# Solar-induced chlorophyll fluorescence exhibits a nearly universal relationship with terrestrial photosynthesis across a wide variety of biomes


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## BACKGROUND

- Accurate estimation of gross primary productivity (GPP) is essential for assessing ecosystem functioning, carbon budgets, and food production. The recent advent of satellite-based measurement of solar-induced chlorophyll fluorescence (SIF) has provided tremendous potential for monitoring terrestrial photosynthesis globally.

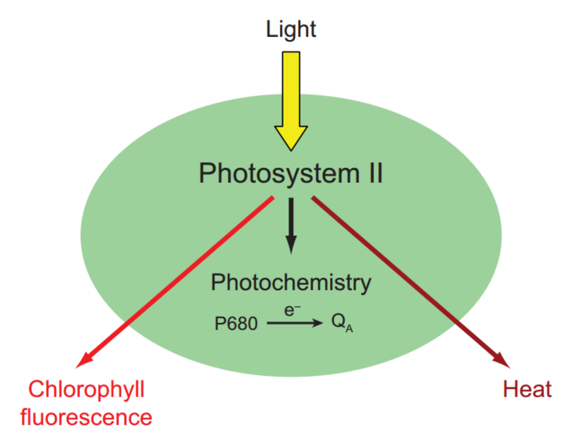



**Fig 1.** Simple model of the possible fate of light energy absorbed by photosystem II (PSII) (Baker 2008).

- The footprint of OCO-2 (1.3 × 2.25 km²) is close to that of eddy covariance flux towers, and therefore OCO-2 provides unique opportunities for better investigating the relationships between SIF and GPP. Several pioneering studies have examined the relationship between OCO-2 SIF and tower GPP at individual sites including crops, grassland, and temperate forests, demonstrating strong relationships between OCO-2 SIF and tower GPP for these biomes.
- Despite these encouraging results, the relationship between OCO-2 SIF and tower GPP has not yet been examined for other major biomes such as evergreen needleleaf forests, evergreen broadleaf forests, shrublands, and savannas due to the lack of OCO-2 overpasses and/or concurrent flux tower observations, and therefore it is also unclear how the SIF–GPP relationship varies across biomes.
- Here we conducted the first global analysis of the relationship between OCO-2 SIF and tower GPP for a total of 64 flux sites across the globe encompassing eight major biomes.

## DATA AND METHODS

- ✓ We screened over 800 EC flux sites across the globe for the concurrent availability of OCO-2 SIF and flux tower observations over the period from September 2014 to 2017, and eventually compiled a database consisting of a total of 64 EC flux tower sites having both OCO-2 and flux observations.
- ✓ For most of flux towers, the OCO-2 SIF retrievals were extracted within a distance of 2–5 km radius from the tower which is generally close to the size of the flux tower footprints. Because OCO-2's global coverage is sparse, we used a larger radius (up to 25 km) to extract SIF for some relatively homogeneous sites.
- ✓ We used SIF data from the OCO-2 Lite products (V7r), and examined the relationship between OCO-2 SIF and tower GPP for both SIF retrieval bands ($SIF_{757}$ and $SIF_{771}$) and two timescales (mid-day and daily), compared the slope of the SIF-GPP relationship across eight major biomes.
- ✓ We also analyzed the relationship between SIF and *f*PAR, APAR (*f*PAR × tower PAR) and two environmental scalars, $f_{Tmin}$ and $f_{VPD}$, representing low temperature and high vapor pressure deficit (VPD) stresses, respectively, to reveal how SIF responds to these factors.

