

Title: Global patterns of forest autotrophic carbon fluxes

Running head:

Authors:

Rebecca Banbury Morgan^{1,2}

Valentine Herrmann¹

Norbert Kunert^{1,3}

Ben Bond-Lamberty⁴

Helene C. Muller-Landau³

Kristina J. Anderson-Teixeira^{1,3*}

Author Affiliations:

1. Conservation Ecology Center; Smithsonian Conservation Biology Institute; Front Royal, VA, USA

2. *Becky- current*

3. Center for Tropical Forest Science-Forest Global Earth Observatory; Smithsonian Tropical Research Institute; Panama, Republic of Panama

4. Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park Maryland 20740 USA

*Corresponding Author:

phone: 1-540-635-6546

fax:1-540-635-6506

email: teixeirak@si.edu

Keywords:

Paper type: Primary Research Article

###Abstract Carbon (C) fixation, allocation, and metabolism by trees set the basis for energy and material flows in forest ecosystems and define their interactions with Earth’s changing climate. However, we lack a cohesive synthesis on how forest carbon fluxes vary globally with respect to climate and one another. Here, we draw upon 1319 records from the Global Forest Carbon Database (ForC), representing all major forest types and the nine most significant autotrophic carbon fluxes, to comprehensively explore how C cycling in mature, undisturbed forests varies with latitude and climate on a global scale. We show that, across all flux variables analyzed, C cycling decreases continuously with absolute latitude – a finding that confirms multiple previous studies but contradicts the idea that net primary productivity (*NPP*) of temperate forests rivals that of tropical forests. C flux variables generally displayed similar trends across latitude and multiple climate variables, with no differences in allocation detected at this global scale. Temperature variables in general, and mean annual temperature (*MAT*) and temperature seasonality in particular, were the best univariate predictors of C flux, explaining 19 - 71% of variation in the C fluxes analyzed. The effects of temperature were modified by moisture availability, with C flux reduced under hot and dry conditions and sometimes under very high precipitation. C fluxes increased with growing season length, but this was never the best univariate predictor. Within the growing season, the influence of climate on C cycling was small but significant for a number of flux variables. These findings clarify how forest C flux varies with latitude and climate on a global scale. In a period of accelerating climatic change, this improved understanding of the fundamental climatic controls on forest C cycling sets a foundation for understanding patterns of change.

Introduction

Carbon (C) cycling in Earth’s forests provides the energetic basis for sustaining the majority of Earth’s terrestrial biodiversity and many human populations (Assessment, 2005), while strongly influencing atmospheric carbon dioxide (CO₂) and climate (Bonan, 2008). Forests’ autotrophic carbon fluxes—that is, carbon fixation, allocation, and metabolism by trees and other primary producers—sets the energy ultimately available to heterotrophic organisms (including microbes), in turn influencing their abundance (Zak et al., 1994; Niedzialkowska et al., 2010) and possibly diversity (Waide et al., 1999; Chu et al., 2018). They are linked to cycling of energy, water, and nutrients, and, critically, influence all C stocks and define forest interactions with Earth’s changing climate. Each year, over 69 Gt of C cycle through Earth’s forests (Badgley et al., 2019)—a flux more than seven times greater than of recent anthropogenic fossil fuel emissions (9.5 Gt C yr⁻¹; Friedlingstein et al., 2019). As atmospheric CO₂ continues to rise, driving climate change, forests will play a critical role in shaping the future of Earth’s climate (Cavaleri et al., 2015; Rogelj et al., 2018). However, our understanding of the climate dependence of forest C cycling on a global scale has been limited by analyses typically considering only one or a few variables at a time, insufficient parsing of related variables, and the mixing of data from forests that vary in stand age, disturbance history, and/or management status, all of which affect C cycling (Litton et al., 2007; Gillman et al., 2015; Šímová and Storch, 2017).

Forest C fluxes decrease with latitude (e.g., Luyssaert et al., 2007; Piao et al., 2010; Gillman et al., 2015; Li and Xiao, 2019), but studies have differed in their conclusions regarding the shape of this relationship - quite possibly because of lack of standardization with respect to methodology and stand history. For instance, studies agree that gross primary productivity (*GPP*) increases continuously with decreasing latitude and is indisputably highest in tropical forests (Luyssaert et al., 2007; Beer et al., 2010; Jung et al., 2011; Badgley et al., 2019; Li and Xiao, 2019). In contrast, some studies have suggested that net primary productivity (*NPP*), or its aboveground portion (*ANPP*), exhibits a less distinct increase from temperate to tropical forests (Luyssaert et al., 2007)—or even a decrease (Huston and Wolverton, 2009, but see Gillman et al. (2015)). A shallower increase in *NPP* than in *GPP* with decreasing latitude would align with the suggestion that tropical forests tend to have low carbon use efficiency ($CUE = NPP/GPP$; De Lucia et al., 2007; Malhi, 2012; Anderson-Teixeira et al., 2016). Such differences among C fluxes their relationship to latitude could have profound implications for our understanding of the C cycle and its climate sensitivity. However, until recently the potential to compare latitudinal trends across C fluxes has been limited by lack of a large database with standardization for methodology, stand history, and management (Anderson-Teixeira et al., 2018).

The latitudinal gradient in forest C flux rates, along with altitudinal gradients (Girardin et al., 2010; Malhi et al., 2017), is driven primarily by climate, which is a significant driver of C fluxes across broad spatial scales (Luyssaert et al., 2007; Cleveland et al., 2011; Wei et al., 2010). However, there is little consensus as to the shapes of these relationships or the best predictor variables. The majority of studies have focused on exploring the relationships of C fluxes to mean annual temperature (MAT) and mean annual precipitation (MAP), as the most commonly reported site-level climate variables. C fluxes increase strongly with *MAT* on the global scale, but whether they saturate or potentially decrease at higher temperatures remains disputed. Some studies have detected no deceleration or decline in *GPP* (Luyssaert et al., 2007), *NPP* (Schuur, 2003), or root respiration (R_{root} ; Wei et al., 2010) with increasing *MAT*. In contrast, others have found evidence of saturation or decline of C flux in the warmest climates; Luyssaert et al. (2007) found *NPP* saturating at around 10°C MAT; Larjavaara and Muller-Landau (2012) found that increases in *GPP* saturate at approximately 25°C MAT, and ? found that, within the tropics, $ANPP_{stem}$ decreases at the highest

maximum temperatures. C fluxes generally saturate at high levels of MAP, though the saturation points identified vary from *MAP* of ~1000 mm for *R_{root}* (Wei et al., 2010) up to 2,445 mm for *NPP* (Schuur, 2003). Interactions between MAT and MAP are also possible; within the tropics, there is a positive interaction between MAT and MAP in shaping *ANPP*, such that high rainfall has a negative effect on productivity in cooler climates, compared to a positive effect in warmer climates (Taylor et al., 2017). There is also evidence that C fluxes also respond to climate variables such as temperature and precipitation seasonality (Wagner et al., 2016), cloud cover (Taylor et al., 2017), solar radiation (Beer et al., 2010; Fyllas et al., 2017), and potential evapotranspiration (Kerkhoff et al., 2005); however, these are not typically assessed in global-scale analyses of annual forest C flux.

As metrics of annual climate, MAT and MAP fail to capture variation in climate on an intra-annual scale, including temperature and precipitation seasonality and growing season length. Some studies have suggested that the apparently strong relationship between MAT and C fluxes is actually a consequence of the correlation between MAT and growing season length (Kerkhoff et al., 2005; Michaletz et al., 2014, 2018). Kerkhoff et al. (2005) and Michaletz et al. (2014) found no significant relationship between growing season temperature and net primary productivity (loosely defined to include a mix of **VARIABLES**) standardized to growing season length. While this suggests that the influence of temperature may be limited to determining the length of the frost-free growing season, analysis with clearly defined variables and standardized forest ages would be necessary to test the veracity and generality of this hypothesis.

The recent development of the Global Forest Carbon database (ForC), which synthesizes multiple variables and including records of stand history (Anderson-Teixeira et al., 2016, 2018), opens up the possibility for a standardized analysis of global scale variation in multiple C fluxes and the principle climatic drivers of these patterns. In order to approach this broad topic, we simplify the major gaps in our knowledge to five broad questions and corresponding hypotheses (Table 1). First, we ask how nine forest autotrophic carbon fluxes in ForC vary with latitude. We then test how these fluxes relate to MAT and MAP, and additionally how they respond to other, less well-studied, climate variables. Finally, we consider the relationship between C flux and seasonality, considering the role of seasonality in explaining variation in carbon fluxes, and the influence of climate on C flux standardized by growing season length.

Table 1: Summary of research questions, corresponding hypotheses, and results. Statistically significant support for/ rejection of hypotheses is indicated with 'yes'/'no', and '-' indicates no significant relationship. Parentheses indicate partial overall support or rejection of hypotheses across all fluxes considered.

