

Table S1 Plant functional type (PFT) specific leaf N:P ratio ($\text{gN g}^{-1}\text{P}$) for ORCHIDEE v1.1 and v1.2: tropical evergreen broadleaf forest (TREBF), tropical raingreen broadleaf forest (TRDBF), temperate evergreen needleleaf forest (TEENF), temperate evergreen broadleaf forest (TEEBF), temperate summergreen broadleaf forest (TEDBF), boreal evergreen needleleaf forest (BOENF), boreal summergreen broadleaf forest (BODBF), boreal summergreen needleleaf forest (BODNF), C3 grassland (C3G), C4 grassland (C4G), C3 cropland (C3C) and C4 cropland (C4C).

	TRE BF	TRDB F	TREN F	TREB F	TRDB F	BOEN F	BODN F	BODBF	C3G	C4G	C3C	C4C	Sources
<i>np_{leaf,min}</i> for v1.1	16.68	16.68	8.34	10.84	10.84	8.34	10.84	10.84	10.84	10.84	-	-	McGrodd et al. (200
<i>np_{leaf,max}</i> for v1.1	22.57	22.57	11.29	14.67	14.67	11.29	14.67	14.67	14.67	14.67	-	-	McGrodd et al. (200
<i>np_{leaf,min}</i> for v1.2	5	5	5	5	5	5	5	5	5	5	5	5	?
<i>np_{leaf,max}</i> for v1.2	30	30	30	30	30	30	30	30	30	30	30	30	?

Table S2 Total GPP and NPP (PgC yr^{-1}) simulated by ORCHIDEE-CNP, ORCHIDEE and from data-driven products averaged over 2001-2010.

	GPP	Sources		NPP	Sources
ORCHIDEE- CNP	119	This study	ORCHIDEE- CNP	48	This study
ORCHIDEE	140	Krinner et al., 2005	ORCHIDEE	60	Krinner et al., 2005
MODIS	110±23	Turner et al., 2006	MODIS	55±11	Turner et al., 2006
MTE	120±6	Jung et al., 2009	BETHY	60±3	Tum et al., 2016
BESS	122±25	Jiang and Ryu, 2016	GIMMS	33~49	Smith et al., 2016

Table S3 Averaged N and P load via drainage and runoff (Tg yr^{-1}) over 2002-2010 simulated by ORCHIDEE-CNP and GOLUM-CNP.

	ORCHIDEE-CNP			GOLUM-CNP
	ALL	Natural biome	Managed biome	
N leaching	55	35	20	30
P leaching	3.5	0.38	3.2	0.39

Table S4 Inorganic sorption dynamic parameters for Oxisols, Molisols and other soils in ORCHIDEE-CNP.

	Oxisols	Molisols	Other soils	References
Freundlich Isotherm coefficient ($\text{LH}_2\text{O kg}^{-1}\text{soil}$)	348.9	185.5	72.3	Kvacik et al. (in prep)

Table S5 Global P inputs and outputs estimated by ORCHIDEE-CNP and previous studies. The estimations by Lun et al. (2018) and Mekonnen et al. (2018) are based on the balance of P inputs and removal of P.

		ORCHIDEE- CNP	Lun et al., (2018)	Mekonnen et al. (2018)
Study period		2002-2010	2002-2010	2002-2010
Study biomes		Both natural and managed biomes	Cropland and pasture	Only cropland
P inputs	P deposition input	3.8	1.4	-
	Sludge P input	-	1.4	1.2
	Chemical fertilizer P input	20.1	16.8	17
	Manure P input	6.7	19.8	5.9
P outputs	P leaching	3.8	-	-
	P leaching from natural land	0.38	-	-
	P leaching from managed land	3.3	-	-
	P erosion loss	-	-	-
	P runoff and leaching loss	3.8	5.4	-
	P erosion, leaching and runoff loss	-		0.6
P erosion-runoff-leaching to freshwater from diffuse sources			12.5%	2.8%

