Supplementary information for "Lagged effects dominate the inter-annual variability of the 2010-2015 tropical carbon balance."

The following document includes (i) a technical description of the DALEC model version 2a (DALEC2a), and (ii) supplementary figures and tables ancillary to the primary results presented in the main body of the manuscript.

S1. Description for DALEC2a model

The equations presented here have been adapted based on the DALEC version presented by Bloom et al. (2016). Advances to the model structure are explicitly discussed in the main body of the manuscript and the corresponding appendices. For a full description of the previous DALEC model versions, we refer the reader to Bloom & William (2015), Williams et al. (2005) and Williams et al. (1997). The DALEC2a parameters and the carbon and water pool symbols are summarized in Table S1. All other terms are explicitly introduced.

S1.1 Carbon pools

$$C_{lab}^{(t+1)} = f_{lab}F_{gpp}^{(t)} + (1 - \phi_{onset}^{(t)})C_{lab}^{(t)}$$

$$C_{fol}^{(t+1)} = \phi_{onset}^{(t)}C_{lab}^{(t)} + (1 - \phi_{fall}^{(t)})C_{fol}^{(t)} + f_{fol}F_{gpp}^{(t)}$$

$$C_{roo}^{(t+1)} = (1 - \theta_{roo})C_{roo}^{(t)} + f_{roo}F_{gpp}^{(t)}$$

$$C_{woo}^{(t+1)} = (1 - \theta_{woo})C_{woo}^{(t)} + f_{woo}F_{gpp}^{(t)}$$

$$C_{lit}^{(t+1)} = \left(1 - (\theta_{lit} + \theta_{\min})\rho^{(t)}\right)C_{lit}^{(t)} + \phi_{fall}^{(t)}C_{fol}^{(t)}$$

$$C_{som}^{(t+1)} = \left(1 - \theta_{som}\,\rho^{(t)}\right)C_{som}^{(t)} + \theta_{woo}\,C_{woo}^{(t)} + \theta_{\min}\rho^{(t)}C_{lit}^{(t)}$$

$F_{gpp}^{(t)}$ is the gross primary production (see S1.2). The time-dependent phenological functions $\phi_{onset}^{(t)}$ and $\phi_{fall}^{(t)}$ are summarized in section 1.3. The formulation of $\rho^{(t)}$ is described in Appendix A2.

S1.2 Fluxes

$$F_{gpp}^{(t)} = F_{gpp(max)}^{(t)} \min\left(\frac{W^{(t)}}{\omega}, 1\right)$$

$$F_{rau}^{(t)} = f_{auto}F_{gpp}^{(t)}$$

$$F_{npp}^{(t)} = F_{gpp}^{(t)} - F_{rau}^{(t)}$$

$$F_{rhe}^{(t)} = \theta_{lit}\rho^{(t)} C_{lit}^{(t)} + \theta_{SOM}\rho^{(t)} C_{SOM}^{(t)}$$

$$F_{nbe}^{(t)} = F_{rhe}^{(t)} + F_{fir}^{(t)} - \mathrm{F}_{npp}^{(\mathrm{t})}$$

The derivation of $F_{gpp(max)}^{(t)}$ is based on the Aggregated Canopy Model (Williams et al., 1997). The specific implementation of ACM in CARDAMOM is described in Bloom et al., (2016) and reference therein. $F_{nbe}^{(t)}$, $F_{rau}^{(t)}$, $F_{rhe}^{(t)}$, $F_{npp}^{(t)}$ and $F_{fir}^{(t)}$ are the net biospheric exchange (NBE), autotrophic respiration (RAU), heterotrophic respiration (RHE), net primary production (NPP) and fire C fluxes respectively. $F_{fir}^{(t)}$ is described in section 1.4.

S1.3 Phenology functions

$$\phi_{onset}^{(t)} = \left(1 - \Phi_{onset}(t, d_{onset}, c_{ronset}, c_{lr})\right)$$

$$\phi_{fall}^{(t)} = \left(1 - \Phi_{fall}\left(t, d_{fall}, c_{fall}, c_{ll}\right)\right)$$

The analytical formulations of Φ_{onset} and Φ_{fall} are described in Bloom & Williams (2015).

