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Observed Water and Light Limitation Across Global Ecosystems

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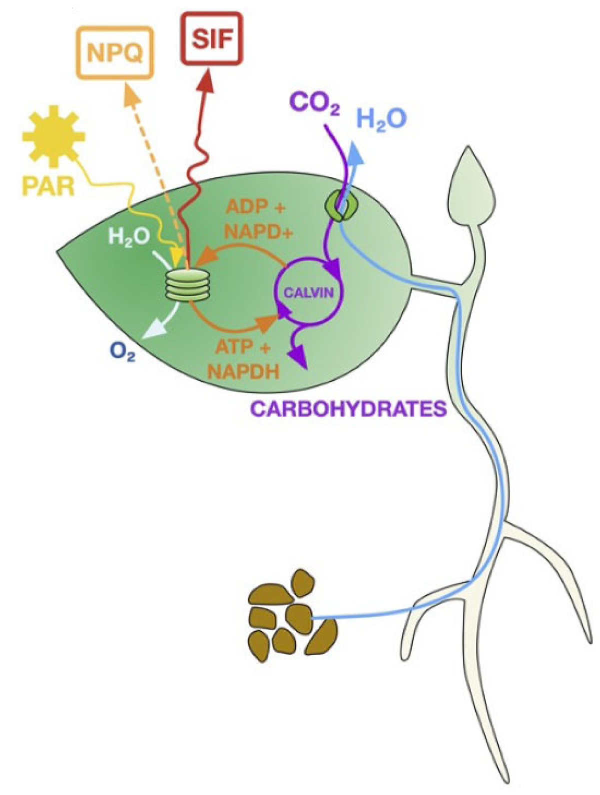
Introduction

Vegetation plays a large role in the Earth's system, modulating land-atmosphere exchanges of water, carbon, and energy. With a changing climate, it is becoming increasingly critical to understand vegetation responses to limiting environmental factors.

Remote sensing has proven to be a useful tool for mapping and monitoring vegetation function across the globe. Satellite observations of sun-induced chlorophyll fluorescence (SIF) –radiation emitted at wavelengths of 650 to 800 nm from plant photosystems– are valuable indicators of ecosystem photosynthetic activity. Surface soil moisture (SM) can also be derived globally from low-frequency microwave radiometer observations.

In this study, we investigate the spatial and temporal patterns of light and water limitation on photosynthesis using an observational framework. Our study is unique in characterizing the nonlinear relationships between photosynthesis and water and light, acknowledging approximately two regime behaviors (no limitation and varying degrees of limitation).

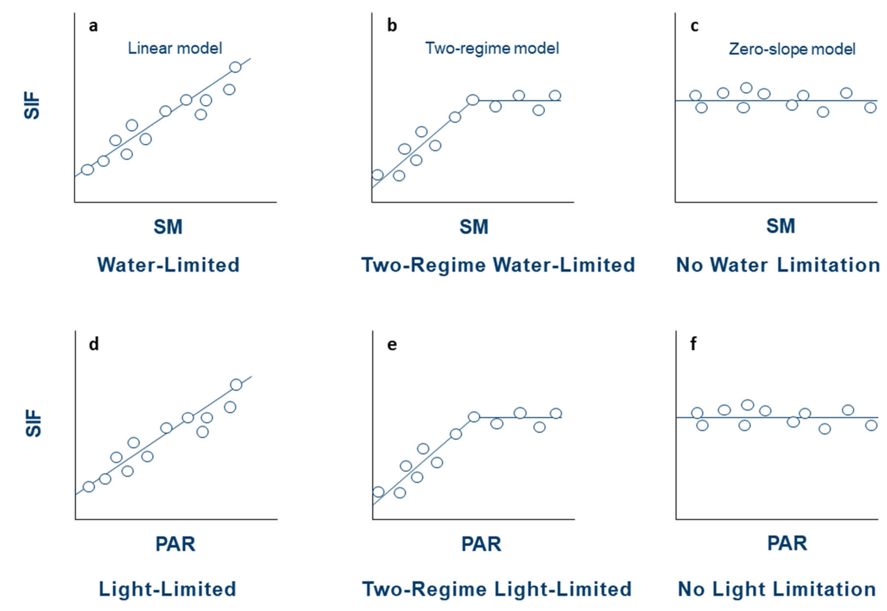


Satellite Data & Methods

Satellite-based data were collected and analyzed for our main per-pixel approach for a 2.5-year period from April 2018 to September 2020 (determined by the concurrently available TROPOMI and SMAP data). Climatology information from decade-long time series was used as auxiliary datasets.