Questions and hypotheses (with related references)	Forest autotrophic carbon fluxes										Support
	Overall	<i>GPP</i>	<i>NPP</i>	<i>ANPP</i>	<i>ANPP_{stem}</i>	<i>ANPP_{foliage}</i>	<i>BNPP</i>	<i>BNPP_{fine.root}</i>	<i>R_{auto}</i>	<i>R_{root}</i>	
Q1. How do C fluxes vary with latitude?											
H1.1. C fluxes decrease continuously with latitude. ^{1,2,3,10}	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	Fig. 2
Q2. How do C fluxes vary with mean annual temperature (MAT) and precipitation (MAP)?											
H2.1. C fluxes increase continuously with MAT. ^{1,4,9}	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	Figs. 4, S4, S5
H2.2. C fluxes increase with precipitation up to at least 2000 mm yr ⁻¹ . ^{1,4}	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	Figs. 4, S4, S5
H2.3. Temperature and precipitation jointly shape C fluxes. ⁵	(yes)	yes	yes	yes	yes	-	-	-	yes	-	Fig. 3, Table S3
Q3. How are C fluxes related to other annual climate variables?											
H3.1. C fluxes display a decelerating increase or unimodal relationship with PET.	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	Figs. 4, S4, S5
H3.2. C fluxes display a decelerating increase or unimodal relationship with vapour pressure deficit.	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	Figs. 4, S4, S5
H3.3. C fluxes increase with solar radiation.	(yes)	yes	yes	yes	yes	yes	yes	yes	yes	-	Figs. S4, S5
Q4. How does seasonality influence annual C fluxes?											
H4.1. C fluxes decrease with temperature seasonality.	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	Figs. 4, S6, S7
H4.2. C fluxes decrease with precipitation seasonality.	-	-	-	-	no	-	-	-	-	-	Figs. S6, S7
H4.3. C fluxes increase with growing season length. ^{6,7,8}	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	Figs. 4, S6, S7
H4.4. Growing season length is a better predictor of C fluxes than MAT. ^{7,8}	(no)	no	no	no	-	no	no	no	no	no	Table S4
Q5. When standardised by growing season length, how do annual C fluxes vary with climate?											
H5.1. Growing season C fluxes increase with temperature. ⁸	(yes)	-	-	yes	-	yes	-	-	-	-	Figs. S8, S9
H5.2. Growing season C fluxes increase with PET.	(yes)	yes	yes	-	yes	-	yes	yes	-	-	Figs. S8, S9
H5.3. Growing season C fluxes increase with precipitation.	(yes)	-	-	yes	-	yes	-	-	-	-	Figs. S8, S9
H5.4. Growing season C fluxes increase with solar radiation.	(yes)	-	-	-	-	-	yes	yes	-	-	Figs. S8, S9

¹ Luyssaert et al. (2007) ² Gillman et al. (2015) ³ Simova and Storch (2017) ⁴ Schuur (2003) ⁵ Taylor et al. (2016) ⁶ Malhi (2012) ⁷ Michaletz et al. (2014) ⁸ Chu et al. (2016) ⁹ Piao et al. (2010) ¹⁰ Huston & Wolverton (2009)

Materials and Methods

Forest carbon flux data

This analysis focused on nine C flux variables included in the open-access ForC database (Table 2) (Anderson-Teixeira et al., 2016, 2018). ForC contains records of field-based measurements of forest carbon stocks and annual fluxes, compiled from original publications and existing data compilations and databases. Associated data, such as stand age, measurement methodologies, and disturbance history, are also included. The database was significantly expanded since the publication of Anderson-Teixeira et al. (2018) through integration with the Global Soil Respiration Database (Bond-Lamberty and Thomson, 2010). Additional targeted literature searches were conducted to identify further available data on the fluxes analyzed here, with particular focus on mature forests in temperate and boreal regions, which were not included in the review of Anderson-Teixeira et al. (2016). We used ForC v3.0, archived on Zenodo with DOI 10.5281/zenodo.3403855. This version contained 29,730 records from 4,979 plots, representing 20 distinct ecozones across all forested biogeographic and climate zones.

This analysis focused on mature forests with no known history of significant disturbance or management. There is evidence that stand age influences patterns of C flux and allocation in forest ecosystems, and can confound relationships between latitude and primary productivity (De Lucia et al., 2007; Gillman et al., 2015). To reduce any biasing effects of stand age, we included only stands of known age ≥ 100 years and those described by terms such as “mature”, “intact”, or “old-growth”. Since management can alter observed patterns of C cycling (Šímová and Storch, 2017), sites were excluded from analysis if they were managed, defined as plots that were planted, managed as plantations, irrigated, fertilised or including the term “managed” in their site description. Sites that had experienced significant disturbance within the past 100 years were also excluded. Disturbances that qualified sites for exclusion included major cutting or harvesting, burning, flooding, drought and storm events with site mortality $>10\%$ of trees. Grazed sites were retained.

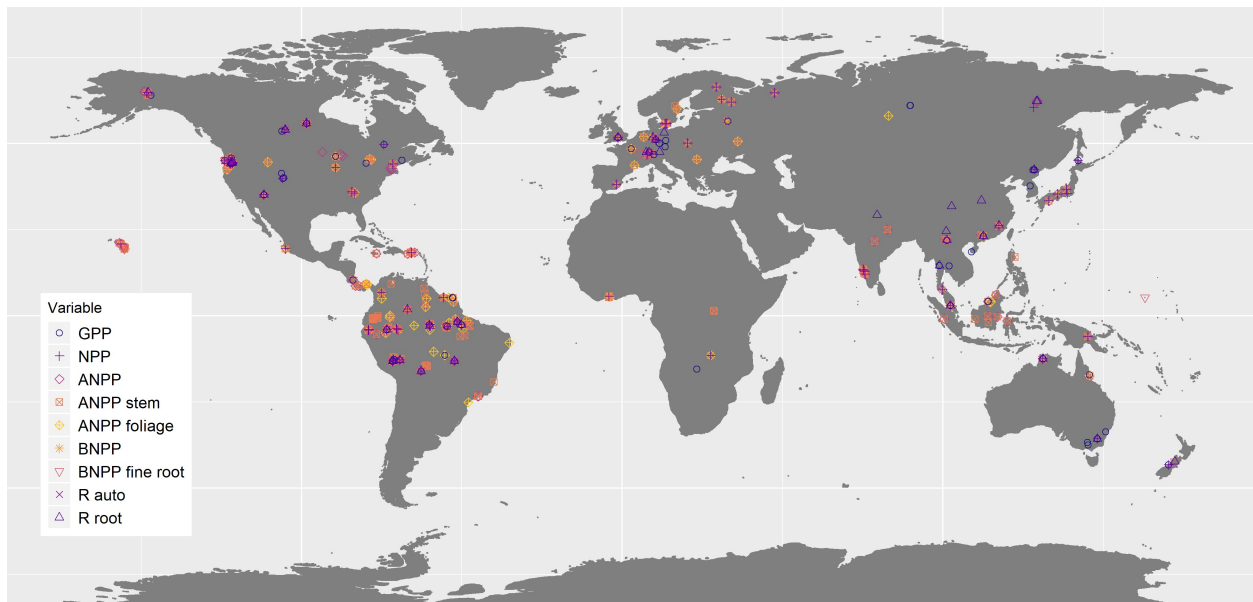


Figure 1: Map showing all data used in the analysis, coded by variable. Variables are plotted individually in Fig. S1.

Climate data

Table 2: Definitions and sample sizes of carbon flux variables used in analysis. All variables are in units of $\text{Mg C ha}^{-1} \text{ yr}^{-1}$.

Variable	Definition	Components included	Methodologies	Sample size	
				records	geographic areas*
<i>GPP</i>	Gross Primary Production	full ecosystem	flux partitioning of eddy-covariance; $NPP + R_{auto}$	243	49
<i>NPP</i>	Net Primary Production	stem, foliage, coarse root, fine root, optionally others (e.g., branch, reproductive, understory)	$ANPP + BNPP$ (majority); $GPP - R_{auto}$	161	56
<i>ANPP</i>	Aboveground <i>NPP</i>	stem, foliage, optionally others (e.g., branch, reproductive, understory)	$ANPP_{stem} + ANPP_{foliage}$ (+ others)	278	86
$ANPP_{stem}$	Stem growth component of <i>ANPP</i>	woody stems down to DBH $\leq 10\text{cm}$ (no branch turnover)	stem growth measurements scaled to biomass using allometries	264	96
$ANPP_{foliage}$	Foliage component of <i>ANPP</i>	foliage	litterfall collection, with separation into components	98	49
<i>BNPP</i>	Belowground <i>NPP</i>	coarse and fine roots	coarse roots estimated indirectly using allometries based on aboveground stem increment measures ; fine roots as below	101	48
$BNPP_{fine.root}$	Fine root component of <i>BNPP</i>	fine roots	measurements combined one or more of the following: soil cores, minirhizotrons, turnover estimates, root ingrowth cores	88	41
R_{auto}	Autotrophic respiration	foliage, stem, and root	chamber measurements of foliage and stem gas exchange + R_{root} (as below)	22	13
R_{root}	Root respiration	(coarse and) fine roots	partitioning of total soil respiration (e.g., through root exclusion), scaling of root gas exchange; excluded alkali absorption and soda lime methods for measuring soil respiration	64	26

* Geographic areas group geographically proximate sites, defined using a hierarchical cluster analysis on the distance matrix of the sites, and a cutoff of 25km

ForC contains geographic coordinates associated with each measurement record and, when available, mean annual temperature (MAT) and mean annual precipitation (MAP) as reported in the primary literature (Anderson-Teixeira et al., 2018). Based on the geographic co-ordinates for each site, data on twelve climate variables—including MAT, MAP, temperature and precipitation seasonality, annual temperature range, solar radiation, cloud cover, annual frost and wet days, potential evapotranspiration (PET), aridity (MAP/PET), and vapor pressure deficit (VPD)—were extracted from five open-access climate datasets: WorldClim (Hijmans et al., 2005), WorldClim2 (Fick and Hijmans, 2017), the Climate Research Unit time-series dataset (CRU TS v4.03 (Harris et al., 2014), the Global Aridity Index and Potential Evapotranspiration Climate Database (Trabucco and Zomer, 2019), and TerraClimate (Abatzoglou et al., 2018) (Table S1). From these data, we derived maximum VPD, defined as the VPD of the month with the largest deficit, and the number of water stress months, defined as the number of months annually where precipitation was lower than PET. Where site-level data was missing for MAT or MAP, we used values from the WorldClim dataset.

