## S1  Flux Tower Locations

**Table S1.** List of Eddy Covariance Towers used in model development and validation of model improvements.

| EC Tower Name | Latitude | Longitude | PFT | Reference | Source |
|---|---|---|---|---|---|
| Development | | | | | |
| US-EML | 63.8784°N | -149.2536°W | Shrub/Grass | Belshe et al. (2012) | http://ameriflux.lbl.gov/sites/siteinfo/US-EML |
| CA-OAS | 53.62889°N | -106.19779°W | BDT | Black (2016) | http://sites.fluxdata.org/CA-Oas/ |
| CA-QC2 | 49.7598°N | -74.5711°W | NET/BDT | Margolis (2018) | http://ameriflux.lbl.gov/sites/siteinfo/CA-Qc2 |
| RU-SKP | 62.2550°N | 129.1680°E | NDT | Maximov (2016) | http://sites.fluxdata.org/RU-SkP/ |
| Towers Witheld | | | | | |
| US-ATQ | 70.4696°N | -157.40896°W | Shrub/Grass | Oechel et al. (2014) | http://sites.fluxdata.org/US-Atq/ |
| CA-NS1 | 55.87917°N | -98.48389°W | NET | Goulden (2016b) | http://sites.fluxdata.org/CA-NS1/ |
| CA-NS6 | 55.91667°N | -98.96444°W | Shrubs | Goulden (2016a) | http://sites.fluxdata.org/CA-NS6/ |
| CA-NS7 | 55.63583°N | -99.94833°W | Shrubs | Goulden (2016a) | http://sites.fluxdata.org/CA-NS7/ |
| CA-SF1 | 54.4850300°N | -105.81757°W | NET | Amiro (2016) | http://sites.fluxdata.org/CA-SF1/ |
| CA-QFO | 49.6925°N | -74.34206°W | NET | Margolis (2016) | http://sites.fluxdata.org/CA-Qfo/ |
| CA-GRO | 48.2167°N | -82.1556°W | NET | McCaughey (2016) | http://sites.fluxdata.org/CA-Gro/ |
| RU-SAM | 72.3738°N | 126.4958°E | Grass | Kutzbach et al. (2002-2014) | http://sites.fluxdata.org/RU-Sam/ |
| RU-TKS | 71.59427°N | 128.88782°E | Grass | Aurela (2016) | http://sites.fluxdata.org/RU-Tks/ |
| RU-COK | 70.82914°N | 147.49428°E | Shrub | Dolman et al. (2016) | http://sites.fluxdata.org/RU-Cok/ |
| FI-SOD | 67.36239°N | 26.63859°E | NET | Aurela et al. (2016) | http://sites.fluxdata.org/FI-Sod/ |

## S2  Model Development Supporting Information
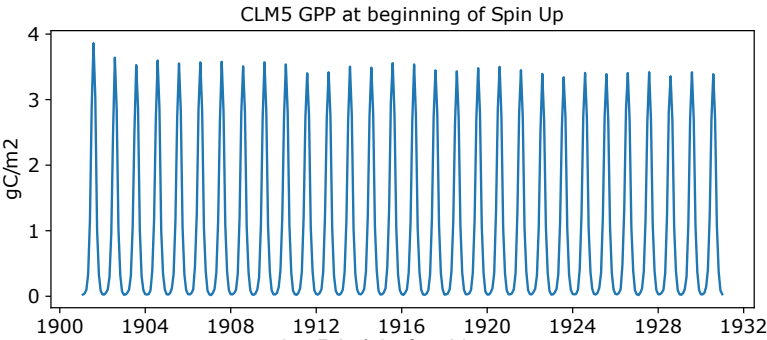
**Figure S1.** CLM5.0 Output During Spin-Up of Model Development. We see an initial spike in GPP at the start of the simulation. Within 20 years, the variability is due to climate forcing from cycling the years 1901 to 1920.
