Radiative transfer and viewing geometry considerations for the SIF/GPP relationship

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Abstract

Solar-Induced chlorophyll Fluorescence (SIF) provides a powerful proxy for determining forest gross primary production (GPP), particularly in evergreen ecosystems where traditional measures of greenness fail. The dynamics of the SIF/GPP relationship, however, are poorly understood under varying viewing directions and light conditions. This is, in large part, due to challenges in measuring SIF at the spatiotemporal scale that is necessary to understand these effects. Therefore, the aim of this work is to utilize high-temporal and spatial resolution SIF measurements to better constrain the response of SIF to ambient canopy illumination and viewing geometry. We use a PhotoSpec instrument and eddy covariance measurements to explore the SIF/GPP relationship under various viewing directions and light conditions during the 2019 and 2020 growing seasons at the Old Black Spruce site in Saskatchewan, Canada. PhotoSpec is a tower-based 2-D scanning spectrometer system capable of taking Fraunhofer-line based SIF retrievals in the red and far-red wavelength ranges with a 0.7 degree field of view at a ~30 second time resolution. Measured SIF and GPP are combined with SCOPE modelling results to provide a mechanistic understanding of the physical and ecophysiological drivers for the SIF/GPP relationship in the Boreal Forest. Our results show that viewing direction and solar zenith/azimuth angles are important for the SIF signal under direct light conditions, but not under diffuse. Furthermore, the SIF/GPP relationship changes under direct and diffuse light conditions at a 30 minute, daily, and monthly resolution. Our ability to use SIF as a proxy for GPP depends on a quantitative understanding of radiative transfer within the canopy and how scanning geometry impacts SIF measurements. These results provide an important insight into these relationships in the Boreal forest, a region where GPP has been traditionally difficult to track using remote sensing.

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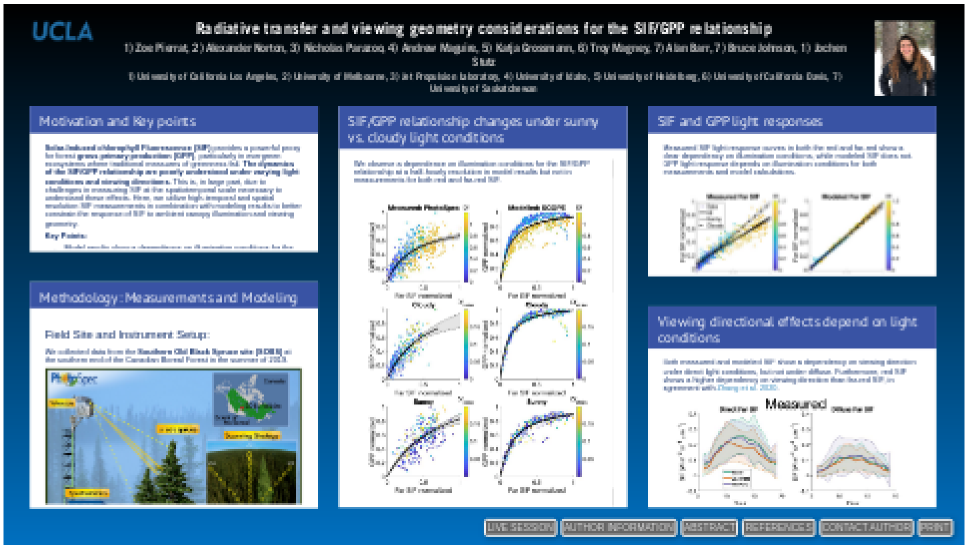

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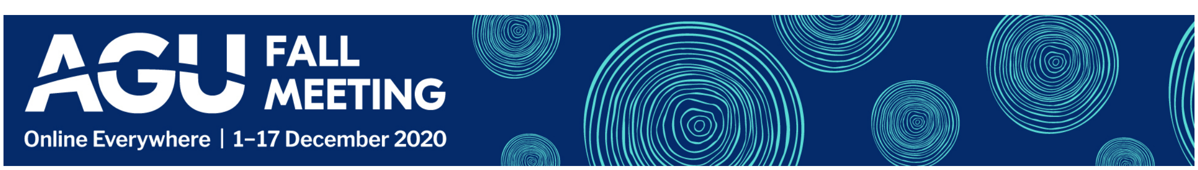

MOTIVATION AND KEY POINTS

Solar-Induced chlorophyll Fluorescence (SIF) provides a powerful proxy for forest **gross primary production (GPP)**, particularly in evergreen ecosystems where traditional measures of greenness fail. **The dynamics of the SIF/GPP relationship are poorly understood under varying light conditions and viewing directions.** This is, in large part, due to challenges in measuring SIF at the spatiotemporal scale necessary to understand these effects. Here, we utilize high-temporal and spatial resolution SIF measurements in combination with modeling results to better constrain the response of SIF to ambient canopy illumination and viewing geometry.

Key Points:

- Model results show a dependence on illumination conditions for the SIF/GPP relationship while measurements do not.
- The light response of GPP depends on illumination conditions in both measurements and model results. The light response of SIF depends on illumination conditions in measurements but not model results.
- Viewing directional effects are important under direct light conditions, but not under diffuse.

METHODOLOGY: MEASUREMENTS AND MODELING

Field Site and Instrument Setup:

We collected data from the **Southern Old Black Spruce site (SOBS)** at the southern end of the Canadian Boreal Forest in the summer of 2019.