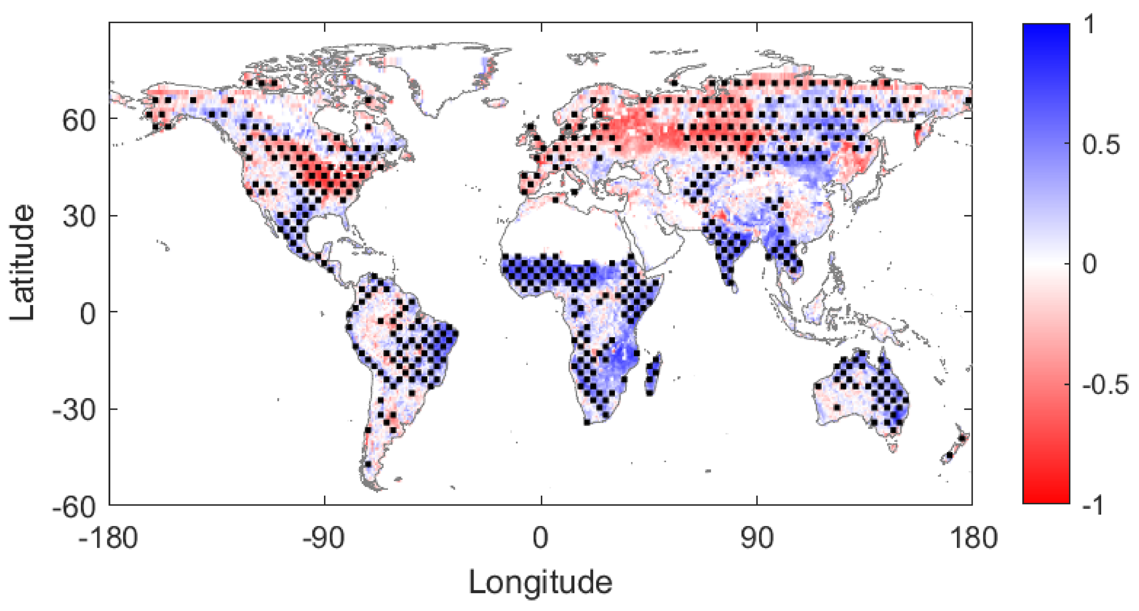
Variable	Source of data	Spatial resolution
Sun-induced chlorophyll fluorescence	Sentinel-5P satellite TROPOMI	$7 \times 3.5\,km^2$
Soil moisture	SMAP satellite L-band radiometer	$36 \times 36\,km^2$
Normalized difference vegetation index	Terra satellite MODIS	0.05°
Photosynthetically active radiation	MERRA-2 global reanalysis	$0.5° \times 0.625°$
Precipitation	GPM satellite constellation IMERG product	$0.1° \times 0.1°$

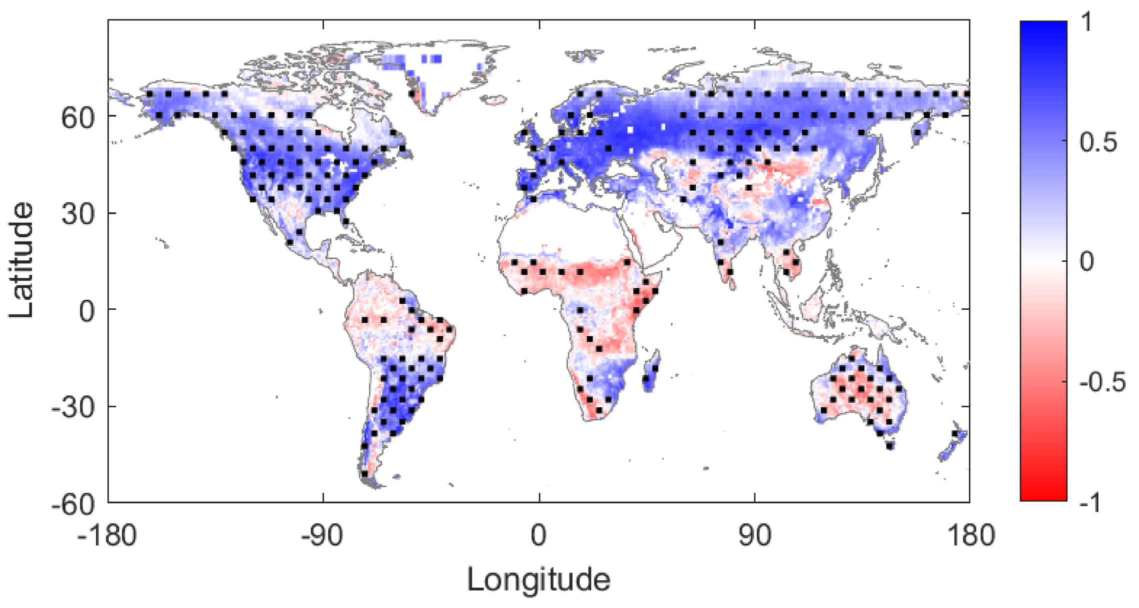
Three distinct models were tested, representing three scenarios for each limitation (water and light). The Bayesian information criterion (BIC) is used to avoid overfitting among models during statistical selection.