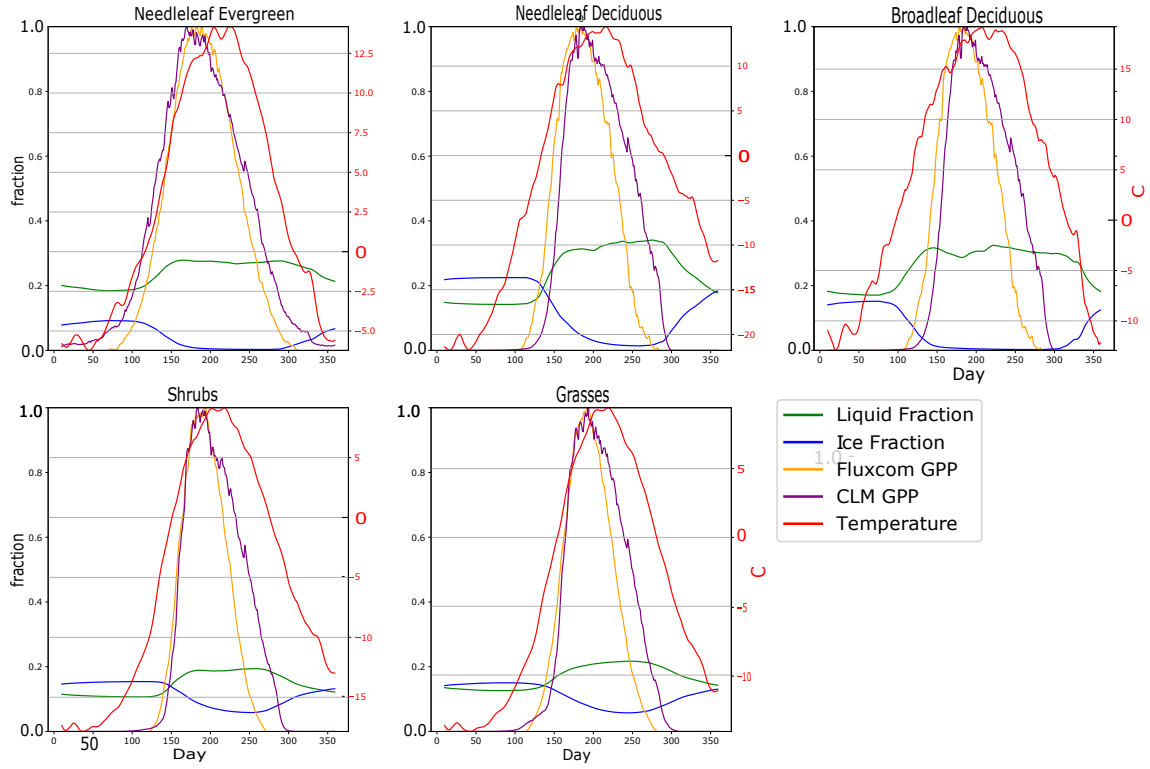
**Figure S2.** The timing of daily GPP throughout the year in FluxCom and CLM compared to 3rd layer soil temperature, soil ice and soil water. Panels are contain yearly time series sorted by each PFT and latitude band. GPP and soil water/ice have been scaled to be fractional, since timing of photosynthesis was the focus of this analysis.
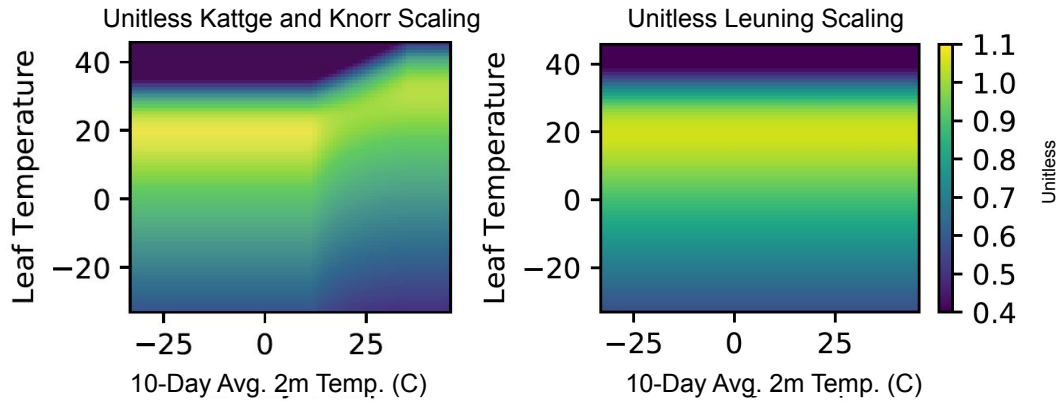
**Figure S3.** The temperature acclimation scaling for Kattge and Knorr (2007) (left) Below $11°C$, $J_{max}$ and $V_{cmax}$ are scaled high with this unitless values with a visible discontinuity going to warmer temperatures. In the parameterization from Leuning (2002) (right), the maximum scale value is decreased and contains no discontinuity.