For consistency with previous studies (Table 1, H5), length of the growing season was estimated to the nearest month, where growing season months were defined as months with mean minimum temperature $> 0.5^\circ\text{C}$. We experimented with a definition of growing season months including a moisture index, defined as $(\text{MAT} - \text{PET})/\text{PET}$, > -0.95 (Kerckhoff et al., 2005; see also Michaletz et al., 2014). However, we found that including a moisture index had minimal effect on the estimates of growing season length, and so chose to exclude it. Monthly data for PET, precipitation, and temperature from CRU v 4.03 (Harris et al., 2014) and solar radiation from WorldClim2 (Fick and Hijmans, 2017) were used to calculate mean monthly PET,

precipitation, temperature and solar radiation during the growing season. Total growing season precipitation and solar radiation were also calculated.

Analyses

The effects of latitude and climate on C fluxes were analysed using mixed effects models using the package ‘lme4’ (Bates et al., 2015) in R v.3.5.1 (?). The basic model for all analyses included a fixed effect of latitude or climate and a random effect of plot nested within geographic area. Geographic areas—*i.e.*, spatially clustered sites—are defined within ForC using a hierarchical cluster analysis on the distance matrix of the sites and a cutoff of 25km (Anderson-Teixeira et al., 2018). We experimented with inclusion of altitude as a fixed effect, but excluded it from the final models because it added very little explanatory power—that is, the difference in AIC (Δ AIC) relative to models excluding altitude was generally small (often Δ AIC < 2). Effects were considered significant when inclusion of the fixed effect of interest resulted in $p \leq 0.05$ and Δ AIC ≥ 2.0 relative to a corresponding null model. All R^2 values presented here are marginal R^2 values, and refer to the proportion of variation explained by only the fixed effects. Specific analyses are as described below.

We first examined the relationship between latitude and C fluxes (Q1; Table 1). We tested models with latitude as a first-order linear, second-order polynomial, and logarithmic term. For brevity, we henceforth refer to first-order linear models as “linear” and second-order polynomial models as “polynomial”. We selected as the best model that with the highest Δ AIC relative to a null model with no fixed term, with the qualification that a polynomial model was considered an improvement over a linear model only if it reduced the AIC value by 2.0 or more.

To test whether trends in component fluxes across latitude sum to match those of larger fluxes, regression lines for smaller component fluxes were summed to generate new estimates of larger fluxes. Because no fluxes were significantly better predicted by a logarithmic or polynomial fit than by a linear fit, we used linear fits for all fluxes. We then determined whether these summed predictions fell within the 95% CI for the larger flux across the entire latitudinal range. Confidence intervals for the line of best fit for the larger flux were estimated using the ‘bootMer’ function, a parametric bootstrapping method for mixed models (Bates et al., 2015). This function carried out 2000 simulations estimating the line of best fit, using quantiles at 0.025 and 0.975 to estimate 95% CIs. This analysis was applied to the following sets of fluxes: (1) $GPP = NPP + R_{auto}$, (2) $NPP = ANPP + BNPP$, and (3) $ANPP = ANPP_{foliage} + ANPP_{stem}$. In addition, we estimated total belowground C flux (TBCF, not analyzed due to limited data) as $TBCF = BNPP + R_{root}$.

Variation in allocation to component carbon fluxes was explored for three groupings: (1) $GPP = NPP + R_{auto}$, (2) $NPP = ANPP + BNPP$, and (3) $ANPP = ANPP_{foliage} + ANPP_{stem}$. For each group, measurements taken at the same site and plot, and in the same year were grouped together. For groups (1) and (2), where 2 of the 3 flux measurements were available for a given site, plot, and year, these measurements were used to calculate the third. The ratio of each pair of component fluxes was calculated. The log of these ratios were regressed against latitude and climate variables, using the linear model specified above. Cook’s distance analyses were carried out for each of the models, and extreme outliers removed,

We next examined the relationships of C fluxes to climate variables (Q2-Q4; Table 1). We tested first-order linear, second-order polynomial, and logarithmic fits for each climate variable. Again, polynomial fits were considered superior to first-order linear fits only if inclusion of a second-order polynomial term resulted in Δ AIC ≥ 2.0 relative to a first-order linear model. We tested relationships of each C flux (Table 2) against each climate variable (Table S1). Variables which were not significant explanatory variables or which explained

<20% of variation in C fluxes are only presented in SI.

Multivariate models were used to investigate the potential joint and interactive effects of MAT and MAP on carbon fluxes. An additive model including MAP in addition to MAT was accepted when $\Delta AIC > 2$ relative to a null including only MAT as a fixed effect. An interactive model including an MAT x MAP interaction was accepted when $\Delta AIC > 2$ relative to a null including MAT and MAP as fixed effects.

To test whether and how C flux varied with climate when standardised by growing season length (Q5), we first standardized all annual C fluxes by dividing by growing season length (as defined above). We then derived four variables to describe growing season climate, specifically growing season temperature, precipitation, solar radiation, and PET (Table S1). We tested for correlations between these standardised fluxes and growing season climate variables, using only first-order linear models.

All analyses were conducted in R (Version). Code and data necessary to reproduce all results are archived on GitHub....

###Results

In total, we analyzed 1319 records from nine forest autotrophic C flux variables taken from forests that had experienced no major anthropogenic disturbances within the past 100 years. These records represented a total of 255 plots in 154 distinct geographic areas across all forested biogeographic and climate zones (Fig. 1, Table 2).

How does C flux vary with latitude?

All major carbon fluxes decreased with latitude (Fig. 2; Table S2). Latitude was a strong predictor for many of the carbon fluxes, particularly the larger fluxes (Table S2). Specifically, latitude explained 64% of variation in GPP ($n = 243$, $p < 0.0001$), 50% in NPP ($n = 161$, $p < 0.0001$) and 44% in ANPP ($n = 278$, $p < 0.0001$). The C fluxes that were most poorly predicted by latitude were $BNPP_{fine.root}$ ($R^2 = 0.17$) and $ANPP_{stem}$ ($R^2 = 0.18$). The relationship with latitude was best fit by the first-order linear model, with the exception of NPP and R_{root} , for which a logarithmic model was a slightly - but not significantly - better fit.

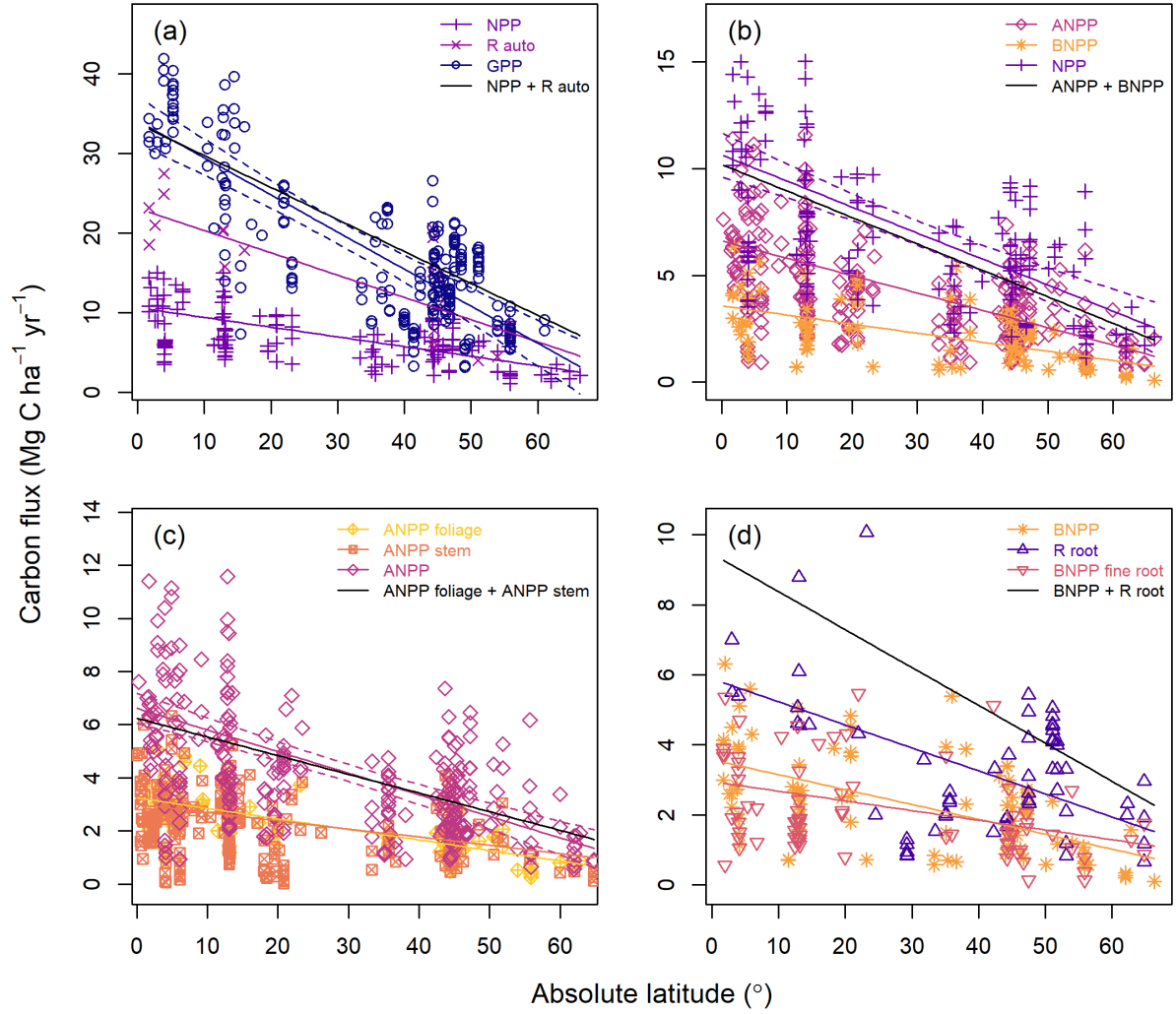


Figure 2: Latitudinal trends in forest autotrophic carbon flux. Plotted are linear models, all of which were significant ($p < 0.05$) and had AIC values within 2.0 of the best model (for two fluxes, logarithmic fits were marginally better; Table S2). Each panel shows major C fluxes together with component fluxes. Also plotted are predicted trends in the major C fluxes based on the sum of component fluxes. 95% confidence intervals are plotted for the major flux for comparison with predicted trends. In (d), which shows three belowground fluxes, the major flux, total belowground carbon flux, has insufficient data ($n=9$) to support a regression

In general, smaller component fluxes summed approximately to larger fluxes across the latitudinal gradient (Fig. 2). That is, modeled estimates of GPP , generated from the sum of NPP and R_{auto} ; NPP , generated from the sum of $ANPP$ and $BNPP$; and $ANPP$, generated from the sum of $ANPP_{foliage}$ and $ANPP_{stem}$, fell almost completely within the confidence intervals of the regressions of field estimates of GPP , NPP , and $ANPP$, respectively.