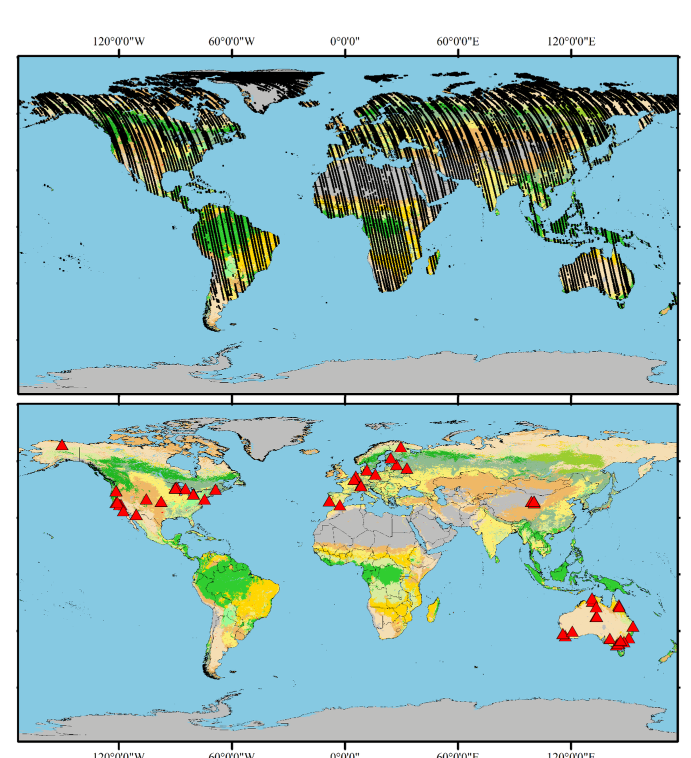
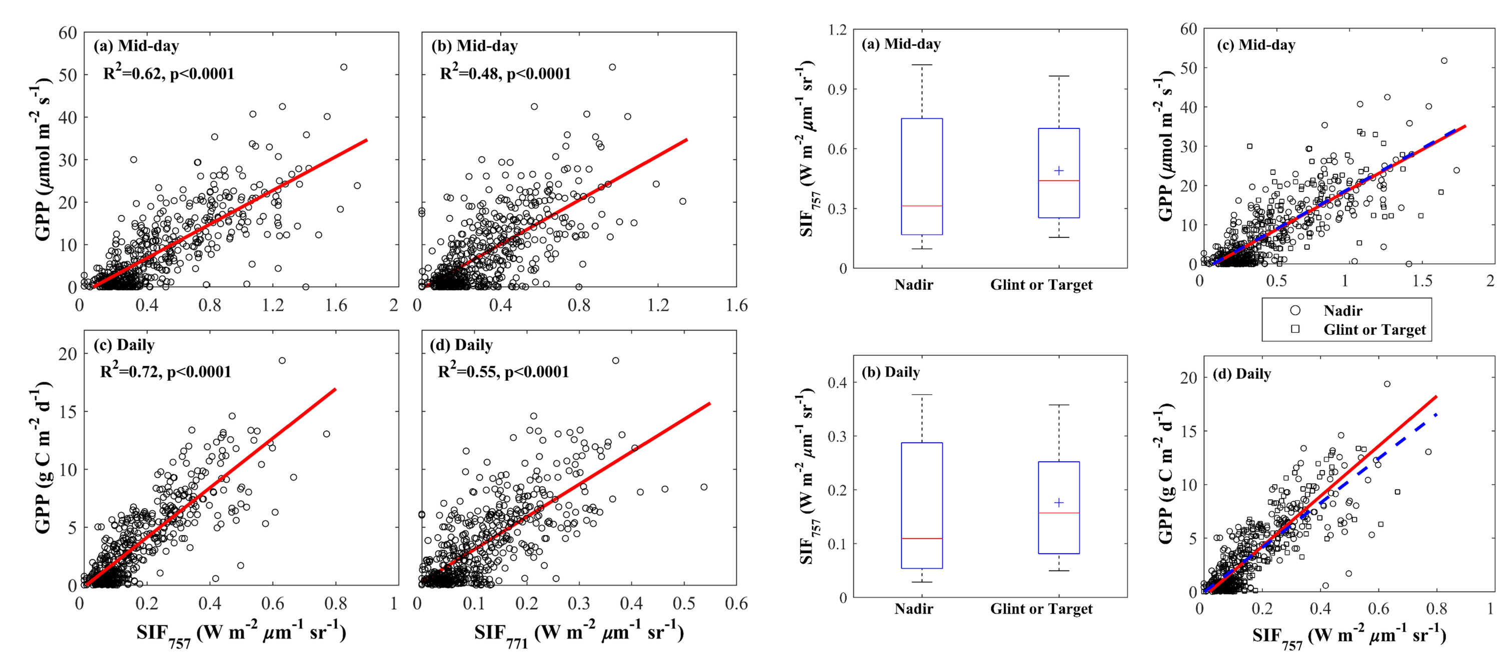