**Table S2.** Model Development Effects on maximum summer GPP compared to CLM5.0 release by PFT. The model names represent the type of model improvement and correspond to the list of model improvements in Section 3.3. For example, "Onset" indicates that improvements were made to the phenology onset scheme. Each model development listed builds on the the simulation before it. ↓ signifies a $< 25\%$ change in model simulation. ⇓ signifies a $> 25\%$ change in model simulation.

| Model Dev. Name | NET | NDT | BDT | Shrubs | Grass |
|---|---|---|---|---|---|
| 1. Onset | - | ↑ | ↑ | ↑ | ↑ |
| 2. Offset | - | ↓ | ↓ | ↓ | ↓ |
| 3. Maximum day | ↓ | ↓ | ↓ | ↓ | ⇓ |
| 4. Leuning Scaling | ↓ | ↓ | ↓ | ↓ | ↓ |
| 5. Predictive Spring $J_{max}$/$V_{cmax}$ | - | ↑ | ↑ | ↓ | ↓ |
| 6. Dynamic Stem Leaf Ratio | - | ↑ | ↑ | ↓ | - |
| 7/8. Realistic Root-Leaf Ratio | - | ↑ | ↑ | ⇓ | ⇓ |
| All Development | ↓ | ↑ | ↑ | ⇓ | ⇓ |

## S3  Night-time Temperature Scaling

We also find that there is a bug in the computation of the 10-day leaf temperature, where the day time temperature was double
5   counted in Equation 1, and we corrected it to have both $T_{daytime}$ and $T_{nighttime}$ included.

$$T_{leaf,10day} = \frac{daylength * T_{daytime} + (86400 - daylength) * T_{nighttime}}{86400} \tag{1}$$

We find that correcting this 10-day leaf temperature calculation, generally increases productivity in CLM5.0 PFTs in the
Arctic, but by less than 0.5 gC/m$^2$. $T_{leaf,10day}$ is used to calculate the maximum daily change in J$_{max}$ and V$_{cmax}$ by calculating
