**Criteria of selecting publications**

1. New publications were searched on web of science (www.webofknowledge.com), google scholar (https://scholar.google.com/) and www.cnki.net (Chinese publications).

2. Carbon use efficiency (CUE = NPP/GPP) is calculated from the observational values or directly taken from publications. NPP and GPP is based on an annual scale, or growing season for Tundra or boreal area assuming very low GPP and NPP in non-growing season.

3. If NPP is not reported, but Ra (autotrophic respiration), CUE is calculated as:

$$CUE = \frac{GPP - Ra}{GPP} = 1 - \frac{Ra}{GPP}$$

4. GPP is based on eddy covariance or component based (Malhi et al., 2015;Xu et al., 2016).

5. NPP is biometric or harvesting (grass/crop) based estimates (Zanotelli et al., 2013), rather than any model based estimate.

6. Sites with multi-year measurements, an observation of each year was taken as independent value (Campioli et al., 2011). If only the average is given, the mean value will be taken or writing to corresponding author for original data.

7. Only eddy covariance derived-GPP is used if multiple approaches report GPP for the same study.

8. If NPP and GPP are graphically presented, (1) writing to corresponding author for original data; (2) if not, grab tool, such as WebPlotDigitizer (http://arohatgi.info/WebPlotDigitizer/), will be used, however, there might be a small random error.

## Plausibility check

GPP is separated into different components, shown in Figure S1, suggested by(Van Oijen et al., 2010):
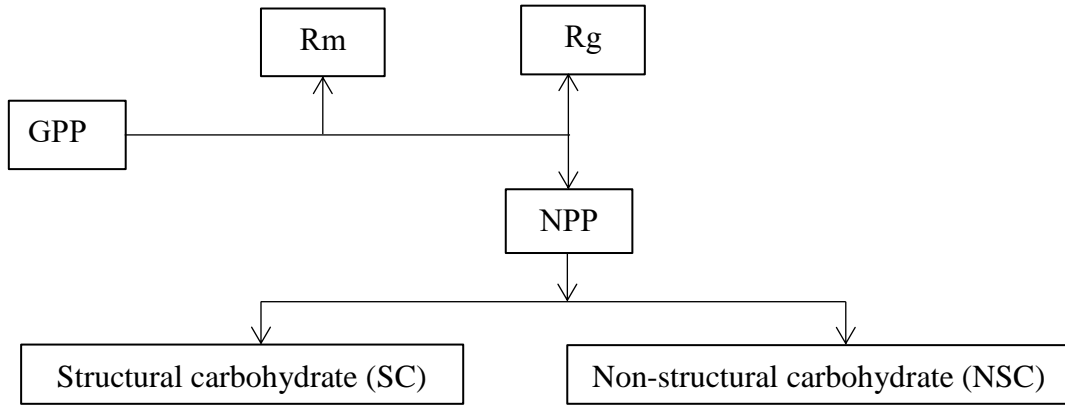
**Figure S1.** Ecosystem carbon flow in terms of maintenance respiration, growth respiration, allocation of NPP to structural carbohydrate (SC) and non-structural carbohydrate (NSC)

The total GPP can be expressed as the sum of respiration and net primary production (NPP):

$$GPP = Rg + Rm + NPP = Rg + Rm + SC + NSC \qquad (1)$$

$$NPP = SC + NSC \qquad (2)$$

$$CUE = NPP/GPP \qquad (3)$$

Assumption: sugars and mineral nutrients are required to produce biomass. Therefore, the growth yield can be expressed by:

$$Yg = \frac{SC}{Rg+SC} \leq 1 \qquad \rightarrow \qquad SC = \frac{Rg \cdot Yg}{1-Yg} \qquad (4)$$

Yg can be measured in the terrestrial ecosystems; i.e. the amount of structural biomass formed per unit of photosynthates. Yg is independent of environmental conditions(De Vries et al., 1974).

Combining (2), (3) and (4) to introduce the carbon use efficiency (CUE) term:

$$NPP = SC + NSC = Yg \cdot \frac{Rg}{1-Yg} + NSC = GPP \cdot CUE \qquad (5)$$

Solving Rg:

$$Rg = \frac{(GPP \cdot CUE - NSC)(1-Yg)}{Yg} \qquad (6)$$

Dividing GPP:

$$\frac{Rg}{GPP} = \frac{(CUE - NSC/GPP)(1-Yg)}{Yg} \geq 0 \qquad (7)$$

40    Defining a unitless term of $\beta$:

$$\beta = \frac{NSC}{GPP} \qquad (8)$$

If the $\beta$ term is known, we know how the photosynthesis (GPP) is allocated to NSC.

