Opportunities and challenges of high-resolution remote sensing of sun-induced fluorescence

Xinchen Lu[1], Xiao Cheng[1], Petri Pellikka[2], Xianglan Li[1*] and Jianwu Tang[3*]

[1] State Key Laboratory of Remote Sensing Science, and College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, China

[2] Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland

[3] The Ecosystems Center, Marine Biological Laboratory, Woods Hole, Massachusetts, USA

Correspondence and request of materials should be addressed to Xianglan Li (xlli@bnu.edu.cn) and Jianwu Tang (jtang@mbl.edu)

Abstract

Estimating plant photosynthesis and gross primary production (GPP) regionally and globally remains challenging despite its primary role in driving ecosystem productivity and carbon cycling. Recently, satellite-derived sun-induced fluorescence (SIF) provides an alternative approach to investigate GPP from space. However, our ability to apply SIF to estimating GPP at large scales is still lacking, primarily because the SIF-GPP relationships at various spatial and temporal scales is not fully understood. The coarse spatial representativeness (around 0.5 degrees or coarser) of previous remotely sensed SIF data makes it difficult to compare and validate the eddy covariance (EC) based GPP measurements. Orbiting Carbon Observatory-2 (OCO-2) has shown prospects in providing remotely sensed SIF at significantly improved spatial resolutions (around 1.3 km by 2.25 km) that are comparable to ground-based GPP measurements. However, OCO-2 operates at a 16-day revisiting schedule at a sparse spatial sampling strategy. We found that for most EC sites, the observations of OCO-2 passing through are extremely limited. The average number of successfully retrieved SIF by OCO-2 encompassing each site within a year is only 3.17. For EC sites with high companion OCO-2 coverages, we found a strong correlation between GPP and SIF. Despite challenges, the emerging new, high-spatial-resolution remotely sensed SIF data provide unprecedented opportunities to estimate GPP over time and space and its underlying mechanism. We recommend that to fully use the remotely sensed SIF data, a research agenda is critically needed to improve our understanding of the relationship between SIF and GPP across biomes, ecosystems, and even species. We recommend maintaining and upgrading the current EC sites and adding ground-based SIF measurements to provide another scale of SIF observation. We also recommend construction of new EC sites to be within the belts of the observations of OCO-2 or other remotely sensed SIF products to fully use the satellite information.

Main Text

Estimating photosynthesis of global vegetation remains challenging despite its primary role in driving ecosystem productivity and its importance towards understanding the global carbon cycle[1]. Over the past decades, remotely sensed estimations of the photosynthetic potential of the global vegetation based on Vegetation Indexes (VIs) have been reported[2-5]. For vegetation where the greenness and carbon uptake were strongly connected, reflectance-based retrievals of VIs provided accurate estimates of the seasonality of the gross primary productivity (GPP). Most VIs, however, reflects canopy structure rather than the photosynthetic capacity, an ecosystem function that changes with ecosystem types, the environment, and over time. Thus, the VI-based estimation of photosynthesis shows a strong uncertainty on different spatial and temporal scales and rarely represents the interannual variability[6].

Recently, global consistent measurements of satellite-derived sun-induced fluorescence (SIF) that are deemed to directly represent photosynthesis processes provide an alternative approach to investigate GPP from space[7-12]. Despite previous studies that found significant relationships between SIF and GPP at smaller scales, given the complex underlying physiological processes of mechanisms that drive and determine their relationships, our ability to apply SIF to estimating GPP at global scales is still lacking. Let alone the effects of differential environmental factors, plant functional types, canopy structures, photosynthetic pathways (C3 and C4 plants) on the SIF-GPP relationships at various spatial and temporal scales[10,12,13]. Remotely sensed SIF encompassing different vegetation provides a useful means to investigate their relationships globally through comparison and validation with ground-based canopy measurements[14,15]. Previous efforts on applying the satellite-derived SIF as a proxy to estimate GPP were mainly based on measurements from the Global Ozone Monitoring Experiment 2 (GOME-2), Greenhouse Gases Observing Satellite (GOSAT) or SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY)[16,17]. The coarse spatial representativeness (around 0.5 degrees or coarser) of these measurements makes it challenging to compare and validate with the state-of-art eddy covariance (EC) based canopy measurements, a ground-based technology to measure carbon dioxide (CO_2) changes at ecosystem levels that usually cover a smaller footprint than the above remotely sensed SIF products[9].