the enzyme turnover rate at a particular temperature. Colder temperatures allow J$_{max}$ and V$_{cmax}$ to change less each time step,
10  and as we noted previously, the default winter predictions are high for the Arctic. Thus, without our modification of average
J$_{max}$ and V$_{cmax}$ in winter, this bug fix would increase the high productivity bias.
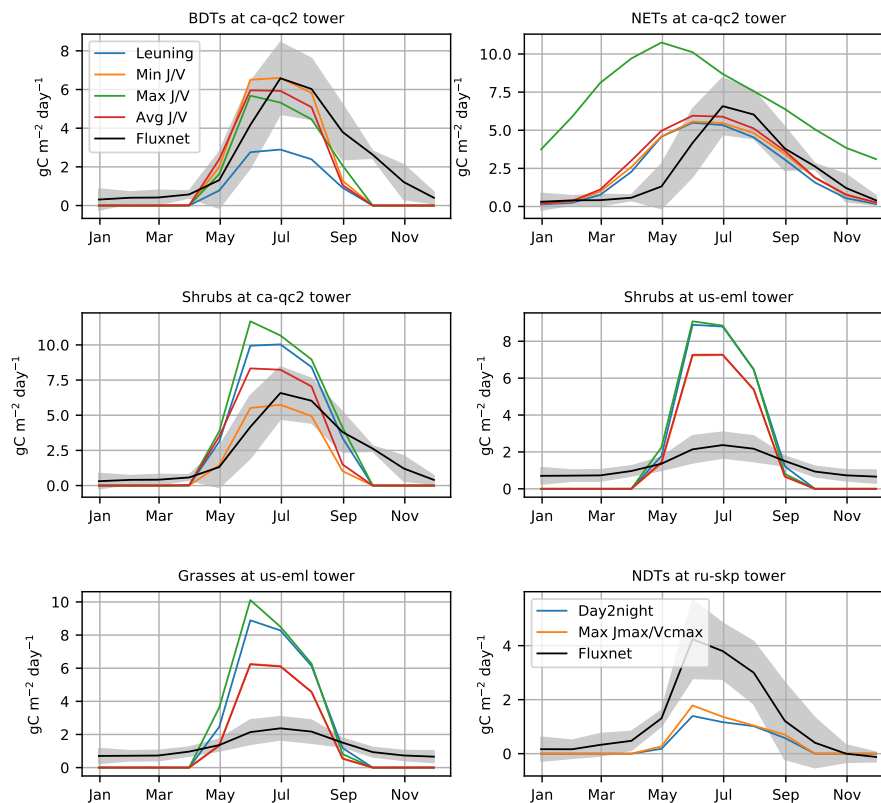
**Figure S4.** GPP from Intermediate Model Development Steps at Flux Towers for initializing $J_{max}$ and $V_{cmax}$ in spring. Sensitivity test involved increasing the default value (max test in orange) and decreasing the default value (min. test in green) compared to simulations incorporating on the daylight and Leuning scaling changes (blue). The red line depicts the model recommendation choice from the main paper text, where $J_{max}$ and $V_{cmax}$ are initialized on the average values from the previous year. The GPP measured (black) at specific flux towers is included for comparison. Bottom right panel only includes a point test of increasing the default spring value (orange)
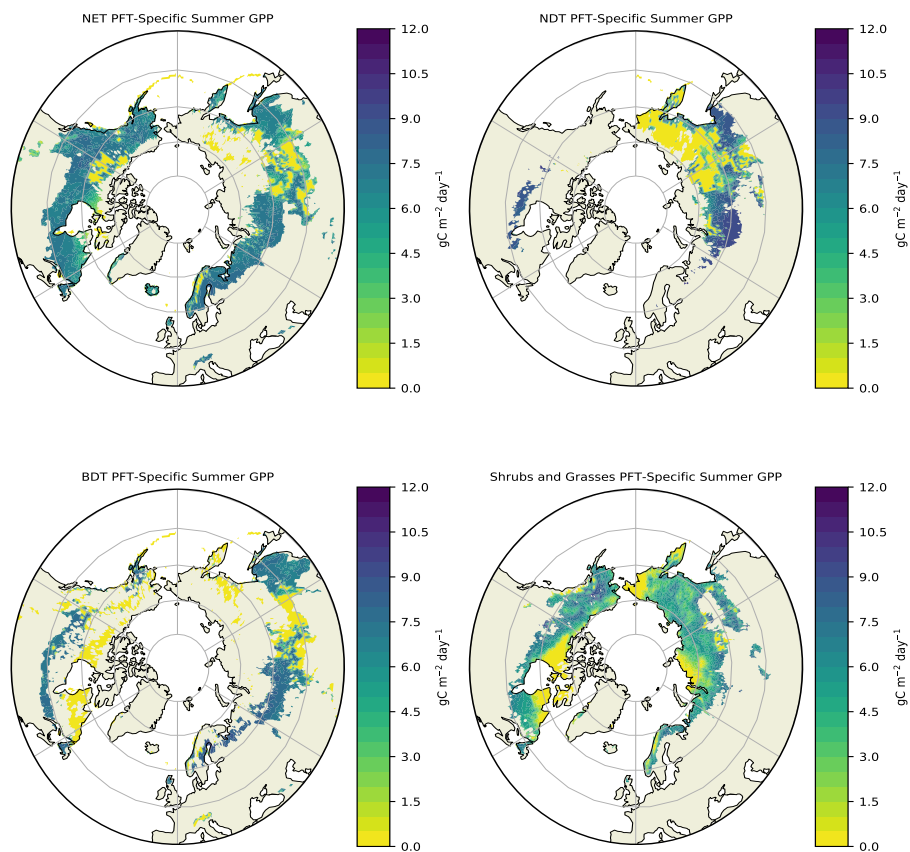
**Figure S5.** Summer GPP in our model recommendation for PFT specific output. Note large areas of GPP=0 in the top right panel for NDT indicating the "dead zones" in CLM5.0 where we were not successful in bringing alive again systematically. NET, BDT, shrubs and grasses also contain "dead zones", but not in as critical of an area as the larch forest of Siberia.
