From leaves to ecosystems: what can we learn about fluxes using remote sensing?

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What is remote sensing?

• Remote sensing: the acquisition of information about an object without making physical contact with the objects.
Remote sensing measures radiation

Remote sensing *products* of fluxes (e.g., GPP and ET) are not *measurements*, but rather modeling results using remote sensing measurements of radiation based on certain assumptions.
RS and Flux Tower complement each other

Satellite vs. Flux Tower

Tower measurements: flux responses; meteorological drivers, e.g. temperature, humidity

Remote sensing grids: land surface drivers, e.g. temperature, vegetation indices

Optical tower-based instruments vs. Flux Tower

Source: Wayne Dawson
An exciting era for remote sensing

Novel technology and algorithms open new windows

The next generation satellite sensors

Drones!

Global networks of tower-based remote sensing

What can we learn about fluxes with remote sensing?
Remote sensing of global photosynthesis

Schimel et al., 2015
How is photosynthesis estimated? — leaf scale

Portable Photosynthesis System

Not-so-portable Photosynthesis System

Source: Li-Cor; Joe Berry
Remote sensing of global photosynthesis

NDVI developed in the 1970s

Normalized Difference Vegetation Index

\[
\text{NDVI} = \frac{(\text{NIR} - \text{R})}{(\text{NIR} + \text{R})}
\]

Tucker 1979 RSE
Remote sensing of global photosynthesis

Global mapping of vegetation in the 1980s
Remote sensing of global photosynthesis

Global mapping of vegetation in the 1980s

**Relationship between atmospheric CO₂ variations and a satellite-derived vegetation index**

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**Fig. 1** Variation of global atmospheric CO₂ concentrations with latitude and time based on the NOAA/GMCC flask measurements for 1982–84.

**CO₂ concentration**

**NDVI**

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**Fig. 4** The globally averaged atmospheric CO₂ concentration plotted against the globally averaged NDVI with a time lag of 3 month. The CO₂ data are from the global network of 20 NOAA/GMCC stations.

**A negative relationship between CO₂ concentration and NDVI**
Remote sensing of global photosynthesis
MODIS in the 2000s

\[ GPP = \text{PAR} \times f\text{APAR} \times \varepsilon_p \]

**Absorbed PAR**

\( \text{PAR: Photosynthetically Active Radiation} \)

\( f\text{APAR: Fraction of PAR absorbed by leaves} \)

\( \varepsilon_p: \text{f} \text{(plant functional type, temperature, water availability)} \)
The vegetation index is a measure of the “greenness” of tree canopy

\[ \text{Normalized Difference Vegetation Index} = \frac{(\text{NIR}-\text{R})}{(\text{NIR}+\text{R})} \]

GPP = PAR \times f\text{APAR} \times \varepsilon_p

Estimated in a similar way as Vegetation Index

PAR: Photosynthetically Active Radiation
f\text{APAR}: Fraction of PAR absorbed by leaves

Myneni et al. 2002

Leaf area
Vegetation index is about potential photosynthesis

Is there a tool that can help us to tell the real-time photosynthesis of plants globally?
Fluorescence in nature

Source: Matt Reinbold; Wikipedia; NASA
Chlorophyll absorb mainly blue and red photons

Absorption by chlorophyll a

Absorption / Emission

Absorption by chlorophyll a

Wavelength

430

662

400 500 600 700 (nm)
SIF is emitted in a longer wavelength

Absorption by chlorophyll a

Fluorescence

Not to scale
Satellite measurements of SIF

**SIF from GOSAT**

A Chlorophyll a fluorescence at 755 nm, June 2009 through May 2010 average

Frankenberg et al., 2011

**SIF from GOME-2**

Joiner et al., 2011

**SIF from OCO-2**

OCO-2 Solar-Induced Fluorescence Aug-Oct 2014

NASA JPL

**SIF from TROPOMI**

8-15 July 2019, CF<0.5

Gunter et al., 2020
Solar-induced chlorophyll fluorescence (SIF) is a small fraction of reflected light absorbed photons = photosynthesis (0~82%) + heat (17.5~98%) + fluorescence (~0.5~2%).