Since Yg=[0,1]

$$0 \leq \frac{(1-Yg)}{Yg} \qquad \text{with (7)} \quad \rightarrow \quad CUE - \beta \geq 0 \quad \rightarrow$$

45    $$\beta \leq CUE \qquad (9)$$

$$Rm = GPP - GPP \cdot CUE(NPP) - Rg = GPP(1 - CUE) - \frac{(GPP \cdot CUE - S)(1-Yg)}{Yg} \qquad (10)$$

$$\frac{Rm}{GPP} = 1 - CUE - \frac{(CUE-\beta)(1-Yg)}{Yg} \geq 0 \qquad (11)$$

From the different publications, measured Rg = 0.8 is taken as the most favorable value: (Schnapp et al., 1991) (Rambal et al., 2004) (Cannell and Thornley, 2000) (Gifford, 1995) (Lavigne and Ryan, 1997)
50    (Thornley and Cannell, 2000)

Thus, equation (11) can be further simplified:

$$1 - CUE - \frac{(CUE-\beta)}{4} \geq 0 \qquad \rightarrow \quad CUE \leq \frac{4+\beta}{5} \qquad (12)$$

Combing (9) and (12):

$$\beta \leq CUE \leq \frac{4+\beta}{5} \qquad (13)$$

55    $\beta$, the allocation of GPP to NSC, determines CUE.

In the publications, the NSC is often expressed by percentage, which is:

$$NSC\% = \frac{NSC}{Biomass} \qquad \rightarrow \quad NSC = Biomass \times NSC\% \qquad (14)$$

For any time t (year, for consistence to GPP),

$$NSC_t = Biomass_t \times NSC\%_t \qquad (15)$$

60    And for one year after: t+1

$$NSC_{t+1} = Biomass_{t+1} \times NSC\%_{t+1} \qquad (16)$$

Therefore, the changes of NSC as a result of photosynthesis (GPP) could be:

$$NSC_{t+1} - NSC_t = Biomass_{t+1} \times NSC\%_{t+1} - Biomass_t \times NSC\%_t \qquad (17)$$

It is assumed that NSC% between two near years is the same or similar, thus eq. (17) is further simplified:

$$\Delta NSC = NSC_{t+1} - NSC_t = (Biomass_{t+1} - Biomass_t) \times NSC\%_t = NPP \times NSC\% \quad (18)$$

From eq. (8), based on one year scale:

$$\beta = \frac{NSC}{GPP} = \frac{\Delta NSC}{GPP} = \frac{(Biomass_{t+1} - Biomass_t) \times NSC\%}{GPP} \quad (19)$$

In view of ecosystem scale, biomass should include different carbon components, such as overstory, understory, roots and litter(Roxburgh et al., 2005). Therefore, since the loss of carbon from other fluxes, such as volatile organic C compounds and root exudations, is difficult to measure and only account a small amount of carbon pool, $Biomass_{t+1} - Biomass_t \approx NPP$. Thus, Eq. 19 can be further simplified:

$$\beta = \frac{NPP \times NSC\%}{GPP} \quad (20)$$

From the physiological view, NPP*NSC% is considered as the amount of GPP to non-structural carbohydrate.

Combining eq. 13,

$$CUE_{max} = f(\beta_{max}) = f(NSC\%_{max}) \quad (21)$$

$$CUE_{min} = f(\beta_{min}) = f(NSC\%_{min}) \quad (22)$$

From the measured data by averaging for different seasons for different species, NSC% = [2%, 23%], detailed as follows:

15% of the total net radiation for maize and 7% for soybean(Meyers, 2004)

Stem NSC of 85 wood species: S/P=2.4-23% (Poorter and Kitajima, 2007)

Total tree NSC of ten species: 5%-14% (O'Brien et al., 2014)

For all organs of NSC of four species: 5%-20%(Newell et al., 2002)

NSC for shrubs:16%-18.2% (Marquis et al., 1997)

NSC of Douglas-fir trees at different heights: 4%-15%(Woodruff and Meinzer, 2011)

Three Mediterranean species: 2%-15%(Rosas et al., 2013)