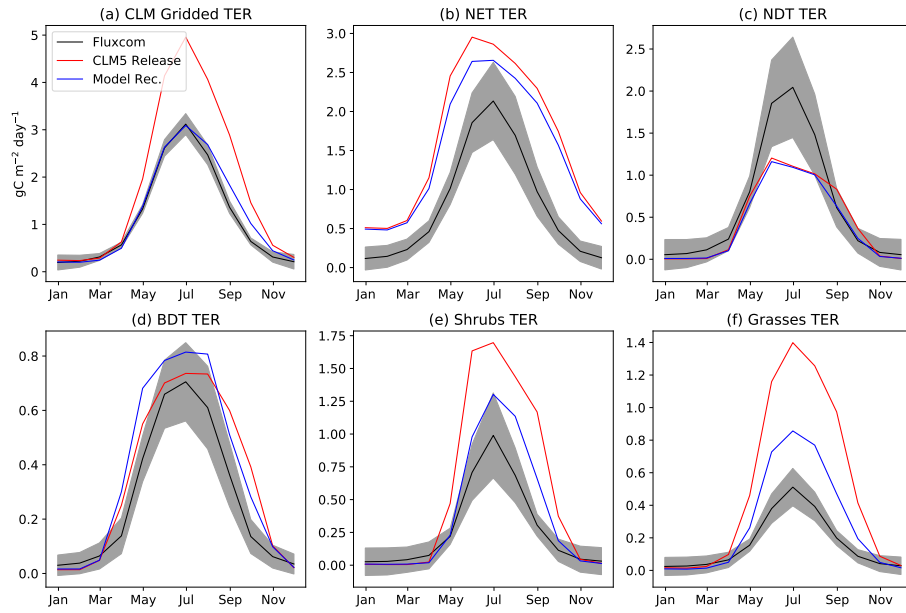
**Figure S6.** Seasonal TER for gridded CLM output and PFT Specific Output. Comparing CLM Release (red) to our Model Recommendation (blue) to FluxCom (black).
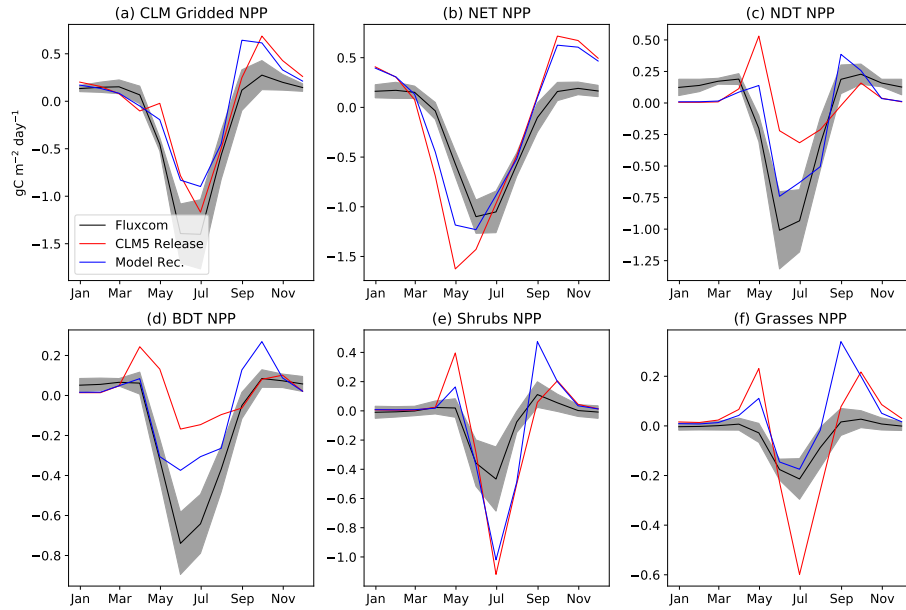
**Figure S7.** Seasonal NEE for gridded CLM output and PFT Specific Output. Comparing CLM Release (red) to our Model Recommendation (blue) to FluxCom (black).