Results & Discussion

Correlation Maps

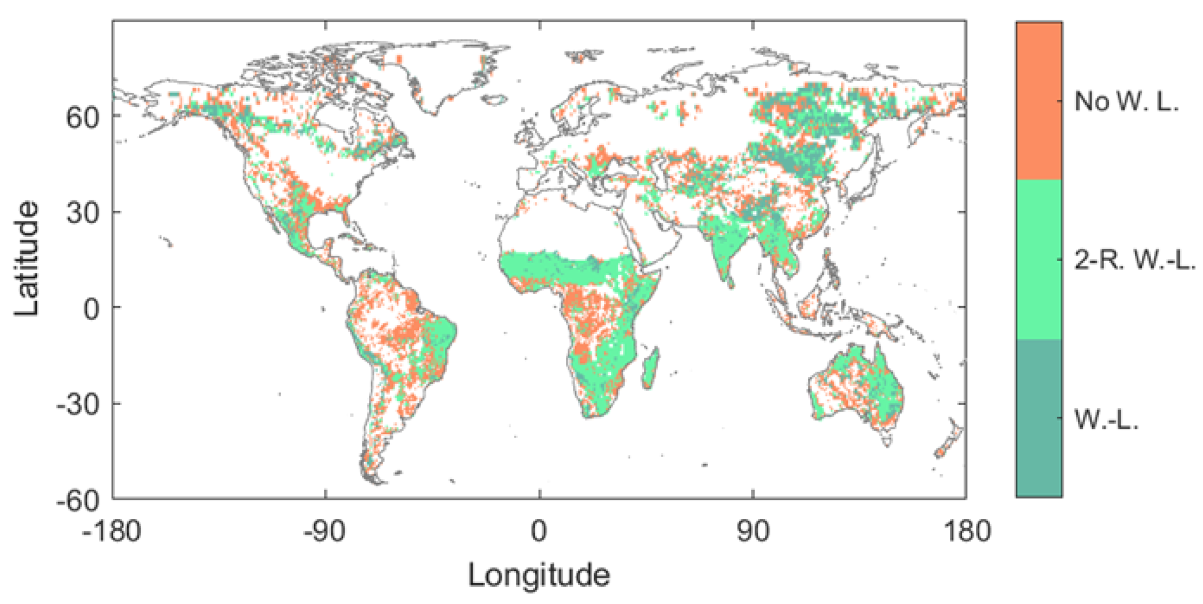


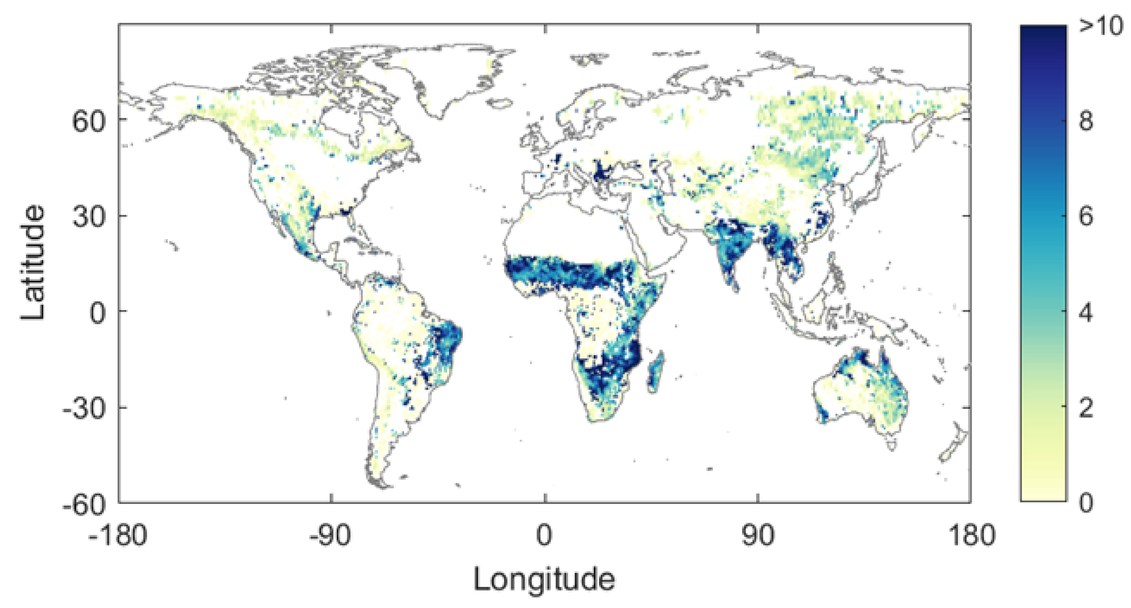


TROPOMI SIF and SMAP-MT-DCA SM (top), and TROPOMI SIF and MERRA-2 PAR (bottom) growing-season correlation.

Pearson correlation provides information about the degree to which a variable linearly limits SIF. However, in many cases, nonlinear relationships are present where the strength of limitation may decrease above a certain threshold of SM or PAR. Therefore, this can bias linear correlations and obscure their interpretation.

