Studying diurnal variations of ecosystem processes from space

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Emerging satellite observations for diurnal cycling of ecosystem processes

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Diurnal cycling of plant carbon uptake and water use, and their responses to water and heat stresses, provide direct insight into assessing ecosystem productivity, agricultural production and management practices, carbon and water cycles, and feedbacks to the climate. Temperature, light, atmospheric water demand, soil moisture and leaf water potential vary over the course of the day, leading to diurnal variations in stomatal conductance, photosynthesis and transpiration. Earth observations from polar-orbiting satellites are incapable of studying these diurnal variations. Here, we review the emerging satellite observations that have the potential for studying how plant functioning and ecosystem processes vary over the course of the diurnal cycle. The recently launched ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) and Orbiting Carbon Observatory-3 (OCO-3) provide land surface temperature, evapotranspiration (ET), gross primary production (GPP) and solar-induced chlorophyll fluorescence data at different times of day. New generation operational geostationary satellites such as Himawari-8 and the GOES-R series can provide continuous, high-frequency data of land surface temperature, solar radiation, GPP and ET. Future satellite missions such as GeoCarb, TEMPO and Sentinel-4 are also planned to have diurnal sampling capability of solar-induced chlorophyll fluorescence. We explore the unprecedented opportunities for characterizing and understanding how GPP, ET and water use efficiency vary over the course of the day in response to temperature and water stresses, and management practices. We also envision that these emerging observations will revolutionize studies of plant functioning and ecosystem processes in the context of climate change and that these observations and findings can inform agricultural and forest management and lead to improvements in Earth system models and climate projections.

Motivation

- Plant scientists and ecologists have been intrigued by the circadian rhythms (i.e., circadian clock) of plants for decades.
- Many compelling science questions have arisen regarding the diurnal (i.e., diel) patterns of plant photosynthesis and transpiration.
- Addressing these questions is increasingly important in the context of climate change.
- Elucidating diurnal cycling of plant water loss by transpiration and carbon gain by photosynthesis is of fundamental importance for understanding how plants interact with ambient and changing environmental conditions.

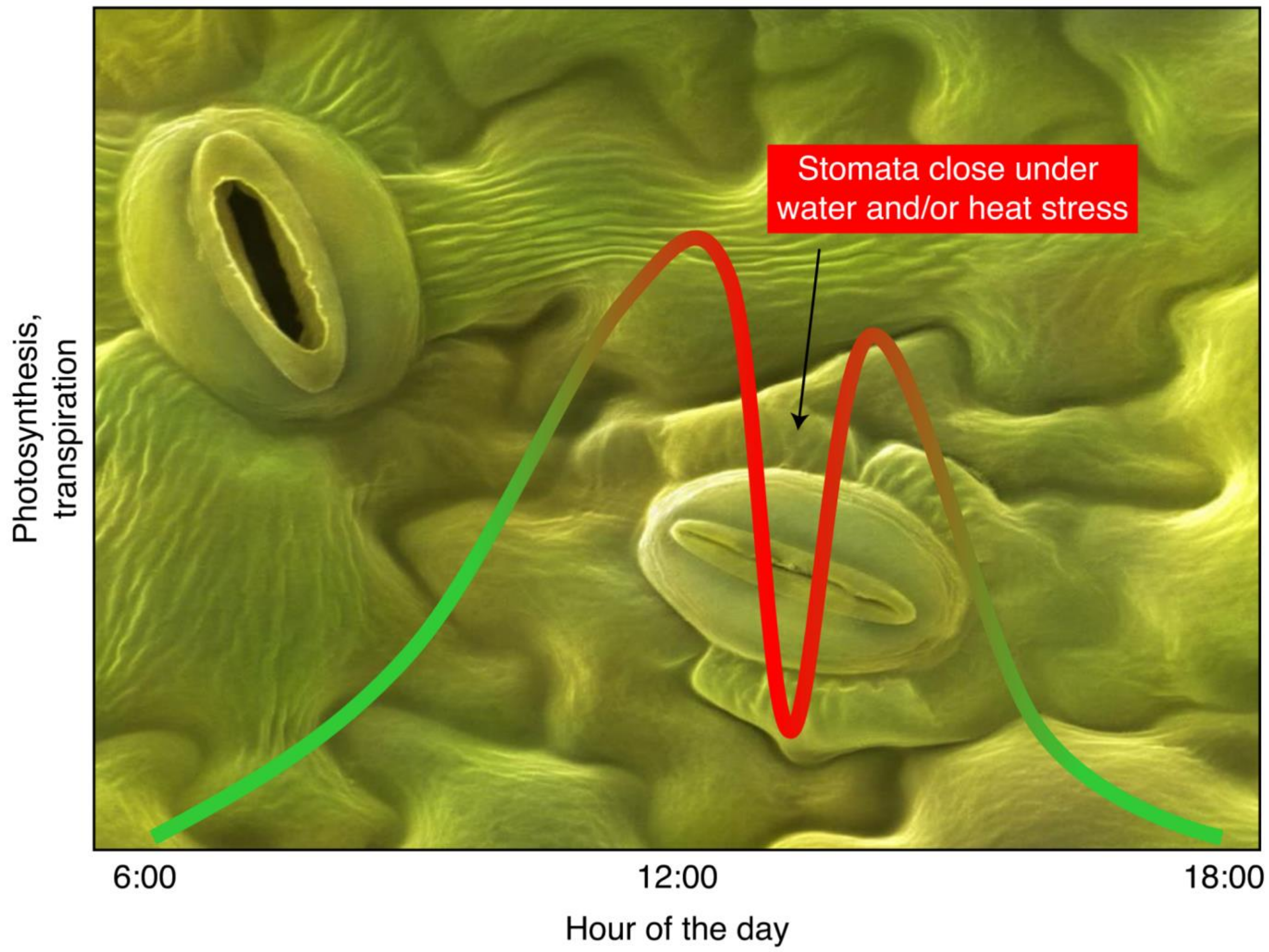
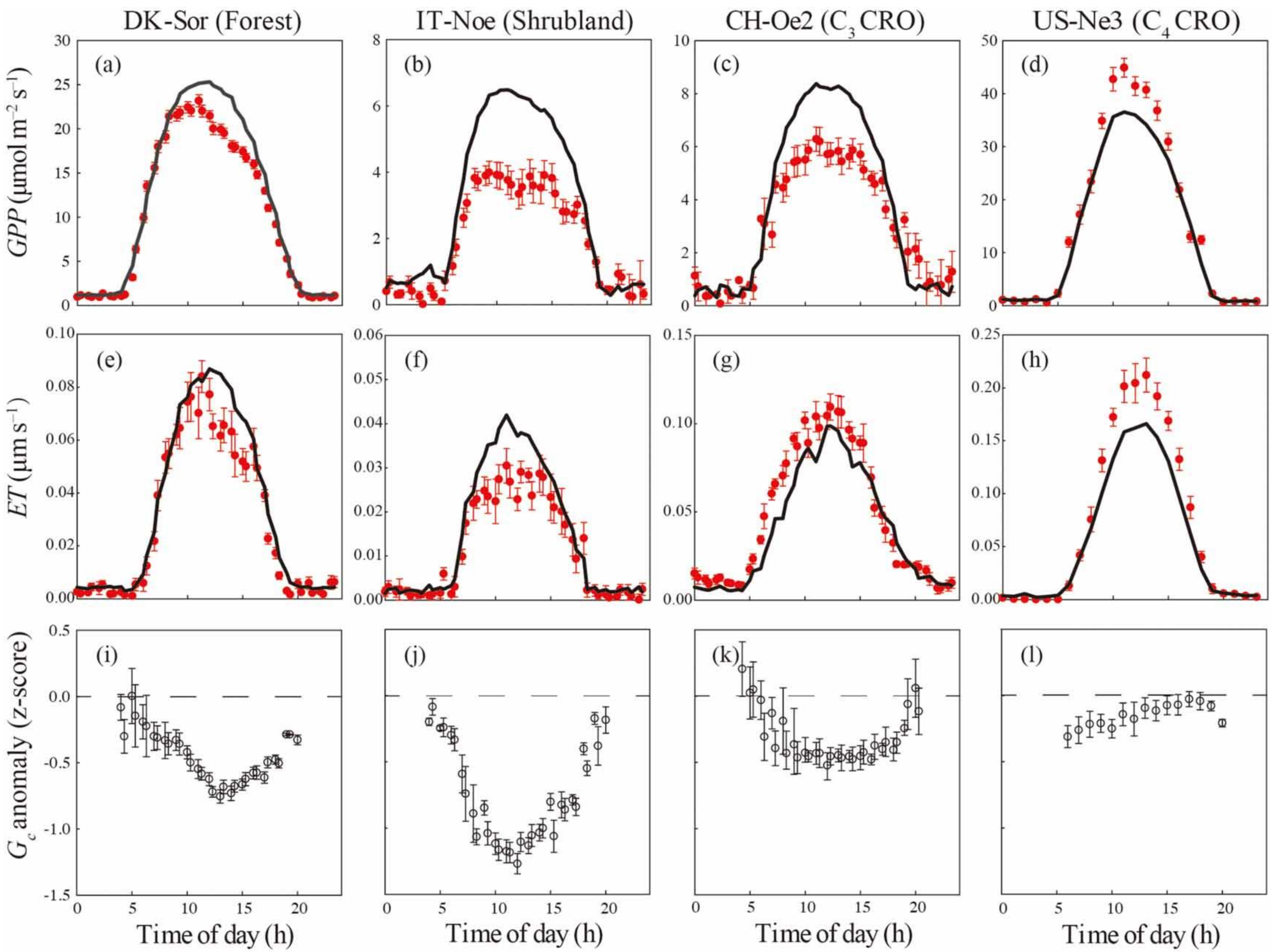