We found no evidence of systematic variation in C allocation with latitude or climate (Fig. S3). Of 12 relationships tested (3 ratios among C flux variables regressed against latitude, MAT, MAP and temperature seasonality), none were significant.

How does C flux relate to MAT and MAP?

227 All fluxes increased with MAT (all $p < 0.05$; Figs. 3-4, S4-S5, Table S2). For eight of the nine fluxes, this
 228 relationship was linear. For only one variable, $BNPP$, did a lognormal fit provide significant improvement
 229 over a first-order linear relationship. *As with latitude, MAT tended to explain more variation in the larger*
 230 *fluxes (GPP , NPP , $ANPP$, R_{auto}) and $ANPP_{foliage}$ (all $R^2 > 0.4$) than in subsidiary and belowground*
 231 *fluxes ($ANPP_{stem}$, R_{root} , $BNPP_{fine.root}$; all $R^2 < 0.25$). **update this – NB these values are correct**
 232 MAP was a significant ($p < 0.05$) predictor of all fluxes (Figs. 4a, S4-S5; Table S2). However, it explained
 233 little variation: with the exception of R_{auto} , MAP explained at most 25% of variation in C flux. All fluxes
 234 increased with MAP up to at least 2000 mm, above which responses were variable (Figs. 4, S4-S5).
 235 There was a significant additive effect of MAT and MAP on GPP , $ANPP$ and R_{auto} (Fig. 3, Table S3), and
 236 a significant interactive effect between MAT and MAP for NPP and $ANPP_{stem}$ (Fig. 3, Table S3). The
 237 interaction was negative for NPP and positive for $ANPP_{stem}$. For $ANPP_{foliage}$, $BNPP$, $BNPP_{fine.root}$,
 238 and R_{root} , MAP did not have a significant effect when accounting for MAT (Fig. 3, Table S3).*

249 Vapour pressure deficit was a significant predictor of all C fluxes. $ANPP_{foliage}$, $BNPP_{fine.root}$ and R_{root}
250 showed a logarithmic relationship with vapour pressure deficit, but all other fluxes showed a polynomial
251 relationship (Figs. 4d, S4-5; Table S2). C fluxes initially increased with vapour pressure deficit, before
252 saturating at around 0.8 kPa, after which point they began to decrease.

253 All fluxes, with the exception of R_{root} , showed a significant positive relationship with solar radiation (Figs.
254 S4-S5, Table S2). Solar radiation explained a low proportion of variability in all C fluxes, explaining less
255 than 30% of the variation in each flux

256 Annual wet days, cloud cover, aridity, and water stress months were poor or non-significant explainers of
257 variation in C fluxes, explaining less than 20% of the variation in each of the carbon fluxes (Figs. S4-S5;
258 Table S2).

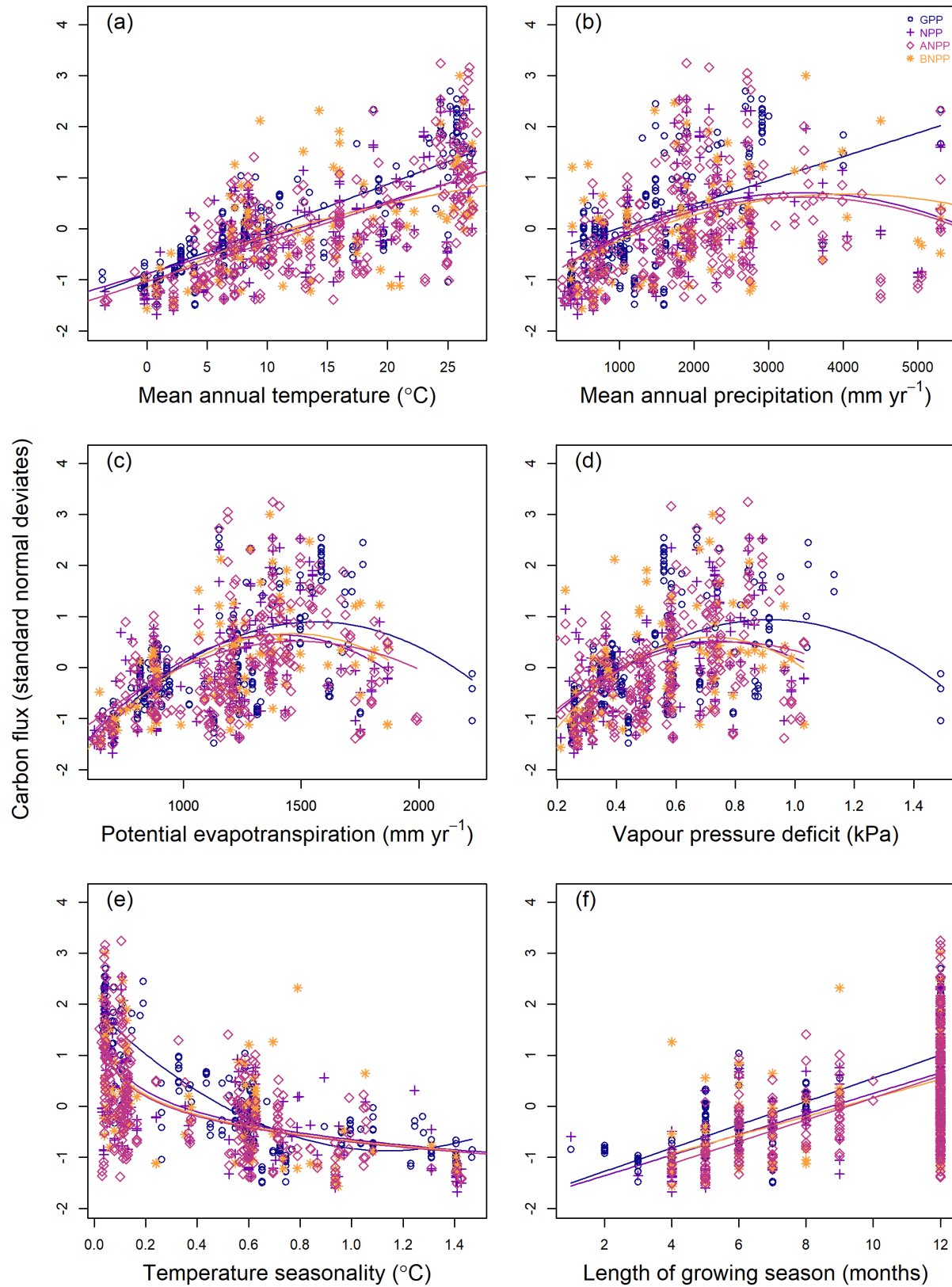


Figure 4: Plots of carbon fluxes against (a) mean annual temperature; (b) mean annual precipitation; (c) potential evapotranspiration; (d) vapour pressure deficit; (e) temperature seasonality; (f) length of growing season. For visualization purposes, data for each flux was rescaled with a mean of 0 and standard deviation of 1. Lines of best fit are plotted according to the best model selected during analysis (**see issue 47**). All regressions are significant ($p < 0.05$).

What is the role of seasonality in explaining C fluxes?

Temperature seasonality was a strong predictor of annual C fluxes. All fluxes decrease with increasing seasonality, though the shape of this relationship varies (all $p < 0.05$; Figs. 4e, S6-7; Table S2). Temperature seasonality was strongly correlated with annual temperature range, which was likewise a similarly strong predictor of C fluxes (Table S2). C fluxes were highest where temperature seasonality = 0, and at an annual temperature range of 15°C or lower. **BBL: perhaps put this into an ecosystem context; what are these? Aseasonal subtropical places?**

In contrast, there was no significant effect of precipitation seasonality on C fluxes, and both maximum vapour pressure deficit, and water stress months were poor or non-significant predictors of variation in C fluxes (Figs. S6-S7; Table S2).

We found a significant relationship between length of growing season and C fluxes, with all fluxes showing a positive relationship with length of growing season (Figs. 4e, S6-S7; Table S2). Length of growing season was a strong predictor of C fluxes, explaining 53% of variation in GPP, 38% of variation in NPP, and 34% of variation in ANPP (all $p < 0.05$; Table S2), but it was a weaker predictor than MAT for all fluxes analysed (Table S4).

Within the growing season, how do C fluxes vary with climate?

When annual C fluxes were standardized by growing season length (in monthly increments), correlations with growing season climate were generally weak (Figs. S8-S9). $ANPP$ increased with growing season temperature ($R^2 = 0.09$, $p < 0.001$) and precipitation ($R^2 = 0.04$, $p < 0.05$). Similarly, $ANPP_{foliage}$ increased slightly with growing season temperature ($R^2 = 0.16$, $p < 0.01$) and precipitation ($R^2 = 0.09$, $p < 0.05$). Growing season solar radiation had a positive influence on $BNPP$ ($R^2 = 0.17$, $p < 0.001$) and $BNPP_{fine.root}$ ($R^2 = 0.13$, $p < 0.01$). Growing season PET had a positive influence on GPP ($R^2 = 0.15$, $p < 0.01$), NPP ($R^2 = 0.07$, $p < 0.01$), $BNPP$ ($R^2 = 0.23$, $p < 0.0001$), $BNPP_{fine.root}$ ($R^2 = 0.10$, $p < 0.05$), and $ANPP_{stem}$ ($R^2 = 0.06$, $p < 0.05$). All other relationships were non-significant.