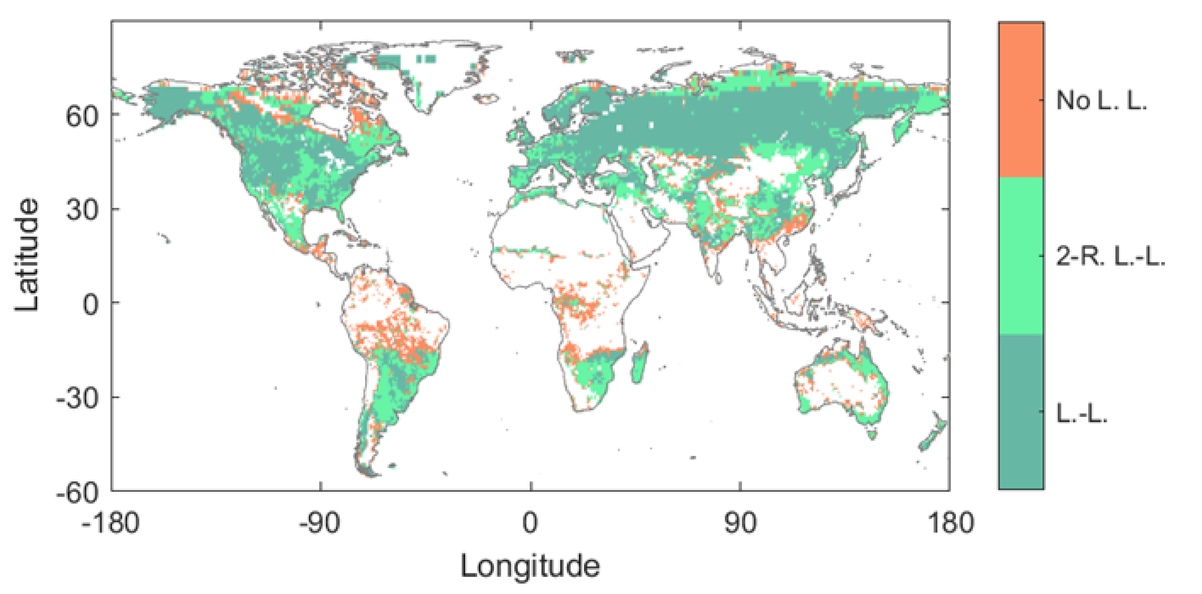
Water-Limited Regimes

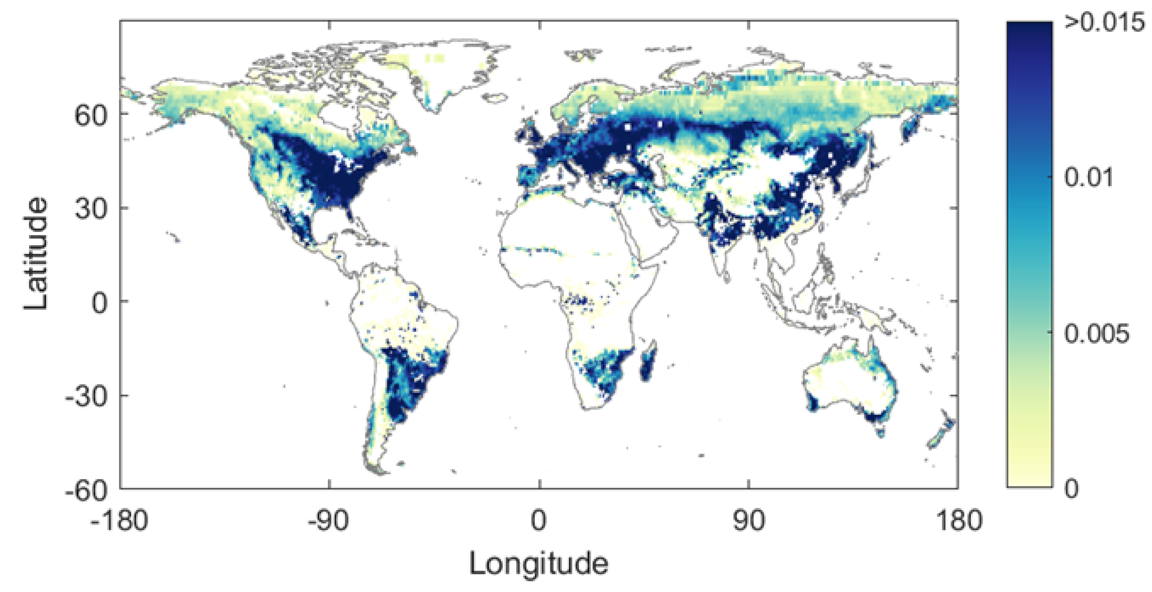




Estimated SIF–SM relationship features; (left) model type (W.-L.: water-limited; 2-R. W.-L.: two-regime water-limited; NoW. L.: no water limitation) and (right) model slope (mWm^{-2} nm^{-1} sr^{-1}) in the water-limited regime. Two-regime behavior is detected in 73% of the cases for water limitation on photosynthesis.

