Exploring Diurnal Dynamics of Solar-induced Chlorophyll Fluorescence and Photosynthesis in a Maize Canopy

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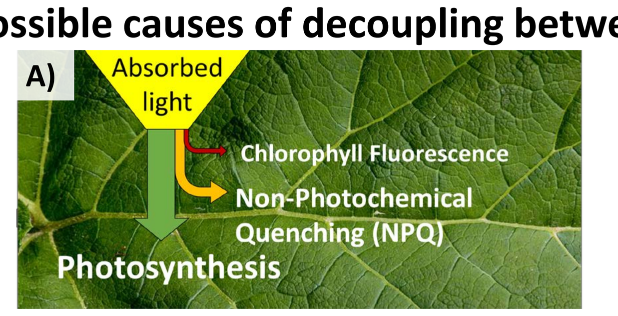
Background

- Monitoring the productivity of terrestrial ecosystems crucial to assess impacts of climate change. Established methods of estimating global photosynthesis rely on upscaling from ground-based eddy covariance (EC) flux measurements, or satellite measurements of greenness-based indices.
- However, EC data are unevenly biased towards the Northern hemisphere and temperate regions, while greenness-based indices track chlorophyll content rather than actual plant productivity.
- Solar-induced chlorophyll fluorescence (SIF) is currently being explored as a functional proxy of photosynthesis. Chlorophyll fluorescence consists of a small fraction of light absorbed by the leaf which is not used for photochemistry or dissipated by non-photochemical quenching (NPQ) (Fig. 1a). Both SIF and gross primary productivity (GPP) can be expressed using light use efficiency (LUE) models (Fig. 1b).
- The similarity between SIF and GPP models suggests a linear relationship between the two parameters, which has been supported by satellite level measurements (e.g. Sun et al. 2018). However, satellite data is limited to coarse temporal and spatial scales (Fig. 1c), which may mask variability in SIF and GPP at finer scales. Furthermore, satellite data is typically estimated as a daily average extrapolated from a discrete daily measurement (Fig. 1d). This may lead to errors from atmospheric contamination and possible under- or over-estimation if there is indeed decoupling at the diurnal scale (Fig. 1e).
- **Here we explore the diurnal dynamics of SIF and GPP at the canopy scale and report cases and possible causes of decoupling between SIF and GPP.**



B)
$$GPP = LUE_p * APAR$$
$$SIF = LUE_f * APAR * \varepsilon$$

C)

SIF-capable satellites	GOME-2	GOSAT	OCO-2
Overpass time	9:30	13:00	13:30
Revisit cycle	3 days	3 days	16 days