Launched on July 2, 2014, Orbiting Carbon Observatory-2 (OCO-2) has shown prospects in providing remotely sensed SIF at significantly improved spatial resolutions (around 1.3 km by

2.25 km)[18] that are comparable to ground-based GPP measurements. While the primary objective of OCO-2 is to serve as the first mission of National Aeronautics and Space Administration that dedicates to the monitoring of column-averaged CO_2 mole fraction (X_{CO2}) from space, the retrieval of sun-induced chlorophyll fluorescence from high-resolution spectra is also within the scopes of its missions.

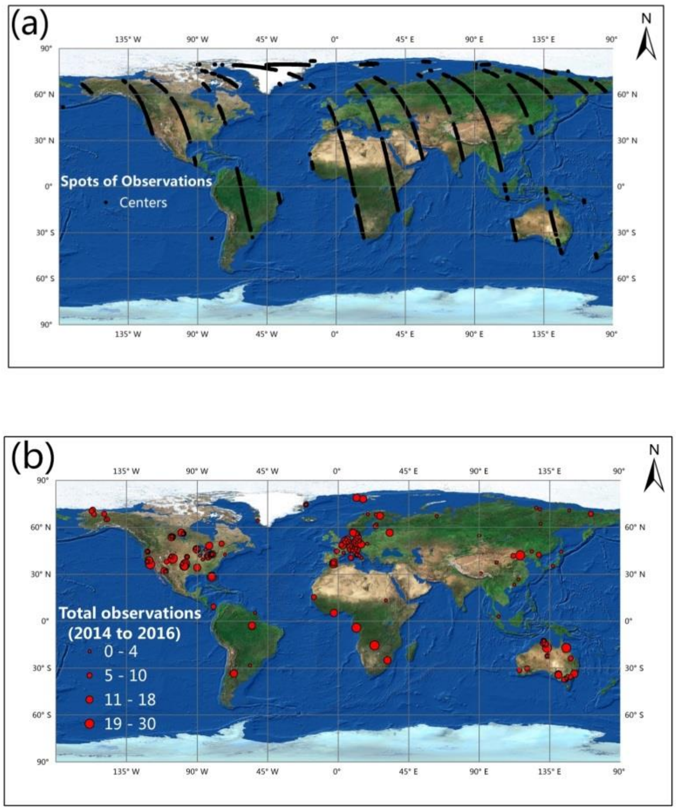

Figure 1: **(a)** OCO-2 observation swaths on July 31, 2016; **(b)** the number of observation times of OCO-2 over Fluxnet eddy covariance sites from late 2014 to 2016. Both figures were generated using ArcMap 10.2 (www.esri.com)

The optimization of observing strategy and instrument calibration were conducted to improve the accuracy of products during the first year of OCO-2's missions. Two modes of observations were strategized for OCO-2: the nadir observations that provide the best spatial resolution and are expected to yield more useful X_{CO2} and SIF topographically round areas over land; and the glint modes that have much greater signal-to-noise ratios over dark and specular surfaces and are expected to yield more useful soundings over ocean. In addition, OCO-2 can also target selected surface calibration and validation sites and collect thousands of observations as the satellite passes. The previous observation modes were a 16-day Nadir observation followed by a 16-day Glint observation. After July of 2015, the modes of Nadir and Glint are generated within a 16-day revisiting cycle. Meanwhile, the thermal conditions of instruments have also been altered. In order to produce the data over ocean more consistently and to change the thermal conditions of the observatory less often, the measurements pattern changed on July 2, 2015. Despite the improved spatial representativeness of OCO-2, similar to data products of GOSAT, it is noted that this satellite is not a global continuous imager and the daily coverage is extremely limited. Currently, OCO-2 operates at a 16-day revisiting schedule at a sparse spatial sampling strategy. Figure 1(a) shows typical swath coverage within a day[19].

