



Supplement of

TECO-CNP Sv1.0: a coupled carbon-nitrogen-phosphorus model with data assimilation for subtropical forests

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Section S1

Data assimilation and parameter equifinality

We conducted data assimilation for different model configurations to examine how parameter equifinality affects model performance. This analysis further aimed to demonstrate the ecological necessity of incorporating phosphorus dynamics in terrestrial ecosystem models. The target parameters included all parameters listed in Table 6 except for maximum rate of carboxylation (V_{cmax}). V_{cmax} was excluded to avoid confounding effects arising from parameter equifinality (Fig. 8). Data assimilation methods are detailed in Section 2.3.3. Observational SLA data were derived from a 5-hectare forest dynamics plot comprising 60 subplots (each $20\text{m} \times 20\text{m}$). Community-weighted mean SLA values were calculated from individual-level measurements and scaled up from species level to community level. We compared the constrained parameter posterior distributions with the observed posterior distributions and employed the Kolmogorov-Smirnov statistic (D) to quantify distributional similarity. Lower D values indicate greater distributional concordance.

We found that while all three model configurations achieved similar performance in terms of flux predictions (Fig. S1), this similarity stems from compensatory parameter behavior that compromises ecological realism (Fig. S2). Specifically, the CNP model configuration's SLA posterior distribution exhibited the closest agreement with observations, with a mean difference of 3.276 and the smallest D value (0.282, Fig. S2). In contrast, the C-only and CN model configurations required SLA values far outside the observed community-level distribution, with their posterior distributions significantly deviating from observations and displaying left-skewed characteristics with mean differences of 58.498 and 53.463, respectively. This reflects the well-documented issue of parameter equifinality (Luo et al., 2016; Sierra et al., 2015), where simpler models can match outputs by adjusting parameters to unrealistic values. These findings highlight that the ecological interpretability and transferability of the optimized C-only and CN models are limited, especially under changing environmental conditions where nutrient dynamics play a key role.