###Discussion

Our analysis of a large global database (ForC) clarifies how autotrophic C fluxes in mature forests vary with latitude and climate on a global scale. We show that, across all nine variables analyzed, annual C flux decreases continually with latitude (Fig. 2)—a finding that confirms multiple previous studies but contradicts the idea that productivity of temperate forests rivals or even exceeds that of tropical forests (Luyssaert et al., 2007; Huston and Wolverton, 2009). At this global scale, C fluxes increase approximately in proportion to one another, with component fluxes summing appropriately to larger fluxes and no detectable differences in allocation across latitude or climates (Figs. 2, 4, S3). Similarly, we show broad - albeit not complete - consistency of climate responses across C fluxes, with the observed latitudinal variation primarily attributable to temperature and its seasonality (Figs. 3-4). Water availability is also influential, but of secondary importance across the climate space occupied by forests (Figs. 3-4). Contrary to prior suggestions that the majority of variation in C cycling is driven by the length of the growing season (**REFS**), we find modest explanatory power of growing season length and small but sometimes significant influence of climate within the growing season (Figs. 4f, S6-S9). Together, these findings yield a unified understanding of climate's influence on forest C cycling.

Our findings indicate that, among mature, undisturbed stands, forest C fluxes are unambiguously highest in

the tropical regions, and the relationship with both latitude and MAT is approximately linear (Figs. 2, 4). This contrasts with the suggestion that C fluxes (e.g., NPP , $ANPP$, $ANPP_{stem}$) of temperate forests are similar to or even greater than that of tropical forests (Luyssaert et al., 2007; Huston and Wolverton, 2009). Previous indications of such a pattern may have been an artifact of differences in stand age across biomes. Compared to tropical forests, the temperate forest biome has experienced more widespread anthropogenic disturbance and has a larger fraction of secondary stands (Potapov et al., 2008; Poulter et al., 2018), so analyses comparing across latitudinal gradients without controlling for stand age risk confounding age with biome effects. Because carbon allocation varies with stand age (De Lucia et al., 2007; Anderson-Teixeira et al., 2013; Doughty et al., 2018), age differences may introduce systematic biases into analyses of C fluxes across latitude or global climatic gradients. For example, woody productivity tends to be higher in rapidly aggrading secondary stands than in old-growth forests, where proportionally more C is allocated to respiration and non-woody productivity (De Lucia et al., 2007; Piao et al., 2010; Doughty et al., 2018; Kunert et al., 2019). Thus, findings that temperate forest productivity rivals that of tropical forests are likely an artifact of different forest ages across biomes.

We show that C fluxes are broadly consistent in their responses to climate drivers on the global scale, with no trends in C allocation among the variable pairs tested (Figs. 2, 4, S3). This parallels the observation that C allocation across multiple C fluxes varies little with respect to climate along a steep tropical elevational gradient (Malhi et al., 2017; but see Moser et al., 2011), and is not surprising given that carbon allocation within forest ecosystems is relatively constrained (Enquist and Niklas, 2002; Litton et al., 2007; Malhi et al., 2011). We find no trend in the allocation of GPP between production and respiration across latitude or climate ($NPP:R_{auto}$; Fig. S3), refuting the idea that tropical forests have anomalously low CUE (De Lucia et al., 2007; Malhi, 2012; Anderson-Teixeira et al., 2016). Rather, differences in CUE between old-growth tropical forests relative to (mostly younger) extratropical forests are likely an artifact of comparing stands of different age, as CUE is known to decline with forest age (De Lucia et al., 2007; Piao et al., 2010; Collalti and Prentice, 2019). Another previously observed pattern for which we find no support is a tendency for belowground C allocation to decrease with increasing temperature (Moser et al., 2011; Gill and Finzi, 2016); rather, we observe no trends in allocation between $ANPP$ and $BNPP$ across latitudes. Failure to detect significant trends in C allocation with respect to climate in this analysis does not imply that none exist; rather, it suggests that

Despite the broad consistency of climate responses across C fluxes, climate explains lower proportions of variability among some of the subsidiary C fluxes (e.g., $ANPP_{stem}$, $BNPP$, $BNPP_{fine.root}$; Fig. 2; Tables S2, S6). There are two, non-exclusive, potential explanations for this. First, it may be that methodological variation is larger relative to flux magnitude for some of the subsidiary fluxes. Belowground fluxes in particular are difficult to quantify, and measurement methods for the belowground fluxes considered here may use fundamentally different approaches in different sites (e.g., minirhizotrons, ingrowth cores, or sequential coring for $BNPP_{fine.root}$; root exclusion, stable isotope tracking, or gas exchange of excised roots for R_{root}), and sampling depth is variable and often insufficient to capture the full soil profile. $ANPP_{stem}$, which is also poorly explained by latitude or climate, is more straightforward to measure but is subject to variability introduced by differences such as biomass allometries applied and minimum plant size sampled (Clark et al., 2001). However, methodological variation and uncertainty affect all of fluxes considered here, and some of the larger fluxes that vary more strongly with respect to climate ($ANPP$, NPP) are estimated by summing uncertain component fluxes. Second, differences among variables in the proportion of variation explained

by climate may be attributable to more direct climatic control over *GPP* than subsidiary fluxes. That is, subsidiary fluxes may be shaped by climate both indirectly through its influence on *GPP* and respiration and directly through any climatic influence on C allocation, as well as many other local- and regional-scale factors (e.g., Moser et al., 2011) (**REFS-BECKY, know any?**).

Temperature and its seasonality were the primary drivers of C flux on the global scale (Figs. 2-4), consistent with a long legacy of research identifying temperature as a primary driver of forest ecosystem C cycling (e.g., Lieth, 1973; Luyssaert et al., 2007; Wei et al., 2010). We find little evidence of any non-linearity in temperature’s influence on C flux. The relationship of all fluxes to *MAT* as an individual driver were best described by a linear function (Table S2) - with the exception of *BNPP*, whose response to *MAT* was close to linear (Fig. 4a). This result contrasts with the idea that fluxes saturate with *MAT* below approximately 25°C *MAT* (Luyssaert et al., 2007; Huston and Wolverton, 2009). It remains possible that flux declines above this threshold (Larjavaara and Muller-Landau, 2012; ?), as is also consistent with tree-ring records indicating that tropical tree growth declines at high temperatures (e.g., Vlam et al., 2014). However, these higher temperatures also tend to be associated with high PET and VPD, both of which are associated with reduced C fluxes (Figs. 4c-d, S4-S5). Indeed, while temperature responses dominate at this global scale and with the climate space occupied by forests, the effects of temperature are moderated by moisture availability (Table 1; Figs 3-4). Specifically, C fluxes are reduced under relatively dry conditions (*i.e.*, low *MAP*; high *VPD*) and sometimes under very high precipitation (Figs. 3-4). The observed positive interaction between *MAT* and *MAP* for *ANPP_{stem}* on the global scale (Fig. 3) is consistent with an analysis showing a similar interaction for *ANPP* in tropical forests, also with a cross-over point at ~20°C (Taylor et al., 2017). However, we detect no such interaction for *ANPP* or most other C fluxes, and we find a contrasting negative interaction for *NPP* (Fig. 3), suggesting that more data are required to sort out potential differences in the interactive effects of *MAT* and *MAP* on C fluxes in the tropics.

Forest autotrophic C fluxes decline with temperature seasonality (Table 1, *H4*; Fig. 4e), and are minimal during cold- or dry- dormant seasons. To account for this, a number of analyses seeking to characterize global-scale effects of climate on productivity have examined the relationship of C flux per month of the growing season with growing season climatic conditions (Table 1, *H5*; Kerkhoff et al., 2005; Anderson et al., 2006; Enquist et al., 2007; Michaletz et al., 2014). The sort of simple metric that has been used to define growing season at a global scale (Kerkhoff et al., 2005) is coarse with respect to temperature because it is calculated on a monthly timescale and problematic with respect to moisture because it doesn’t capture temporal lags between precipitation and plant water use caused by storage in soil or snow. We found that a temperature-defined growing season length had strong positive correlation with C fluxes (Fig. 4f), but was never the best univariate predictor. Dividing annual fluxes by growing season length to yield average flux per growing season month removed the majority of climate-related variation, supporting the idea that the latitudinal gradient in carbon flux is attributable more to shorter growing seasons at high latitudes than to inherently lower rates of photosynthesis or respiration by high-latitude forests (Enquist et al., 2007). However, there remained a number of significant correlations with growing season climatic conditions, indicating that climatic conditions remain influential within the growing season (Figs. S8-S9). We conclude that while correcting for growing season length takes analyses a step closer to mechanistic linkage of instantaneous C flux rates to environmental conditions, it remains crude relative to the timescales on which climate affects plant metabolism, and does not advance statistical predictive power. Mechanistic accounting for climatic effects on global forest carbon flux patterns instead requires models representing physiologically meaningful

timescales (e.g., Medvigy et al., 2009; Longo et al., 2019).

