Supplement of

Decomposing reflectance spectra to track gross primary production in a subalpine evergreen forest

Rui Cheng et al.

Correspondence to: Rui Cheng (rui.cheng@caltech.edu) and Christian Frankenberg (cfranken@caltech.edu)

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S1. GCC convolution functions

Figure S1. The convolution function of RGB channels used in GCC (Sonnentag et al., 2012) is overlaid with the chlorophyll Jacobian \( \frac{\partial \log(R)}{\partial c_{chl}} \) (dashed-dotted) and the carotenoid Jacobian \( \frac{\partial \log(R)}{\partial c_{car}} \) (dotted).

S2. Three regimes of LUE

S2.1. APAR measurement

Seven pairs of up and down-looking PAR sensors (SQ-500-SS; Apogee Instruments, Utah, US) above and below the canopy was used to calculate fPAR in half-hourly intervals. One pair of sensors was installed above the canopy on the same tower where PhotoSpec is located (measuring incoming PAR and reflected PAR). The other six pairs of sensors were installed below the canopy (measuring reflected and transmitted PAR). The derivation of APAR is shown in the following graph. fPAR was smoothed with an 8-point (4 hour) running mean and 20-day running mean to remove the noise in the measurements. The first fPAR measurement started on 8 Aug 2017 (DOY 220).
Figure. S2a. A demonstration for APAR calculation.

**S2.2. Light limited and daily averaged LUE**

At low light intensity, photosynthesis is light limited. We followed the format of Eq. (1) to define light-limited LUE ($\text{LUE}_{\text{light}}$) as the fitted slope of APAR against GPP at PAR between 100 and 500 $\mu$mol m$^{-2}$ s$^{-1}$. We calculated $\text{LUE}_{\text{light}}$ from half-hourly GPP and APAR for each day. We also defined a more generalized effective daily LUE ($\text{LUE}_{\text{total}}$) as the daily averaged ratio of GPP to APAR during the day. This effective daily LUE would be most applicable for empirical LUE models that work on daily time-steps.

$\text{LUE}_{\text{light}}$ is the fitted slope of GPP and APAR when PAR is between 100-500 $\mu$mol m$^{-2}$ s$^{-1}$. The fit was forced to go through the origin as the equation has no intercept.

$\text{LUE}_{\text{total}}$ is the daily average of $\frac{GPP}{APAR}$ during the day.

Here is a demonstration of how $\text{LUE}_{\text{light}}$ and $\text{LUE}_{\text{total}}$ were calculated. Given a day (DOY = 278 as an example), we selected the GPP measurements when the PAR level is between 100-500 $\mu$mol m$^{-2}$ s$^{-1}$. Then, we did a linear regression of those GPP measurements with their APAR levels (the cyan dots and dashed line). The slope of this regression is $\text{LUE}_{\text{light}}$. On the same day, all the GPP measurements that happened when the PAR level is above 100 $\mu$mol m$^{-2}$ s$^{-1}$ are the orange crosses in the plot. We calculated the ratio of GPP and APAR of those orange points, and the daily mean of the ratio is the $\text{LUE}_{\text{total}}$. 
S2.3. Two ways calculating GPP\textsubscript{max}

There were only a few days when PAR is so low that LUE did not reach light saturation for most of the day, when LUE\textsubscript{total} is more comparable to LUE\textsubscript{light}. Also, there is a 26-day gap in APAR measurement in the beginning period of our study. Therefore, we only showed the results of GPP\textsubscript{max} in the main text as it is more representative than LUE\textsubscript{light}, and more physiology-driven than LUE\textsubscript{total}. Because of the missing APAR, we did not normalize GPP\textsubscript{max} with APAR. However, the normalized GPP\textsubscript{max} and unnormalized GPP\textsubscript{max} are significantly linearly correlated (Fig. S2b). Although GPP normalized by PAR results in the correct unit of LUE, it is easily mistaken as fPAR has been considered. To avoid this confusion, we chose to use mean GPP at PAR between 1000 and 1500 µmol m\textsuperscript{-2} s\textsuperscript{-1}. 
2.4. Comparing the three regimes of LUE

Needles use light most efficiently at low light levels (LUE_{light}) for a fraction of the day. We started to observe a photosynthetic saturation at low PAR values (\approx 500 \, \mu\text{mol m}^{-2} \, \text{s}^{-1}; \text{Fig.} \, 2), which is represented by GPP_{max}, resulting in low efficiencies under high light conditions. LUE_{total} represents the mean light use scheme throughout the day. Hence, LUE_{light} was slightly higher than LUE_{total} during most of the growing season (Fig. S2c).