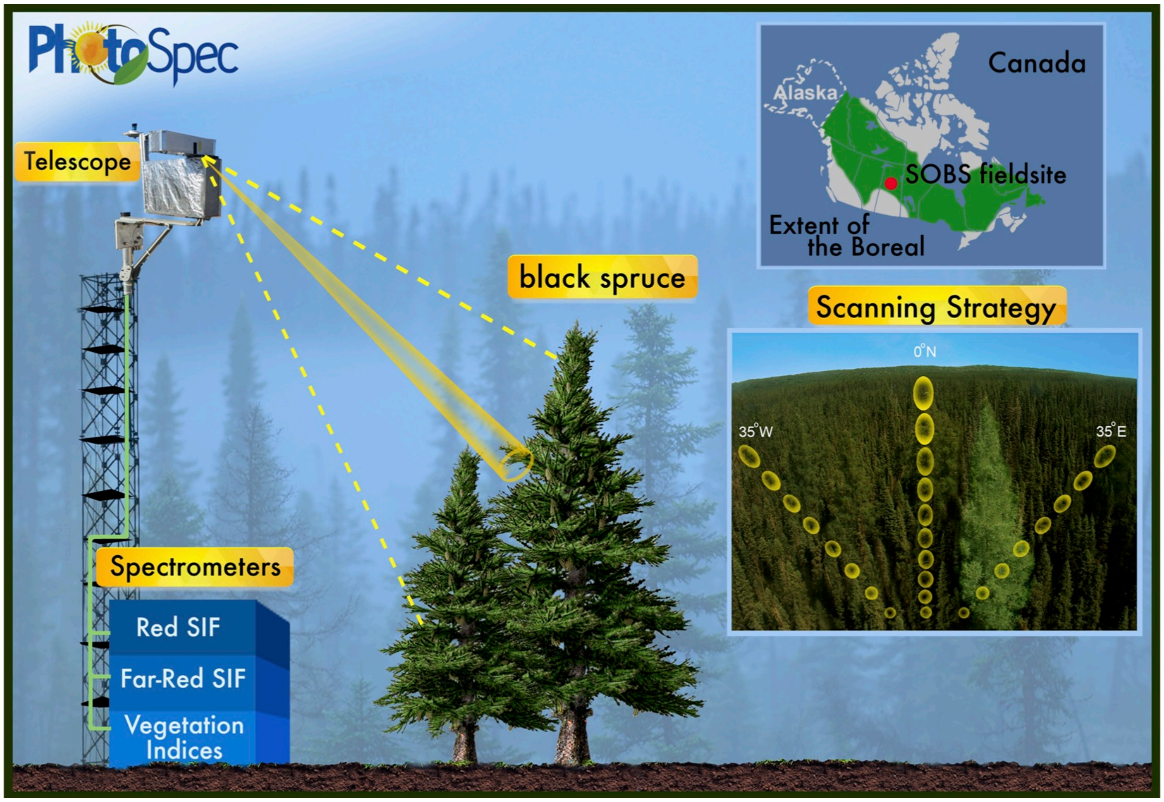

Figure 1: Southern Old Black Spruce (SOBS) field station instrumental setup with insets of site location and scan strategy

Measurements and Modeling:

1. SIF in the far-red (745-758 nm) and red (680-686 nm) wavelength ranges were recorded using **PhotoSpec**, a tower-based 2-D scanning spectrometer system. PhotoSpec uses a Fraunhofer-line based SIF retrieval which makes it less sensitive to atmospheric scattering, essential for exploring SIF dynamics under cloudy sky conditions. PhotoSpec has a narrow FOV (0.7 deg), and took measurements ~every 20 seconds on the scan sequence in Figure 2 which takes ~30 minutes to complete (Grossmann et al. 2018) (https://www.sciencedirect.com/science/article/abs/pii/S0034425718303298)

- To compare with GPP, measurements across all scan directions were averaged together to report half-hourly SIF data.
- To explore angular effects, we calculated the average diurnal profile of SIF for each azimuthal scan direction under direct or diffuse light conditions.

2. Illumination conditions: We separated sunny (direct) from cloudy (diffuse) illumination conditions by developing a clear sky comparison metric, D_f. D_f reflects the deviation of PAR at a given solar zenith angle from the expected PAR during a clear sky reference day so that $D_f = 1$ is clear sky conditions. We used D_f to classify measurements with $D_f < 0.6$ as cloudy, and $D_f > 0.8$ as sunny. Df values were calculated for every PhotoSpec measurement (~20 second resolution) but averaged together in 30-minute windows to compare with GPP and SCOPE (Figure 2).