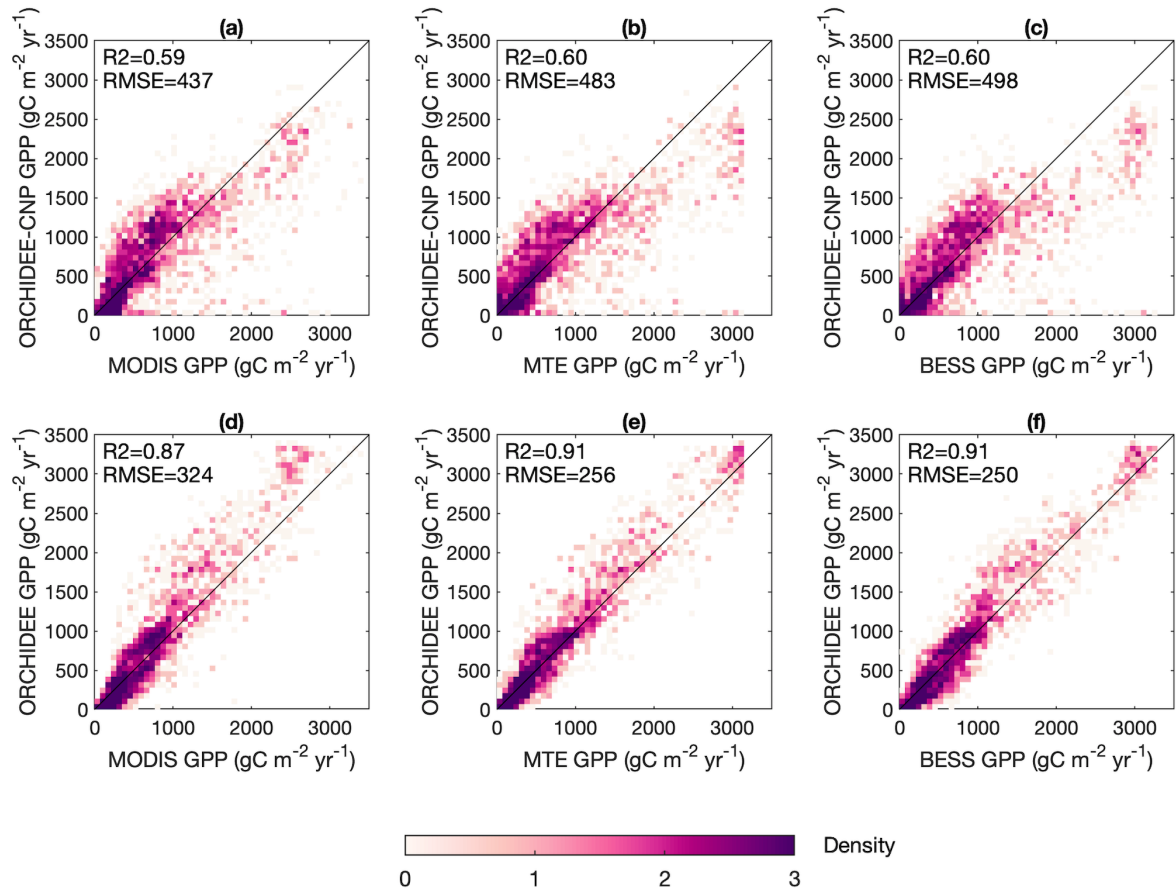


Figure S1 Comparisons between data-driven estimates and simulations by ORCHIDEE-CNP (a, b, c) and ORCHIDEE (d, e, f) for GPP. The color scale shows the point density. Black lines indicate the 1:1 line.

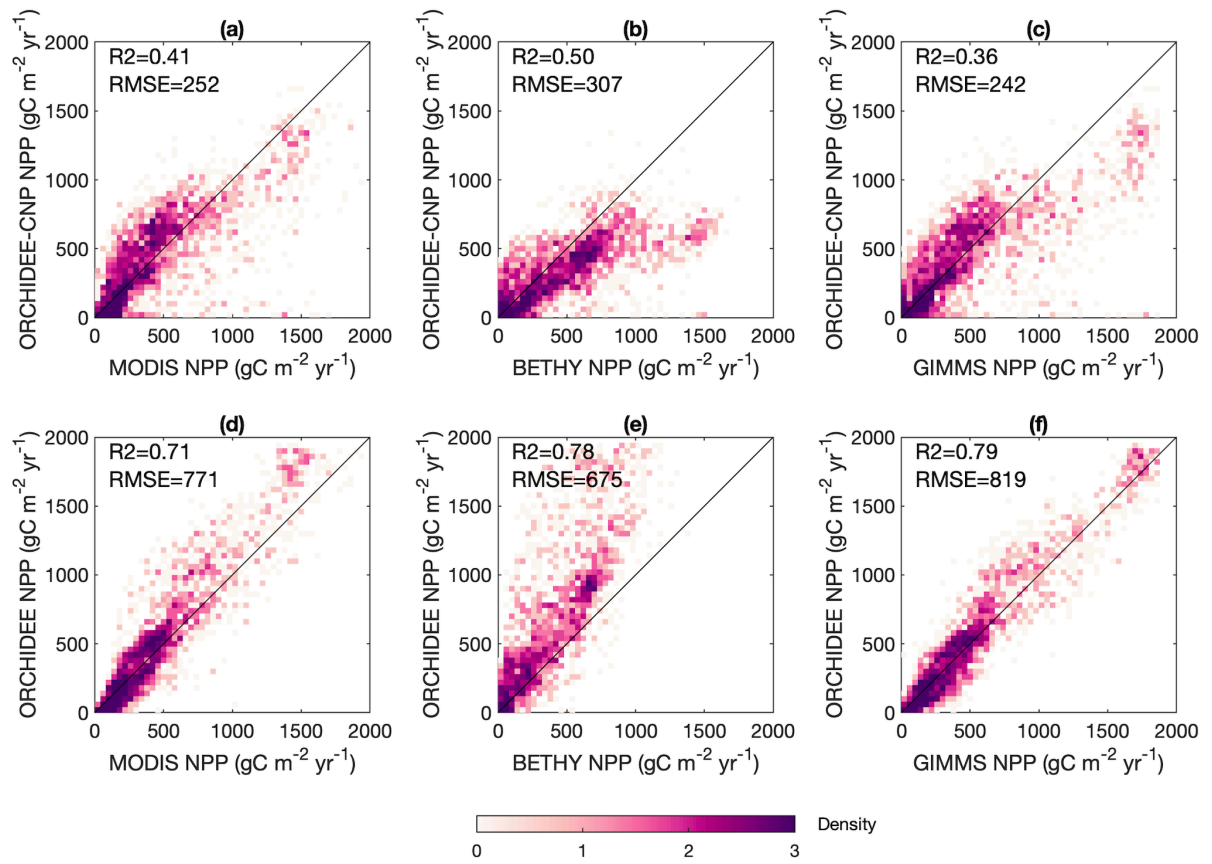


Figure S2 Comparisons between data-driven estimates and simulations by ORCHIDEE-CNP (a, b, c) and ORCHIDEE (d, e, f) for NPP. The color scale shows the point density. Black lines indicate the 1:1 line.

