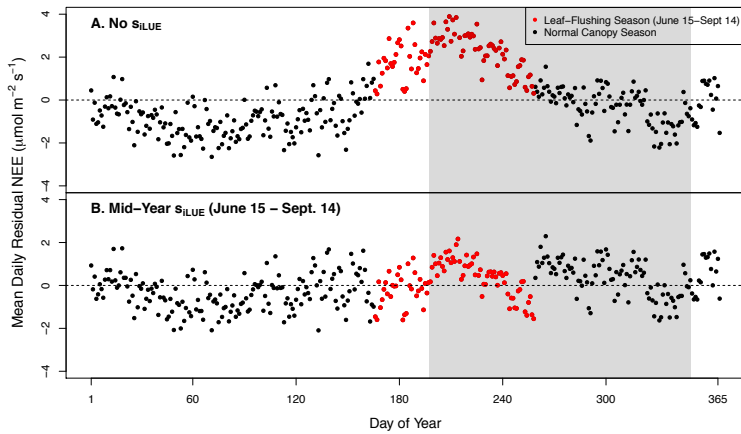
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714 | **Figure 4.** Example time series of  $NEE_{obs}$  and  $NEE_{Model}$  for 9 days of the wet season in 2008. Pearson correlation coefficient between  
 715  $NEE_{obs}$  and  $NEE_{Model}$  is  $R=0.90$  over the entire 7.5 year time series.

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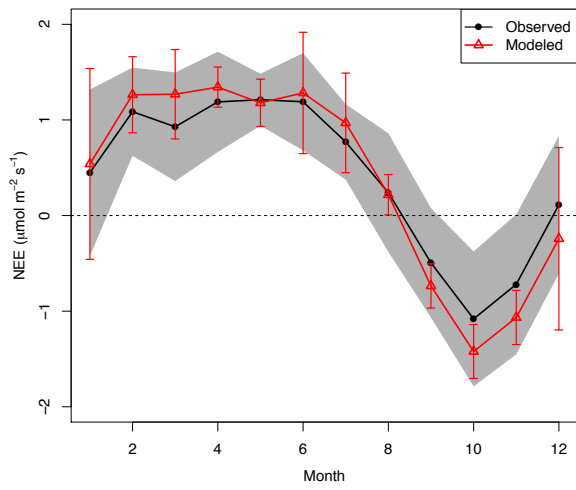
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719 **Figure 5.** Mean daily data-model residuals averaged over all 7.5 years: (a) lacks an adjustment for phenological change in LUE. Leaf-  
 720 flush period only partially overlaps the dry season (grey shaded area). (b) The best-fitting parameterization of the model contained a  
 721 mid-year phenology scaling factor ( $1-k_{pheno} \cdot s_{pheno} = 0.84$ ; Table 2), which was asynchronous with the dry season (red points).

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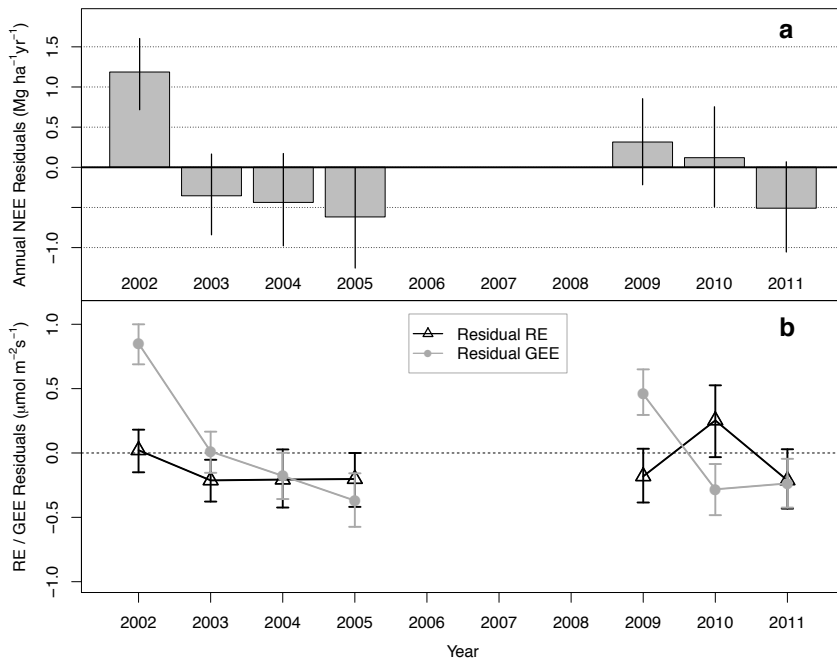
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Figure 6. (a) Mean seasonal cycle of  $NEE_{obs}$  (black dots) and  $NEE_{Model}$  (red triangles). Grey shaded areas are standard deviations of interannual variability for the mean  $NEE_{obs}$  for each respective month. Error bars are standard deviations of the interannual variability in monthly mean  $NEE_{Model}$ .