S1.4 Fire module

Fire C removals are estimated as

$$C_{lab}^{(t+1)} = C_{lab}^{(t+1)'} - FE_{lab}^{(t)} - FM_{lab}^{(t)}$$

$$C_{fol}^{(t+1)} = C_{fol}^{(t+1)'} - FE_{fol}^{(t)} - FM_{fol}^{(t)}$$

$$C_{roo}^{(t+1)} = C_{roo}^{(t+1)'} - FE_{roo}^{(t)} - FM_{roo}^{(t)}$$

$$C_{woo}^{t+1} = C_{woo}^{t+1'} - FE_{woo}^{(t)} - FM_{woo}^{(t)}$$

$$C_{lit}^{t+1} = C_{lit}^{t+1'} - FE_{lit}^{(t)} - FM_{lit}^{(t)} + FM_{lab}^{(t)} + FM_{fol}^{(t)} + FM_{roo}^{(t)}$$

$$C_{som}^{t+1} = C_{som}^{t+1'} - FM_{som}^{(t)} + FM_{lit}^{(t)} + FM_{woo}^{(t)}$$

where FE and FM represent fire emission and fire mortality fluxes, and the “’” denotes the pre-fire estimate of C_i^{t+1} for each pool *i* (see S1.1). Fire emissions for each pool *i* are derived as

$$FE_i^{(t)} = C_i^{(t+1)'} BA_i \, k_{factor(i)}$$

where $k_{factor(i)}$ is the combustion factor for carbon pool *i.* Fire induced mortality rates for each pool *i* are calculated as

$$FM_i^{(t)} = C_i^{(t+1)'} BA_i \left(1 - k_{\, factor(i)}\right) r$$

In Bloom et al., (2016), k_{factor} values are prescribed; here we summarize the uncertainty of combustion factors as three parameters: π_{foliar}, $\pi_{biomass}$ and π_{soil} (see section 2.1 in the main text). Specifically

$k_{factor(lab,roo,woo)} = \pi_{biomass}$
$k_{foliar(fol)} = \pi_{foliar}$
$k_{factor(lit)} = (\pi_{SOM} + \pi_{foliar})/2$
$k_{factor(som)} = \pi_{SOM}$.

Prior ranges for parameters $\pi_{biomass}$, π_{soil} and *r* are reported in Table S1. As stated in the main text, we appended the ecological and dynamical constraints (EDCs) used by Bloom et al., (2016) to include the following conditions:

$$\pi_{foliar} > \pi_{biomass}$$
$$\pi_{foliar} > \pi_{SOM}$$

S1.5 Plant-available water

The DALEC2a water module is described in Appendix A1 of the main text. For the sake of completes, the equations are re-stated here:

$$W^{(t+1)} = W^{(t)} + (P^{(t)} - ET^{(t)} - R^{(t)})\Delta t$$

$$ET^{(t)} = F_{gpp}^{(t)} \frac{VPD^{(t)}}{\upsilon_e}$$
$$R^{(t)} = aW^{(t)^2}$$

where $W^{(t)}$ is the plant-available water, and $P^{(t)}, ET^{(t)}$, $R^{(t)}$ are the plant-available water, precipitation, evapotranspiration and runoff water fluxes respectively.

Table S1: Optimized parameters and initial conditions, corresponding prior ranges, and resulting state variables.

	Parameter	Description	Prior range
Allocation fractions	fauto	Autotrophic respiration	0.2 – 0.8
	flab	NPP fraction to labile C	0.01 – 0.5*
	ffol	NPP fraction to foliar C	0.01 – 0.5*
	froo	NPP fraction to fine root C	0.01 – 0.5*
	fwoo[1]	NPP fraction to stem C	0.01 – 0.5*
Turnover rates	θwoo	Stem C turnover rate	2.5×10^{-5} - 10^{-3}
	θroo	Fine root C turnover rate	10^{-4} - 10^{-2}
	θlit	Litter C turnover rate at $\overline{\boldsymbol{T}}$, $\overline{\boldsymbol{P}}$	10^{-4} - 10^{-2}
	θsom	Soil organic matter (SOM) turnover rate at $\overline{\boldsymbol{T}}$, $\overline{\boldsymbol{P}}$	10^{-7} - 10^{-3}
	θmin	Mineralization of litter to SOM at $\overline{\boldsymbol{T}}$, $\overline{\boldsymbol{P}}$	10^{-5} - 10^{-2}
	Θ	Heterotrophic temperature dependence factor	0.018 – 0.08
	s_p	Heterotrophic precipitation dependence factor	0.01 - 1
Canopy parameters	d_{onset}	Leaf onset day	0 – 365.25
	d_{fall}	Leaf fall day	0 – 365.25
	c_{eff}	Canopy efficiency	5 – 50
	c_{LMA}	Leaf C mass per area	5 – 200 gC/m^2
	c_{ll}	Leaf loss fraction	1/8 - 1
	[2]c_{lr}	Annual labile C release fraction	1/8 - 1
	c_{ronset}	Labile release period	10 – 100 days
	c_{rfall}	Leaf fall period	20 – 150 days
Fire paramet	π_{foliar}	Combustion factors of foliar C	0.01 – 1
	$\pi_{biomass}$	Combustion factors of non-foliar biomass C	0.01 – 1
	π_{SOM}	Combustion factor of soil C	0.01 – 1
	r	Resilience factor	0.01 – 1
Water paramet	ω	Water stress threshold	$1 – 10^4$ Kg H_2O m^{-2}
	υ_e	Inherent water-use efficiency	10 – 50 hPa gC/kg H_2O
	α	[4]Second order runoff decay constant	3×10^{-7} – 0.03 mm^{-1} day^{-1}
State variables[3]	$C_{lab}^{(t)}$	Labile C at time *t*	1 – 2000 gC/m^{-2}
	$C_{fol}^{(t)}$	Foliar C at time *t*	1 – 2000 gC/m^{-2}
	$C_{roo}^{(t)}$	Fine root C at time *t*	1 – 2000 gC/m^{-2}
	$C_{woo}^{(t)}$	Above- and below-ground woody C at time *t*	$1 – 10^5$ gC/m^{-2}
	$C_{lit}^{(t)}$	Litter C at time *t*	1 – 2000 gC/m^{-2}
	$C_{som}^{(t)}$	Soil organic C at time *t*	$1 – 2\times10^5$ gC/m^{-2}
	$W^{(t)}$	Plant-available water at time *t*	$1 – 10^4$ mm