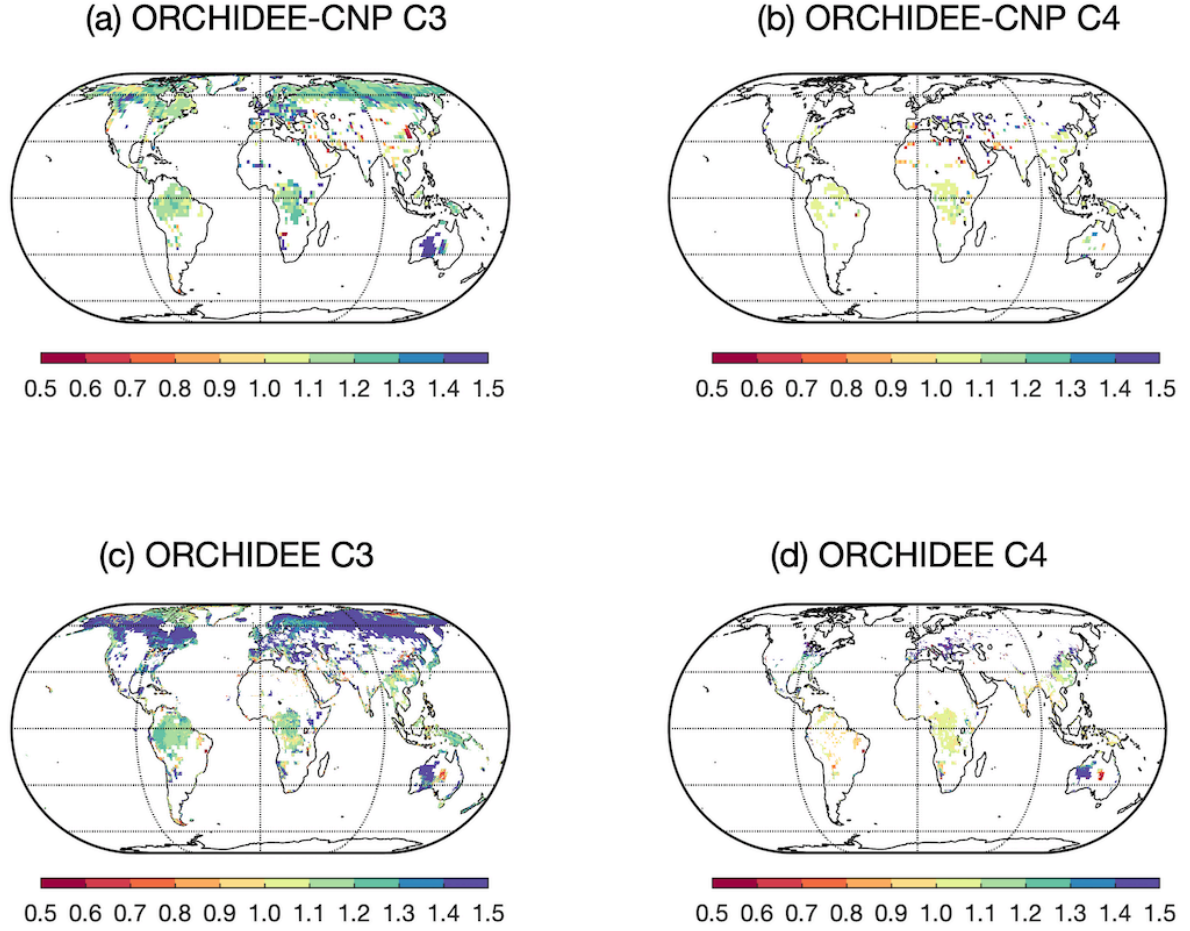


Figure S3 Global pattern of CO₂ fertilization effect (E_{CO_2}), defined as the ratio of current GPP with atmospheric CO₂ concentration of 396 ppm (GPP_{396}) and GPP under pre-industrial atmospheric CO₂ concentration of 296 ppm (GPP_{296}), for natural C3 plants (a, c) and natural C4 plants (b, d) by ORCHIDEE-CNP (a, b) and ORCHIDEE (c, d).

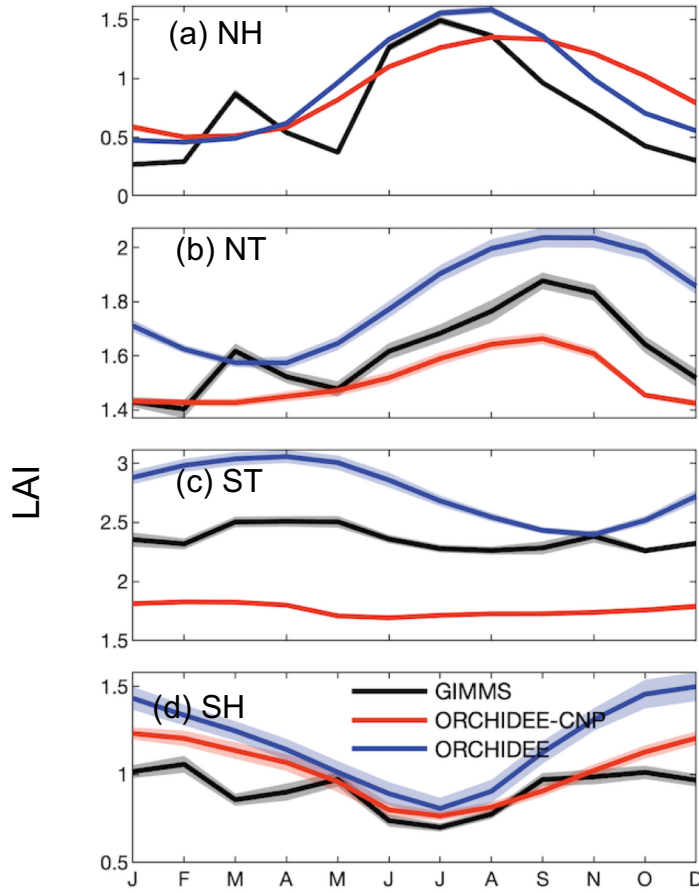


Figure S4 Seasonal cycle of LAI derived from GIMMS, ORCHIDEE and ORCHIDEE-CNP for the northern hemisphere (30°N-90°N; a), the north tropical (0°-30°N; b), the south tropical (0°-30°S; c) and the southern hemisphere (30°S-90°S; d).