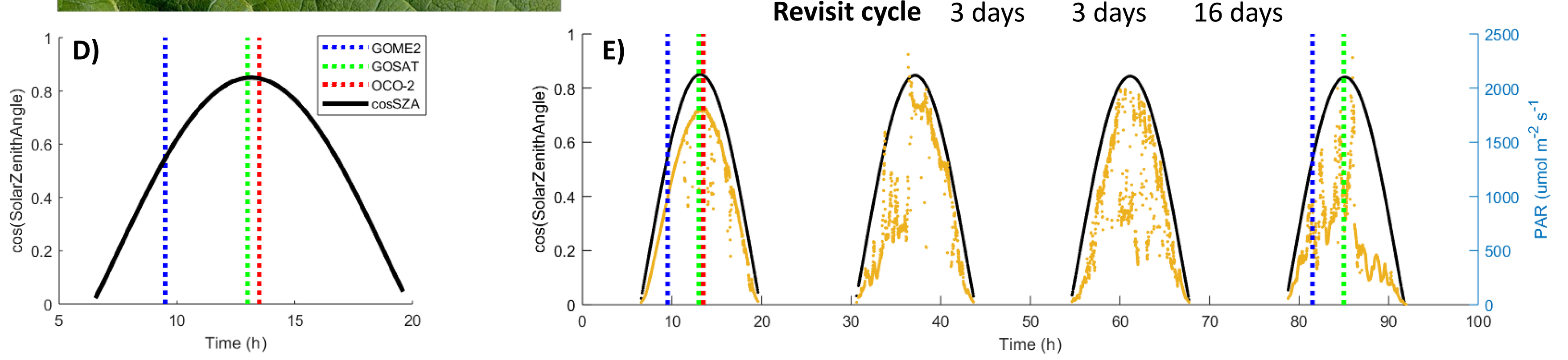


Fig. 1: A) Schematic of light partitioning among photosynthesis, NPQ and chlorophyll fluorescence; B) LUE models for GPP and SIF; C) Overpass times and revisit cycles for current SIF-capable satellites; D) Overpass times during a diurnal cycle calculated by cosine of the solar zenith angle; E) Four days of actual PAR measured at our field site.

Methods

SIF, GPP and meteorological variables were continuously measured in a rain-fed maize field located at Cornell Musgrave Research Farm, Aurora, NY (42° 43' 22" N, 76° 39' 46" W) from July 10 to October 2, 2018 (DOY 191-275). The field was planted on May 25 (DOY 145) with north-south row orientation, 30 inches spacing between and 6 inches spacing within rows. Raw spectral measurements were collected using the Fluorescence Auto-Measurement Equipment (FAME, described in Gu et al. 2018). The core of FAME is a QE Pro spectrometer (Ocean Optics) equipped with a longpass filter (>695 nm), 25 µm slit, and H15 grating to capture a wavelength range of 730-784 nm with a spectral resolution of ~0.15nm FWHM (full width at half maximum). The fiber optic was fitted with an opaline glass cosine corrector (CC-3, Ocean Optics) and rotated using a motor between zenith and nadir positions. The SIF system was set up at a height of 15 ft (~4.6m), with the nadir-pointing fiber situated ~1.5-2m from the top of the mature crop canopy. The dehumidified instrument enclosure was maintained at 25±0.02°C using a heating/cooling thermoelectric cooler (TE Technology); the onboard detector temperature was maintained at -10°C. Radiometric calibrations were performed prior to installation and every 1-2 months on site with HL-2000-CAL halogen lamp (Ocean Optics). Wavelength calibrations were performed at the start and end of the growing season with HG-1 mercury argon lamp (Ocean Optics). SIF retrieval at 760nm was performed using the spectral fitting method with a fitting window of 759-767.76nm (Meroni and Columbo 2006). Flux measurements, measured using 7500A open-path CO_2/H_2O analyzer (Licor) at 10Hz intervals, were aggregated to 30 minutes. De-spiking and pre-processing of flux measurements were performed using FReddyPro R package (Xenakis 2016); U* filtering, gap-filling and GPP calculation was performed using the REddyProc package (Reichstein and Moffat 2014) in R v.3.3.3. APAR was measured using line quantum sensors (Apogee) above and below the canopy, following Gitelson et al. 2015. From DOY 191 to 271, soil water content and leaf water potential were monitored bi/weekly using a PR2/4 probe (Dynamax) and Scholander pressure bomb (PMS Instruments), respectively. Diurnal leaf level gas exchange and chlorophyll fluorescence were measured on DOY 236 at ambient temperature and PAR using a GFS-3000 portable photosynthesis system (Walz).

Summary

- At the diurnal scale, SIF and GPP can become decoupled.
- In a corn field with north-south rows, diurnal dynamics of SIF were consistently characterized by a midday dip and hysteresis.
- However, this diurnal pattern of midday dip and hysteresis only appeared in GPP when plants were water stressed.
- Canopy structure and physiology drive diurnal dynamics of SIF.

SIF and GPP decoupled at midday across the growing season

Across the growing season, SIF exhibited a strong midday dip and hysteresis on clear days, but GPP only exhibited a clear midday depression when both air temperature and VPD were high and plants were experiencing water stress (DOY 201, Fig. 2, 3). The 2018 growing season at Aurora, NY was characterized by an early period of drought during the first two weeks of July, followed by frequent rain events and/or cloudy days for the rest of the growing season (Fig. 3).