Our analysis clarifies how forest autotrophic carbon fluxes vary with latitude and climate on a global scale, with some important implications for how forest carbon cycling relates to climate and, by extension, how it is likely to respond to climatic warming. To the extent that patterns across broad scale climatic gradients can foretell how ecosystem responses to climate change, our findings suggest that higher temperatures with similar moisture availability result in a generalized acceleration of forest C cycling (Figs. 2-3). This is consistent with observations of continental- to global-scale increases over time in *GPP* (Li and Xiao, 2019) and *ANPP_{stem}* (Brienen et al., 2015; Hubau et al., 2020), along with some C cycle components not considered here—tree mortality (Brienen et al., 2015; McDowell et al., 2018), soil respiration (Bond-Lamberty and Thomson, 2010), and heterotrophic soil respiration (Bond-Lamberty et al., 2018). However, increasing C flux rates are by no means universal (e.g., Rutishauser et al., 2020; Hubau et al., 2020), likely because other factors are at play, including changes to other aspects of climate, atmospheric pollution (CO₂, SO₂, NO_x), and local disturbances. Moreover, forest ecosystem responses to climatic changes outside the temperature range to which forest communities are adapted and acclimatized will not necessarily parallel responses across geographic gradients in climate. Indeed, tree-ring studies from forests around the world indicate that tree growth rates - along with *ANPP_{stem}* and possibly other ecosystem C fluxes - respond negatively to temperature (Sniderhan and Baltzer, 2016; Helcoski et al., 2019). Furthermore, in the tropics, climate change will push forests beyond any contemporary climate, and there are some indications that this could reduce C flux rates (Mau et al., 2018; ?). Thus, while further research is required to understand the extent to which forest responses to climate change will track global gradients, and the time scale on which they will do so, understanding the fundamental climatic controls on annual C cycling in Earth’s forests sets a firmer foundation for understanding forest C cycle responses to accelerating climate change.

Acknowledgements

We gratefully acknowledge all researchers who originally collected the data used in this analysis. This study was funded by a Smithsonian Scholarly Studies grant to KJAT and HCML and by Smithsonian’s Forest Global Earth Observatory (ForestGEO). Original compilation of the ForC database was funded by **DOE grant to KAT**.

References

- Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., and Hegewisch, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Scientific Data*, 5(1):170191.
- Anderson, K. J., Allen, A. P., Gillooly, J. F., and Brown, J. H. (2006). Temperature-dependence of biomass accumulation rates during secondary succession. *Ecology Letters*, 9(6):673–682.
- Anderson-Teixeira, K. J., Miller, A. D., Mohan, J. E., Hudiburg, T. W., Duval, B. D., and DeLucia, E. H. (2013). Altered dynamics of forest recovery under a changing climate. *Global Change Biology*, 19(7):2001–2021.
- Anderson-Teixeira, K. J., Wang, M. M. H., McGarvey, J. C., Herrmann, V., Tepley, A. J., Bond-Lamberty,

- B., and LeBauer, D. S. (2018). ForC: a global database of forest carbon stocks and fluxes. *Ecology*, 99(6):1507–1507.
- Anderson-Teixeira, K. J., Wang, M. M. H., McGarvey, J. C., and LeBauer, D. S. (2016). Carbon dynamics of mature and regrowth tropical forests derived from a pantropical database (TropForC-db). *Global Change Biology*, 22(5):1690–1709.
- Assessment, M. E. (2005). Ecosystems and Human Well-being: Biodiversity Synthesis. Technical report, World Resources Institute, Washington DC.
- Badgley, G., Anderegg, L. D. L., Berry, J. A., and Field, C. B. (2019). Terrestrial gross primary production: Using NIR_v to scale from site to globe. *Global Change Biology*, 25(11):3731–3740.
- Bates, D., Mächler, M., Bolker, B., and Walker, S. (2015). Fitting Linear Mixed-Effects Models Using **lme4**. *Journal of Statistical Software*, 67(1).
- Beer, C., Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rodenbeck, C., Arain, M. A., Baldocchi, D., Bonan, G. B., Bondeau, A., Cescatti, A., Lasslop, G., Lindroth, A., Lomas, M., Luyssaert, S., Margolis, H., Oleson, K. W., Rouspard, O., Veenendaal, E., Viovy, N., Williams, C., Woodward, F. I., and Papale, D. (2010). Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate. *Science*, 329(5993):834–838.
- Bonan, G. B. (2008). Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *Science*, 320(5882):1444–1449.
- Bond-Lamberty, B., Bailey, V. L., Chen, M., Gough, C. M., and Vargas, R. (2018). Globally rising soil heterotrophic respiration over recent decades. *Nature*, 560(7716):80–83.
- Bond-Lamberty, B. and Thomson, A. (2010). A global database of soil respiration data. *Biogeosciences*, 7(6):1915–1926.
- Brienen, R. J. W., Phillips, O. L., Feldpausch, T. R., Gloor, E., Baker, T. R., Lloyd, J., Lopez-Gonzalez, G., Monteagudo-Mendoza, A., Malhi, Y., Lewis, S. L., Vázquez Martínez, R., Alexiades, M., Álvarez Dávila, E., Alvarez-Loayza, P., Andrade, A., Aragão, L. E. O. C., Araujo-Murakami, A., Arets, E. J. M. M., Arroyo, L., Aymard C., G. A., Bánki, O. S., Baraloto, C., Barroso, J., Bonal, D., Boot, R. G. A., Camargo, J. L. C., Castilho, C. V., Chama, V., Chao, K. J., Chave, J., Comiskey, J. A., Cornejo Valverde, F., da Costa, L., de Oliveira, E. A., Di Fiore, A., Erwin, T. L., Fauset, S., Forsthofer, M., Galbraith, D. R., Grahame, E. S., Groot, N., Hérault, B., Higuchi, N., Honorio Coronado, E. N., Keeling, H., Killeen, T. J., Laurance, W. F., Laurance, S., Licona, J., Magnussen, W. E., Marimon, B. S., Marimon-Junior, B. H., Mendoza, C., Neill, D. A., Nogueira, E. M., Núñez, P., Pallqui Camacho, N. C., Parada, A., Pardo-Molina, G., Peacock, J., Peña-Claros, M., Pickavance, G. C., Pitman, N. C. A., Poorter, L., Prieto, A., Quesada, C. A., Ramírez, F., Ramírez-Angulo, H., Restrepo, Z., Roopsind, A., Rudas, A., Salomão, R. P., Schwarz, M., Silva, N., Silva-Espejo, J. E., Silveira, M., Stropp, J., Talbot, J., ter Steege, H., Teran-Aguilar, J., Terborgh, J., Thomas-Caesar, R., Toledo, M., Torello-Raventos, M., Umetsu, R. K., van der Heijden, G. M. F., van der Hout, P., Guimarães Vieira, I. C., Vieira, S. A., Vilanova, E., Vos, V. A., and Zagt, R. J. (2015). Long-term decline of the Amazon carbon sink. *Nature*, 519(7543):344–348.
- Cavaleri, M. A., Reed, S. C., Smith, W. K., and Wood, T. E. (2015). Urgent need for warming experiments in tropical forests. *Global Change Biology*, 21(6):2111–2121.

- Chu, C., Lutz, J. A., Král, K., Vrška, T., Yin, X., Myers, J. A., Abiem, I., Alonso, A., Bourg, N., Burslem,
D. F., Cao, M., Chapman, H., Condit, R., Fang, S., Fischer, G. A., Gao, L., Hao, Z., Hau, B. C., He, Q.,
Hector, A., Hubbell, S. P., Jiang, M., Jin, G., Kenfack, D., Lai, J., Li, B., Li, X., Li, Y., Lian, J., Lin, L.,
Liu, Y., Liu, Y., Luo, Y., Ma, K., McShea, W., Memiaghe, H., Mi, X., Ni, M., O'Brien, M. J., de Oliveira,
A. A., Orwig, D. A., Parker, G. G., Qiao, X., Ren, H., Reynolds, G., Sang, W., Shen, G., Su, Z., Sui, X.,
Sun, I., Tian, S., Wang, B., Wang, X., Wang, X., Wang, Y., Weiblen, G. D., Wen, S., Xi, N., Xiang, W.,
Xu, H., Xu, K., Ye, W., Zhang, B., Zhang, J., Zhang, X., Zhang, Y., Zhu, K., Zimmerman, J., Storch, D.,
Baltzer, J. L., Anderson-Teixeira, K. J., Mittelbach, G. G., and He, F. (2018). Direct and indirect effects of
climate on richness drive the latitudinal diversity gradient in forest trees. *Ecology Letters*, page ele.13175.
- Clark, D. A., Brown, S., Kicklighter, D. W., Chambers, J. Q., Thomlinson, J. R., and Ni, J. (2001). Measuring
net primary production in forests: concepts and field methods. *Ecological Applications*, 11(2):15.
- Cleveland, C. C., Townsend, A. R., Taylor, P., Alvarez-Clare, S., Bustamante, M. M. C., Chuyong, G.,
Dobrowski, S. Z., Grierson, P., Harms, K. E., Houlton, B. Z., Marklein, A., Parton, W., Porder, S., Reed,
S. C., Sierra, C. A., Silver, W. L., Tanner, E. V. J., and Wieder, W. R. (2011). Relationships among
net primary productivity, nutrients and climate in tropical rain forest: a pan-tropical analysis: Nutrients,
climate and tropical NPP. *Ecology Letters*, 14(9):939–947.
- Collalti, A. and Prentice, I. C. (2019). Is NPP proportional to GPP? Waring's hypothesis 20 years on. *Tree
Physiology*, 39(8):1473–1483.
- De Lucia, E. H., Drake, J. E., Thomas, R. B., and Gonzalez-Meler, M. (2007). Forest carbon use efficiency:
is respiration a constant fraction of gross primary production? *Global Change Biology*, 13(6):1157–1167.
- Doughty, C. E., Goldsmith, G. R., Raab, N., Girardin, C. A. J., Farfan-Amezquita, F., Huaraca-Huasco, W.,
Silva-Espejo, J. E., Araujo-Murakami, A., da Costa, A. C. L., Rocha, W., Galbraith, D., Meir, P., Metcalfe,
D. B., and Malhi, Y. (2018). What controls variation in carbon use efficiency among Amazonian tropical
forests? *Biotropica*, 50(1):16–25.
- Enquist, B. J., Kerkhoff, A. J., Huxman, T. E., and Economo, E. P. (2007). Adaptive differences in plant
physiology and ecosystem paradoxes: insights from metabolic scaling theory. *Global Change Biology*,
13(3):591–609.
- Enquist, B. J. and Niklas, K. J. (2002). Global Allocation Rules for Patterns of Biomass Partitioning in Seed
Plants. *Science*, 295(5559):1517–1520. Publisher: American Association for the Advancement of Science
Section: Report.
- Fick, S. E. and Hijmans, R. J. (2017). WorldClim 2: new 1-km spatial resolution climate surfaces for
global land areas: New climate surfaces for global land areas. *International Journal of Climatology*,
37(12):4302–4315.
- Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Hauck, J., Peters, G. P., Peters, W.,
Pongratz, J., Sitch, S., Quéré, C. L., Bakker, D. C. E., Canadell, J. G., Ciais, P., Jackson, R. B., Anthoni,
P., Barbero, L., Bastos, A., Bastrikov, V., Becker, M., Bopp, L., Buitenhuis, E., Chandra, N., Chevallier,
F., Chini, L. P., Currie, K. I., Feely, R. A., Gehlen, M., Gilfillan, D., Gkritzalis, T., Goll, D. S., Gruber,
N., Gutekunst, S., Harris, I., Haverd, V., Houghton, R. A., Hurtt, G., Ilyina, T., Jain, A. K., Joetzjer,
E., Kaplan, J. O., Kato, E., Klein Goldewijk, K., Korsbakken, J. I., Landschützer, P., Lauvset, S. K.,
Lefèvre, N., Lenton, A., Lienert, S., Lombardozzi, D., Marland, G., McGuire, P. C., Melton, J. R., Metzl,