Based NPP and GPP dataset of 434 observations,

$$\beta_{max} = 0.2146$$

$$\beta_{min} = 0.0038$$

Therefore, $0 \le CUE \le 0.843$

**Table S1. Variables used for predicting temporal and spatial CUE.**

| | Variables | Abbreviation | Type | Type of variability | Sources |
|---|---|---|---|---|---|
| Climate | Annual mean temperature | AMT | Split | Yearly | https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.01/, (Harris et al., 2014) |
| | Annual mean precipitation | AMP | Split | Yearly | |
| | Potential evapotranspiration | PET | Split | Yearly | |
| | Diurnal temperature range | DTR | Split | Yearly | |
| | Vapour-pressure deficit | VPD | Split | Yearly | NCEP/NCAR reanalysis Sheffield et al. (2006) |
| | Nitrogen deposition | Ndep | Split | Yearly | https://www.isimip.org/gettingstarted/details/24/(Lamarque et al., 2013) |
| | Sensible heat flux | Heat | Split | Yearly | BGC-Jena[7] |
| | Palmer Drought Severity Index | PDSI | Split | Yearly | https://www.esrl.noaa.gov/psd/data/gridded/data.pdsi.html(Dai et al., 2004) |
| Satellite | GIMMS leaf area index | GimmsLAI | Split | Yearly | http://sites.bu.edu/cliveg/datacodes/(Zhu et al., 2013) |
| | GIMMS normalized difference vegetation index | GimmsNDVI | Split | Yearly | |
| | GIMMS Fraction of Absorbed Photosynthetically Active Radiation | GimmsfPAR | Split | Yearly | |
| Soil | Soil carbon stock (0-30 cm) | SoilST | - | Static | https://soilgrids.org/#!/?layer=TAXNWRB_250m(Hengl et al., 2017) |
| Site | Management | Manag | - | Static | Publications |
| | Climate zone | CliZ | - | Static | |
| | Ecosystem type | EcoT | - | Static | |

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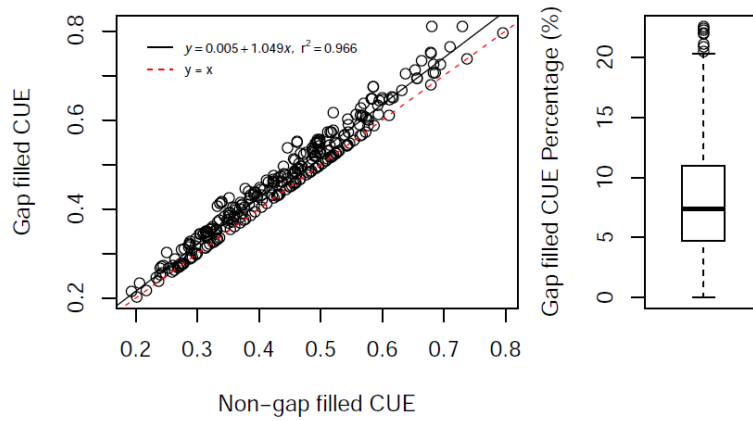

**Figures**

**Figure S2.** Carbon use efficiency (CUE) change after gap-filling in forest ecosystem. The gap-filling
process followed Vicca et al. (2012). There was a strong correlation between the gap filled CUE and
non-gap filled CUE ($R^2$=0.967). After the gap-filling, the mean CUE increased by 7% and there is no
significant impact on CUE trend.