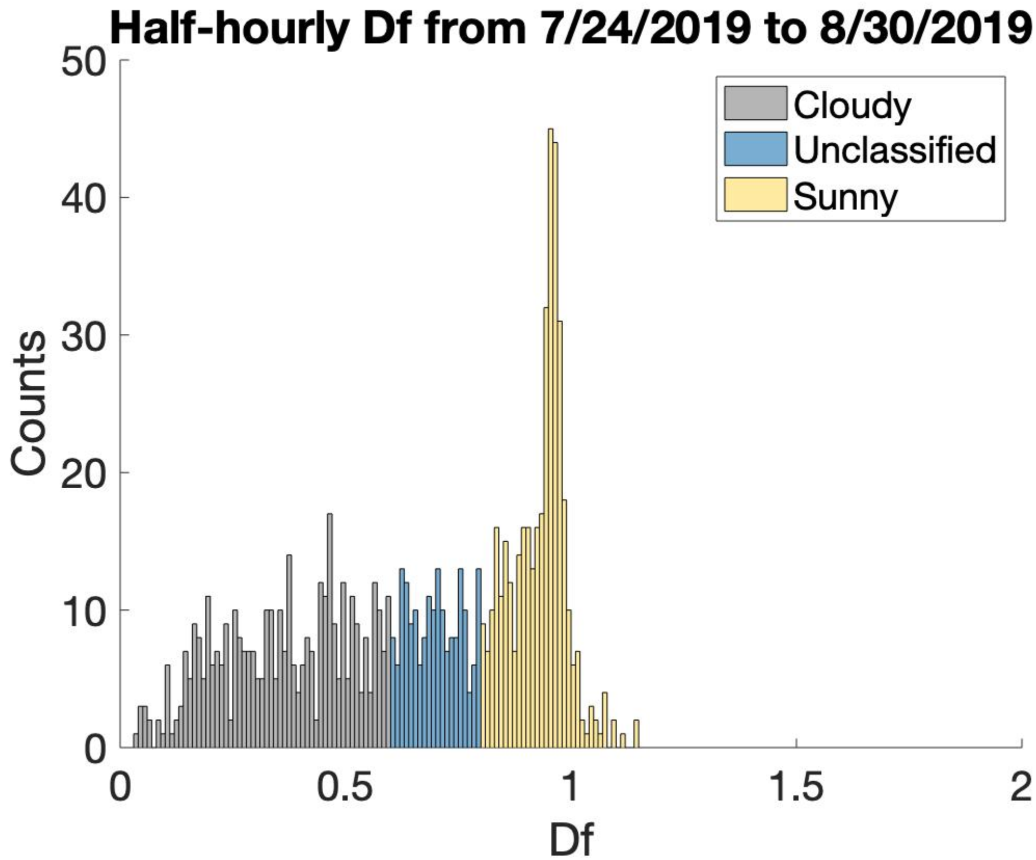

Figure 2: Histogram of half-hourly Df values showing points classified as sunny or cloudy sky conditions.

3. GPP measurements were calculated from eddy-covariance (EC) measurements atop the sites 25m scaffold tower using the Fluxnet-Canada method at a half-hourly resolution (Barr et al. 2004). (https://www.researchgate.net/publication/222396185_Inter-annual_variability_in_the_leaf_area_index_of_a_boreal_aspen-hazelnut_forest_in_relation_to_net_ecosystem_production)

4. Model comparisons, were calculated using the Soil Canopy Observation, Photochemistry, and Energy fluxes model **(SCOPE)** (van der Tol et al. 2009) (https://bg.copernicus.org/articles/6/3109/2009/).

- We modified SCOPE to **mimic PhotoSpec's viewing strategy**.
- **To simulate the effects of diffuse vs. direct illumination** conditions we applied two top-of-canopy incoming spectra with differing diffuse fractions (55% and 15%). This simplified approach represents two somewhat extreme cases, useful for sensitivity analysis, but does not represent the full temporal variability of diffuse radiation observed at the site. We used measured D_f values to determine which SCOPE timesteps would use a high or low diffuse fraction.

SIF/GPP RELATIONSHIP CHANGES UNDER SUNNY VS. CLOUDY LIGHT CONDITIONS

We observe a dependence on illumination conditions for the SIF/GPP relationship at a half-hourly resolution in model results but not in measurements for both red and far-red SIF.