Fig. 1 | Conceptual diagram of plant photosynthesis and transpiration over the course of a day. Both transpiration and photosynthesis may show

- Drought and heatwaves are projected to be more frequent
- Observations at multiple times of the day are essential for understanding the diurnal cycles of plant water use and carbon uptake.

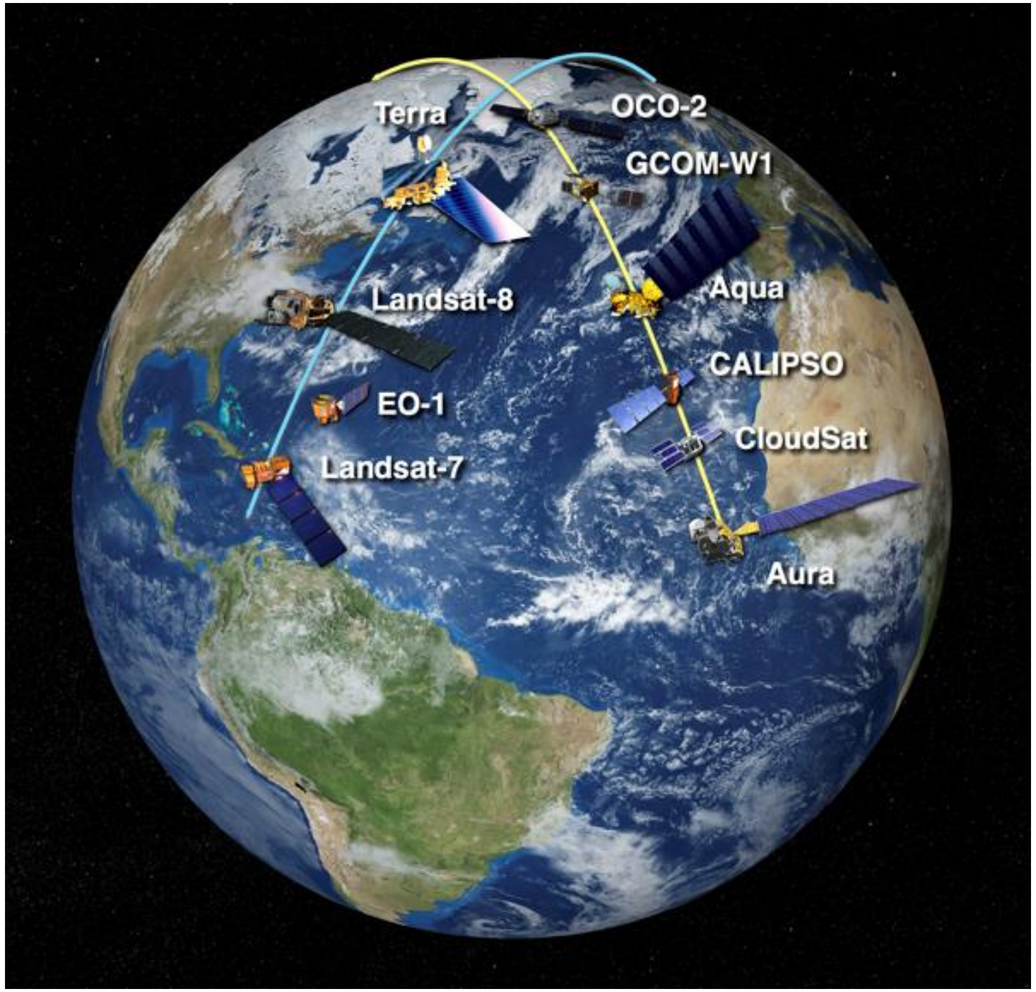
In-situ measurements

- Portable instruments
- Eddy covariance (EC)
- Diurnal variations
- Spatially sparse



Xu, Xiao, Zhang, ERL, 2020

Polar-orbiting satellites are incapable of studying diurnal variations of ecosystem processes



https://satellitesafety.gsfc.nasa.gov

Emerging satellite observations for diurnal cycling of ecosystem processes

Table 1 | Specifications of the instruments/platforms that have diurnal sampling capability in studying plant functioning and ecosystem processes

Instrument	Platform	Launch date	Wavelength	Spatial resolution	Repeat cycle	Spatial extent
ECOSTRESS	ISS	29 June 2018	TIR	70 m	1–5 days	Global (52° N–52° S)
OCO-3	ISS	4 May 2019	Far red, SWIR	2 km	~5 days	Global (52° N–52° S)
AHI	Himawari-8	7 October 2014	Visible, NIR, SWIR, TIR	0.5–2 km	10 min[a]	Eastern Asia and Oceania
ABI	GOES-16	19 November 2016	Visible, NIR, SWIR, TIR	0.5–2 km	10 min[b]	Western Hemisphere
ABI	GOES-17	1 March 2018	Visible, NIR, SWIR, TIR	0.5–2 km	10 min[b]	Western Hemisphere
AGRI	FY-4	10 December 2016	Visible, NIR, SWIR, TIR	0.5–4 km	15 min	Eastern Hemisphere
FCI	MTG	≥2022	Visible, NIR, SWIR, TIR	0.5–2 km	10 min[c]	Europe and Africa
GeoCarb	TBD[d]	≥2022	Far red, SWIR	5–10 km	<1 day	Americas (52° N–52° S)
TEMPO	TBD[d]	≥2022	Red, far red	2.1 × 4.4 km	Hourly	North America
UVN	Sentinel-4	≥2022	Visible, NIR	8 km	Hourly	Europe and North Africa