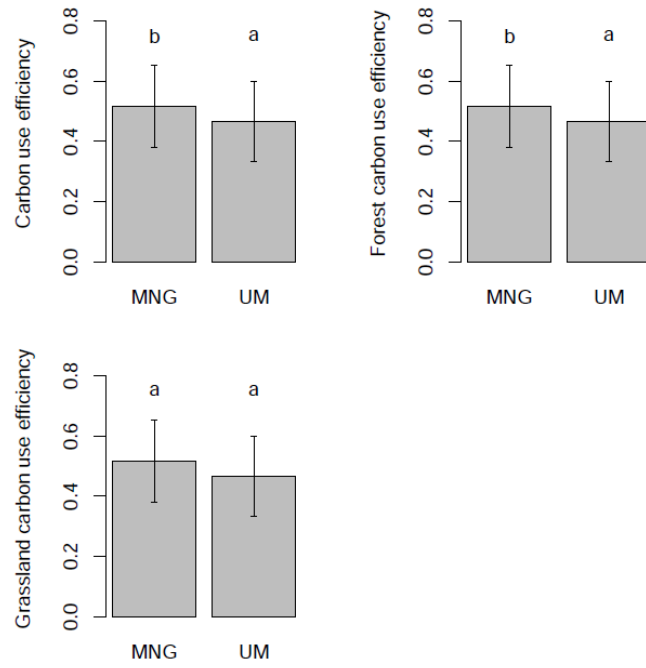
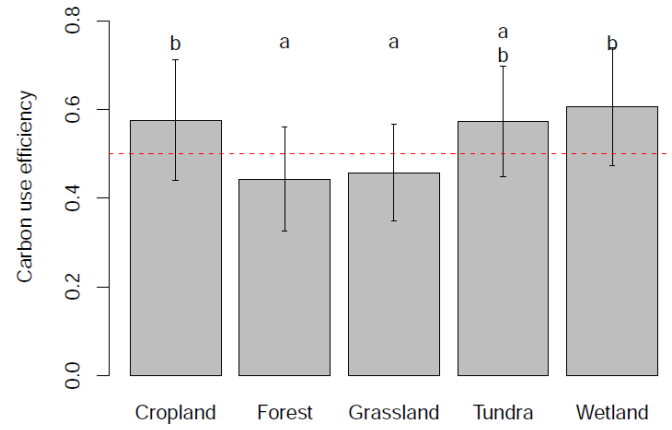



**Figure S3.** Effects of site management on CUE of all ecosystem types, forest and grass ecosystem. Different letters above the plots indicate significant difference at $p < 0.05$. MNG = managed, UM = unmanaged. Values are mean ± 1 standard deviation. This result indicated that site management significantly increased CUE in forest ecosystems, but not in grass ecosystems. Therefore, managed forest sites were excluded for spatial modelling (details in Methods).

110 **Figure S4.** One-way ANOVA analysis of CUE after removing managed forest sites. Different letters above the plots indicate significant difference at $p < 0.05$. Values are mean ± 1 standard deviation. This results indicated that after removing the managed forest site, the significance of CUE among different ecosystem types did not change (Fig. 1) and removing the managed forest sites for modelling CUE is appropriate.