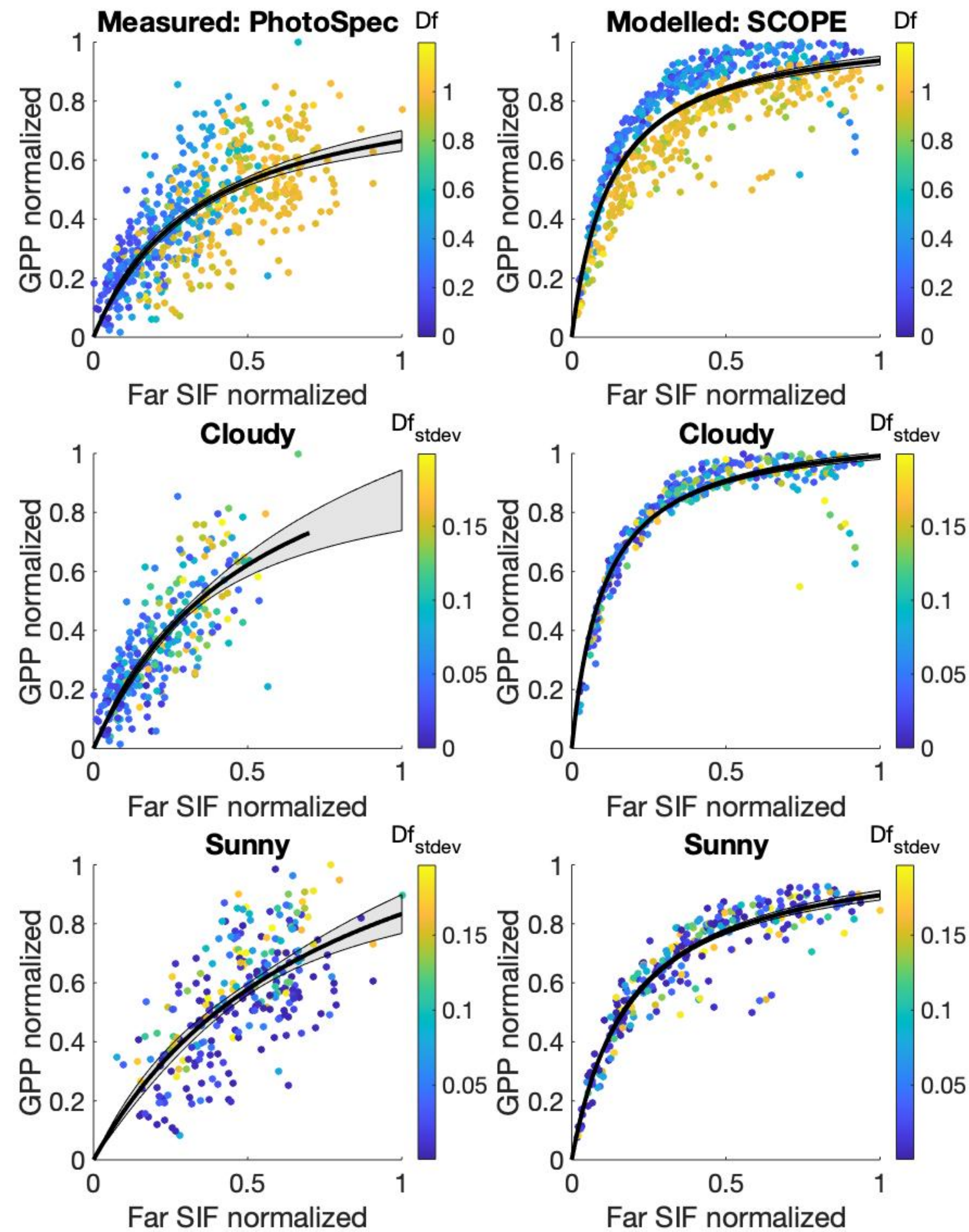

Figure 3: The SIF/GPP relationship for far-red SIF (745-758 nm).

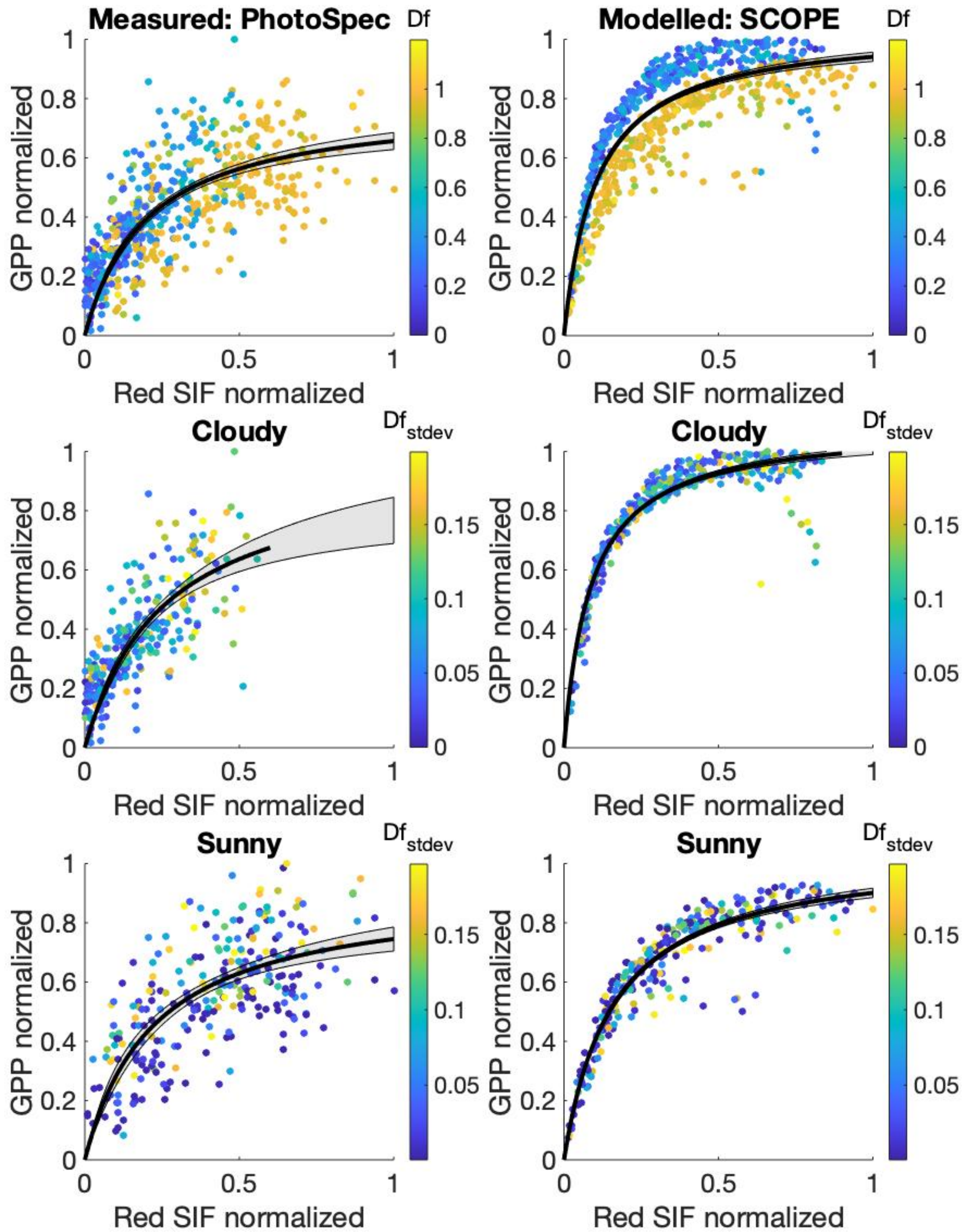

Figure 4: The SIF/GPP relationship for red SIF (680-686 nm).