**Fig 2.** OCO-2 overpasses in July 1, 2015 (a) and the location and distribution of 64 EC flux sites across the globe (b). The triangles stand for EC flux sites.

- ✓ We chose two flux tower sites with a larger number of temporal OCO-2 overpasses, FI-Hyy (23 daily SIF observations) and AU-Das (19 daily SIF observations), to examine how variations in GPP and SIF were determined by changes in the APAR and two environmental factors. The chosen sites have different environmental controls on photosynthesis.

## RESULTS

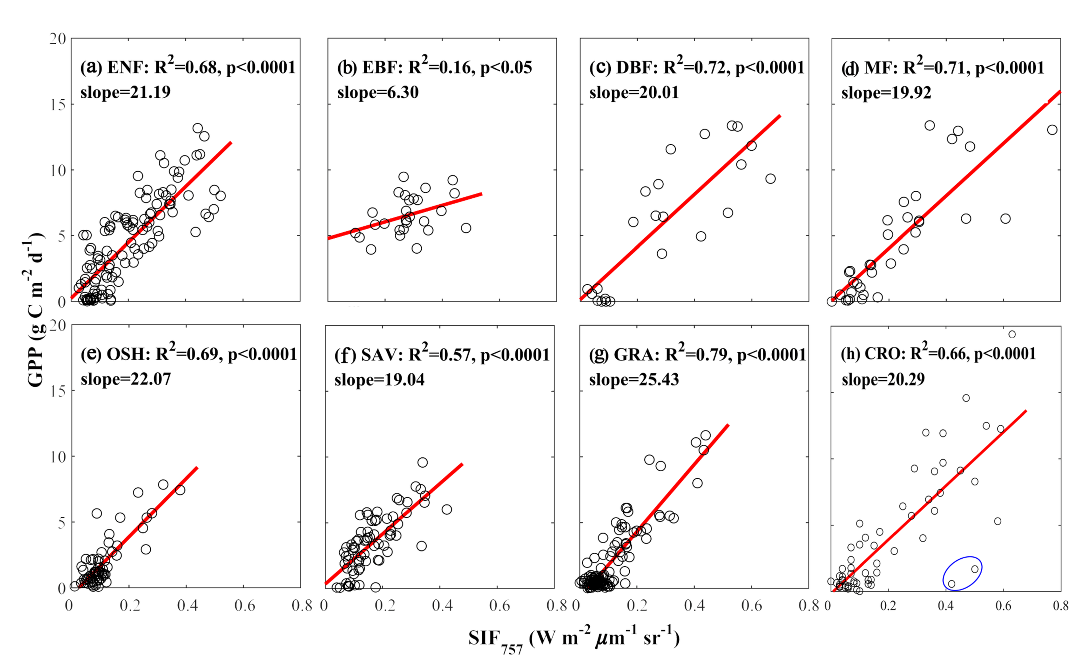
### Relationships of OCO-2 SIF with tower GPP




OCO-2 SIF showed strong correlations with tower GPP at both mid-day and daily timescales, with the strongest relationship observed for daily SIF at the 757 nm ($R^2$ = 0.72, p < 0.0001).