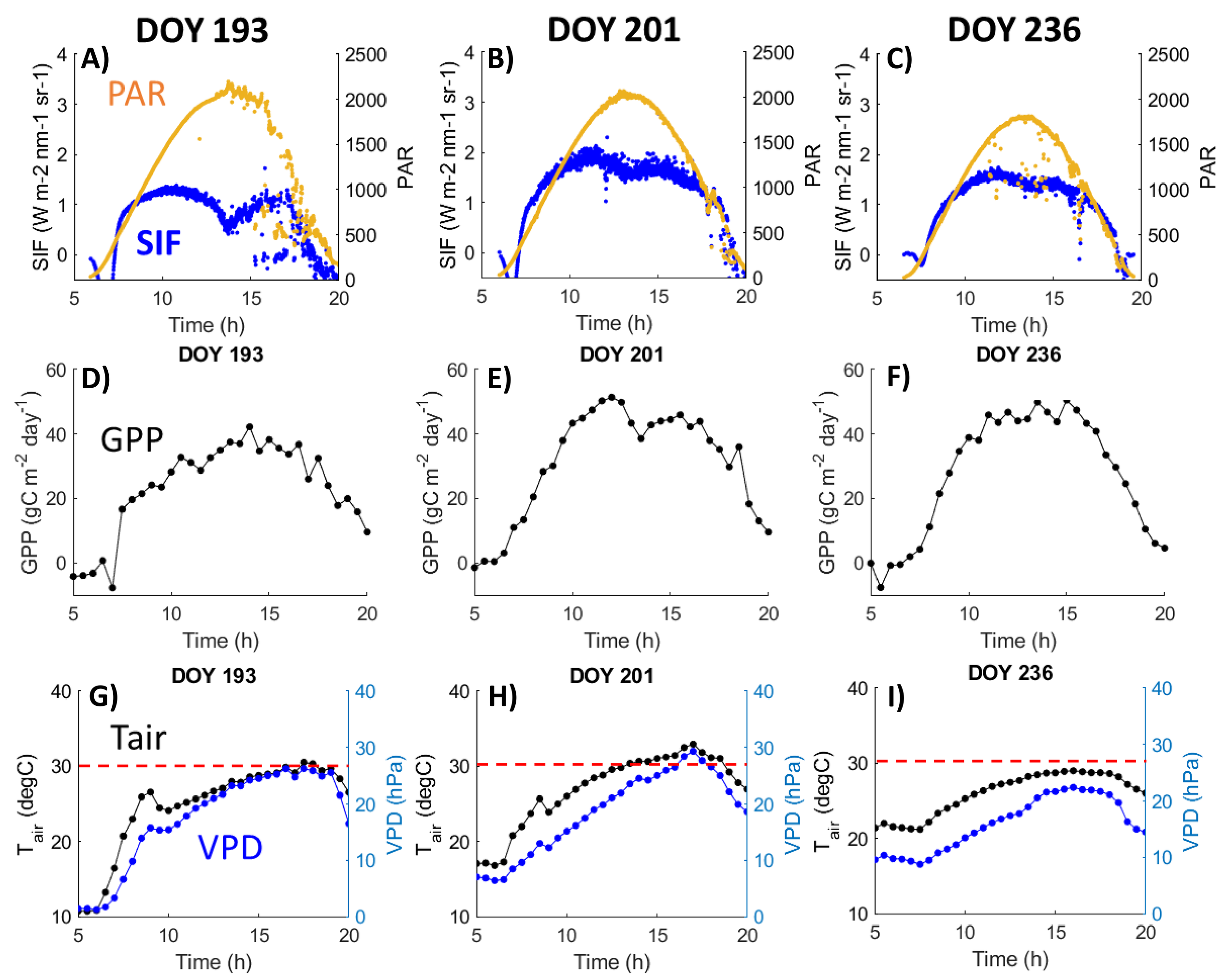


Fig. 2: Diurnal patterns of (A-C) PAR and SIF, (D-F) GPP, and (G-I) air temperature (T_{air}) and vapor pressure deficit (VPD) on three clear days over the growing season. Dashed red lines in G-I indicate 30°C.