We fit the curve $GPP = \frac{a*SIF}{b+SIF}$ (Damm et al. 2015) (https://www.sciencedirect.com/science/article/pii/S0034425715300341) and analyzed the fit parameters a and b to determine the significance of the change in the SIF/GPP relationship between sunny and cloudy conditions (Table 1).

The curve changed significantly between sunny and cloudy conditions in the model results, but not in the measurements. Furthermore, the model results showed an overall improvement in R^2 when the data were broken up by light conditions, which was not observed in the measurements.

Measured: Red	a	b	R^2
All	0.79 ± 0.06	0.20 ± 0.04	0.54
Cloudy	0.96 ± 0.16	0.26 ± 0.08	0.54
Sunny	0.91 ± 0.09	0.23 ± 0.07	0.46

Measured: Far	a	b	R^2
All	0.90 ± 0.10	0.35 ± 0.08	0.55
Cloudy	1.30 ± 0.33	0.54 ± 0.21	0.63
Sunny	1.49 ± 0.41	0.79 ± 0.37	0.43

Modelled: Red	a	b	R^2
All	1.04 ± 0.02	0.10 ± 0.01	0.77
Cloudy	1.10 ± 0.02	0.08 ± 0.01	0.90
Sunny	1.04 ± 0.03	0.16 ± 0.01	0.90

Modelled: Far	a	b	R^2
All	1.06 ± 0.03	0.13 ± 0.01	0.79
Cloudy	1.10 ± 0.02	0.10 ± 0.01	0.91
Sunny	1.06 ± 0.03	0.19 ± 0.02	0.89

Table 1: Fit parameters for the SIF/GPP relationship for red and far-red SIF, under diffuse (cloudy) sky conditions vs. direct (sunny) sky conditions in both measurements and model results.

To explore the differing response between measurements and model results in the SIF/GPP relationship, we looked at the light response of both SIF and GPP.

SIF AND GPP LIGHT RESPONSES

Measured SIF light response curves in both the red and far-red show a clear dependency on illumination conditions, while modeled SIF does not. GPP light response depends on illumination conditions for both measurements and model calculations.

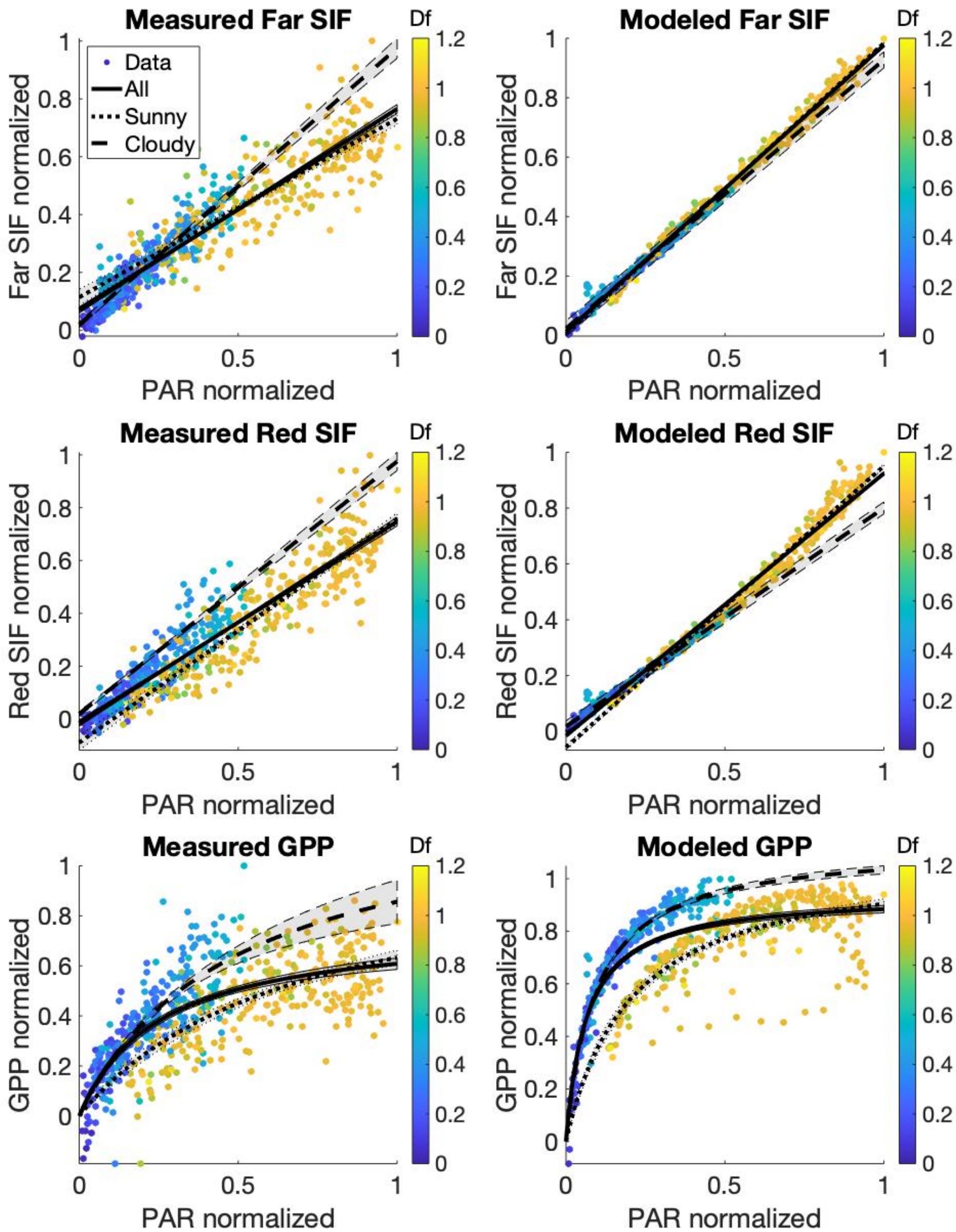

Figure 6: Light responses of SIF and GPP for both measurements and model results.