[a]Himawari-8: 10 min for full disk and 2.5 min for Japan. [b]GOES-16 and GOES-17: 10 min for full disk (with 15 min for full disk before April 2019), 5 min for the conterminous United States and 30 or 60 s at the mesoscale. [c]MTG: 10 min for full disk (Europe and Africa) and 2.5 min for Europe. [d]TBD, to be determined. Both GeoCarb and TEMPO will be deployed on commercial geostationary satellites. NIR, near infrared; SWIR, shortwave infrared.

ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)

- Launched on June 29, 2018
- Land surface temperature (LST) (Hulley et al, 2021)
- ET (Fisher et al., WRR, 2020)
- GPP (Li, Xiao, et al., RSE, 2021)
- Different times of day
- 70m resolution
- Between ~52°N and ~52°S
- Return frequency every 1–5 days

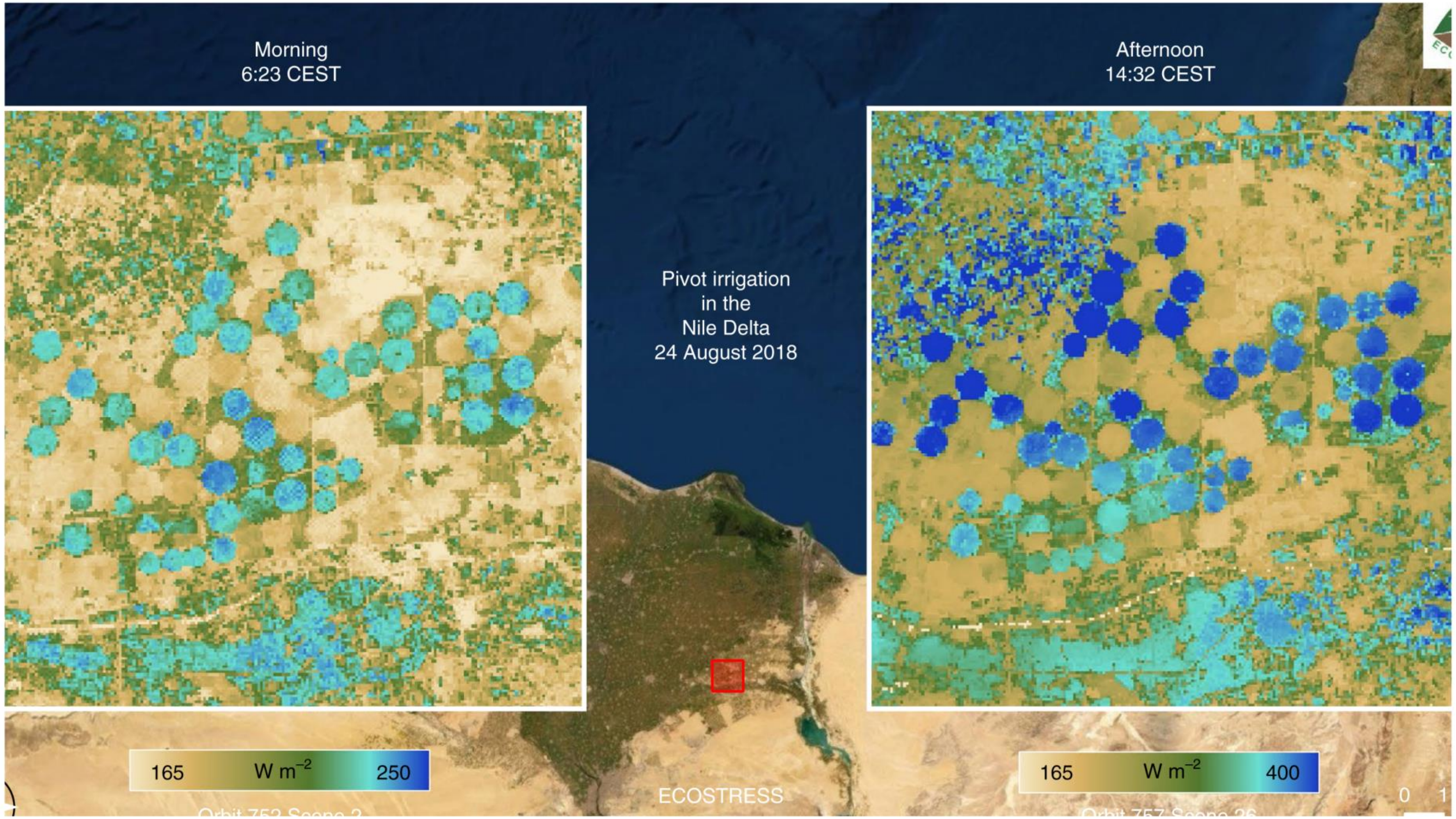


Fig. 2 | ECOSTRESS images from the Nile Delta within the same day. NASA's ECOSTRESS captured changes in ET from agricultural fields of the Nile Delta, Egypt, from the ISS in the morning and afternoon on 24 August 2018. The image on the left is from 6:23 central European summer time (CEST) and the image on the right is from 14:32 CEST. There are larger differences in ET between the agricultural fields in the afternoon than in the morning. Some fields show much more ET while some fields are drying out in the afternoon. The geographical coordinates of the centre of the ECOSTRESS images Orbit 752, Scene 2 (left) and Orbit 757, Scene 26 (right) are 30.54° N and 31.85° E, respectively. The scale bar applies to the background map; the pixel size of the inset maps is 70 m.