- N., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., Neill, C., Omar, A. M., Ono, T., Peregon, A., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rödenbeck, C., Séférian, R., Schwinger, J., Smith, N., Tans, P. P., Tian, H., Tilbrook, B., Tubiello, F. N., Werf, G. R. v. d., Wiltshire, A. J., and Zaehle, S. (2019). Global Carbon Budget 2019. *Earth System Science Data*, 11(4):1783–1838. Publisher: Copernicus GmbH.
- Fyllas, N. M., Bentley, L. P., Shenkin, A., Asner, G. P., Atkin, O. K., Díaz, S., Enquist, B. J., Farfan-Rios, W., Gloor, E., Guerrieri, R., Huasco, W. H., Ishida, Y., Martin, R. E., Meir, P., Phillips, O., Salinas, N., Silman, M., Weerasinghe, L. K., Zaragoza-Castells, J., and Malhi, Y. (2017). Solar radiation and functional traits explain the decline of forest primary productivity along a tropical elevation gradient. *Ecology Letters*, 20(6):730–740.
- Gill, A. L. and Finzi, A. C. (2016). Belowground carbon flux links biogeochemical cycles and resource-use efficiency at the global scale. *Ecology Letters*, 19(12):1419–1428.
- Gillman, L. N., Wright, S. D., Cusens, J., McBride, P. D., Malhi, Y., and Whittaker, R. J. (2015). Latitude, productivity and species richness: Latitude and productivity. *Global Ecology and Biogeography*, 24(1):107–117.
- Girardin, C. A. J., Malhi, Y., Aragão, L. E. O. C., Mamani, M., Huaraca Huasco, W., Durand, L., Feeley, K. J., Rapp, J., Silva-Espejo, J. E., Silman, M., Salinas, N., and Whittaker, R. J. (2010). Net primary productivity allocation and cycling of carbon along a tropical forest elevational transect in the Peruvian Andes. *Global Change Biology*, 16(12):3176–3192.
- Harris, I., Jones, P., Osborn, T., and Lister, D. (2014). Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset: Updated high-resolution grids of monthly climatic observations. *International Journal of Climatology*, 34(3):623–642.
- Helcoski, R., Tepley, A. J., Pederson, N., McGarvey, J. C., Meakem, V., Herrmann, V., Thompson, J. R., and Anderson-Teixeira, K. J. (2019). Growing season moisture drives interannual variation in woody productivity of a temperate deciduous forest. *New Phytologist*, 223(3):1204–1216.
- Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., and Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, 25(15):1965–1978.
- Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., Daniels, A. K., Ewango, C. E. N., Fauset, S., Mukinzi, J. M., Sheil, D., Sonké, B., Sullivan, M. J. P., Sunderland, T. C. H., Taedoumg, H., Thomas, S. C., White, L. J. T., Abernethy, K. A., Adu-Bredu, S., Amani, C. A., Baker, T. R., Banin, L. F., Baya, F., Begne, S. K., Bennett, A. C., Benedet, F., Bitariho, R., Bocko, Y. E., Boeckx, P., Boundja, P., Brien, R. J. W., Brncic, T., Chezeaux, E., Chuyong, G. B., Clark, C. J., Collins, M., Comiskey, J. A., Coomes, D. A., Dargie, G. C., de Haulleville, T., Kamdem, M. N. D., Doucet, J.-L., Esquivel-Muelbert, A., Feldpausch, T. R., Fofanah, A., Foli, E. G., Gilpin, M., Gloor, E., Gonmadje, C., Gourlet-Fleury, S., Hall, J. S., Hamilton, A. C., Harris, D. J., Hart, T. B., Hockemba, M. B. N., Hladik, A., Ifo, S. A., Jeffery, K. J., Jucker, T., Yakusu, E. K., Kearsley, E., Kenfack, D., Koch, A., Leal, M. E., Levesley, A., Lindsell, J. A., Lisingo, J., Lopez-Gonzalez, G., Lovett, J. C., Makana, J.-R., Malhi, Y., Marshall, A. R., Martin, J., Martin, E. H., Mbayu, F. M., Medjibe, V. P., Mihindou, V., Mitchard, E. T. A., Moore, S., Munishi, P. K. T., Bengone, N. N., Ojo, L., Ondo, F. E., Peh, K. S.-H., Pickavance, G. C., Poulsen, A. D., Poulsen, J. R., Qie, L., Reitsma, J., Rovero, F., Swaine, M. D., Talbot, J., Taplin, J., Taylor,

- D. M., Thomas, D. W., Toirambe, B., Mukendi, J. T., Tuagben, D., Umunay, P. M., van der Heijden, G. M. F., Verbeeck, H., Vleminckx, J., Willcock, S., Wöll, H., Woods, J. T., and Zemagho, L. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, 579(7797):80–87.
- Huston, M. A. and Wolverton, S. (2009). The global distribution of net primary production: resolving the paradox. *Ecological Monographs*, 79(3):343–377.
- Jung, M., Reichstein, M., Margolis, H. A., Cescatti, A., Richardson, A. D., Arain, M. A., Arneth, A., Bernhofer, C., Bonal, D., Chen, J., Gianelle, D., Gobron, N., Kiely, G., Kutsch, W., Lasslop, G., Law, B. E., Lindroth, A., Merbold, L., Montagnani, L., Moors, E. J., Papale, D., Sottocornola, M., Vaccari, F., and Williams, C. (2011). Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. *Journal of Geophysical Research*, 116:G00J07.
- Kerkhoff, A. J., Enquist, B. J., Elser, J. J., and Fagan, W. F. (2005). Plant allometry, stoichiometry and the temperature-dependence of primary productivity: Plant allometry, stoichiometry and productivity. *Global Ecology and Biogeography*, 14(6):585–598.
- Kunert, N., El-Madany, T. S., Aparecido, L. M. T., Wolf, S., and Potvin, C. (2019). Understanding the controls over forest carbon use efficiency on small spatial scales: Effects of forest disturbance and tree diversity. *Agricultural and Forest Meteorology*, 269-270:136–144.
- Larjavaara, M. and Muller-Landau, H. C. (2012). Temperature explains global variation in biomass among humid old-growth forests: Temperature and old-growth forest biomass. *Global Ecology and Biogeography*, 21(10):998–1006.
- Li and Xiao (2019). Mapping Photosynthesis Solely from Solar-Induced Chlorophyll Fluorescence: A Global, Fine-Resolution Dataset of Gross Primary Production Derived from OCO-2. *Remote Sensing*, 11(21):2563.
- Lieth, H. (1973). Primary production: Terrestrial ecosystems. *Human Ecology*, 1(4):303–332.
- Litton, C. M., Raich, J. W., and Ryan, M. G. (2007). Carbon allocation in forest ecosystems. *Global Change Biology*, 13(10):2089–2109.
- Longo, M., Knox, R. G., Medvigy, D. M., Levine, N. M., Dietze, M. C., Kim, Y., Swann, A. L. S., Zhang, K., Rollinson, C. R., Bras, R. L., Wofsy, S. C., and Moorcroft, P. R. (2019). The biophysics, ecology, and biogeochemistry of functionally diverse, vertically and horizontally heterogeneous ecosystems: the Ecosystem Demography model, version 2.2 – Part 1: Model description. *Geoscientific Model Development*, 12(10):4309–4346.
- Luyssaert, S., Inglis, I., Jung, M., Richardson, A. D., Reichstein, M., Papale, D., Piao, S. L., Schulze, E. D., Wingate, L., Matteucci, G., Aragao, L., Aubinet, M., Beer, C., Bernhofer, C., Black, K. G., Bonal, D., Bonnefond, J. M., Chambers, J., Ciais, P., Cook, B., Davis, K. J., Dolman, A. J., Gielen, B., Goulden, M., Grace, J., Granier, A., Grelle, A., Griffis, T., Grünwald, T., Guidolotti, G., Hanson, P. J., Harding, R., Hollinger, D. Y., Hutryra, L. R., Kolari, P., Kruijt, B., Kutsch, W., Lagergren, F., Laurila, T., Law, B. E., Le Maire, G., Lindroth, A., Loustau, D., Malhi, Y., Mateus, J., Migliavacca, M., Misson, L., Montagnani, L., Moncrieff, J., Moors, E., Munger, J. W., Nikinmaa, E., Ollinger, S. V., Pita, G., Rebmann, C., Rouspard, O., Saigusa, N., Sanz, M. J., Seufert, G., Sierra, C., Smith, M. L., Tang, J., Valentini, R., Vesala, T.,