GPP Light Response:

- Both measured and modeled GPP show a higher efficiency under cloudy (diffuse) conditions compared with sunny (direct). Under diffuse conditions, the canopy is more evenly illuminated which allows for lower canopy levels to contribute more to carbon uptake when compared with the same light levels but direct conditions.
- Canopy level photosynthetic capacity (GPP_{sat}) occurs at a much lower PAR value in the model calculations than measurements. Furthermore, measured GPP under diffuse light does not have a clearly defined GPP_{sat}, which likely contributes to the uncertainties observed in the measured SIF/GPP relationship.

- Differences between the measured and modeled GPP light responses are likely due to uncertainties in model inputs such as Vc_{max} or Chlorophyll content.

SIF Light Response:

- The measured SIF light response shows a dependency on illumination conditions that is not observed in the model.
- We suggest this may be attributed to the highly clumped nature of the forest, which is not currently included in the SCOPE model. Under diffuse conditions, carbon assimilation is more evenly distributed within the canopy, therefore, lower canopy elements will be emitting more SIF under diffuse conditions than they would in direct. In a highly clumped forest, more SIF photons emanating from these lower canopy elements may be able to escape, thereby increasing the SIF signal under diffuse conditions.
- Introducing a clumping parameter into SCOPE may improve the model response.

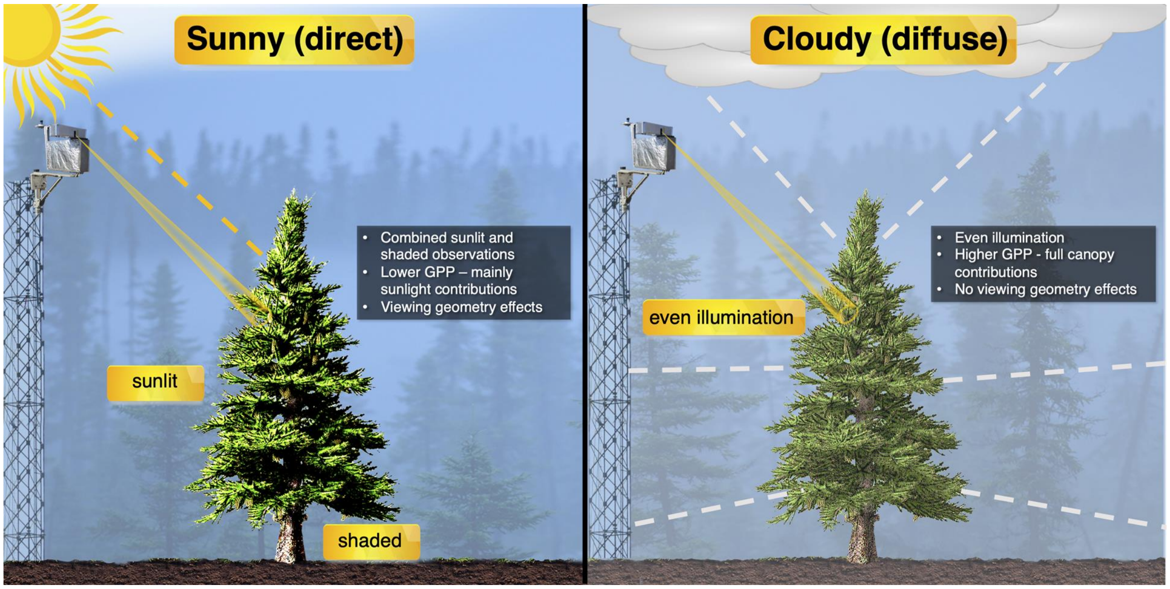

Figure 7: Summary of differences between direct and diffuse light conditions

VIEWING DIRECTIONAL EFFECTS DEPEND ON LIGHT CONDITIONS

Both measured and modeled SIF show a dependency on viewing direction under direct light conditions, but not under diffuse. Furthermore, red SIF shows a higher dependency on viewing direction than far-red SIF, in agreement with Zhang et al. 2020 (https://www.researchgate.net/publication/344201578_Assessing_bi-directional_effects_on_the_diurnal_cycle_of_measured_solar-_induced_chlorophyll_fluorescence_in_crop_canopies).