The retrieval of SIF within the channel encompassing the vicinity of the O_2 A-band from space has been reported in previous publications[20,21]. Similar to these approaches, the retrieval strategy of OCO-2 is based on a simplified foreword transition model exploiting the in-filling of Fraunhofer lines by SIF centred at 757 nm and 771 nm[18]. The retrieved SIF at 771 nm is about a factor of 1.4 to 1.7 lower than at 757 nm. The small footprints of OCO-2 products make it possible to provide, for the first time, the remotely sensed SIF that can be directly compared with EC based canopy measurements.

To reveal the potential and possibility to compare OCO-2 observations with EC based measurements, here we investigate the synchronous measurements of OCO-2 from late 2014 to 2016 that encompass all flux sites within the Fluxnet (fluxnet.ornl.gov), an international network of EC-based measurements (see Fig. 1b and Text S1). We found that for most EC sites, the observations of OCO-2 passing through are extremely limited. The average number of successfully retrieved SIF by OCO-2 encompassing each site within a year is 3.17. From late 2014 to 2016, the sites that have most records of OCO-2 data are ZM-Mon (30 times yet no longer operating since 2009), US-ARM (29 times), US-NR1 (26 times), CN-DU2 and CU-DN3 (both 23 times, but stopped functioning since 2010) (see Table S1).

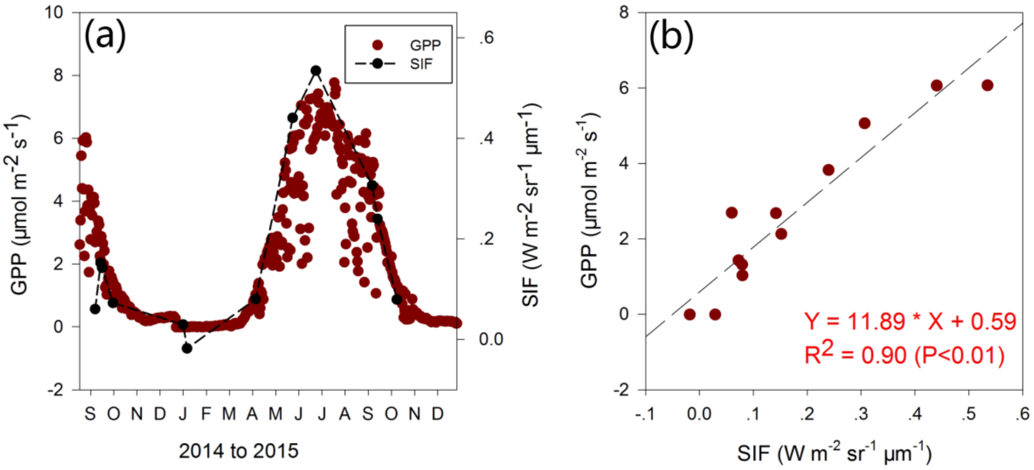

Figure 2: (a) the seasonal trajectories of GPP and remotely sensed fluorescence at an EC site in a mixed temperate forest (US-PFa) during the period from 2014 to 2015; (b) the seasonal relationships between remotely sensed SIF and eddy measured GPP (US-PFa).

For EC sites with high companion OCO-2 coverages, we found strong correlation between GPP and SIF. For example, we investigated the relationships between remotely sensed SIF from OCO-2 and EC based estimations of GPP in an EC site of a mixed forest (US-PFa) that contains 12 times of OCO-2 SIF data between late 2014 to 2016. The EC instruments of site US-PFa are located on a 447 m tall tower within a mixed temperate forest in northern Wisconsin, USA (45.95° N , 90.27° W). We found that the remotely sensed SIF provided accurate estimation of annual cycle of GPP with high correlated SIF-GPP relationships (R^2=0.90, P<0.01, Fig. 2).