Light-Limited Regimes





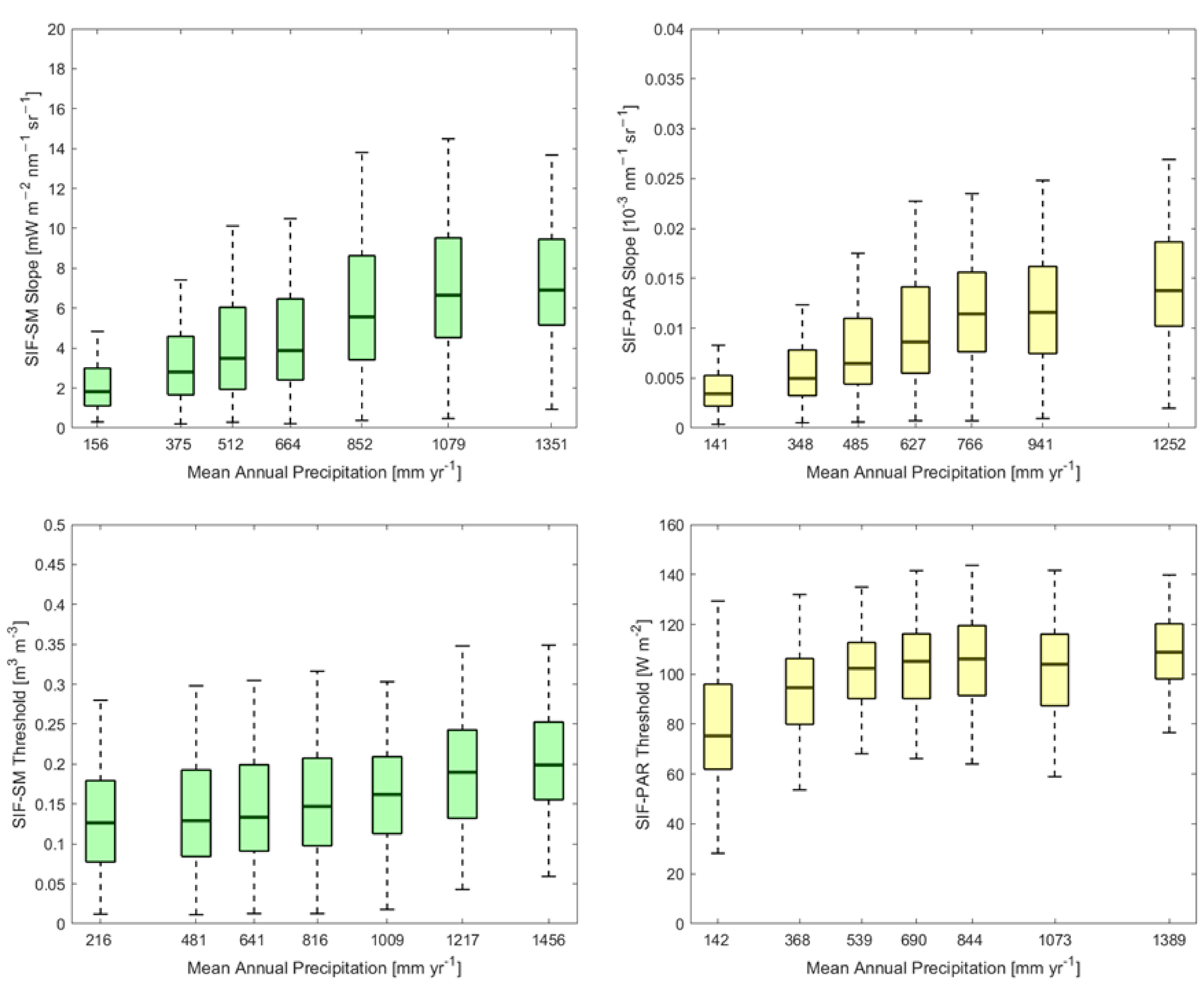
Estimated SIF–PAR relationship features; (left) model type (L.-L.: light-limited; 2-R. L.-L.: two-regime light-limited; No L. L.: no light limitation) and (right) model slope (10^{-3} nm^{-1} sr^{-1}) in the light-limited regime. Two-regime detection is much lower at 41% for light limitation on photosynthesis.

SIF Limitation vs. Mean Annual Precipitation

SIF sensitivity to SM shows a relationship with mean annual precipitation. Sensitivities peak at approximately 1000 mm yr^{-1}. Locations with peak slopes occur in the wetter environments. These larger slopes are likely related to the degree to which vegetation responds to mean moisture and individual storms. It also indicates that these wetter regions may have a stronger plant– water stress response when the land surface becomes drier below the soil moisture threshold.

SIF sensitivity to PAR shows an even stronger relationship with annual precipitation, especially for regions below 1000 mm yr^{-1}. The increasing sensitivities may similarly be an adaptation of the vegetation to utilize light availability, given that moisture is typically less limited in these regions.

Furthermore, the transition point detected between the two regimes is connected to soil type and mean annual precipitation for the SIF–soil moisture relationship and for the SIF–PAR relationship. These thresholds therefore have an explicit relation to properties of the landscape, although they may also be related to finer details of the vegetation and soil interactions not resolved by the spatial scales here.



Conclusion

This study highlights that vegetation function exhibits widespread, nonlinear dependencies on bio-climatic factors that are highly spatially variable. Given that we show vegetation existing in limited and non-limiting states depending on the water or light conditions, linear correlations of photosynthesis with specific resources provide limited views of landscape-scale photosynthesis.

Our study is unique (1) in evaluating the state dependent, coupled controls on SIF; (2) in detecting the nonlinear relationships between plant function and water and light, major controls on global photosynthesis; and (3) in being an observational framework instead of using model-derived parameters. Our spatial maps therefore can serve as a benchmark to directly validate the model emergent controls on terrestrial gross primary production from Earth system models.

More information can be found online at
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