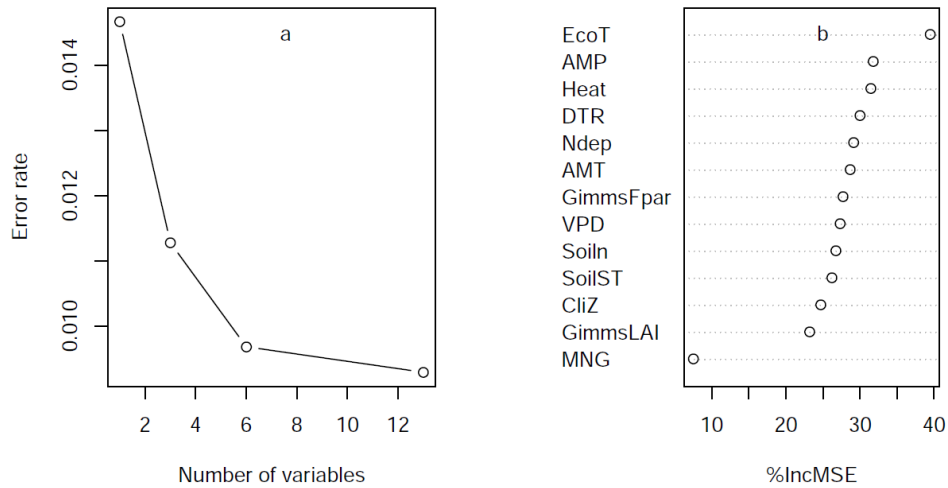



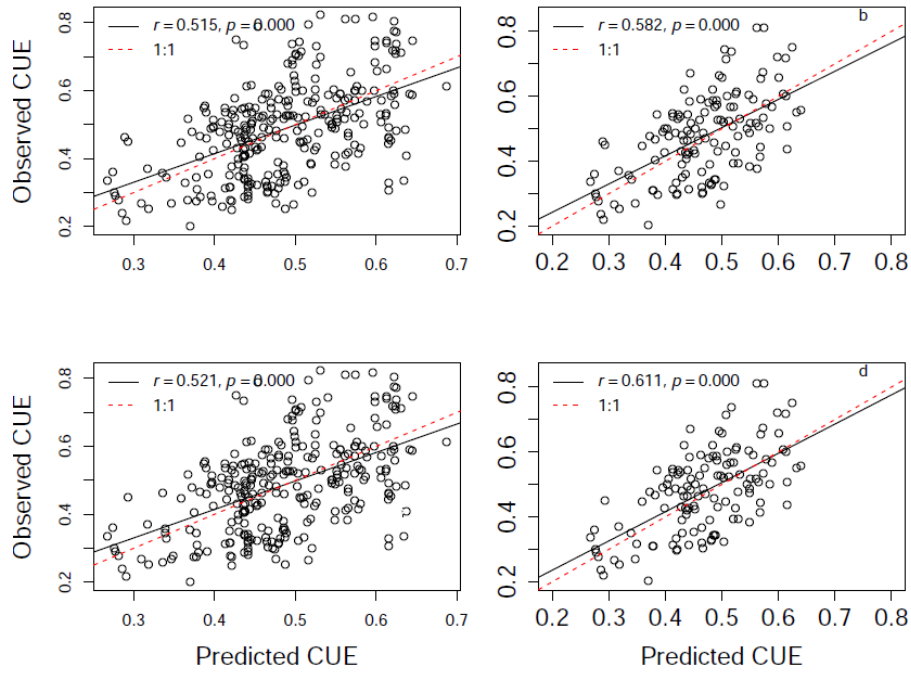
**Figure S5.** (a) The error rate along with the number of the variables used to predict CUE using Random Forest by 10-fold cross-validation, (b) importance values of variables estimated by Random forest expressed by the mean decrease of model accuracy. These selected variables can explain about 51% variance of CUE and the ecosystem type was the most important variables with highest importance value. The higher of %IncMSE is, the higher the variable importance is. After the variables selection, the first six variables with higher importance values were selected to predict CUE and these variables can explain 49% variance of CUE. Noticeably, although management increased CUE, it had little power to explain the variation of CUE analysed by random forest. GIMSS NDVI and PET were removed for modelling due to multi-collinearity.

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**Figure S6.** (a) Leave-one-site-out, (b) mean-site, (c) leave-one-latitude-out and (d) mean-latitude cross-validation of CUE. Leave-one-site-out cross-validation (leave-one-latitude-out) means leaving all year observations out within the same site (latitude) and predicted by the rest observations using RF for each site (latitude). Mean-site cross-validation (mean-latitude) means that building a RF model using all site-year observations and validating mean-site (mean-latitude) CUE as a new dataset (one mean value for each site (latitude) regardless of the number of the observational years).

