A Global, 0.05-Degree Product of Solar-Induced Chlorophyll Fluorescence Derived from OCO-2, MODIS, and Reanalysis Data

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Abstract: Solar-induced chlorophyll fluorescence (SIF) brings major advancements in measuring terrestrial photosynthesis. Several recent studies have evaluated the potential of SIF retrievals from the Orbiting Carbon Observatory-2 (OCO-2) in estimating gross primary productivity (GPP) based on GPP data from eddy covariance (EC) flux towers. However, the spatially and temporally sparse nature of OCO-2 data makes it challenging to use these data for many applications from the ecosystem to the global scale. Here, we developed a new global ‘OCO-2’ SIF data set (GOSIF) with high spatial and temporal resolutions (i.e., 0.05°, 8-day) over the period 2000–2017 based on a data-driven approach. The predictive SIF model was developed based on discrete OCO-2 SIF soundings, remote sensing data from the Moderate Resolution Imaging Spectroradiometer (MODIS), and meteorological reanalysis data. Our model performed well in estimating SIF (R² = 0.79, root mean squared error (RMSE) = 0.07 W m⁻² μm⁻¹ sr⁻¹). The model was then used to estimate SIF for each 0.05° × 0.05° grid cell and each 8-day interval for the study period. The resulting GOSIF product has reasonable seasonal cycles, and captures the similar seasonality as both the coarse-resolution OCO-2 SIF (1°), directly aggregated from the discrete OCO-2 soundings, and tower-based GPP. Our SIF estimates are highly correlated with GPP from 91 EC flux sites (R² = 0.73, p < 0.001). They capture the expected spatial and temporal patterns and also have remarkable ability to highlight the crop areas with the highest daily productivity across the globe. Our product also allows us to examine the long-term trends in SIF globally. Compared with the coarse-resolution SIF that was directly aggregated from OCO-2 soundings, GOSIF has finer spatial resolution, globally continuous coverage, and a much longer record. Our GOSIF product is valuable for assessing terrestrial photosynthesis and ecosystem function, and benchmarking terrestrial biosphere and Earth system models.

Keywords: solar-induced chlorophyll fluorescence; Orbiting Carbon Observatory-2; Moderate Resolution Imaging Spectroradiometer; gross primary productivity; photosynthesis; machine learning; data-driven approach; carbon cycle; trend; benchmarking; FLUXNET
Figure 1. The spatial distribution and land cover types of the 91 eddy covariance (EC) flux tower sites from the FLUXNET 2015 Tier 1 dataset used in this study.

Figure 2. Relationship between solar-induced chlorophyll fluorescence (SIF) from our global Orbiting Carbon Observatory-2 SIF (GOSIF) product and gross primary productivity (GPP) from the FLUXNET 2015 Tier 1 dataset across biomes. The $R^2$ for each biome is as follows: Evergreen needleleaf forests (0.75), evergreen broadleaf forests (0.51), deciduous broadleaf forests (0.85), mixed forests (0.77), open shrublands (0.76), woody savannas (0.84), savannas (0.67), grasslands (0.77), wetlands (0.82), and croplands (0.62). The $p$ value for each biome is less than 0.001.
Table S1. The statistical measures for model development and validation. Model 1 is based on surface reflectance of Moderate Resolution Imaging Spectroradiometer (MODIS) bands 1–7, Model 2 is based on MODIS bands 1–7 and meteorological data (photosynthetically active radiation or PAR, vapor pressure deficit or VPD, and temperature), and Model 3 is based on enhanced vegetation index (EVI) and meteorological data (PAR, VPD, and temperature). The inclusion of meteorological data could improve the estimation of SIF, and the use of EVI, PAR, VPD, and temperature (Model 2) had a slightly higher performance than the use of MODIS bands 1–7 (Model 1) and an identical performance with the use of MODIS bands 1–7 and three meteorological variables (Model 3).

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Table 2. FLUXNET Tier-1 sites used for evaluating GOSIF in this study. Site descriptions include site code (Column 1), site name (Column 2), Biome type (Column 3), years of data available (Column 4), latitude (Column 5), longitude (Column 6), $R^2$ (SIF versus FLUXNET GPP), and references (Column 8) for each flux site. We used the average of night-time (GPP\textsubscript{NT\_VUT\_REF}) and day-time (GPP\textsubscript{DT\_VUT\_REF}) estimates to evaluate the GOSIF. GPP\textsubscript{NT\_VUT\_REF}: GPP from the nighttime (NT) partitioning method, using the Variable Ustar Threshold filtering method, reference selected from GPP versions using model efficiency (MEF). DT indicates the daytime partitioning method.

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<td>US-Ne1</td>
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<td>41.1651</td>
<td>−96.4766</td>
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<td>−96.4701</td>
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<td>CRO</td>
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<td>41.1797</td>
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<td>US-NR1</td>
<td>Niwot Ridge Forest (LTER NWT1)</td>
<td>ENF</td>
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<td>40.0329</td>
<td>−105.5464</td>
<td>0.84</td>
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<td>US-Pfa</td>
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<td>MF</td>
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<td>−90.2723</td>
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<td>Santa Rita Grassland</td>
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<td>2008–2014</td>
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<td>US-SRM</td>
<td>Santa Rita Mesquite</td>
<td>WSA</td>
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<td>−110.8661</td>
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<td>US-Svy</td>
<td>Sylvania Wilderness Area</td>
<td>MF</td>
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<td>−89.3477</td>
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<td>WSA</td>
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<td>WET</td>
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<td>−121.6521</td>
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<td>Willow Creek</td>
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<td>−90.0799</td>
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<td>OSH</td>
<td>2007–2014</td>
<td>31.7438</td>
<td>−110.0522</td>
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<td>SAV</td>
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<td>−25.0197</td>
<td>31.4969</td>
<td>0.63</td>
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References


23. Post, H.; H.-J. Hendricks Franssen; A. Graf; M. Schmidt; H. Vereecken. Uncertainty analysis of eddy covariance CO2 flux measurements for different EC tower distances using an extended two-tower
approach. Biogeosciences. 2015, 12, 1205-1221.


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