Liu et al., 2014

Source: Joe Berry

Credit: NASA
Glowing plants

Other available SIF products:

**SCIAMACHY** (Joiner et al., 2016)

**OCO-2** (Sun et al., 2020)

**TROPOMI** (Kohler et al., 2020)

**GOSAT** (Frankenberg et al., 2012)

**GOSAT-2**

**TanSat** (Liu et al., 2020)

**OCO-3** (First product available)

**GEOCarb** (2024)

**FLEX** (2025)

**TEMPO** (2022)

\[
y = -0.88 + 3.55x; \quad r^2 = 0.92 \\
y = 0.35 + 3.71x; \quad r^2 = 0.79 \\
y = -0.17 + 3.48x; \quad r^2 = 0.87
\]

Source: NASA
Linking SIF to GPP

\[
\text{GPP} = \text{PAR} \times f\text{APAR} \times \phi_p \times \frac{1}{k}
\]

\[
\text{SIF} = \text{PAR} \times f\text{APAR} \times \phi_F \times f_{esc}
\]

PAR: Photosynthetically Active Radiation
fAPAR: Fraction of PAR absorbed by leaves
\(\phi_p\): Photochemical yield
\(k\): assuming the fraction of light used by PSII is 0.5, \(k\) is the number of electron equivalents produced by LEF required to reduce one molecule of CO2.
\(\phi_F\): Fluorescence yield
\(f_{esc}\): escape probability (structure)
Fluorescence provides an optical probe into the photosynthetic machinery

Chloroplast

Light reactions

- Light
- H₂O
- O₂
- Thylakoid Membranes
- Photochemical Quenching (PQ) (0-82%)
- Non-Photochemical Quenching (NPQ) (17.5-98%)

Carbon reactions

- ATP
- NADPH
- ADP
- NADP⁺
- (CH₂O)ₙ
- CO₂
- Calvin-Benson Cycle

Modified from Magney, Barnes, and Yang, GRL, 2020
What does a change in SIF tell you?

Leaf-level physiology: changes in PQ or chlorophyll content
Canopy structure: changes in leaf area and/or leaf angle
Viewing angle: how a sensor is angled wrt the object matters a lot

(SIF = PAR * fAPAR * φF * fesc)

Magney, Barnes, and Yang 2020
Sun-sensor-object geometry is essential in optical remote sensing.
Bidirectional Reflectance Distribution Function (BRDF)

Light Rain in Early Spring
(初春小雨)
by Han Yu

though one sees the color of grass from afar, if one gets closer it is not really there.
Bidirectional Reflectance Distribution Function (BRDF)

http://www.doc.gold.ac.uk/~mas02fl/MSC101/Graphics/Render.html
Sun-sensor-object geometry is essential in optical remote sensing.
What does a change in SIF tell you?

GPP?
Drought?
Transpiration?
Impacts of diffuse radiation?
CO2 fertilization?
Heat stress?
Flooding?
Beetle attack?
Changes in forest composition?
A few considerations when linking RS with Flux tower measurements

Satellite vs. Flux Tower

- RS data should match the footprint of the EC tower measurements
- Optical & thermal satellite measurements are only good on sunny days
- For ecosystems with complicated canopy structures, note that *some* RS measurements are most sensitive to the top of the canopy
- Remember that GPP from EC tower measurements is also “modeled” with assumptions
- SIF and vegetation indices, to the best, tell us about the electron transport part of photosynthesis

Optical tower-based instruments vs. Flux Tower

- Tower-based optical sensors usually have smaller footprints compared with EC towers, but they also can provide measurements of individuals
- With careful consideration, tower-based optical data are good for cloudy days too
- RS data can provide information beyond GPP!
Synergy of RS methods

Figure 1 | Spatial and temporal synergy of observations and their applications. A pretzel diagram of observations (red text) from each instrument (coloured shapes) and the synergistic physical parameters that can be derived (black text) when observations are taken at synchronous and complementary spatial and temporal resolutions.
Trade-off between the spatial & temporal resolutions

Temporal resolution

- Seconds
- Minutes
- Hours
- Days
- Months
- Years

Spatial resolution

- cm
- m
- km
- 100km

Satellites and missions:
- GOES
- MTG
- Hiwarari-8
- TROPOMI
- MODIS
- SMAP
- Sentinel-1 SAR
- Sentinel-2 (MSI)
- Landsat 8 (OLI)
- MODIS
- TROPOMI
- SIF
- Sentinel-2 (MSI)
- Landsat 8 (OLI)
- ECOSTRESS
- HISUI, OCO-3
- SMAP
- NEON AOP
- AVIRIS
- NAIP
- ICESat
- GEDI
- HISUI
- OCO-3
- Planet
- UAVs and TLS
- Phenocam
- Planet
- UAVs and TLS
- NAIP

Applications:
- Vegetation cover
- Classification
- Plant Traits
- Energy balance
- Inundation
- Biomass

Spectral bands:
- VIS-NIR
- SWIR
- TIR
- MW