[1]*fwoo* is equivalent to $1 - f_{auto} - f_{fol} - f_{lab}$

[2]Labile release fraction was previously set to 1.

[3]Only initial conditions (at time t=0) are optimized in DALEC2a.

*Prior ranges are conservative approximations, see Fox et al., (2009) for details on sequential allocation fraction sampling in DALEC models.

Supplementary Figures

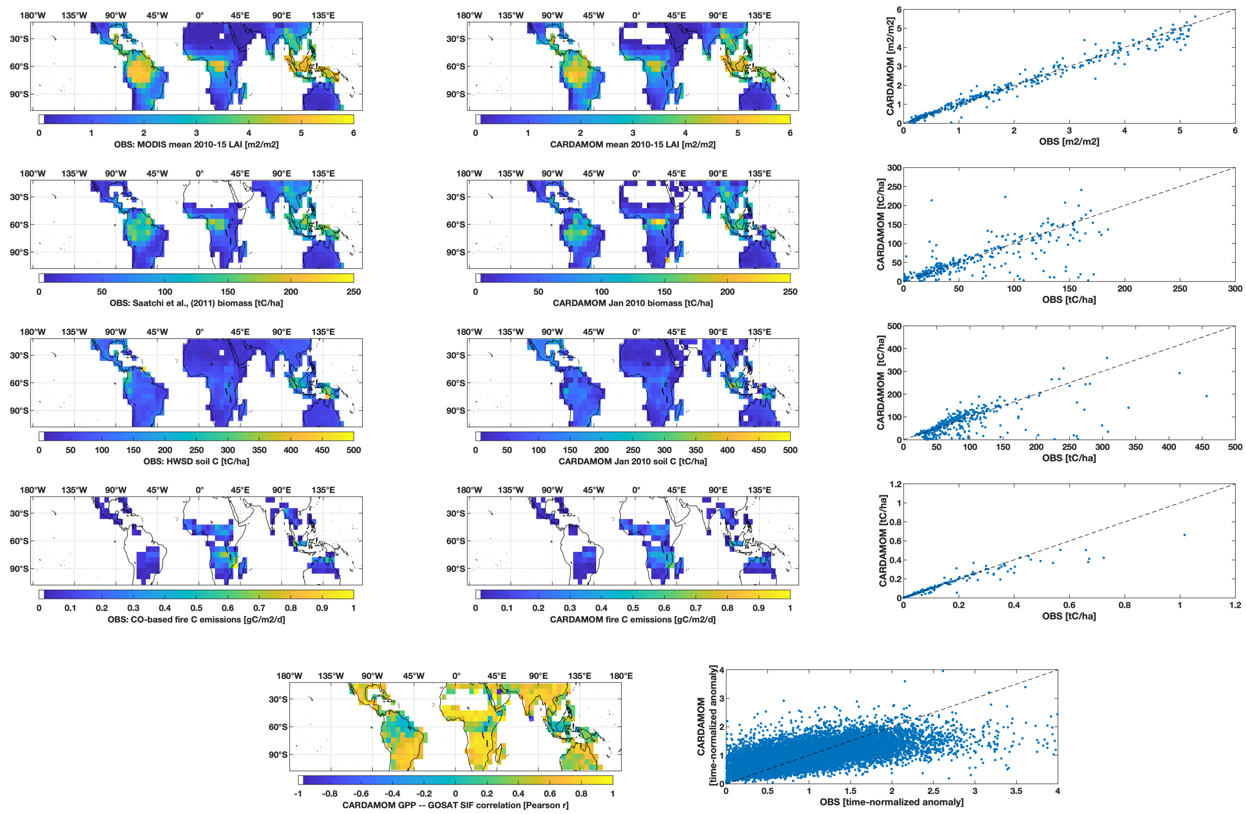

Figure S1: CARDAMOM output comparison against ingested observational constraints, namely MODIS LAI (top row), Saatchi et al. (2011) biomass (second row), soil carbon from the Harmonized World Soil Database (third row) and fire C emissions as estimated by