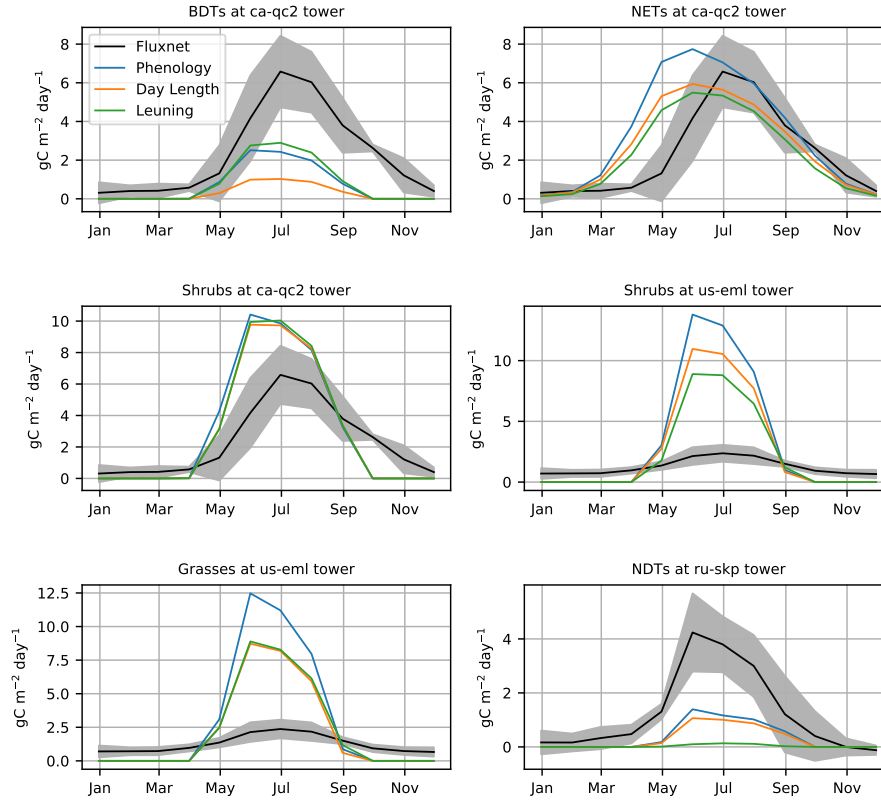
**Figure S8.** GPP from Intermediate Model Development Steps at Flux Towers for scaling $J_{max}$ and $V_{cmax}$ using daylight (orange) and Leuning (green) compared to simulations incorporating on the phenology changes (blue). The GPP measured (black) at specific flux towers is included for comparison.
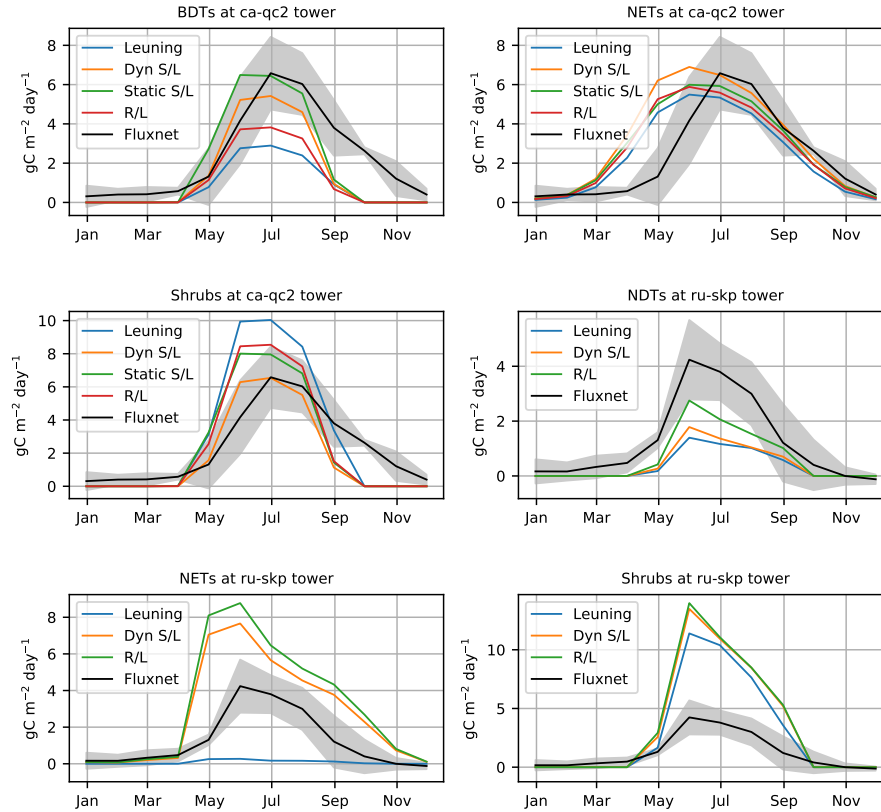
**Figure S9.** GPP from Intermediate Model Development Steps at Flux Towers for carbon allocation parameters. Dynamic Stem Leaf generally improves the GPP simulation (orange). Sensitivity tests are done using a static value (green) for stem-leaf allocation, but static values here were not clearly supported by observations and did not improve the simulation of shrubs. Observationally based values for root-leaf allocation (R/L= red,green) generally increase productivity at these points. Comparisons are done against previous model development step incorporating the Leuning scheme (blue). The GPP measured (black) at specific flux towers is also included for comparison.
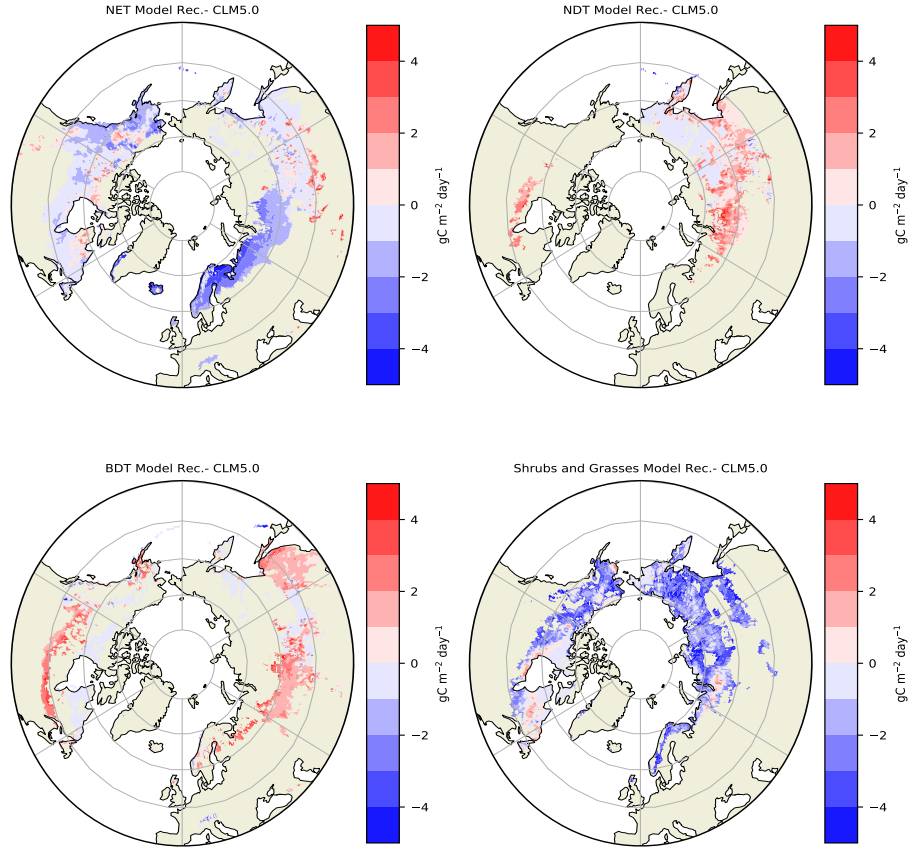
**Figure S10.** PFT Specific Summer GPP difference between CLM5.0 release and Model Rec. (ModelRec.-CLM5.0). Starting in the top left panel and going left to right, we lower the productivity of NETs across most of the ABZ. NDTs increase in productivity, except where GPP=0 in the CLM5.0 release. We did not increase the number of non-productive NDTs grid cells. BDTs also increased in productivity during the summer in line with observations. We lowered the productivity of grasses and shrubs in the tundra substantially.