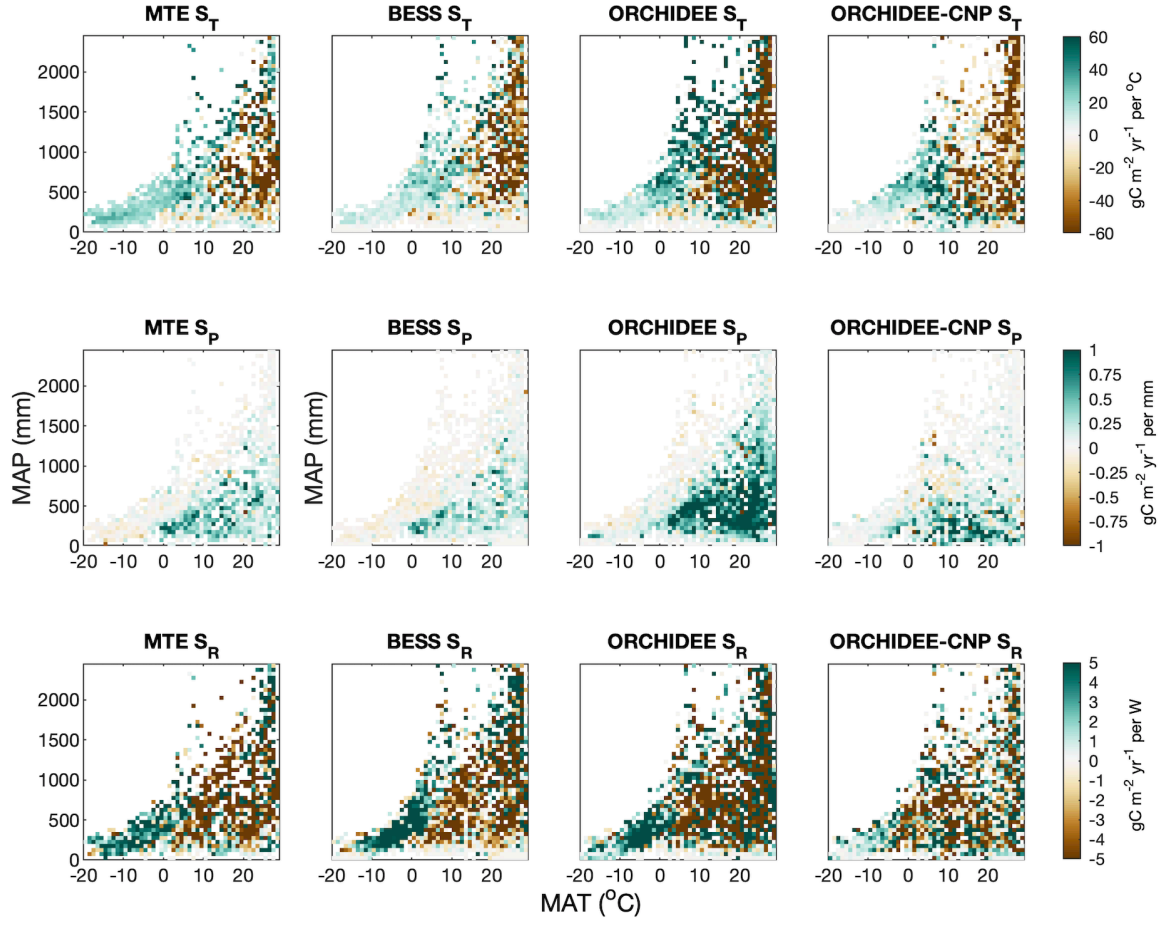


Figure S5 Sensitivity of GPP anomalies to anomalies of mean annual temperature (S_T), annual precipitation (S_P) and shortwave radiation (S_R) plotted in a mean annual temperature (MAT) – mean annual precipitation (MAP) space for MTE-GPP, BESS-GPP, ORCHIDEE and ORCHIDEE-CNP.

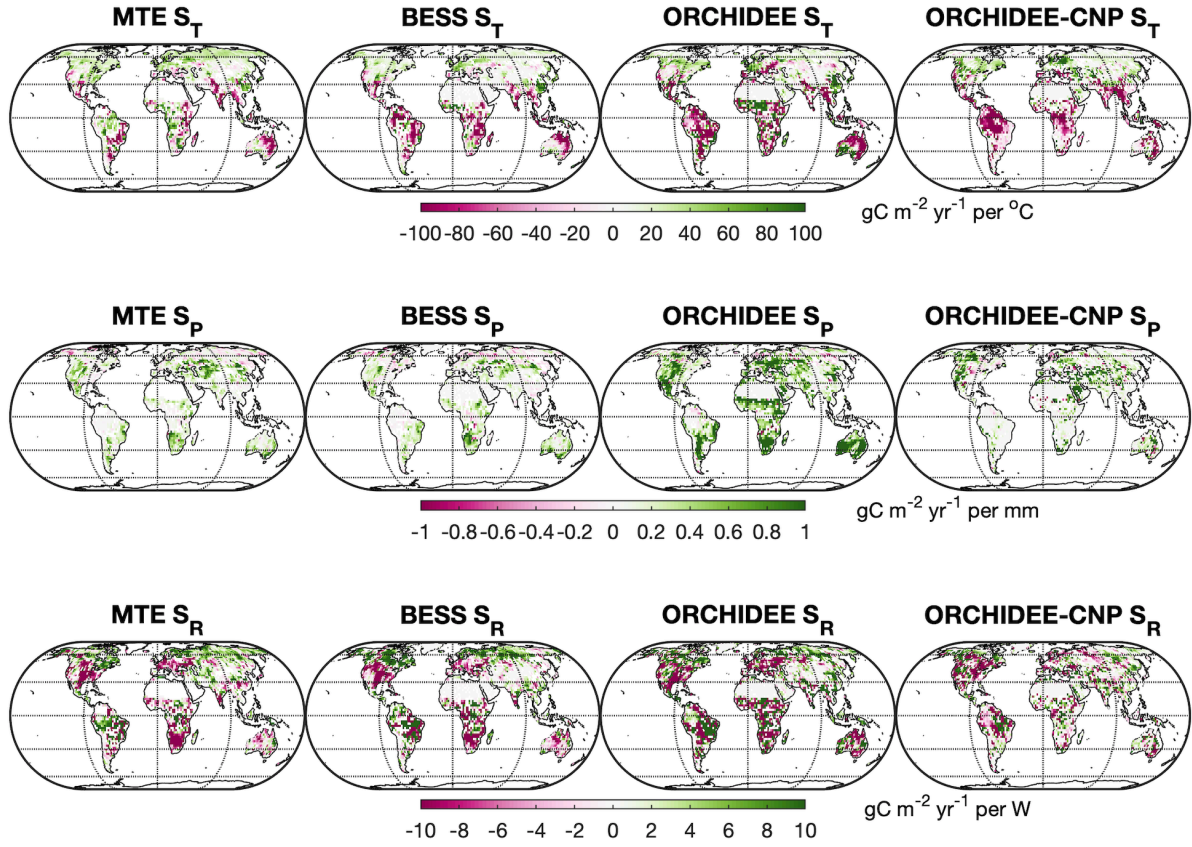


Figure S6 Global patterns of sensitivities of GPP anomalies to anomalies of mean annual temperature (S_T), annual precipitation (S_P) and shortwave radiation (S_R) derived from MTE-GPP, BESS-GPP, ORCHIDEE and ORCHIDEE-CNP.