Worden et al., (2017) (fourth row). CARDAMOM GPP comparison against ingested SIF constraints is summarized in the bottom row: the correlation map denotes the correlation between CARDAMOM GPP and SIF within each grid cell throughout 2010-2015 (bottom row, left panel); comparison between mean-normalized GPP and mean-normalized SIF values across the tropics throughout 2010-2015 (bottom row, right panel).

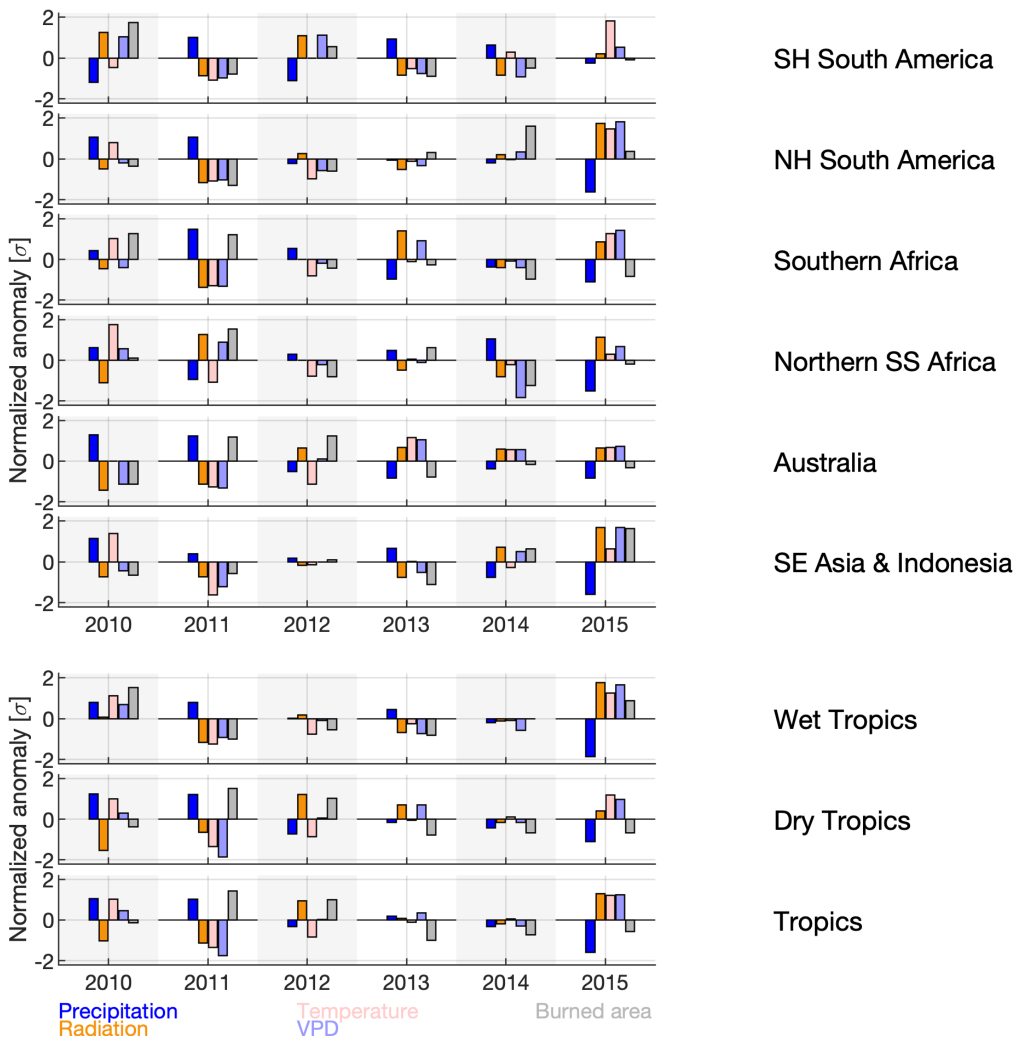

Figure S2. Annual regional and pan-tropical CARDAMOM meteorological forcing anomalies throughout 2010-2015. The geographical extent of each region is shown in Figure C1 in the main text of the manuscript.