- and Janssens, I. A. (2007). CO₂ balance of boreal, temperate, and tropical forests derived from a global database. *Global Change Biology*, 13(12):2509–2537.
- Malhi, Y. (2012). The productivity, metabolism and carbon cycle of tropical forest vegetation: Carbon cycle of tropical forests. *Journal of Ecology*, 100(1):65–75.
- Malhi, Y., Doughty, C., and Galbraith, D. (2011). The allocation of ecosystem net primary productivity in tropical forests. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 366(1582):3225–3245.
- Malhi, Y., Girardin, C. A. J., Goldsmith, G. R., Doughty, C. E., Salinas, N., Metcalfe, D. B., Huaraca Huasco, W., Silva-Espejo, J. E., del Aguilla-Pasquell, J., Farfán Amézquita, F., Aragão, L. E. O. C., Guerrieri, R., Ishida, F. Y., Bahar, N. H. A., Farfan-Rios, W., Phillips, O. L., Meir, P., and Silman, M. (2017). The variation of productivity and its allocation along a tropical elevation gradient: a whole carbon budget perspective. *New Phytologist*, 214(3):1019–1032.
- Mau, A., Reed, S., Wood, T., and Cavaleri, M. (2018). Temperate and Tropical Forest Canopies are Already Functioning beyond Their Thermal Thresholds for Photosynthesis. *Forests*, 9(1):47.
- McDowell, N., Allen, C. D., Anderson-Teixeira, K., Brando, P., Brien, R., Chambers, J., Christoffersen, B., Davies, S., Doughty, C., Duque, A., Espirito-Santo, F., Fisher, R., Fontes, C. G., Galbraith, D., Goodsman, D., Grossiord, C., Hartmann, H., Holm, J., Johnson, D. J., Kassim, A. R., Keller, M., Koven, C., Kueppers, L., Kumagai, T., Malhi, Y., McMahon, S. M., Mencuccini, M., Meir, P., Moorcroft, P., Muller-Landau, H. C., Phillips, O. L., Powell, T., Sierra, C. A., Sperry, J., Warren, J., Xu, C., and Xu, X. (2018). Drivers and mechanisms of tree mortality in moist tropical forests. *New Phytologist*, 219(3):851–869.
- Medvigy, D., Wofsy, S. C., Munger, J. W., Hollinger, D. Y., and Moorcroft, P. R. (2009). Mechanistic scaling of ecosystem function and dynamics in space and time: Ecosystem Demography model version 2. *Journal of Geophysical Research: Biogeosciences*, 114(G1):G01002.
- Michaletz, S. T., Cheng, D., Kerkhoff, A. J., and Enquist, B. J. (2014). Convergence of terrestrial plant production across global climate gradients. *Nature*, 512(7512):39–43.
- Michaletz, S. T., Kerkhoff, A. J., and Enquist, B. J. (2018). Drivers of terrestrial plant production across broad geographical gradients. *Global Ecology and Biogeography*, 27(2):166–174.
- Moser, G., Leuschner, C., Hertel, D., Graefe, S., Soethe, N., and Iost, S. (2011). Elevation effects on the carbon budget of tropical mountain forests (S Ecuador): the role of the belowground compartment. *Global Change Biology*, 17(6):2211–2226.
- Niedziałkowska, M., Kończak, J., Czarnomska, S., and Jędrzejewska, B. (2010). Species diversity and abundance of small mammals in relation to forest productivity in northeast Poland. *Écoscience*, 17(1):109–119.
- Piao, S., Luyssaert, S., Ciais, P., Janssens, I. A., Chen, A., Cao, C., Fang, J., Friedlingstein, P., Luo, Y., and Wang, S. (2010). Forest annual carbon cost: a global-scale analysis of autotrophic respiration. *Ecology*, 91(3):652–661.
- Potapov, P., Yaroshenko, A., Turubanova, S., Dubinin, M., Laestadius, L., Thies, C., Aksenov, D., Egorov, A., Yesipova, Y., Glushkov, I., Karpachevskiy, M., Kostikova, A., Manisha, A., Tsybikova, E., and Zhuravleva, I. (2008). Mapping the World’s Intact Forest Landscapes by Remote Sensing. *Ecology and Society*, 13(2):art51.

- Poulter, B., Aragao, L., Andela, N., Bellassen, V., Ciais, P., Kato, T., Lin, X., Nachin, B., Luyssaert, S., Pederson, N., Peylin, P., Piao, S., Saatchi, S., Schepaschenko, D., Schelhaas, M., and Shvidenko, A. (2018). The global forest age dataset (GFADv1.0), link to NetCDF file.
- Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R., Vilariño, M. V., Calvin, K., Emmerling, J., Fuss, S., Gillett, N., He, C., Hertwich, E., Höglund-Isaksson, L., Huppmann, D., Luderer, G., McCollum, D. L., Meinshausen, M., Millar, R., Popp, A., Purohit, P., Riahi, K., Ribes, A., Saunders, H., Schädel, C., Smith, P., Trutnevyte, E., Xiu, Y., Zhou, W., Zickfeld, K., Flato, G., Fuglestvedt, J., Mrabet, R., and Schaeffer, R. (2018). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. page 82.
- Rutishauser, E., Wright, S. J., Condit, R., Hubbell, S. P., Davies, S. J., and Muller-Landau, H. C. (2020). Testing for changes in biomass dynamics in large-scale forest datasets. *Global Change Biology*, 26(3):1485–1498.
- Schuur, E. A. G. (2003). Productivity and global climate revisited: the sensitivity of tropical forest growth to precipitation. *Ecology*, 84(5):1165–1170.
- Sniderhan, A. E. and Baltzer, J. L. (2016). Growth dynamics of black spruce (*Picea mariana*) in a rapidly thawing discontinuous permafrost peatland: Growth Dynamics Boreal Peatlands. *Journal of Geophysical Research: Biogeosciences*, 121(12):2988–3000.
- Taylor, P. G., Cleveland, C. C., Wieder, W. R., Sullivan, B. W., Doughty, C. E., Dobrowski, S. Z., and Townsend, A. R. (2017). Temperature and rainfall interact to control carbon cycling in tropical forests. *Ecology Letters*, 20(6):779–788.
- Trabucco, A. and Zomer, R. J. (2019). Global Aridity Index and Potential Evapo-Transpiration (ET0) Climate Database v2. page 10.
- Vlam, M., Baker, P. J., Bunyavejchewin, S., and Zuidema, P. A. (2014). Temperature and rainfall strongly drive temporal growth variation in Asian tropical forest trees. *Oecologia*, 174(4):1449–1461.
- Wagner, F. H., Hérault, B., Bonal, D., Stahl, C., Anderson, L. O., Baker, T. R., Becker, G. S., Beeckman, H., Boanerges Souza, D., Botosso, P. C., Bowman, D. M. J. S., Bräuning, A., Brede, B., Brown, F. I., Camarero, J. J., Camargo, P. B., Cardoso, F. C. G., Carvalho, F. A., Castro, W., Chagas, R. K., Chave, J., Chidumayo, E. N., Clark, D. A., Costa, F. R. C., Couralet, C., da Silva Mauricio, P. H., Dalitz, H., de Castro, V. R., de Freitas Milani, J. E., de Oliveira, E. C., de Souza Arruda, L., Devineau, J.-L., Drew, D. M., Dünisch, O., Durigan, G., Elifuraha, E., Fedele, M., Ferreira Fedele, L., Figueiredo Filho, A., Finger, C. A. G., Franco, A. C., Freitas Júnior, J. L., Galvão, F., Gebrekirstos, A., Gliniars, R., Graça, P. M. L. d. A., Griffiths, A. D., Grogan, J., Guan, K., Homeier, J., Kanieski, M. R., Kho, L. K., Koenig, J., Kohler, S. V., Krepkowski, J., Lemos-Filho, J. P., Lieberman, D., Lieberman, M. E., Lisi, C. S., Longhi Santos, T., López Ayala, J. L., Maeda, E. E., Malhi, Y., Maria, V. R. B., Marques, M. C. M., Marques, R., Maza Chamba, H., Mbwambo, L., Melgaço, K. L. L., Mendivelso, H. A., Murphy, B. P., O’Brien, J. J., Oberbauer, S. F., Okada, N., Péliissier, R., Prior, L. D., Roig, F. A., Ross, M., Rossatto, D. R., Rossi, V., Rowland, L., Rutishauser, E., Santana, H., Schulze, M., Selhorst, D., Silva, W. R., Silveira, M., Spann, S., Swaine, M. D., Toledo, J. J., Toledo, M. M., Toledo, M., Toma, T., Tomazello Filho, M., Valdez Hernández, J. I., Verbesselt, J., Vieira, S. A., Vincent, G., Volkmer de Castilho, C., Volland, F., Worbes, M., Zanon,

- M. L. B., and Aragão, L. E. O. C. (2016). Climate seasonality limits leaf carbon assimilation and wood productivity in tropical forests. *Biogeosciences*, 13(8):2537–2562.
- Waide, R. B., Willig, M. R., Steiner, C. F., Mittelbach, G., Gough, L., Dodson, S. I., Juday, G. P., and Parmenter, R. (1999). The Relationship Between Productivity and Species Richness. *Annual Review of Ecology and Systematics*, 30(1):257–300.
- Wei, W., Weile, C., and Shaopeng, W. (2010). Forest soil respiration and its heterotrophic and autotrophic components: Global patterns and responses to temperature and precipitation. *Soil Biology and Biochemistry*, 42(8):1236–1244.
- Zak, D. R., Tilman, D., Parmenter, R. R., Rice, C. W., Fisher, F. M., Vose, J., Milchunas, D., and Martin, C. W. (1994). Plant Production and Soil Microorganisms in Late-Successional Ecosystems: A Continental-Scale Study. *Ecology*, 75(8):2333.
- Šímová, I. and Storch, D. (2017). The enigma of terrestrial primary productivity: measurements, models, scales and the diversity-productivity relationship. *Ecography*, 40(2):239–252.