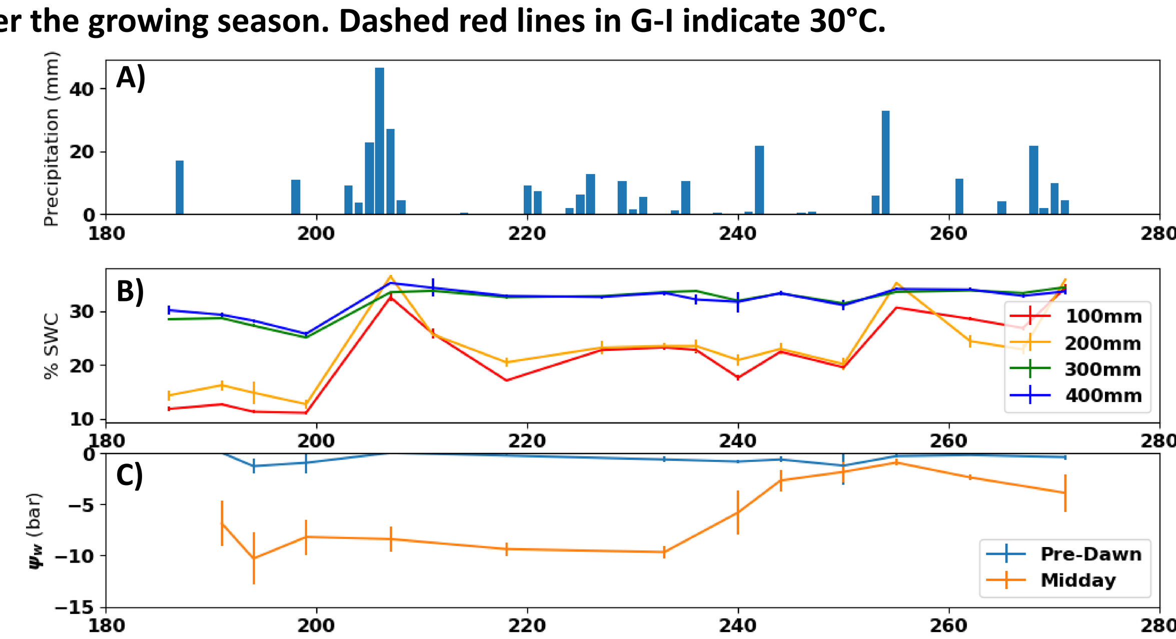


Fig. 3: Seasonal precipitation, soil water content (%) and leaf water potential (Ψ_W).

References

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Acknowledgments

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Canopy structure contributes to midday dip

The amount of photosynthetically active radiation absorbed by the canopy (APAR) exhibited a midday dip which was more severe during the beginning and late growing season (Fig. 4a-c). The "dip" phenomenon was caused by some light being absorbed by bare soil at midday, even after canopy closure, as sun passed from east to west over our north-south planted row structures (Fig. 4d). The severity of the dip changed over the growing season (Fig. 4e) as the canopy developed (DOY 171-201). matured (DOY 218) and senesced (DOY 260).