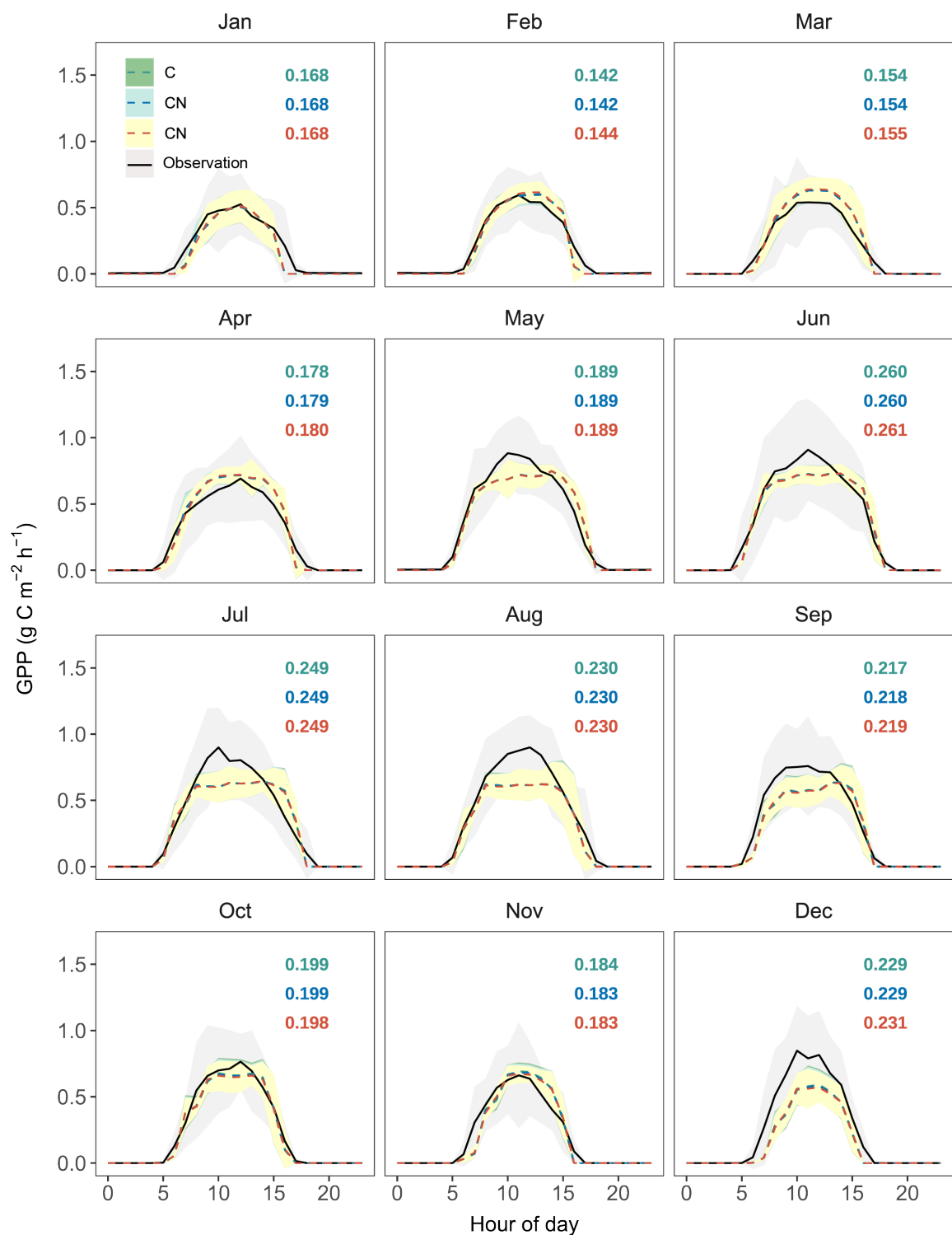


Figure S1. Diurnal GPP patterns across months simulated by three model configurations after data assimilation (C-only, CN, CNP) versus observations. RMSE values for each model (green: C-only, blue: CN, red: CNP) are shown in the upper right of each panel. Black lines with grey shading represent observations (± 1 SD); colored lines and shading represent model means ± 1 SD.

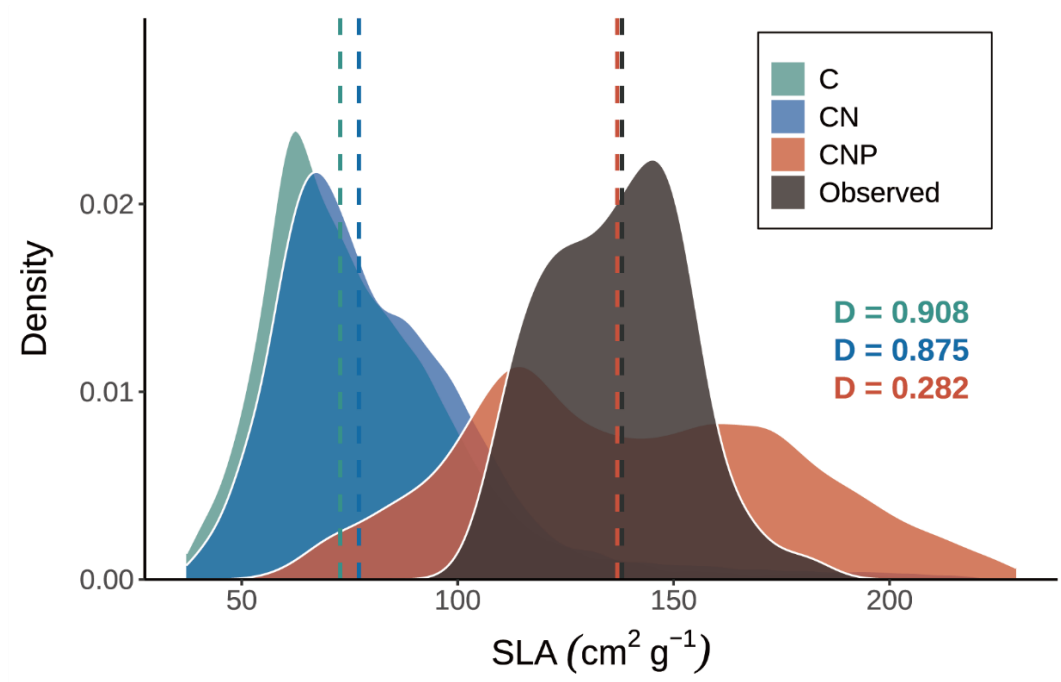


Figure S2. Posterior distribution of constrained specific leaf area (SLA) and observed community-level SLA distribution. Green, blue, red, and gray represent C-only, CN, CNP models and observations, respectively. Vertical lines represent distribution means. D, Kolmogorov-Smirnov statistic.