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Figure 7. (a) Annually summed model residuals. Error bars are 95% bootstrapped confidence intervals. Annual residual NEE in 2002 is statistically different from 0 within random NEE measurement error; all other years are not. (b) Residuals of model representation of partitioned GEE (grey circles) and RE (black triangles).

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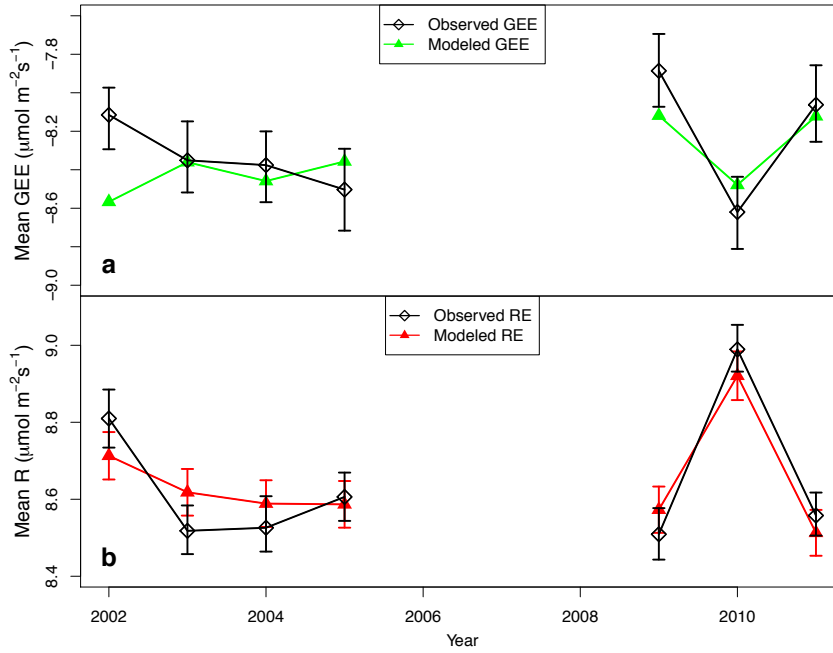
Supplemental Tables and Figures: [Table S1](#) and [Figures S1-S3](#).

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Model Parameters							hourly	monthly
$a_0$	$a_1$	$a_2$	$a_3$	$k_{CI}$	$k_{VPD}$	$k_{pheno}$	$R^2$	$R^2$
9.43 (9.30, 9.56)	-1.32 (-1.49, -1.15)	-79.1 (-81.3, -76.9)	3778 (3613, 3937)	1.34 (1.30, 1.38)	1.72 (1.69, 1.74)	0.132 (0.128, 0.135)	0.83	0.59