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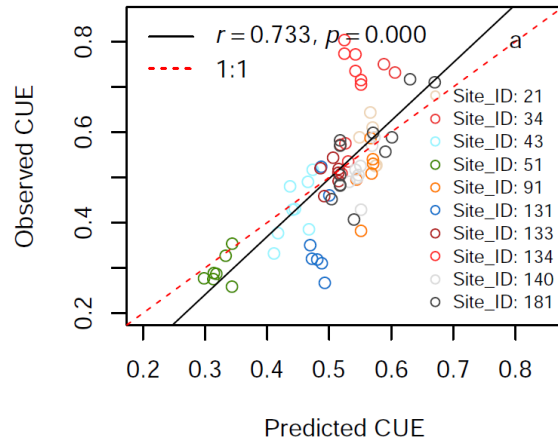
**Figure S7.** The relationship between CUE extracted from the predicted CUE map and CUE observations for sites with multi-year (longer than four years) observations.
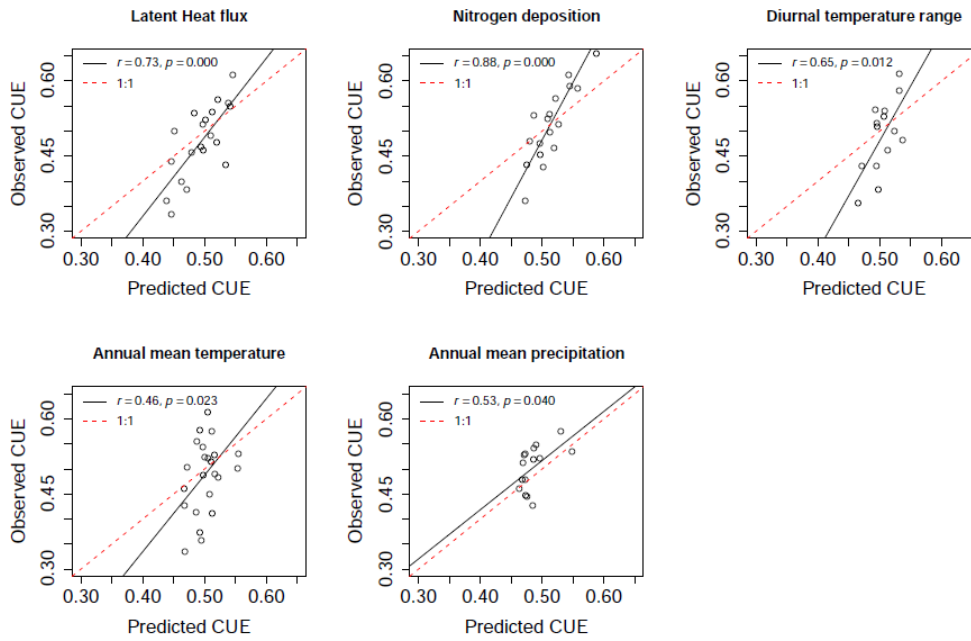
**Figure S8.** The relationships between CUE extracted from the predicted CUE map and CUE observations within the same selected range of the predictors (latent heat flux, annual mean precipitation, annual mean temperature, nitrogen deposition and diurnal temperature range). First, the values of predictors were divided into different ranges; second, the predicted CUE using RF was masked by those ranges; third, the mean masked predicted CUE and mean observed CUE within the same range were plotted.

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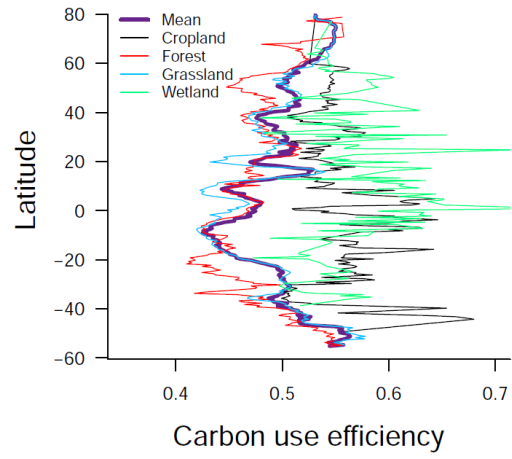
**Figure S9.** Latitudinal distribution of CUE of forest (red), grass (blue), wetland (green), crop (black) and total mean (purple). Due to the limited number of grids of wetland, this figure may not reflect the "real" latitudinal distribution of wetland CUE.