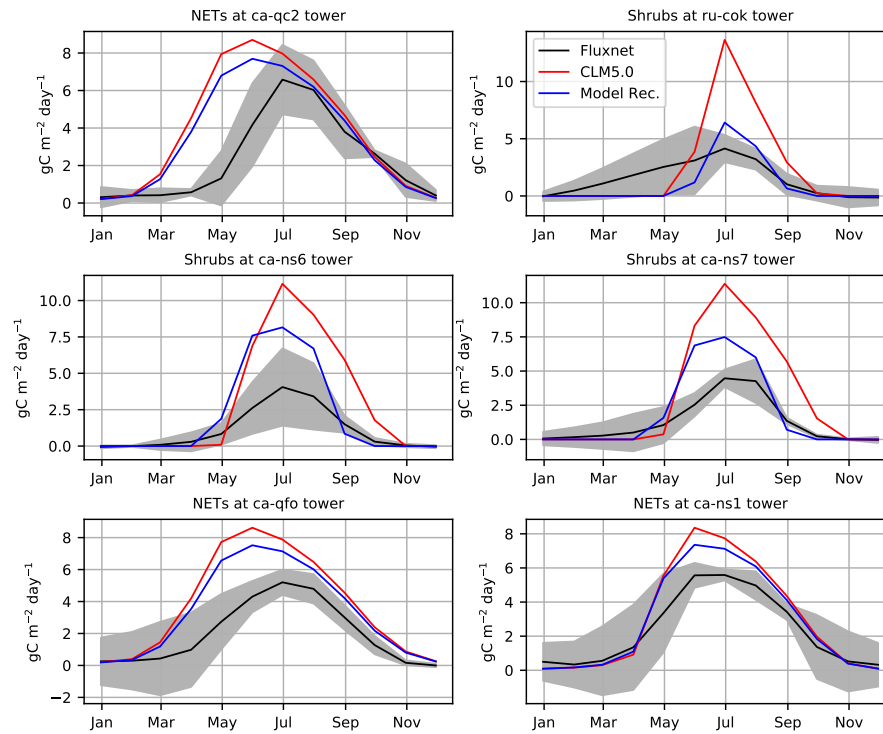
**Figure S11.** Additional Flux Tower Comparisons for PFTs that were not dominant on the gridcell.
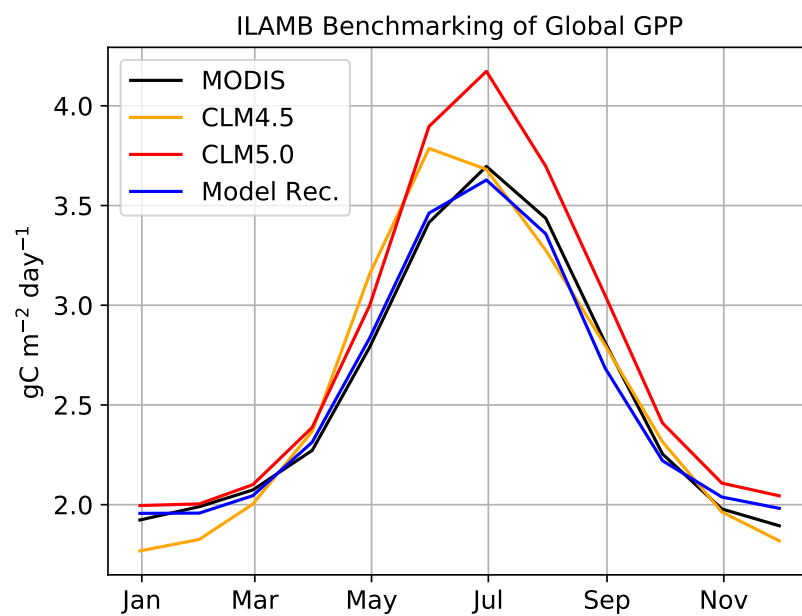
**Figure S12.** Seasonal Global GPP Benchmakred in ILAMB. Our model recommendation for the ABZ is applied globally and compared against MODIS GPP, CLM4.5 and CLM5.0.

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