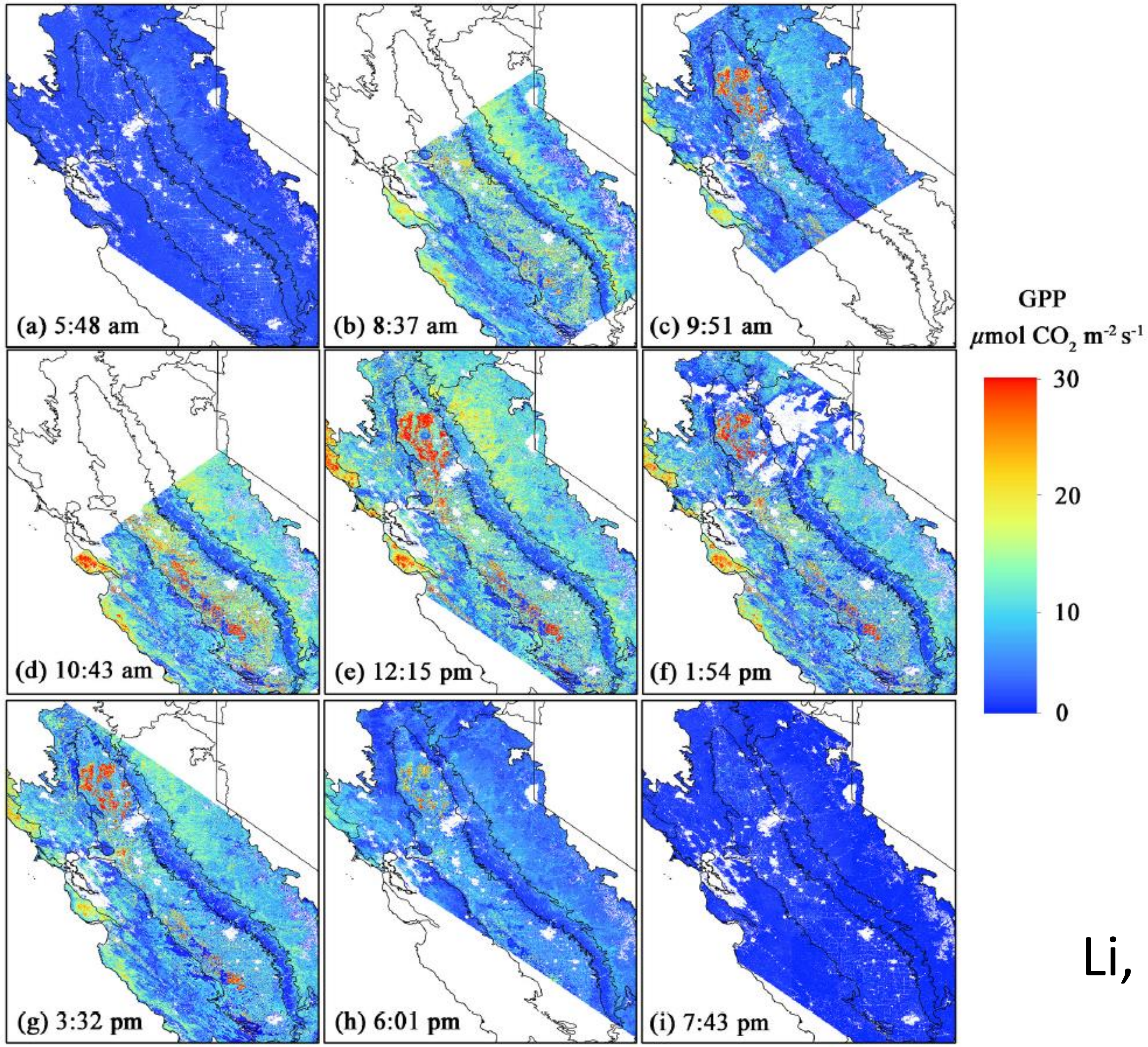


Fig. 5. Magnitude and spatial patterns of predicted ECOSTRESS GPP at different times of day in summer 2019 across the Central Foothills and Coastal Mountains, Central Valley, Sierra Nevada and Coast Range in California.

Li, Xiao, et al., RSE, 2021

Orbiting Carbon Observatory-3 (OCO-3)

- Launched in May 2019
- Solar-induced fluorescence (SIF)
- Different times of day
- Between ~52°N and ~52°S
- 1-2 km footprints
- Also has a Snapshot Area Mode (SAM)

https://www.jpl.nasa.gov

SIF is strongly correlated with GPP at the ecosystem scale

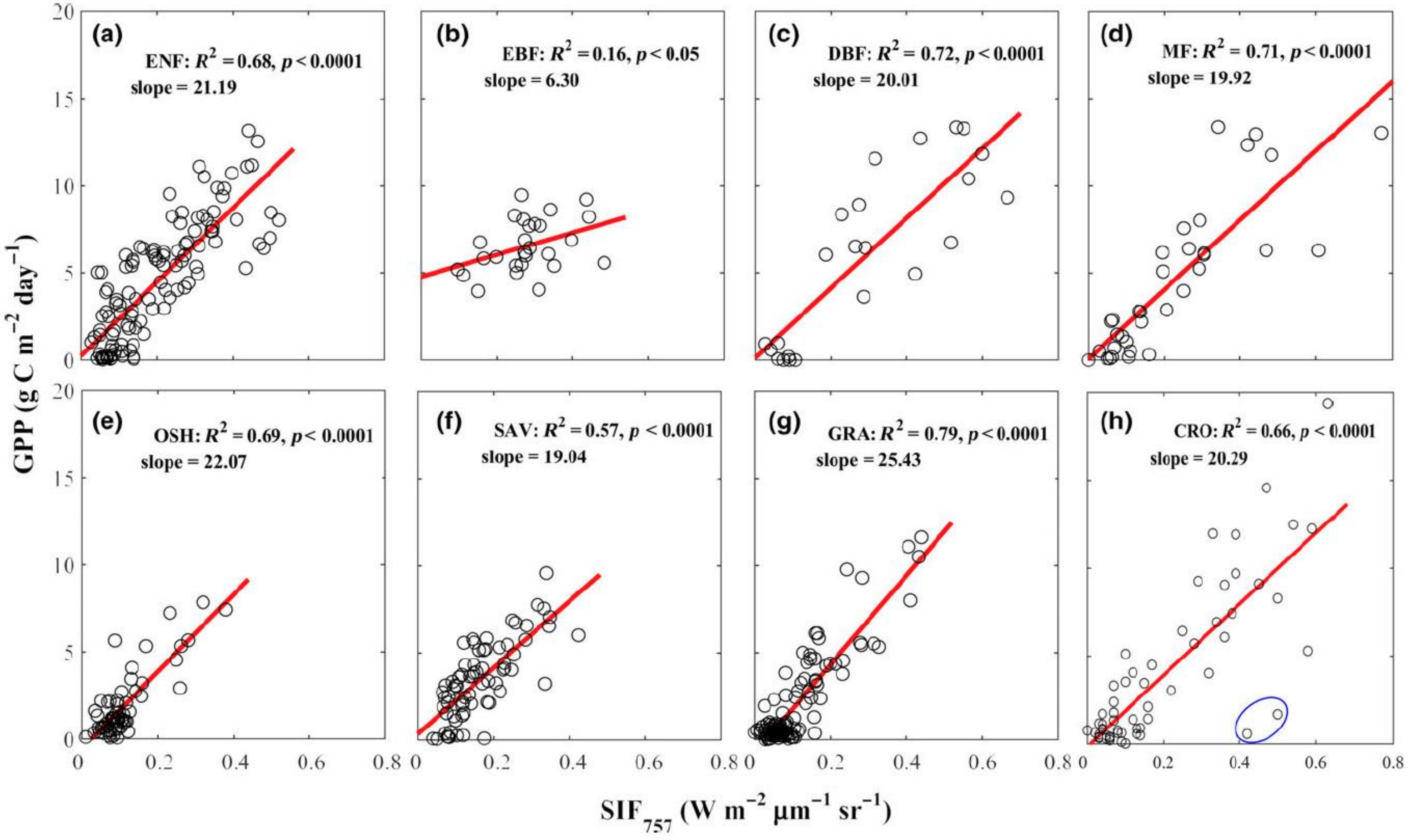


FIGURE 6 Scatter plots of daily tower GPP and OCO-2 SIF for individual biomes: (a) evergreen needleleaf forests (ENF); (b) evergreen broadleaf forests (EBF); (c) deciduous broadleaf forests (DBF); (d) mixed forests (MF); (e) open shrublands (OSH); (f) savannas (SAV); (g) grasslands (GRA); (h) croplands (CRO). The solid lines represent the fitted regression lines. The relationship between SIF and GPP for croplands was stronger (R^2 = 0.79, p < 0.0001) when the two outliers highlighted by the blue circle were removed