There was no significant difference in the mean SIF between the nadir mode and the glint (or target) mode for both midday (ANOVA: p = 0.09) and daily timescales (ANOVA: p = 0.51) (a, b). Consequently, the SIF–GPP relationship did not significantly vary with the measurement mode at both mid-day and daily timescales (c, d).

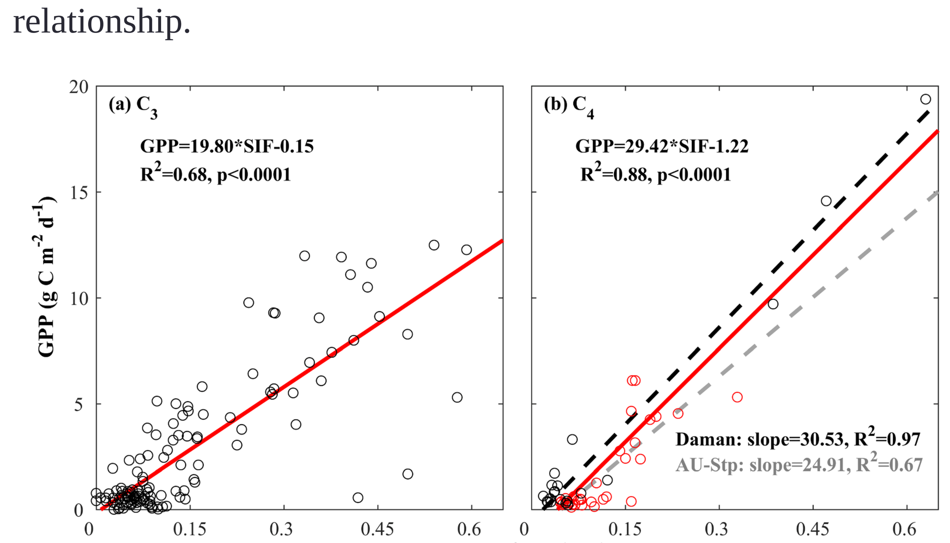
### Biome-specific SIF–GPP relationships




The generally consistent slope of the relationship among biomes suggests a nearly universal rather than biome-specific SIF–GPP relationship.

| | CRO | DBF | ENF | GRA | MF | OSH | SAV |
|---|---|---|---|---|---|---|---|
| CRO | 1.00 | 0.94 | 0.90 | **0.03** | 0.83 | 0.51 | 0.98 |
| DBF | 0.94 | 1.00 | 0.99 | 0.08 | 0.92 | 0.54 | 0.95 |
| ENF | 0.90 | 0.99 | 1.00 | **0.01** | 0.91 | 0.40 | 0.91 |
| GRA | **0.03** | 0.08 | **0.01** | 1.00 | **0.03** | 0.13 | **0.02** |
| MF | 0.83 | 0.92 | 0.91 | **0.03** | 1.00 | 0.41 | 0.84 |
| OSH | 0.51 | 0.54 | 0.40 | 0.13 | 0.41 | 1.00 | 0.48 |
| SAV | 0.98 | 0.95 | 0.91 | **0.02** | 0.84 | 0.48 | 1.00 |

The statistical analyses of the differences in the slope of the SIF-GPP relationship among diverse biomes. The p value of T-test results was provided. The p value less than 0.05 was bolded, indicating that the difference in the slope was significantly different between the two biomes.