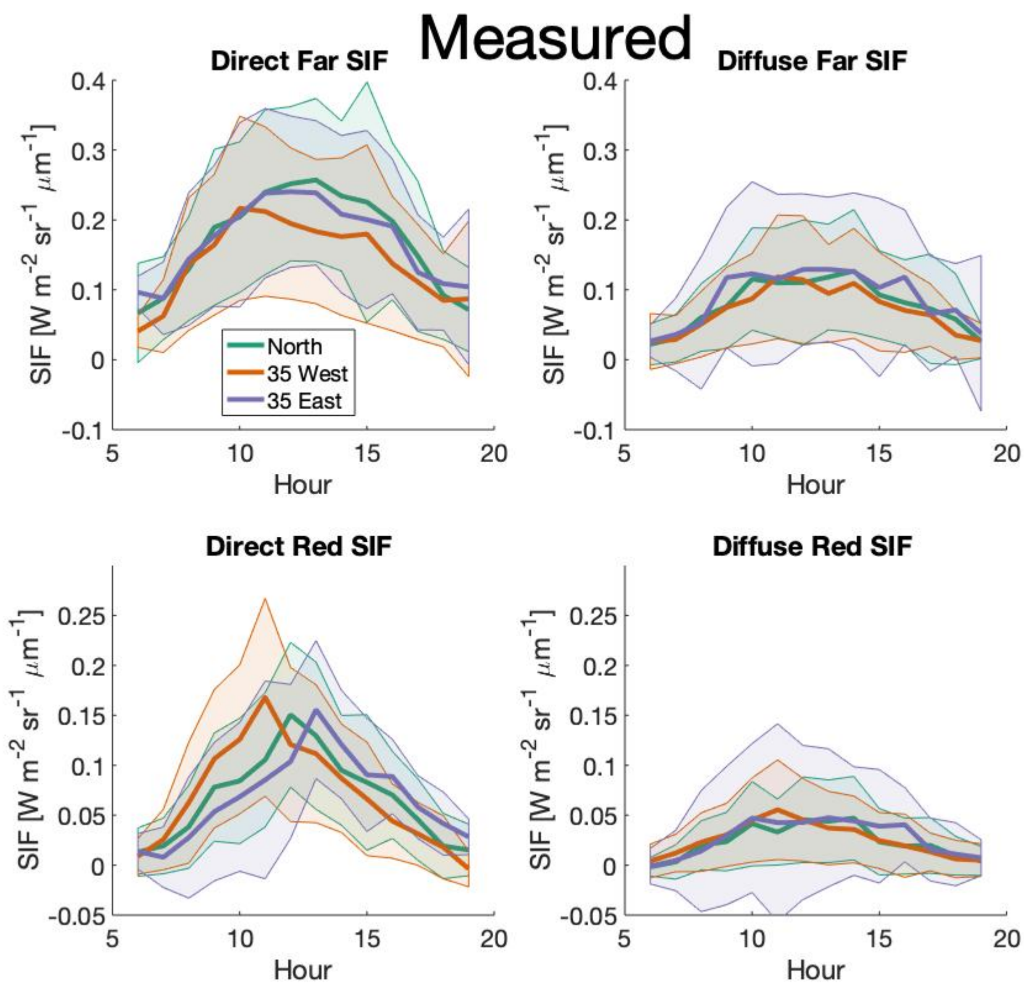

Figure 8: Measured diurnal pattern of SIF in direct vs. diffuse radiative conditions. Shaded error bars are the standard deviation of points in each hour.

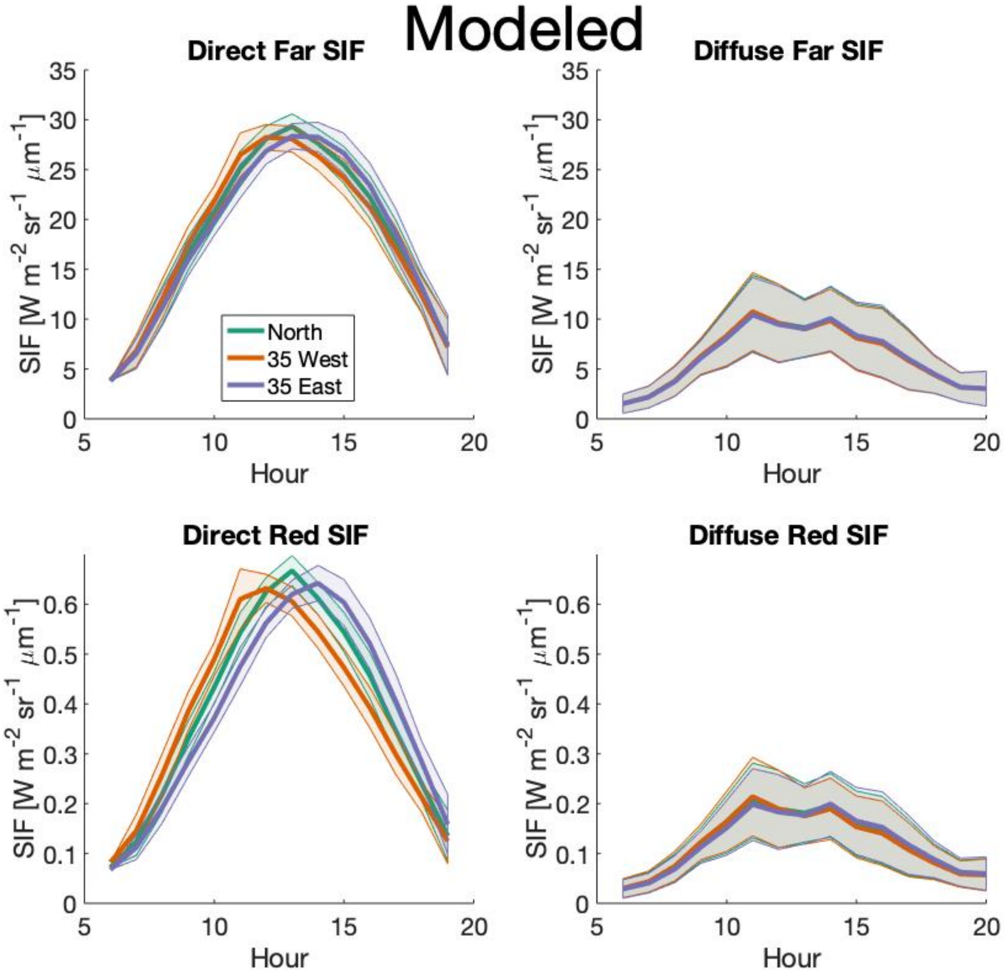

Figure 9: Modeled diurnal pattern of SIF in direct vs. diffuse radiative conditions. Shaded error bars are the standard deviation of points in each hour.