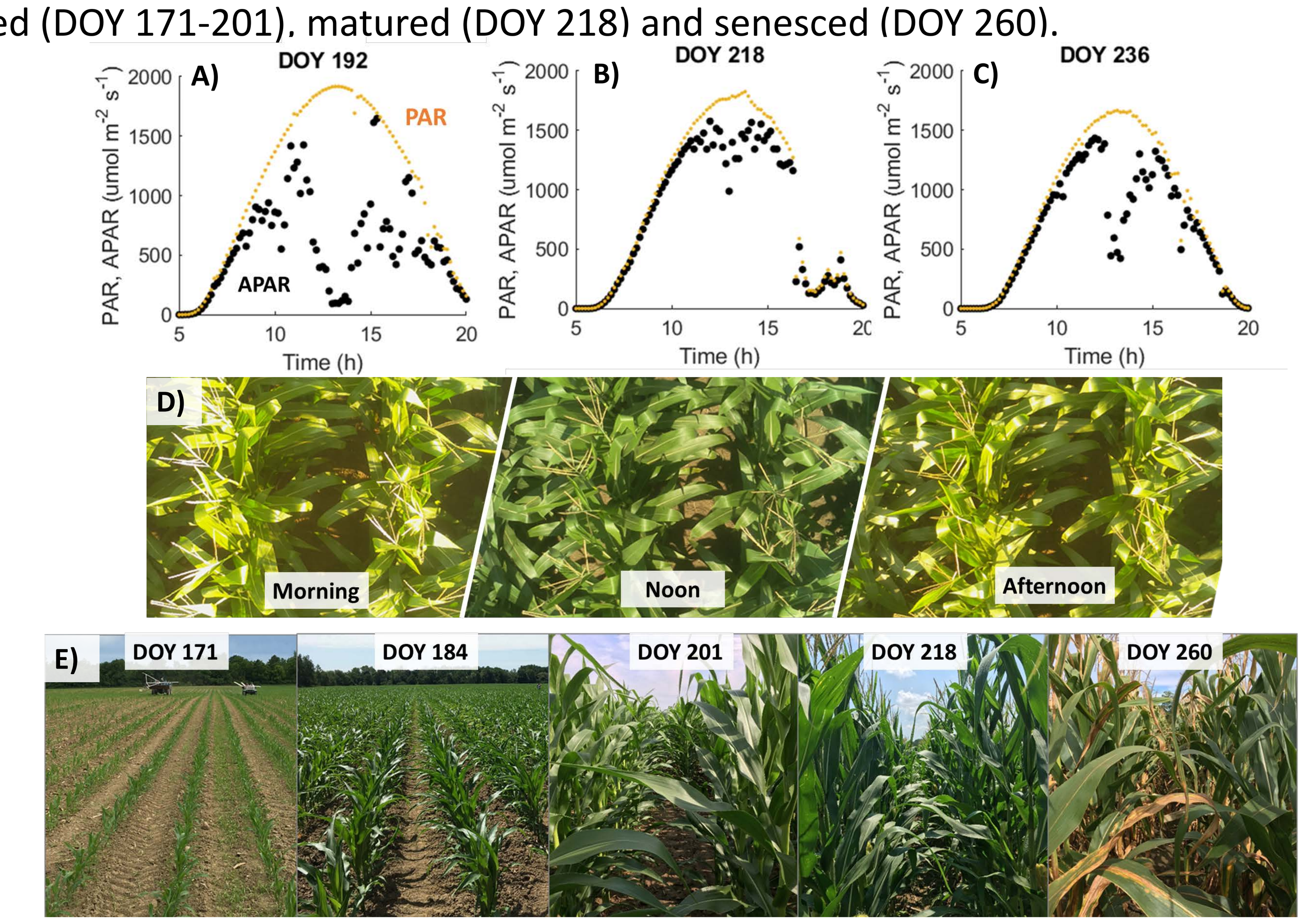

Fig. 4: A-C) Incident and absorbed PAR; D) Light penetration into the canopy at morning, noon and afternoon; E) Seasonal changes in canopy structure.

Physiology contributes to hysteresis and midday dip

Diurnal dynamics of NPQ may affect the diurnal dynamics of SIF. At the leaf level, the top of the canopy exhibited a slight hysteresis, with a higher proportion of light entering photochemistry in the morning and a higher proportion of light dissipated by NPQ in the afternoon (Fig. 5a). In contrast, leaves at the mid canopy exhibited a large boost in NPQ if they became exposed to high light, particularly at midday when light penetrated deeper into the canopy (Fig. 5b).