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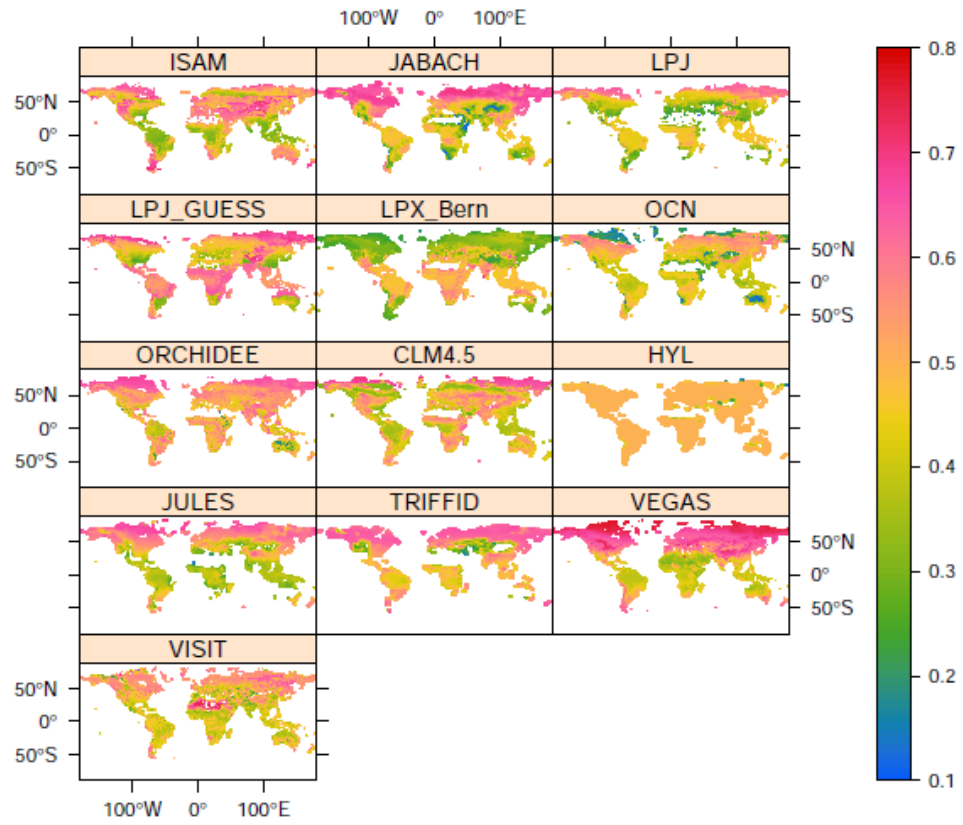
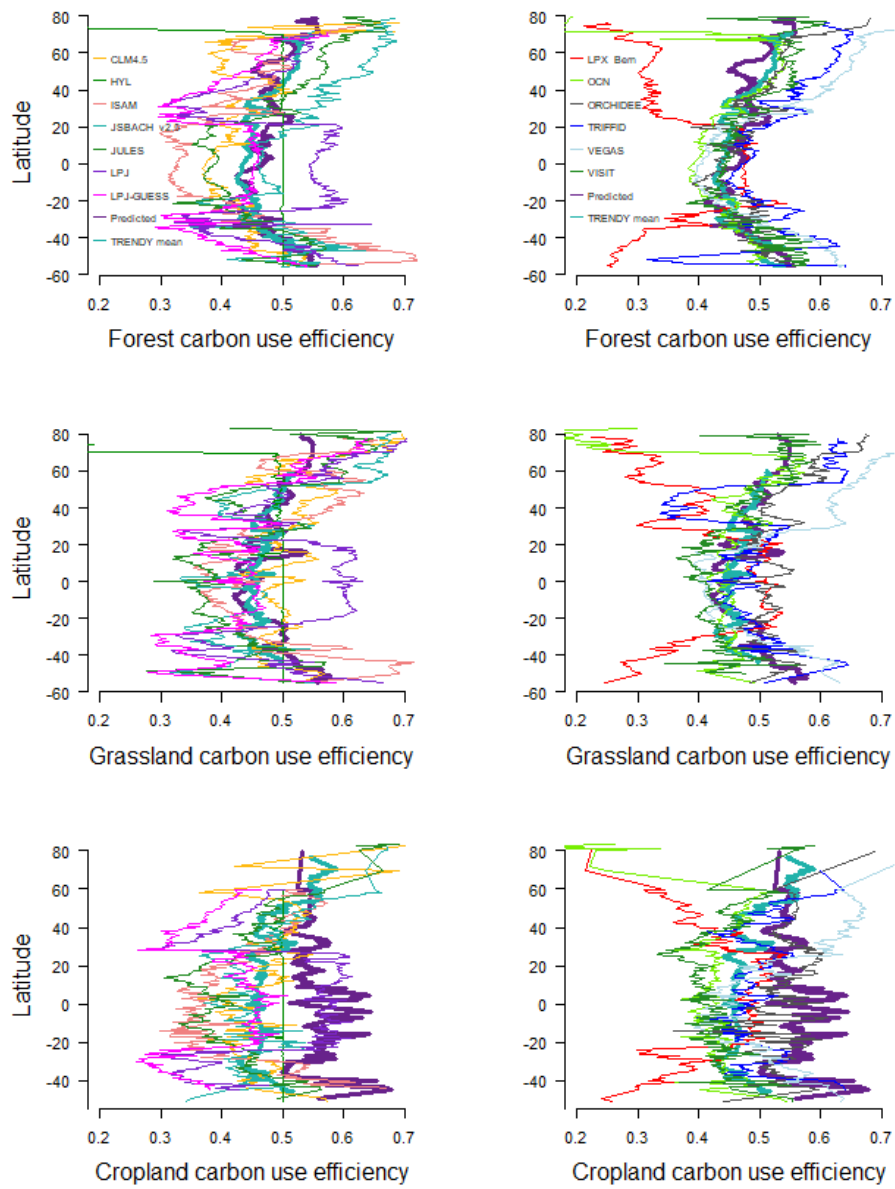


**Figure S10.** CUE of 13 TRENDY models

150 **Figure S11.** Latitudinal pattern of TRENDY-CUE for forest, grass and crop ecosystems. The bold purple line represents predicted CUE. Due to a limited number of grid cells for wetland, the latitudinal CUE was not presented.