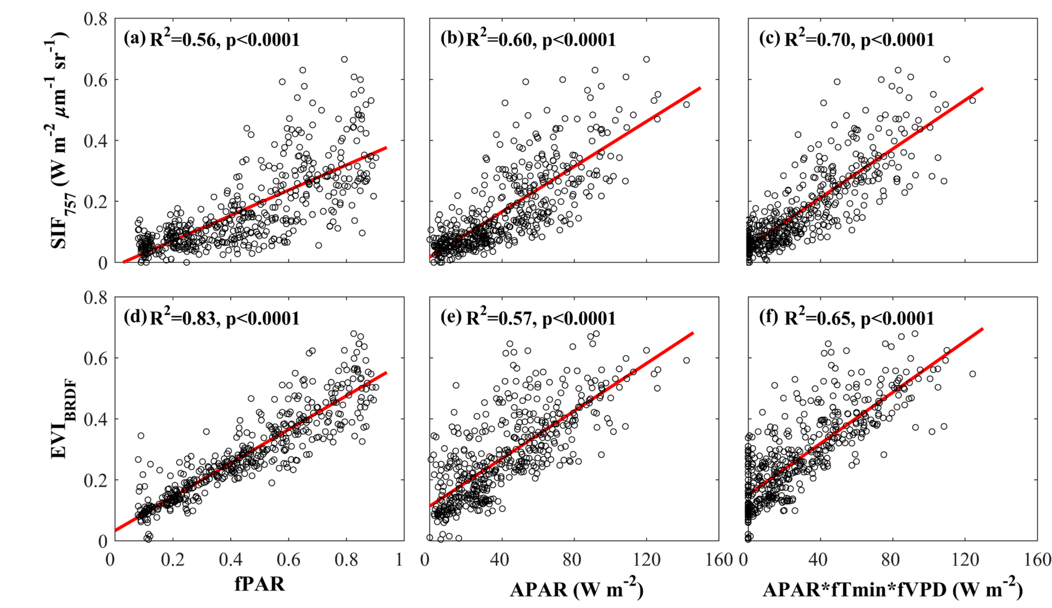



$C_4$-dominated grasslands and crops had a significantly higher slope than $C_3$-dominated grasslands and crops (29.42 g C m$^{-2}$ day$^{-1}$/W m$^{-2}$ μm$^{-1}$ sr$^{-1}$ vs. 19.80 g C m$^{-2}$ day$^{-1}$/W m$^{-2}$ μm-1 sr$^{-1}$, p < 0.0001).

| | CRO | DBF | ENF | GRA | MF | OSH | SAV |
|---|---|---|---|---|---|---|---|
| CRO | 1.00 | 0.74 | 0.97 | 0.85 | 0.78 | 0.80 | 0.25 |
| DBF | 0.74 | 1.00 | 0.68 | 0.81 | 0.66 | 0.94 | 0.31 |
| ENF | 0.97 | 0.68 | 1.00 | 0.81 | 0.64 | 0.71 | 0.11 |
| GRA | 0.85 | 0.81 | 0.81 | 1.00 | 0.46 | 0.90 | 0.13 |
| MF | 0.78 | 0.66 | 0.64 | 0.46 | 1.00 | 0.40 | **0.05** |
| OSH | 0.80 | 0.94 | 0.71 | 0.90 | 0.40 | 1.00 | 0.17 |
| SAV | 0.25 | 0.31 | 0.11 | 0.13 | 0.05 | 0.17 | 1.00 |