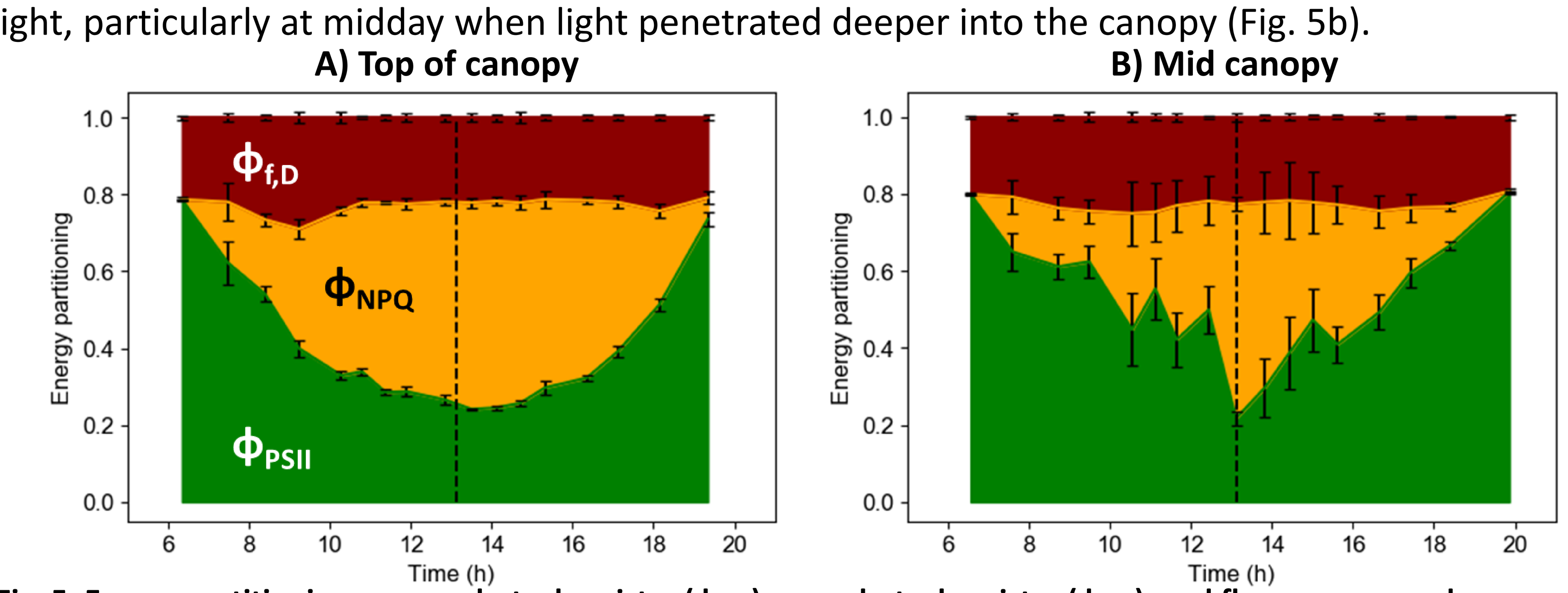

Fig. 5: Energy partitioning among photochemistry (ϕ_{PSII}), non-photochemistry (ϕ_{PSII}), and fluorescence and constitutive heat dissipation ($\phi_{f,D}$) measured on leaves located at the (A) top of canopy and B) mid-canopy. Each point represents 6-12 leaves with standard error bars. Dashed line indicates solar noon.

Implications for satellite SIF

Decoupling of SIF and GPP, particularly in agricultural production areas or other regions with row-structured canopies, could lead to over or underestimation of SIF from satellites depending on overpass time (Fig. 6).

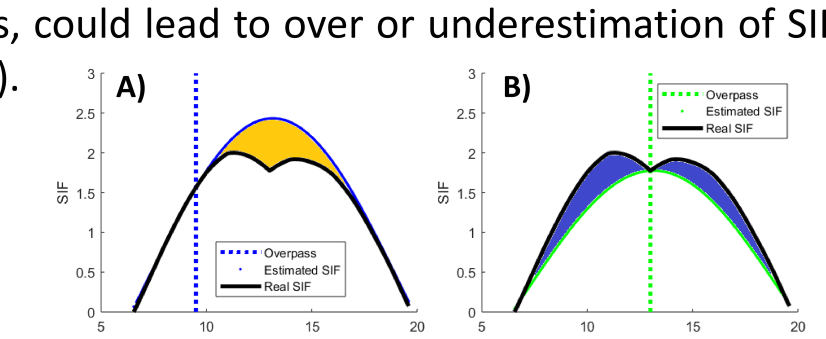

Fig. 6: A) Over- or B) underestimation of daily SIF based on overpass time over a site with midday dip and hysteresis.