Li, Xiao, et al., GCB, 2018

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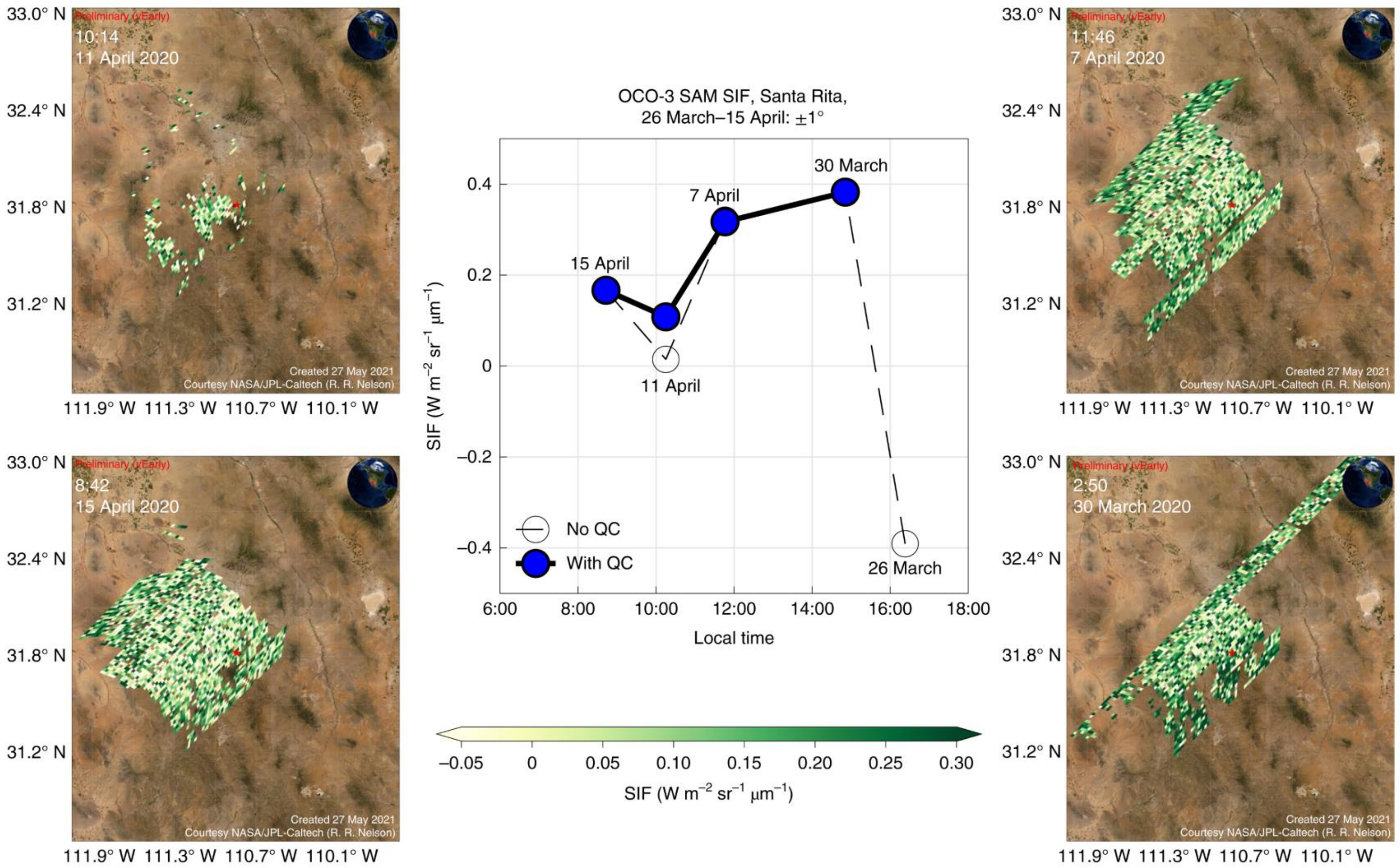
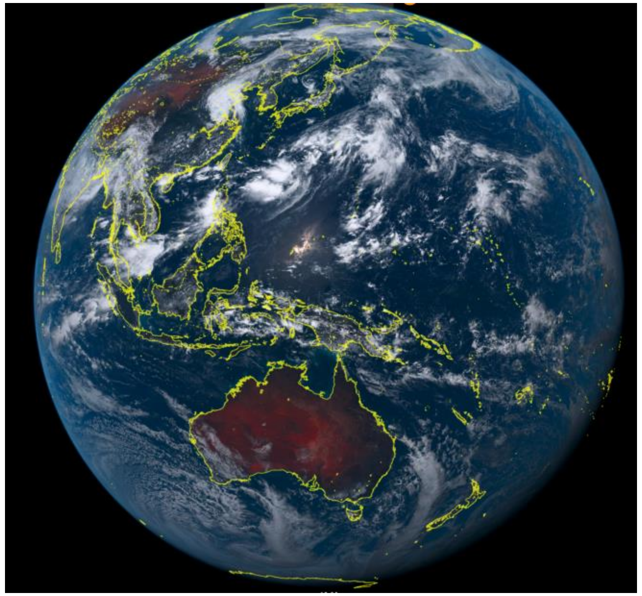


Fig. 3 | SIF at different times of the day as measured by the OCO-3 in SAM mode. The SIF data, a proxy of plant photosynthesis, were acquired surrounding the Santa Rita Experimental Range, Arizona. The four maps show the spatial patterns of SIF at the landscape scale for different times of day in March and April 2020. The centre plot illustrates the diurnal variations of SIF spatially averaged within the 0.1×0.1° area surrounding the Santa Rita Experimental Range research site; the blue and white symbols indicate the uses of data with quality control (QC; solar zenith angle of <70°, view zenith angle of <40° and cloud fraction of <0.1) and no QC, respectively.