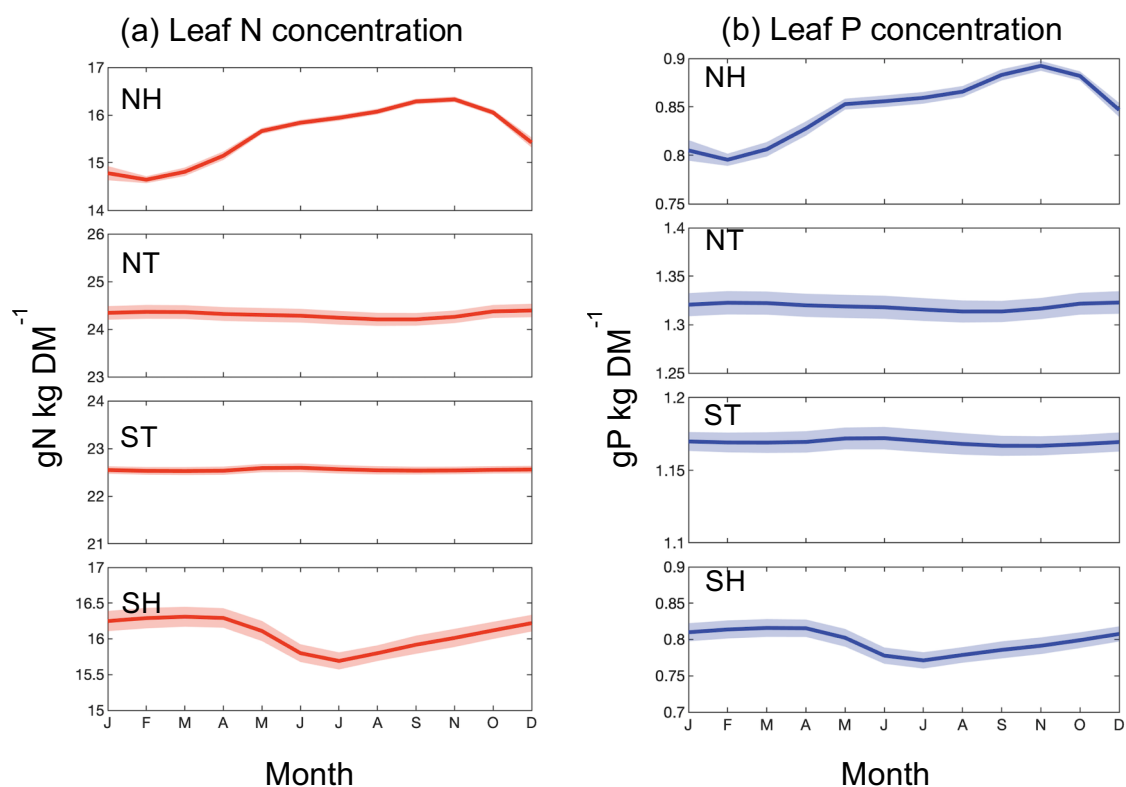


Figure S7 Seasonal cycle of leaf N (a) and P concentration (b) simulated by ORCHIDEE-CNP with excluding managed lands (crop and pastures) for north hemisphere (NH; 30°N-90 °N), north tropical (NT; 0°-30°N), south tropical (ST; 0°-30 °S) and south hemisphere (SH; 30°S-90 °S).

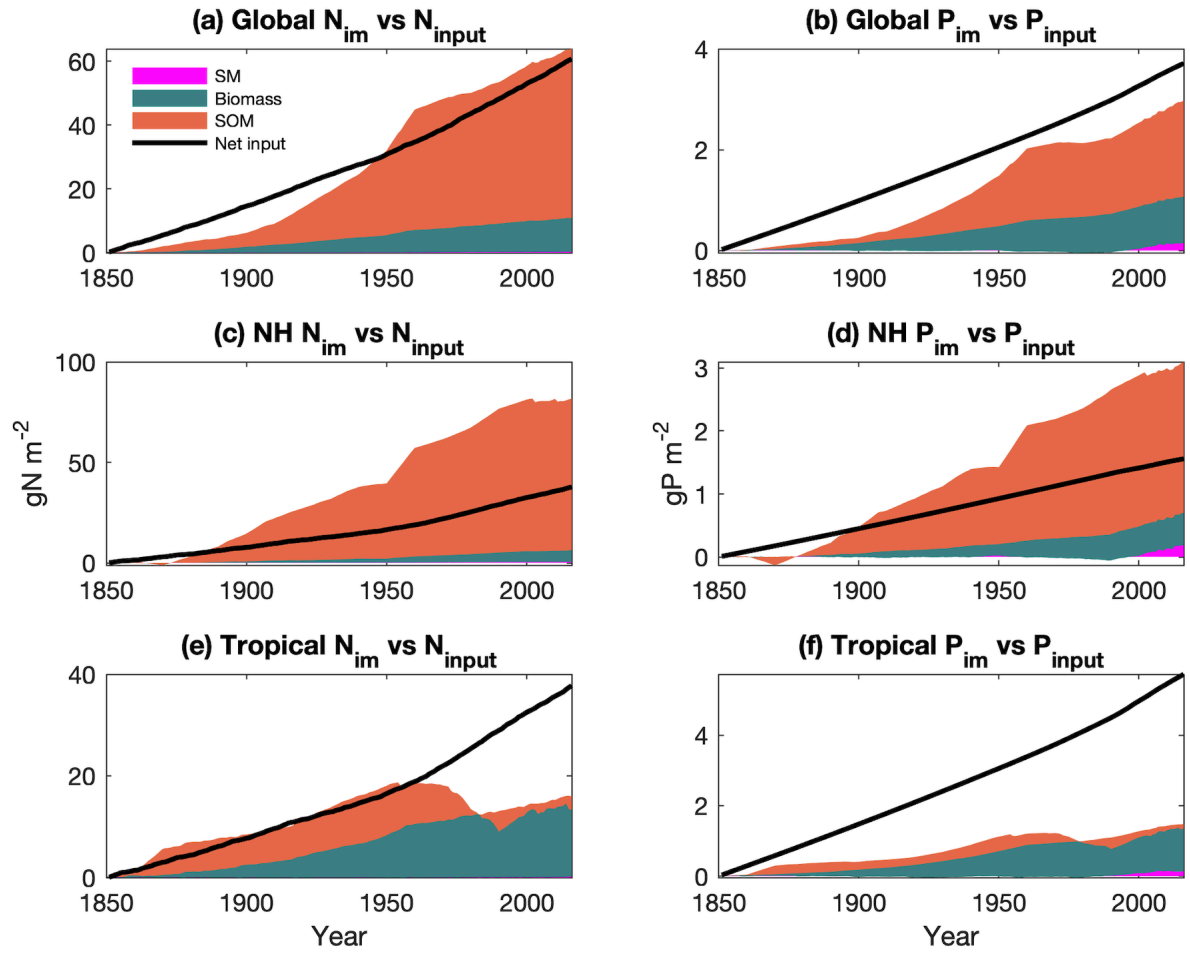


Figure S8 Changes of accumulated immobilized nutrient and net nutrient inputs (area-weighted average) for natural biomes during 1850-2016 on global, north hemisphere (NH, 30°N~90°N) and tropical region (30°S~30°N).