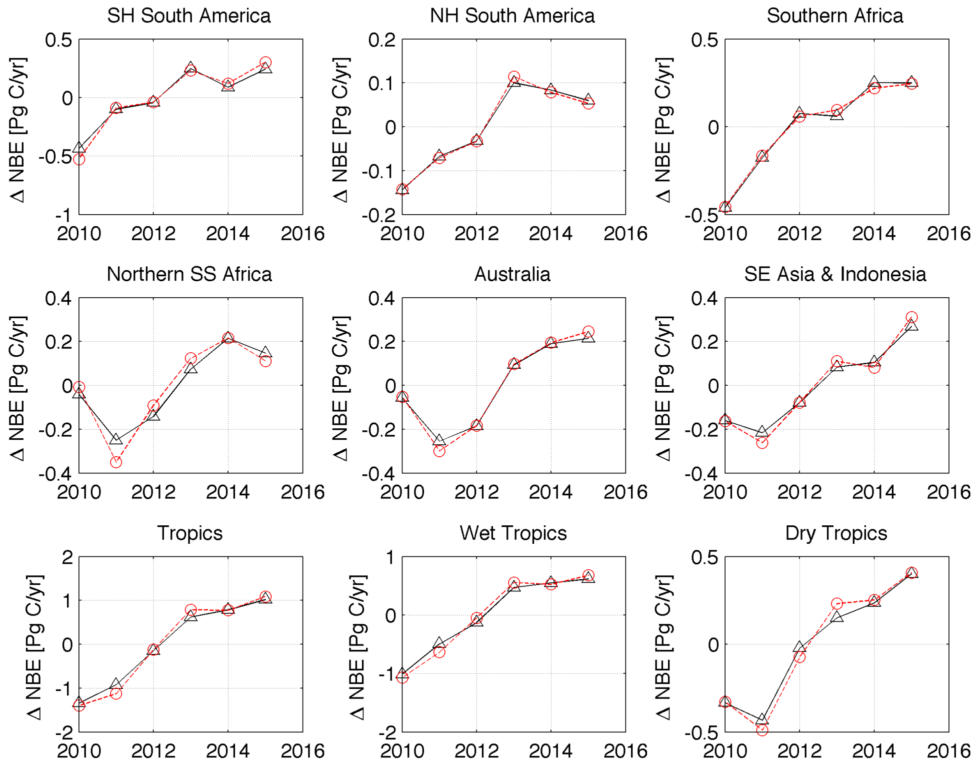

Figure S3: Sum of pool-specific contributions to total NBE lagged effect (red dashed line) and total NBE lagged effects (black solid line) for each region. The geographical extent of each region is shown in figure C1 in the main text of the manuscript.

References

Bloom, A. A. and Williams, M.: Constraining ecosystem carbon dynamics in a data-limited world: integrating ecological “common sense” in a model–data fusion framework, Biogeosciences, 12, 1299–1315, https://doi.org/10.5194/bg-12-1299-2015, 2015.

Bloom, A. A., Exbrayat, J.-F., van der Velde, I. R., Feng, L., and Williams., M.: The decadal state of the terrestrial carbon cycle: Global retrievals of terrestrial carbon allocation, pools, and residence times, P. Natl. Acad. Sci. USA, 113, 1285–1290, https://doi.org/10.1073/pnas.1515160113, 2016.

Fox, A., Williams, M., Richardson, A. D., Cameron, D., Gove, J. H., Quaife, T., Ricciuto, D., Reichstein, M., Tomelleri, E., Trudinger, C. M., and van Wijk, M. T.: The reflex project: com- paring different algorithms and implementations for the inversion of a terrestrial ecosystem model against eddy covariance data, Agr. Forest. Meteorol., 149, 1597–1615, 2009.

Williams, M., Rastetter, E.B., Fernandes, D.N., Goulden, M.L., Shaver, G.R. and Johnson, L.C.: Predicting gross primary productivity in terrestrial ecosystems. *Ecological Applications*, *7*, 882-894, 1997.

Williams, M., Schwarz, P. A., Law, B. E., Irvine, J., and Kurpius, M. R.: An improved analysis of forest carbon dynamics using data assimilation, Glob. Change Biol., 11, 89–105, 2005.