**Table S1. Model parameter values (95% confidence intervals in parentheses) and  $R^2$  fit. Parameters have the following units:  $a_0$ ,  $a_1$ , and  $a_2$ :  $\mu\text{mol-CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ;  $a_3$ :  $\mu\text{mol-photon} \text{ m}^{-2} \text{ s}^{-1}$ ;  $k_{VPD}$ :  $10^{-4} \text{ Pa}^{-1}$ ;  $k_{pheno}$ , and  $k_{CI}$ : unitless.**

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**Figure S1. (a) Annual average partitioned GEE (black diamonds) and annual average modeled GEE (green triangles). (b) Annual average RE (observed nighttime NEE) (black diamonds) and annual average modeled RE (red triangles).**

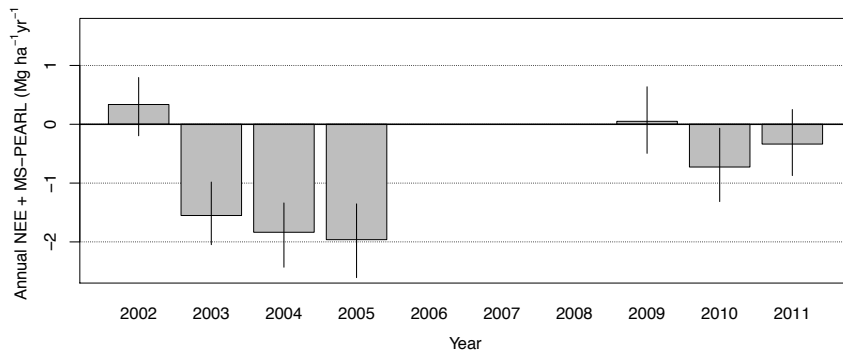


Figure S2. Annual NEE adjusted by alternative bias correction from Hayek et al. (2018).

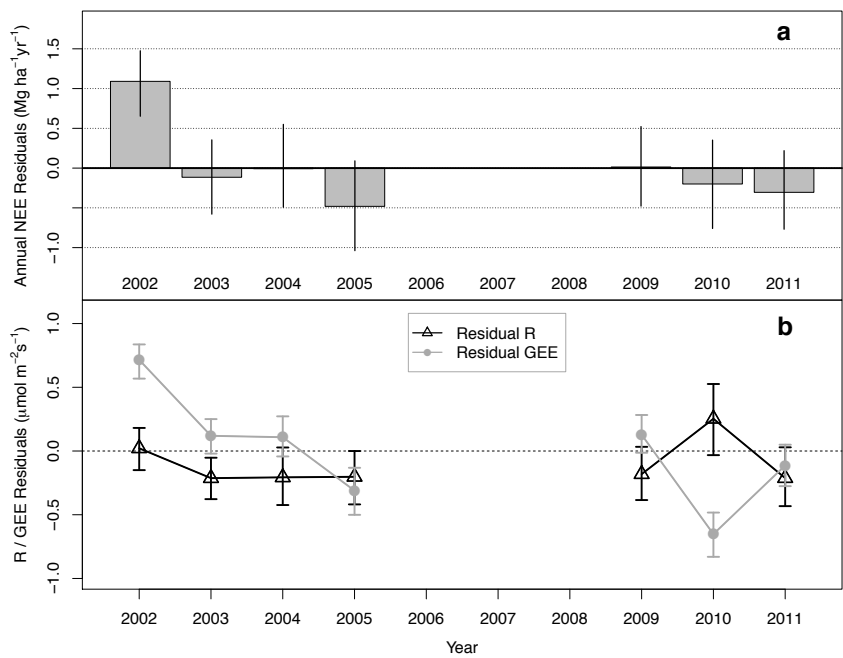


Figure S3. (a) Annually summed model residuals from the higher-parameter light-and-moisture NEE model derived from Wu et al. (2017). Error bars are 95% bootstrapped confidence intervals. Annual residual NEE in 2002 is statistically different from 0 within random NEE measurement error; all other years are not. (b) Residuals of model representation of partitioned GEE (grey circles) and RE (black triangles) of the higher-parameter light-and-moisture derived from Wu et al. (2016b).

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