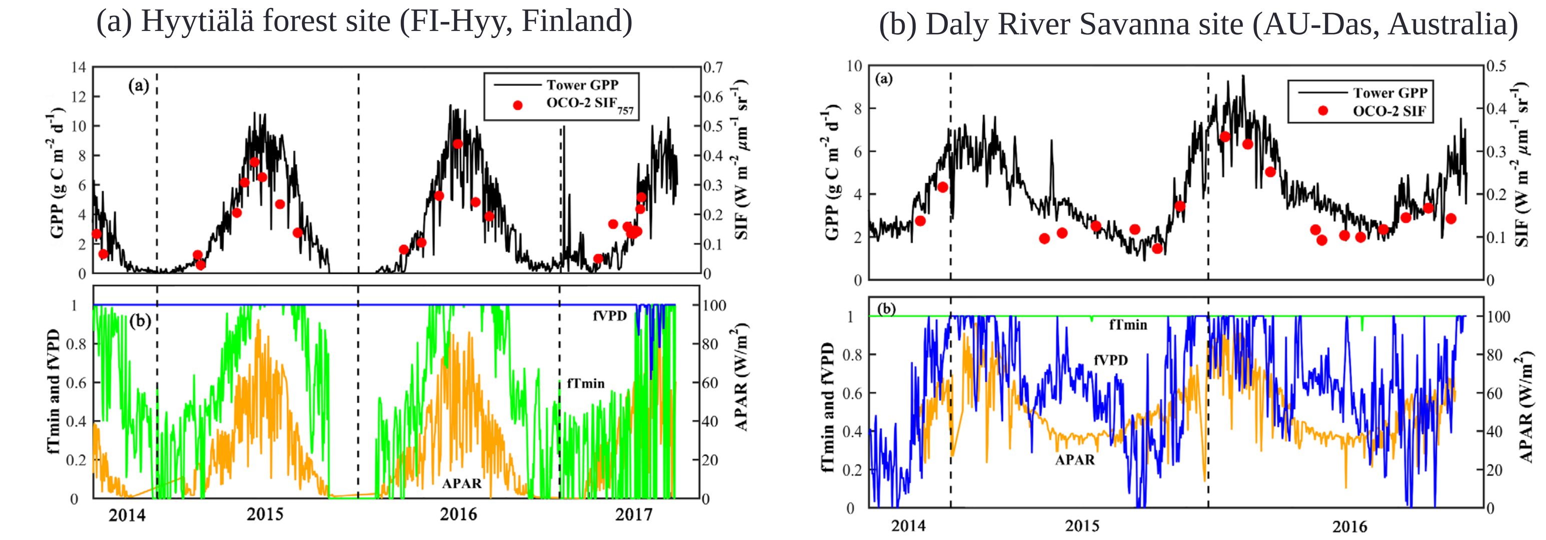
The nearly universal slope among biomes was also observed when only SIF retrievals by nadir mode were used. The slopes for each biome was: CRO: 19.63; DBF: 20.90; ENF:19.77; GRA: 20.29; MF:18.62; OSH: 20.52; SAV: 23.91 g C m$^{-2}$ day$^{-1}$/W m$^{-2}$ μm-1 sr$^{-1}$, respectively.

### Relationships of OCO-2 SIF with APAR and environmental stresses




- ✓ The SIF was mainly driven by APAR and was also influenced by environmental stresses.
- ✓ SIF responded to APAR and environmental scaling factors ($f_{Tmin}$ and $f_{VPD}$) in the same manner as GPP at two representative flux sites with different environmental controls on photosynthesis.

(a) Hyytiälä forest site (FI-Hyy, Finland) (b) Daly River Savanna site (AU-Das, Australia)




## CONCLUSIONS

- The OCO-2 SIF showed strong correlations with tower GPP ($R^2$ = 0.48–0.72, p < 0.0001) at both SIF retrieval bands (757 and 771 nm) and at two timescales (mid-day and daily), with the strongest relationship observed in the 757 nm band at the daily timescale ($R^2$ = 0.72, p < 0.0001).
- We found that the SIF was mainly driven by APAR and was also influenced by environmental stresses (temperature and water stresses) related to light use efficiency. SIF responded to APAR and environmental scaling factors ($f_{Tmin}$ and $f_{VPD}$) in the same manner as GPP at two representative flux sites with different environmental controls on photosynthesis.
- The strong SIF–GPP relationship was found for all eight biomes ($R^2$ = 0.57–0.79, p < 0.0001) except evergreen broadleaf forests ($R^2$ = 0.16, p < 0.05). The slope of the SIF–GPP relationship was generally consistent among biomes, which indicates that a nearly universal relationship between SIF and GPP exists across a wide variety of biomes.
- The universal or biome-specific SIF–GPP relationship would be better elucidated when more SIF observations and EC flux tower data are available in the near future.

## ACKNOWLEDGEMENTS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**Citation**


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