Figure S2d. Time series of GPP_{max}, LUE_{light}, and LUE_{total}. DOY 166 (2017) is the first day of observation. The vertical dashed line divides the observations from Day of Year (DOY) for year 2017 and 2018.

S3. GPP_{max} and PRI as a function of T_{air} and VPD in different seasons

Figure S3a. Scatter plots of GPP_{max} against T_{air} (top left) and VPD (top right). The definition of seasons follows the same convention as in Fig. 1. The onset is the transitioning period from
dormancy to the growing season. The cessation is the transitioning period from the growing season to the dormancy. The Pearson-$r^2$ values are shown in the legend. The statistically insignificant value is in a parenthesis if the p-value is greater than 0.005.

Figure S3b. Scatter plots of PRI against Tair (left) and VPD (right). The definition of seasons follows the same convention as in Fig. (1) and S3a. The onset is the transitioning period from dormancy to the growing season. The cessation is the transitioning period from the growing season to the dormancy. The Pearson-$r^2$ values are shown in the legend. The statistically insignificant value is in a parenthesis if the p-value is greater than 0.005.

The correlations with Tair and VPD are similar because Tair and VPD are significantly correlated.

Figure S3c. Scatter plot of VPD and Tair. The definition of seasons follows the same convention as in Fig. (1) and S3a. The Pearson-$r^2$ values are shown in the legend. The statistically insignificant values are in parenthesis if the p-value is greater than 0.005.

**S4. ICA algorithm**

We used the fastICA algorithm from scikit-learn v0.21.0 (https://scikit-learn.org/stable/modules/generated/sklearn.decomposition.FastICA.html). Because ICA minimizes the dependencies of the second-order moment (variance) and higher, the randomness during the minimization makes the explained variance and order of individual component
unclear. In our calculation, the ICA algorithm reduced the dimension of the input matrix by eigenvalue decomposition first, from which the first three second-order independent/orthogonal components yielded $99.99\%$ of the variance. Then, the algorithm extracted the independent components of high-order moments from these orthogonal components.

**S5. SIF vs relative SIF**

Relative SIF is SIF normalized by the reflected near-infrared radiance at 755nm. This normalization will make SIF more comparable to a ‘SIF yield’, as it is a ratio effectively correcting for incoming irradiance, and sunlit/shaded fraction. The attached plot is similar as we did in Figure 5d but with SIF and relative SIF. The seasonal cycles of relative SIF and SIF are well correlated. Relative SIF is more correlated with the GPPmax in seasonal variations. However, the sub-seasonal change in the growing season is captured more by relative SIF.

![Figure S5. Comparison between SIF and relative SIF, and the correlation of them with GPPmax during the growing season.](image)

**S6. PLSR analysis**

Based on four-fold cross-validations, we set $n_{\text{components}} = 4$ in the analysis of GPP$_{\text{max}}$ and 2 in the analysis of pigment measurements. All the PLSR coefficients are similar (Fig. S4) because $\text{LUE}_{\text{light}}$, $\text{LUE}_{\text{total}}$, and GPP$_{\text{max}}$ are similar in terms of the seasonal trend.
Figure S6. PLSR coefficients of reflectance with $GPP_{\text{max}}$, $\text{LUE}_{\text{light}}$, and $\text{LUE}_{\text{total}}$. The overlaid dash-dotted and dotted lines are chlorophyll and carotenoid Jacobians, respectively. The overlaid solid grey line is the second ICA spectral component. The vertical dashed line divides the observations from DOY for year 2017 and 2018.