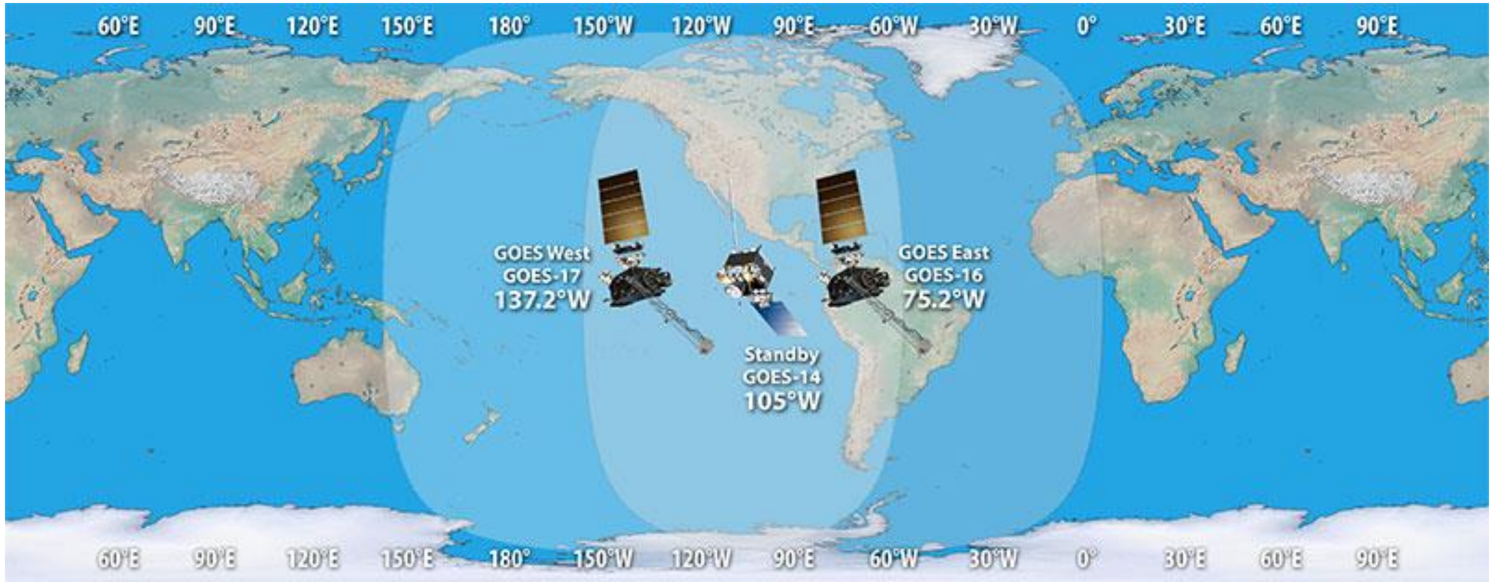
New generation geostationary satellites

- Although ECOSTRESS and OCO-3 have diurnal sampling capabilities, these samples are not continuous throughout the day for a given location.
- Geostationary satellites carry optical sensors with high-frequency observation capability (10 to 15 minutes in full scan mode).
- New generation geostationary satellites offer observations with 0.5 – 2 km resolution
- With high temporal frequency and spectral features, these satellites are expected to improve diurnal monitoring of ecosystem dynamics

Himawari-8
GOES-R Series



https://himawari8.nict.go.jp



https://www.goes-r.gov/mission/mission.html

- Launched in 2014
- Advanced Himawari Imager (AHI)
- 0.5-2 km resolution
- 10 min repeat cycle

- GOES-16 (2016) & GOES-17 (2018)
- Advanced Baseline Imager (ABI)
- 0.5-2 km resolution
- 10 m repeat cycle

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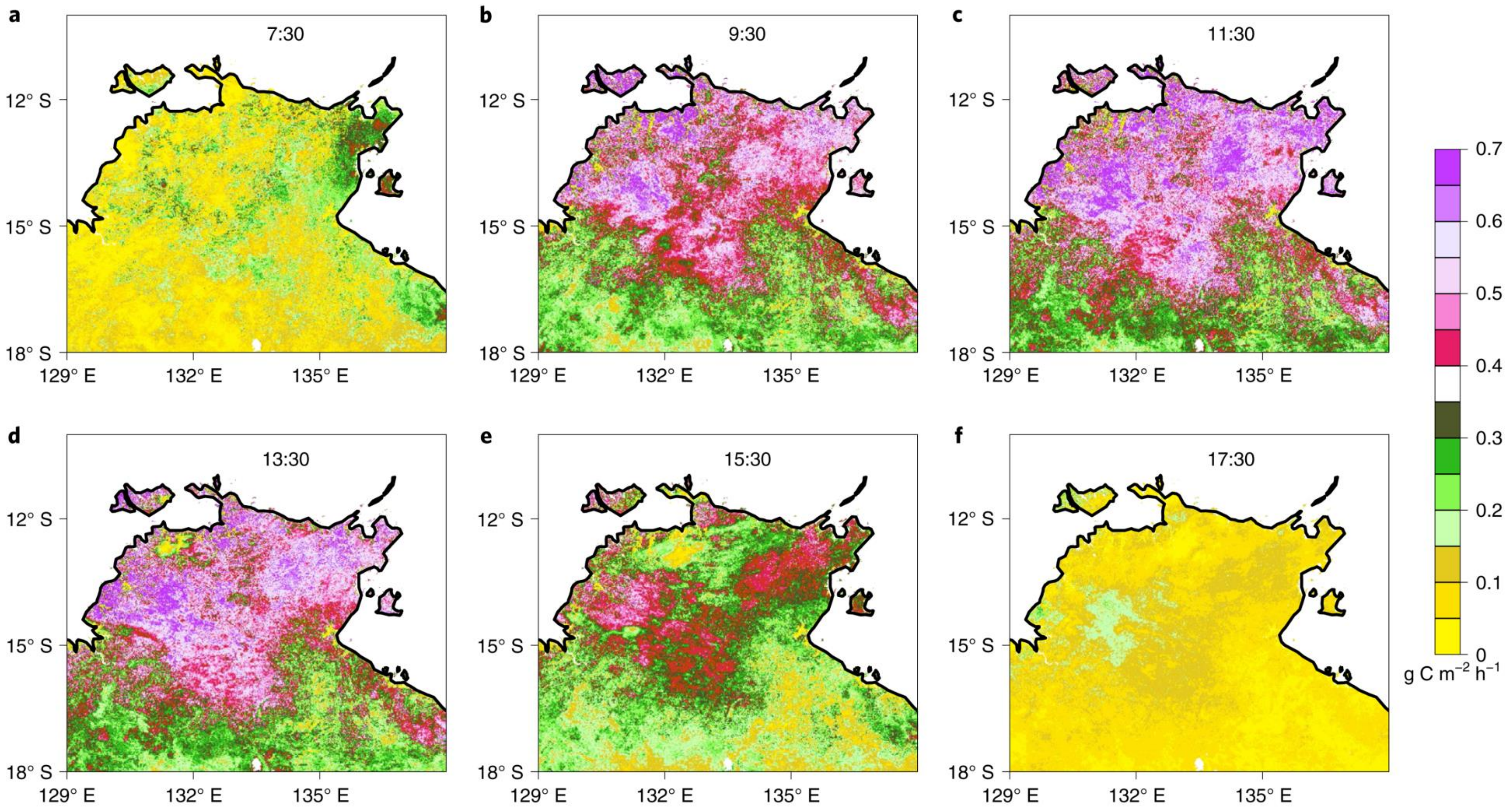
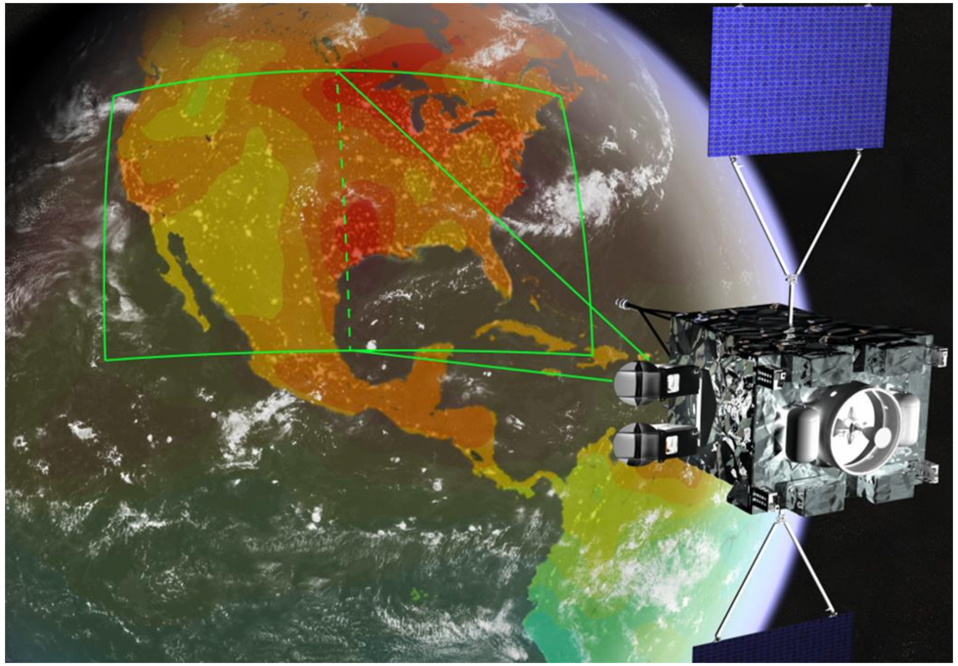