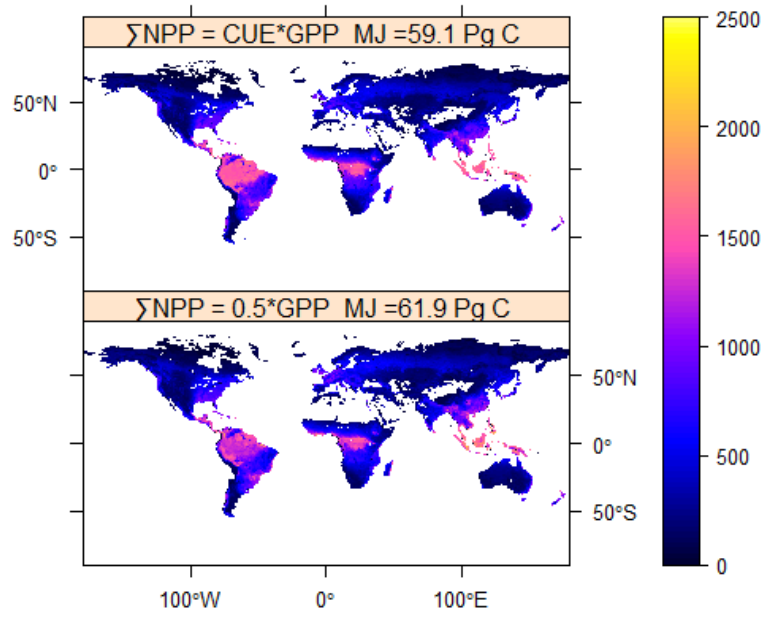



**Figure S12.** Constant and variable CUE based NPP (g C m$^{-2}$ a$^{-1}$). Total constant CUE (0.5*GPP) based estimation of NPP was 61.9 Pg C a$^{-1}$ globally, which was 2.8 Pg C a$^{-1}$ higher than that of variable CUE (data-driven CUE*GPP) based estimation of NPP.

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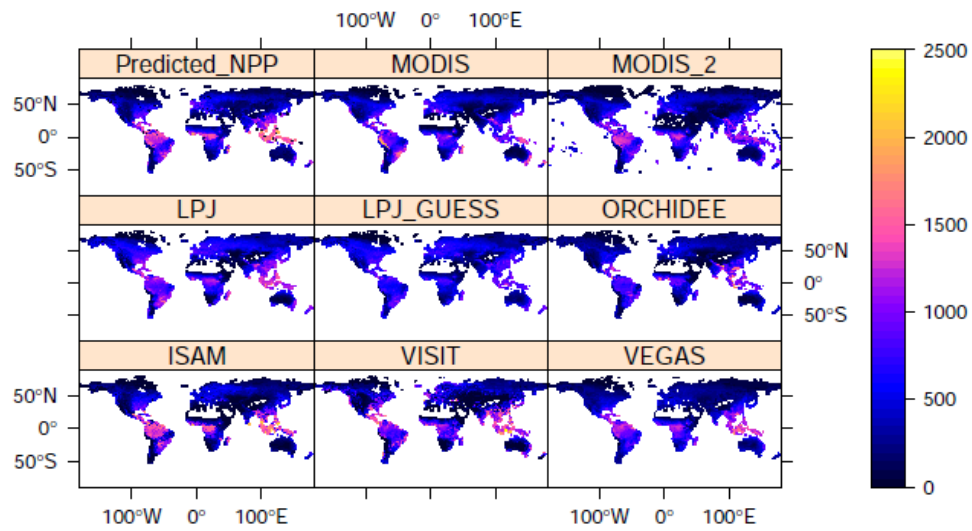
**Figure S13.** Global distribution of predicted NPP, MODIS NPP and TRENDY NPP (g C m$^{-2}$ a$^{-1}$). MODIS_2 NPP estimated from MODIS GPP multiplied by constant CUE (0.5).

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