AUTHOR INFORMATION

Zoe Pierrat is a third year graduate student at the University of California Los Angeles with advisor Dr. Jochen Stutz.

You can follow my research activities on my GoogleScholar (https://scholar.google.com/citations?user=gQ21EZMAAAAJ&hl=en) profile or less formally on my Twitter (https://twitter.com/Zoeapie). You can contact me using the contact author tab or by email at zpierrat@g.ucla.edu

ABSTRACT

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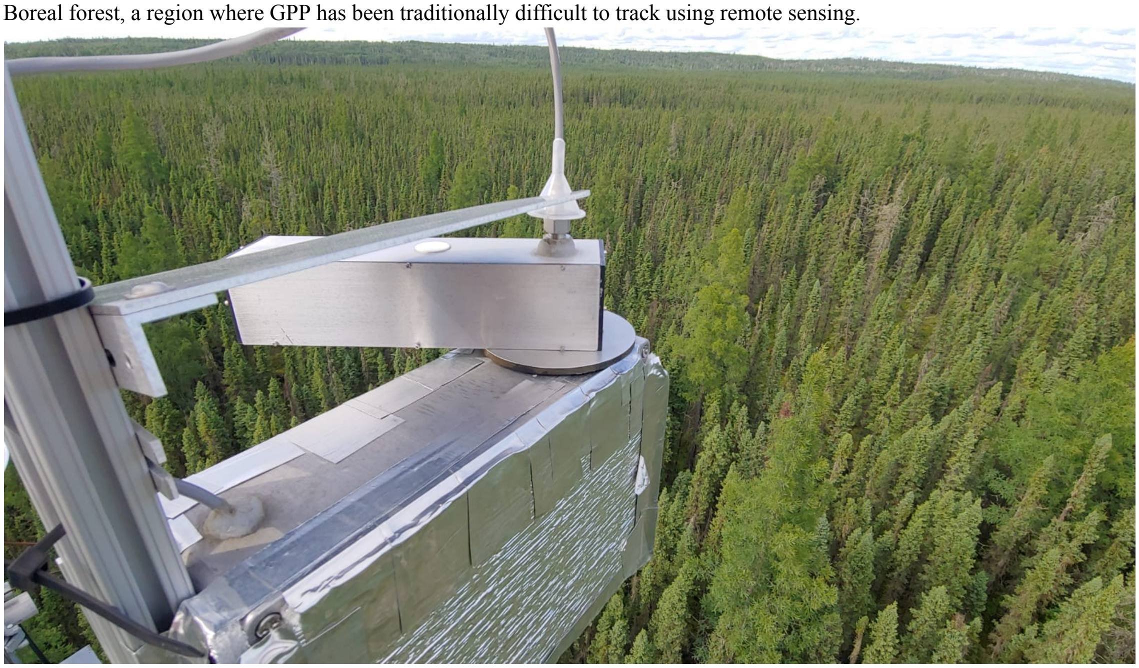

(https://agu.confex.com/data/abstract/agu/fm20/0/1/Paper_673310_abstract_643738_0.png)

REFERENCES

References:

Barr, A. G., Black, T. A., Hogg, E. H., Kljun, N., Morgenstern, K., & Nesic, Z. (2004). Inter-annual variability in the leaf area index of a boreal aspen-hazelnut forest in relation to net ecosystem production. Agricultural and Forest Meteorology, 126(3–4), 237–255. https://doi.org/10.1016/j.agrformet.2004.06.011

Damm, A., Guanter, L., Paul-Limoges, E., van der Tol, C., Hueni, A., Buchmann, N., Eugster, W., Ammann, C., & Schaepman, M. E. (2015). Far-red sun-induced chlorophyll fluorescence shows ecosystem-specific relationships to gross primary production: An assessment based on observational and modeling approaches. Remote Sensing of Environment, 166, 91–105. https://doi.org/10.1016/j.rse.2015.06.004

Gamon, J. A., & Berry, J. A. (2012). Facultative and constitutive pigment effects on the Photochemical Reflectance Index (PRI) in sun and shade conifer needles. Israel Journal of Plant Sciences, 60(1–2), 85–95. https://doi.org/10.1560/IJPS.60.1-2.85

Gamon, J. A., Huemmrich, K. F., Wong, C. Y. S., Ensminger, I., Garrity, S., Hollinger, D. Y., Noormets, A., & Peñuelask, J. (2016). A remotely sensed pigment index reveals photosynthetic phenology in evergreen conifers. Proceedings of the National Academy of Sciences of the United States of America, 113(46), 13087–13092. https://doi.org/10.1073/pnas.1606162113

Grossmann, K., Frankenberg, C., Magney, T. S., Hurlock, S. C., Seibt, U., & Stutz, J. (2018). PhotoSpec: A new instrument to measure spatially distributed red and far-red Solar-Induced Chlorophyll Fluorescence. Remote Sensing of Environment, 216(November 2017), 311–327. https://doi.org/10.1016/j.rse.2018.07.002

Zhang, Z., Zhang, Y., Zhang, Q., Chen, J. M., Porcar-Castell, A., Guanter, L., Wu, Y., Zhang, X., Wang, H., Ding, D., & Li, Z. (2020). Assessing bi-directional effects on the diurnal cycle of measured solar-induced chlorophyll fluorescence in crop canopies. https://doi.org/10.1016/j.agrformet.2020.108147

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