Fig. 4 | Diurnal variations in plant photosynthesis derived from geostationary satellite data and a light-use efficiency model. a–f, The Himawari-8 AHI captured hourly variations in plant photosynthesis (that is, GPP) over the Northern Territory, Australia, every 2 h from 7:30 to 17:30 (Australian central time) on 1 February 2018. The figure indicates that geostationary satellite data can be used to examine diurnal variations of ecosystem functioning.

Future missions

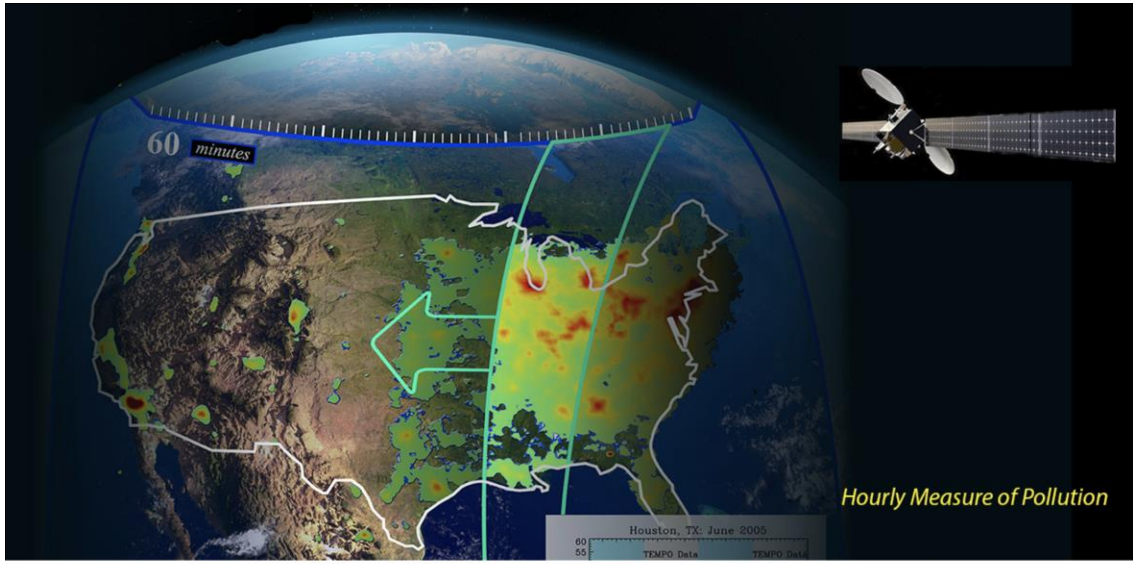
Geostationary Carbon Cycle Observatory (GeoCarb)



Source: NASA

- A NASA mission as early as 2022
- Measure CO2, methane, carbon monoxide, and SIF
- Geostationary orbit
- Measure SIF over North and South America
- 5-10 km resolution

Tropospheric Emissions: Monitoring of Pollution (TEMPO)

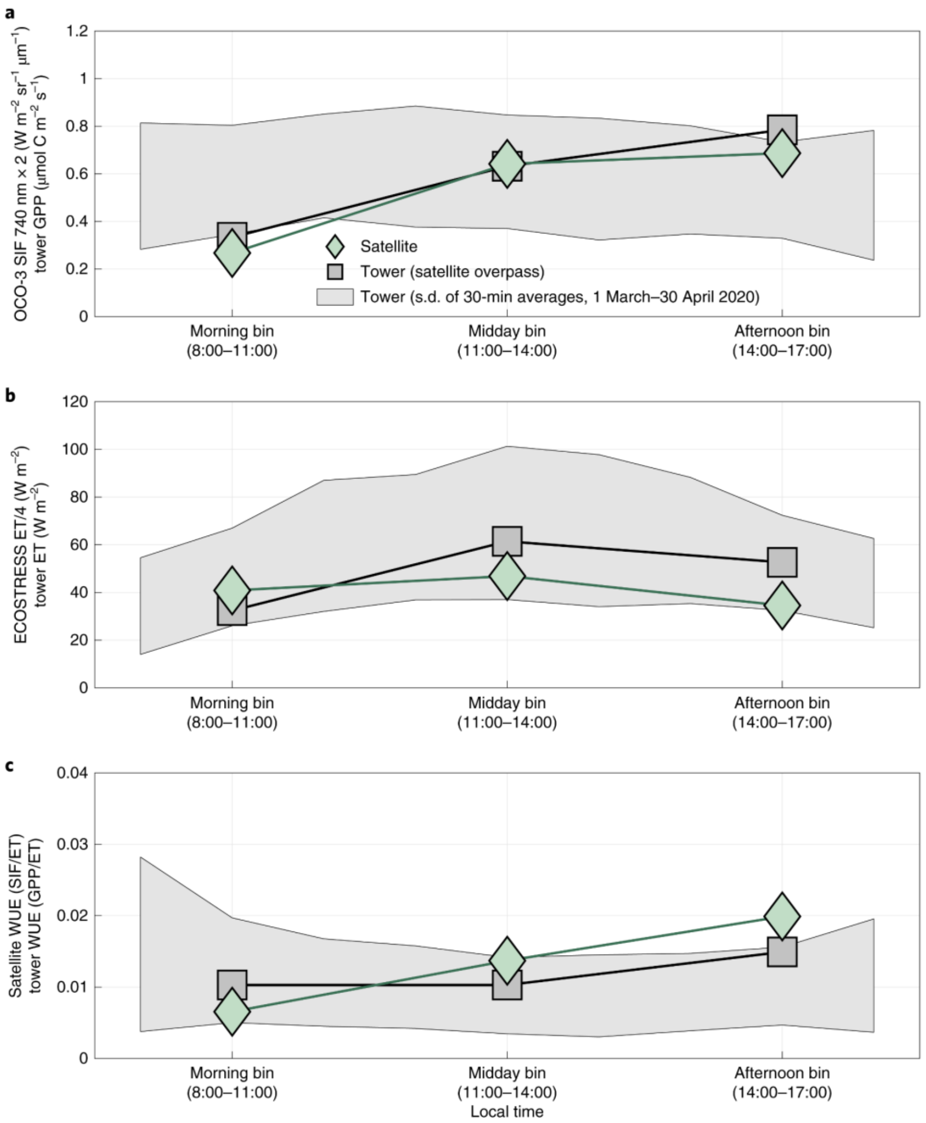


http://tempo.si.edu

- Another NASA mission as early as 2022
- Geostationary orbit
- Mainly designed for monitoring air pollution
- Measure SIF in red and far-red wavelengths
- North America with hourly frequency
- Spectral resolution is coarse (0.6 nm)

Synergies

- Combination of ECOSTRESS and OCO-3 data can allow us to examine plant transpiration and photosynthesis simultaneously and their coupling.
- Synergistic combination of OCO-3 SIF and ECOSTRESS ET can provide a measure of WUE.
- Observations from ECOSTRESS and OCO-3 can also be synergistically used with data from geostationary satellites.
- ECOSTRESS, OCO-3, and geostationary satellite data also have anticipated synergies with those from the forthcoming missions.
- These data can also be used in combination with data from polar-orbiting satellites and in-situ measurements.