Table S1. Carbon cycling observations from study site for model development.

Variables	Value	Unit	Sources	Measured Year
Evaluation				
Leaf C	0.22 ± 0.02	kg C m ⁻²	Zhou, 2020	2013-2017
Wood C	8.67 ± 0.56	kg C m ⁻²	Zhou, 2020	2013-2017
Root C	0.47 ± 0.03	kg kg ⁻¹	Measured data	2007
Root biomass	0.32 ± 0.11	kg m ⁻²	Zeng et al., 2008	2004-2005
Soil C	26.48 ± 10.99	kg C m ⁻²	Measured data	2017
Leaf C litterfall rate	0.23 ± 0.05	kg C m ⁻²	Zheng et al., 2023	2008-2018
Litterfall rate	0.44 ± 0.04	kg C m ⁻² a ⁻¹	Zhou, 2020	2011-2016
Soil respiration	0.99 ± 0.07	g C m ⁻² a ⁻¹	Zhou, 2020	2015-2017
Mean LAI	3.75 ± 0.15	m ² m ⁻²	Measured data	2021
Parametrization & Calibration				
LAI _{max}	5.2	m ² m ⁻²	Measured data	2021
LAI _{min}	2.8	m ² m ⁻²	Measured data	2021
Plant height	19.5±2.33	m	Measured data	2020
SLA	136.65 ± 15.87	cm ² g ⁻¹	Measured data	2020
V _{cmax}	26.2±0.97	μmol m ⁻² s ⁻¹	Measured data	2020
Fruit C	464.25 ± 19.56	g kg ⁻¹	Measured data	2007
J _{max}	38.01±1.75	μmol m ⁻² s ⁻¹	Measured data	2020

Table S2. Nitrogen cycling observations from study site for model development.

Variables	Value	Unit	Sources	Measured Year
Leaf N	6.1 ± 0.5	g N m^{-2}	Zhou, 2020	2013-2017
Wood N	31.42 ± 2.04	g N m^{-2}	Zhou, 2020	2013-2017
Root N	9.28 ± 2.18	g N kg^{-1}	Measured	2007
Fruit N	7.06 ± 0.25	g N kg^{-1}	Measured	2007
Soil N	1860.48 ± 550.90	g N m^{-2}	Measured	2017
Inorganic N	3.45 ± 0.59	g N m^{-2}	Zhou, 2020	2011-2013
Litterfall N rate	6.74 ± 0.68	$\text{g N m}^{-2} \text{ a}^{-1}$	Zhou, 2020	2013-2017
N net immobilization	13.14 ± 0.73	$\text{g m}^{-2} \text{ a}^{-1}$	Li, 2014	2014
Parametrization & Calibration				
CN_{leaf}	35.63 ± 4.23	g C gN^{-1}	Measured; Zhou, 2020	2020
CN_{wood}	275.99 ± 25.37	g C gN^{-1}	Zhou, 2020	2013-2017
CN_{root}	50.56 ± 12.2	g C gN^{-1}	Zhou, 2020	2013-2017
CN_{fruit}	65.76 ± 3.62	g C gN^{-1}	Measured	2007
CN_{soil}	14.24 ± 7.26	g C gN^{-1}	Measured	2017
N resorption rate	35.23 ± 19.42	%	Measured	2020

Table S3. Phosphorus cycling observations from study site for model development.