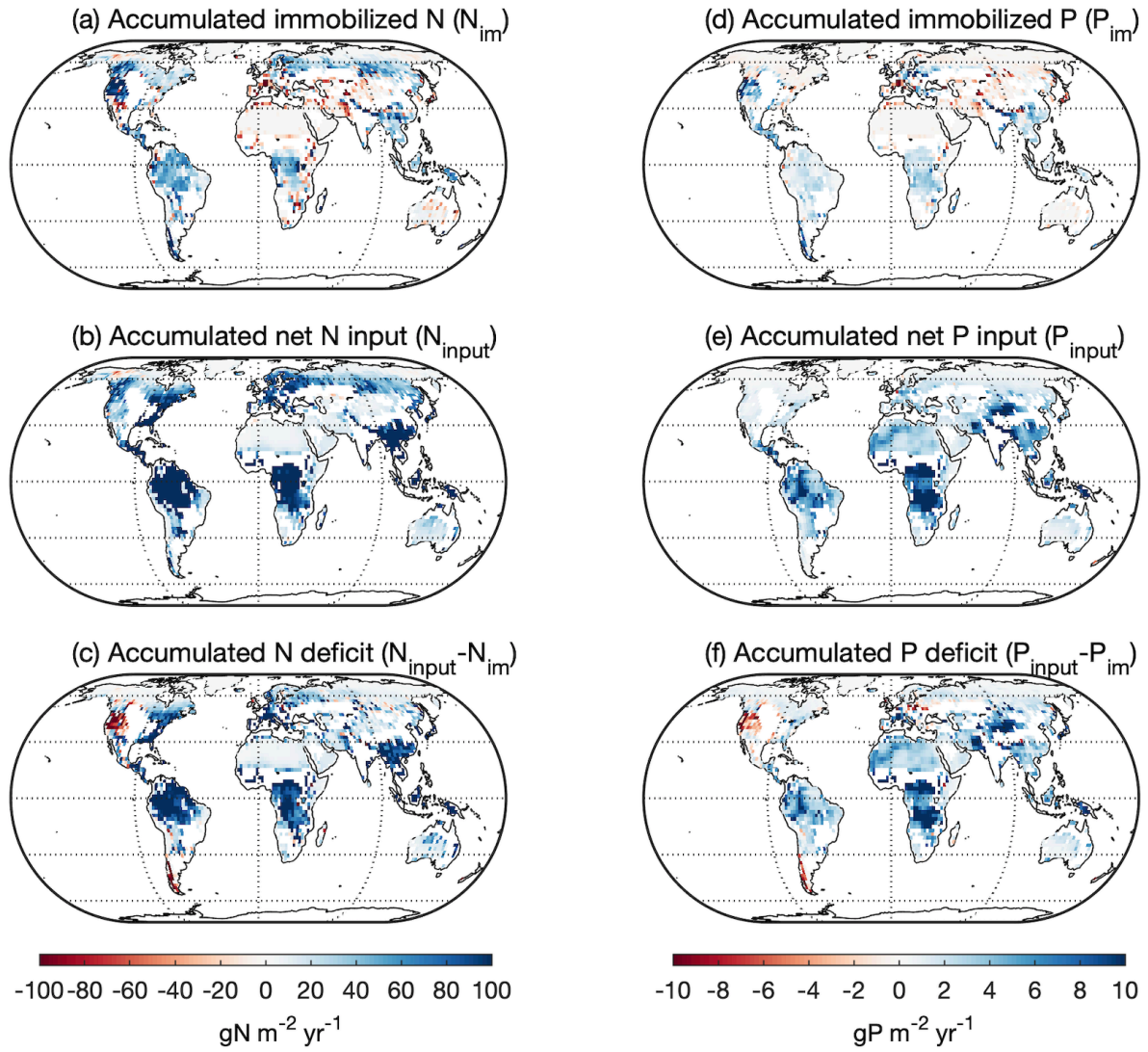


Figure S9 Accumulated immobilized nutrient, net nutrient inputs and deficit during 1850-2016 for N (a, b, c) and P (d, e, f). Grids dominated with managed biomes (cropland and pasture) (area fraction > 50% in 2016) are masked.

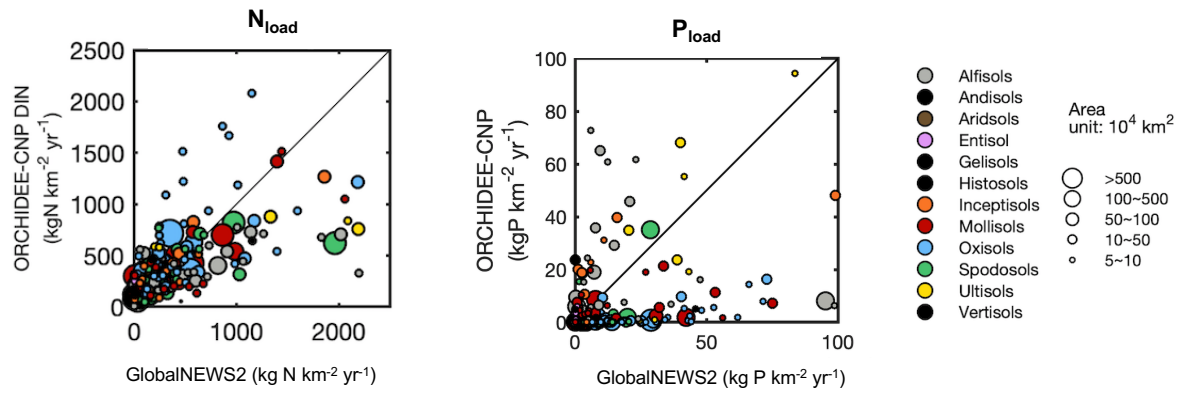


Figure S10 Global pattern of N and P load rates from land to river (N_{load} and P_{load}) on catchment scale for ORCHIDEE-CNP and GlobalNEWS2 model for basins with area larger than 50,000 km². (c) and (f) show the comparisons of N_{load} and P_{load} between ORCHIDEE-CNP and GlobalNEWS2. Black line indicates 1:1 line.