OCO-3 SIF

Tower GPP

ECOSTRESS ET

Tower ET

OCO-3/ECOSTRESS WUE: SIF/ET

Tower WUE: GPP/ET

Fig. 5 | The synergy between ECOSTRESS and OCO-3 data enables diurnal monitoring of WUE of terrestrial ecosystems. a–c, The ECOSTRESS ET, OCO-3 SIF (740 nm) and tower data at the Santa Rita Experimental Range, Arizona (31.82° E, 110.87° W), illustrate how OCO-3 SIF and tower GPP (**a**), ECOSTRESS ET and tower ET **(b)** and satellite and tower WUE **(c)** vary over a portion of the diurnal cycle spanning morning, midday and afternoon hours. Here, satellite-derived WUE (W m^{-2} sr^{-1} μm^{-1}/W m^{-2}) is defined as the ratio of SIF to ET, while tower-based WUE (μmol C m^{-2} s^{-1}/W m^{-2}) is defined as the ratio of GPP to ET. The data were acquired between 1 March and 30 April 2020. The SIF and ET data were grouped into 3-h bins (8:00–11:00, 11:00–14:00 and 14:00–17:00, local time) for the calculation of WUE.

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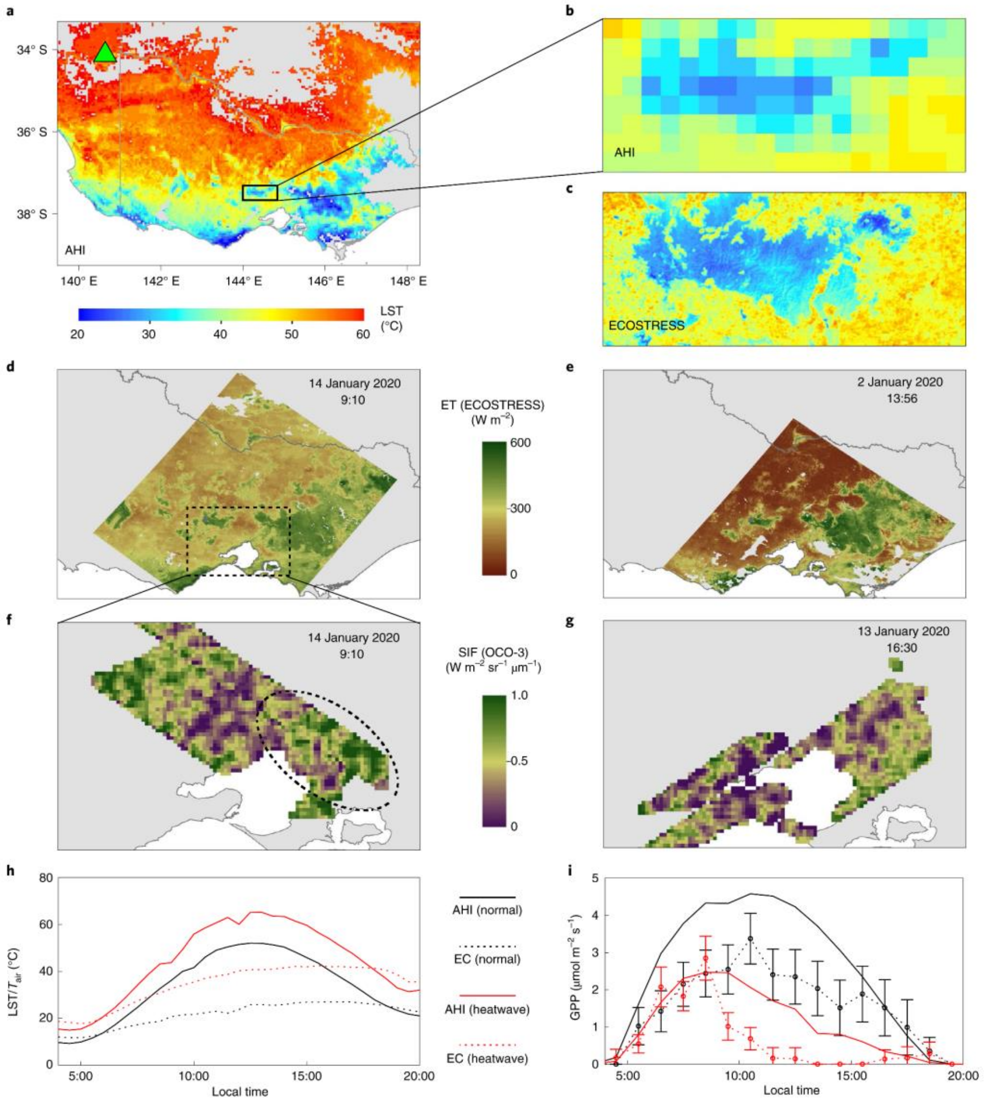

Fig. 6 | Synergistic use of observations from a geostationary satellite and two ISS instruments for studying diurnal cycling of ecosystem processes. Two heatwaves in Australia (2018 and 2020) were studied. **a**, Himawari-8 AHI LST at 13:30 on 2 January 2020 for southern Australia and the location of the EC flux site (Calperum Chowilla, location indicated by the green triangle). **b**,**c**, The coarse-resolution AHI LST (**b**) and fine-resolution (**c**) ECOSTRESS LST (13:55 on 2 January 2020) for the small area highlighted by the rectangle in **a**. **d**,**e**, Instantaneous ECOSTRESS ET for different times of the day. **f**,**g**, Instantaneous OCO-3 SIF for different times of the day. The highlighted area with an ellipse exhibits relatively high SIF in the early morning but low values in the late afternoon. **h**, Diurnal variations in LST (AHI) and air temperature (T_{air}) for a normal day (22 December 2018) and a heatwave day (26 December 2018) at the EC site. **i**, Diurnal variations in AHI-based GPP estimates and flux tower GPP for both the normal and heatwave days at the EC site; the error bars indicate the uncertainty associated with flux partitioning. All times are local time.

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Summary

- We envision that the emerging satellite observations will trigger numerous research efforts aimed at understanding how plant carbon uptake and water use vary over the course of the diurnal cycle.
- Data from ECOSTRESS, OCO-3, geostationary satellites, and future missions with diurnal sampling capability are anticipated to be used both individually and synergistically.
- These observations will likely revolutionize the study of ecosystem processes and carbon and water cycling to a certain extent.