Variables	Value	Unit	Sources	Measured Year
Leaf P	0.19 ± 0.05	g P m^{-2}	Measured data	2020
Leaf N:P	32.84 ± 9.12	g N g P^{-1}	Measured data	2020
Wood P	1.75 ± 0.11	g P m^{-2}	Zhou, 2020	2013-2017
Root P	0.56 ± 0.17	g P kg^{-1}	Measured data	2007
Fruit P	0.68 ± 0.21	g P kg^{-1}	Measured data	2007
Soil P	181.59 ± 60.18	g P m^{-2}	Measured data	2017
Labile P	1.04 ± 0.56	g P m^{-2}	Measured data	2022
Secondary P	9.427 ± 0.521	g P m^{-2}	Wang, 2022	2022
Occluded P	16.123 ± 4.750	g P m^{-2}	Wang, 2022	2022
P flux from plant to litter	0.79 ± 0.24	$\text{g P m}^{-2} \text{ a}^{-1}$	Zhou, 2020	2013-2017
Parametrization & Calibration				
CP_{leaf}	1144 ± 610.05	g C gP^{-1}	Measured; Zhou, 2020	2020
CP_{wood}	4955.15 ± 448.27	g C gP^{-1}	Zhou, 2020	2013-2017
CP_{root}	837.84 ± 258.81	g C gP^{-1}	Zhou, 2020	2013-2017
CP_{fruit}	682.72 ± 212.79	g C gP^{-1}	Measured	2007
CP_{soil}	145.85 ± 77.46	g C gP^{-1}	Measured	2017
P resorption rate	54.53 ± 20.55	%	Measured data	2020

Table S4. Reference codes and corresponding citations used in the main text.

Reference Code	Citation
1	Wang et al., 2010
2	Xu et al., 2020
3	Yan, 2006
4	Zhu et al., 2016a
5	Du et al., 2018
6	Goll et al., 2017
7	Schachtman et al., 1998
8	Olander & Vitousek, 2005
9	Bonan et al., 2014
10	Barracough and Tinker, 1981
11	Mollier et al., 2008

Table S5. Comparison of predicted photosynthetic parameters from area-based empirical relationships with site observations.

Relationships and Variables	Walker et al., (2014)	Ellsworth et al., (2022)
$V_{\text{cmax}} \sim \{N, P\}$	$V_{\text{cmax}} = \exp(3.946 + 0.921 \times \ln(N) + 0.121 \times \ln(P) + 0.282 \times \ln(N) \times \ln(P))$	$V_{\text{cmax}} = \exp(4.308 + 0.298 \times \ln(P) + 0.197 \times \ln(N))$
$J_{\text{max}} \sim \{N, P\}$	/	$J_{\text{max}} = \exp(5.139 + 0.325 \times \ln(P) + 0.112 \times \ln(N))$
Measured N, P concentration (g m ⁻²)	N = 6.1 ± 0.5	
	P = 0.19 ± 0.05	
Measured photosynthetic capacity (μmol m ⁻² s ⁻¹)	$V_{\text{cmax}} = 36.72 \pm 16.73$	
	$J_{\text{max}} = 57.93 \pm 26.28$	
Predicted photosynthetic capacity (μmol m ⁻² s ⁻¹)	$V_{\text{cmax}} = 95.93 \pm 39.12$	$V_{\text{cmax}} = 64.67 \pm 12.36$
		$J_{\text{max}} = 121.73 \pm 23.32$

Table S6. Sensitivity index of selected parameters. SI_{GPP} , SI_{ER} , and SI_{NEE} represent the sensitivity indices of gross primary productivity (GPP), ecosystem respiration (ER), and net ecosystem exchange (NEE) to each parameter, respectively. Bold values indicate sensitivity indices > 0.1 .

	SI_{GPP}	SI_{ER}	SI_{NEE}
Q10	0.009	0.554	0.750
SLA	0.112	0.110	0.115
Vcmax	0.820	0.210	1.669
T1	0.023	0.027	0.091
T2	0.000	0.036	0.050
T3	0.008	0.025	0.055
T4	0.000	0.026	0.037
T5	0.004	0.039	0.065
T6	0.004	0.185	0.268
T7	0.008	0.239	0.313
T8	0.001	0.110	0.150
T9	0.000	0.005	0.006

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