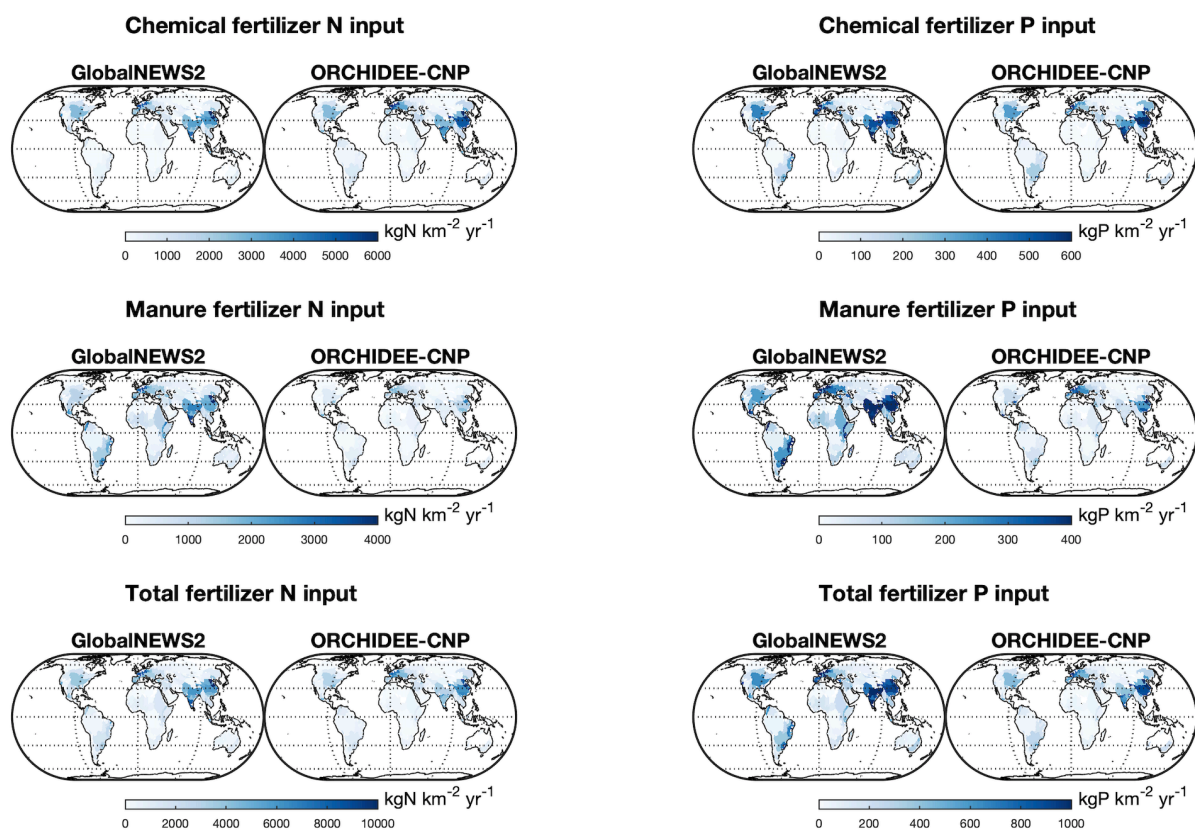


Figure S11 Chemical and manure N and P input on catchment scale by GlobalNEWS2 and ORCHIDEE-CNP.

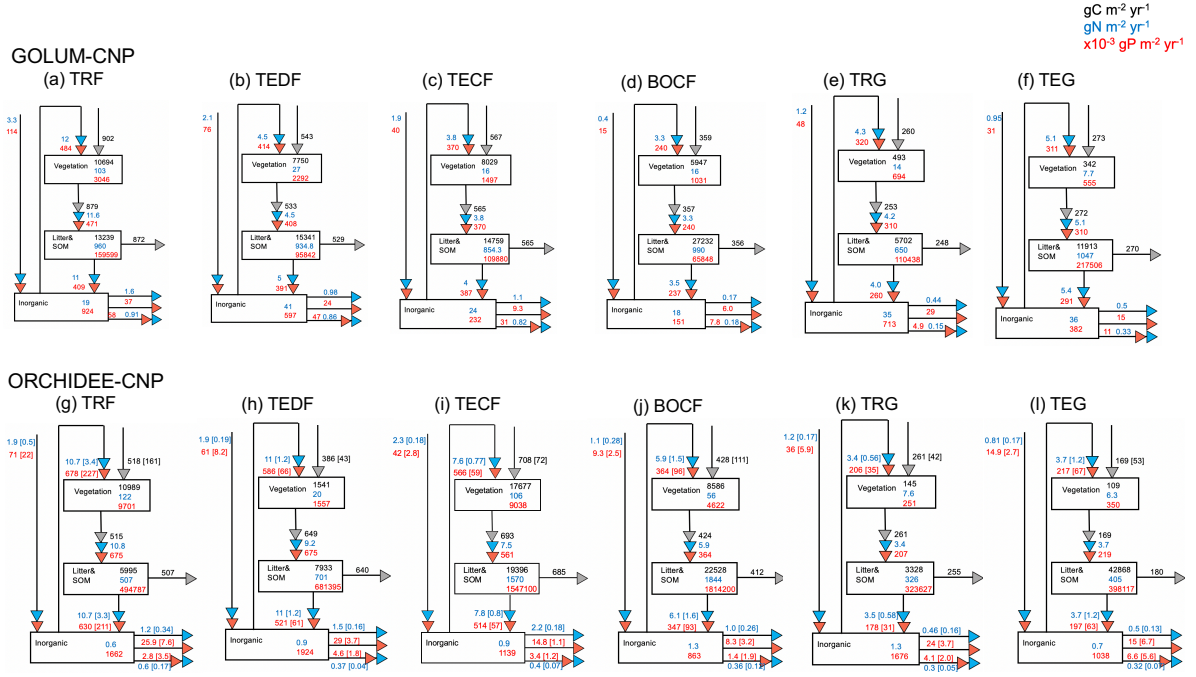


Figure S12 Fluxes and pool sizes of C, N and P for 6 biomes by ORCHIDEE-CNP and GOLUM-CNP. The targeted biomes are tropical rainforests (TRF, a, g), temperate deciduous forests (TEDF, b, h), temperate coniferous forests (TECF, c, i), boreal coniferous forests (BOCF, d, j), tropical/C4 grasslands (TRG, e, k), temperate/C3 grasslands (TEG, f, l). Numbers in square brackets indicate the standard deviations for accounting the spatial spread of C, N and P fluxes.

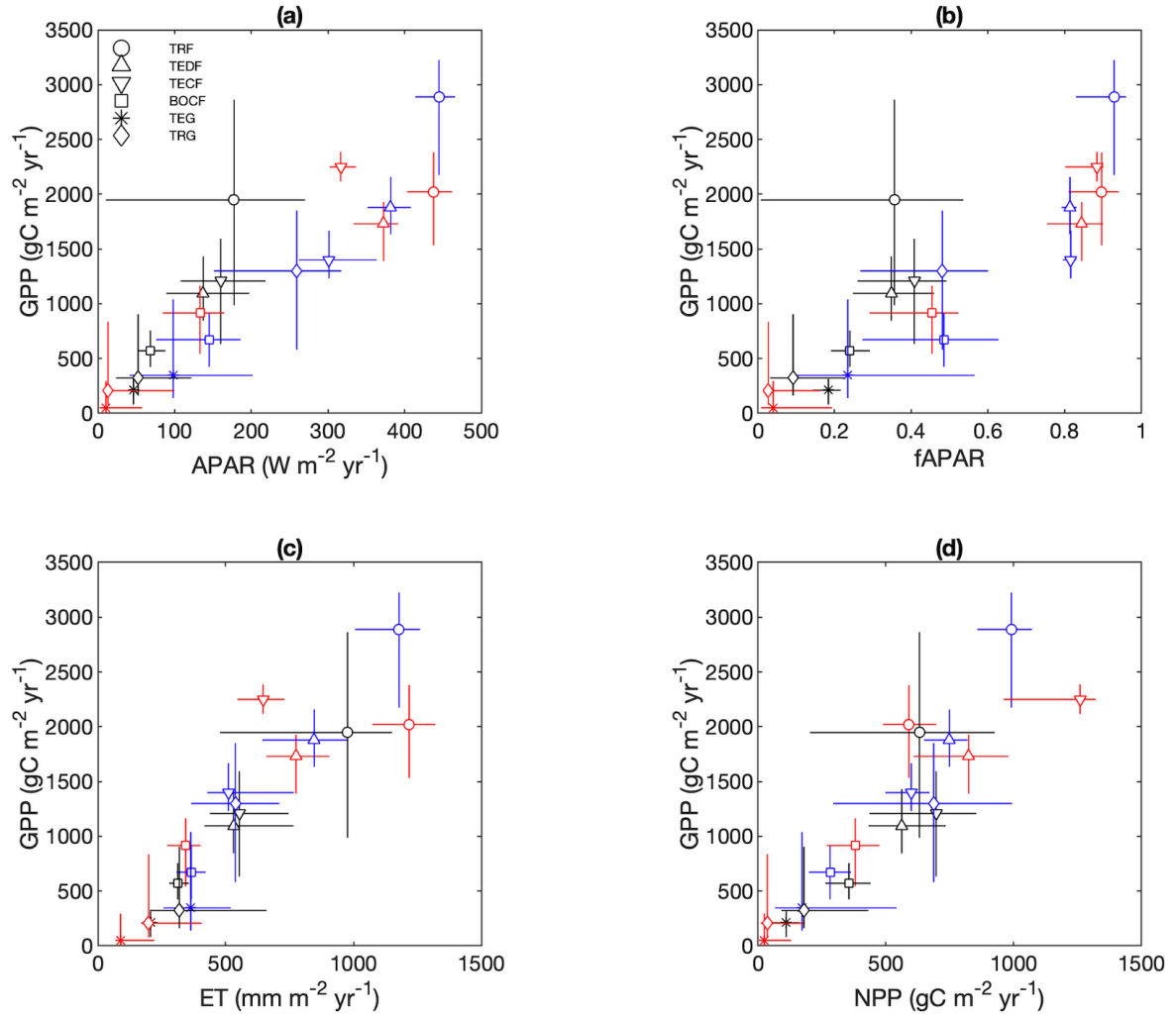


Figure S13 Comparisons between GPP and absorbed light by canopy (APAR; a), fraction of absorbed light by canopy (fAPAR; b) and ecosystem evapotranspiration (ET; c) used by 6 biomes: tropical rainforests (TRF), temperate deciduous forests (TEDF), temperate coniferous forests (TECF), boreal coniferous forests (BOCF), tropical/C4 grasslands (TRG) and temperate/C3 grasslands (TEG). (d) shows the relations between GPP and NPP on biome scale. Reference data (same with Figure 14), ORCHIDEE-CNP and ORCHIDEE are discriminated by color black, red and blue. Error bars indicate the standard deviation of GPP, NPP and resources used by biome.

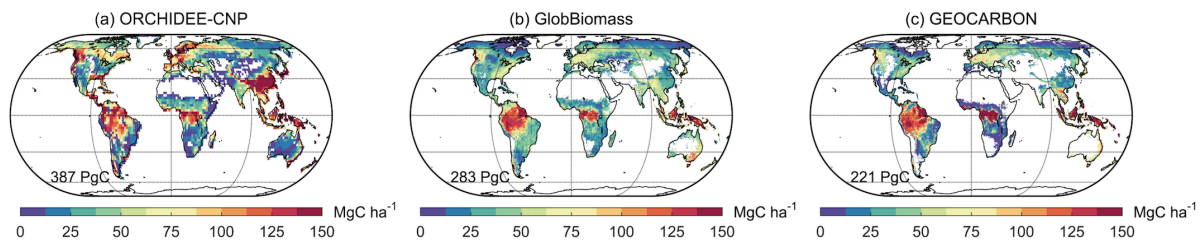


Figure S14 Global pattern of aboveground forest biomass carbon density from ORCHIDEE-CNP and two data-driven map of GlobBiomass and GERCARBON.

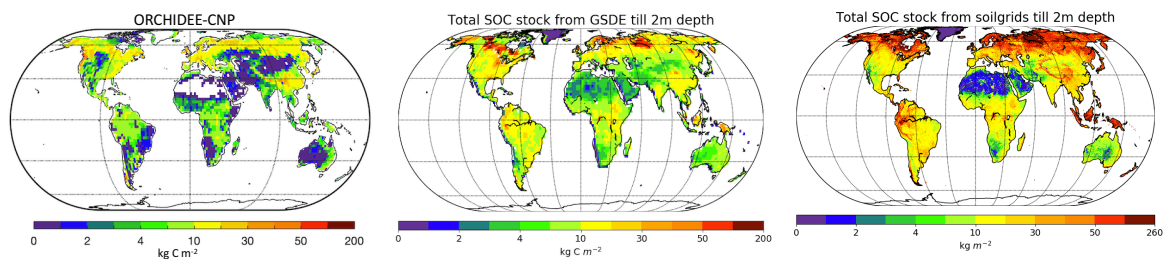


Figure S15 Global pattern of soil organic carbon of 0~2 meters depth from GSDE and Soilgrids and derived from ORCHIDEE-CNP.