For the first time, OCO-2 provides remotely sensed SIF at significantly improved spatial resolutions that enable comparison with ground-based measurement of GPP at a similar resolution. While the spatial representativeness of those measurement, at around 3 km^2, can still be considered as medium, it has substantially improve our ability to understand the relationship between GPP and SIF and thus measure GPP regionally or globally, compared with the coarse SIF measurements from space previously. The high-resolution remote sensing of SIF provide opportunities to investigate and map vegetation photosynthesis as a proxy with potentials of constraining several important factors for modelling such as maximum carboxylation capacity and light use efficiency across vegetation types and biomes. It can be used for comparisons and validations with EC based measurements and thus in turn improve EC measurements of GPP.

Meanwhile, the challenges of using the high-spatial-resolution SIF products lie in their low temporal resolution and sparse coverage. A few previous studies, thus, had to reprocess SIF data from OCO-2 at a relaxed resolution of 2 degrees (or to use the monthly mean values at a spatial resolutions of around 0.25 degrees)[19,22]. The advantage of the similar spatial representativeness of the footprints of OCO-2 instruments and the most EC towers has not been fully taken for comparing SIF and continuous GPP data over different ecosystems. As a result, the observations from OCO-2 in companion with EC data are extremely limited. The sparse spatial resampling strategies and the masks of cloudy measurements are primary reasons. Remotely sensed SIF have also encountered challenges in retrieving models, cloud coverage, sensor degradation, and seasonal variations of sun-view angles and structures of canopies[17]. Balancing space and time to provide useful SIF information for improved understanding of GPP should be carefully deliberated.

Table 1: The spatial resolutions, overpass time in a day, spectral coverages, the types of spatial samplings, sensitivities to clouds and operating periods of GOME-2, GOSAT, SCIAMACHY, OCO-2, TROPOMI and Flex. Typical spatial resolution shows the resolutions in which most previous publications decided for their studies. Revisit presents the revisit cycles of their missions. Note that for Flex, using wider swath can revisit higher latitude regions up to every four days. Time denotes the time of the satellite overpass over equator in a day. Sensitivity indicates the sensitivities of their measurements to clouds. Start year refers to the operating periods or the scheduled time that they will start functioning for these satellites.

Satellites	Spatial resolutions of footprints	Typical spatial resolutions	Revisit	Time	Types of spatial sampling	Spectral coverages	Sensitivity	Start year
GOME-2[17]	Up to 40 km by 40 km	0.5 degrees	1.5 days	9:30	Continuous	650 to 790 nm	High	2007
GOSAT[16]	10 km diam	2 degrees	3 days	13:30	Sparse	757 to 775 nm	Low	2009
SCIAMACHY[23]	30 km by 240 km	1.5 degrees	2 days	9:30	Continuous	650 to 790 nm	High	2002 to 2012
OCO-2[18]	1.3 km by 2.25 km	2 degrees	16 days	13:15	Sparse	757 to 775 nm	Very low	2014
TROPOMI[24]	7 km by 7 km	0.1 degrees	1 day	13:30	Continuous	675 to 775 nm	Medium	2017
Flex[25,26]	300 m by 300 m	300 m	27 days	10:00	Continuous	500 to 780 nm	low	2022

Looking into the near future, several satellites with similar missions of measuring SIF with high-spatial resolutions will start to provide remotely sensed SIF products (Table 1). These include Tropospheric Monitoring Instrument (TROPOMI) scheduled to be launched on-board Sentinel-5 Precursor in September of 2017 and Fluorescence Explorer (Flex) scheduled to be launched around 2022[24,25]. The orbits of the satellites on-board, retrieval strategies of SIF, spatial resolutions, overpass time in a day, spectral coverages, types of spatial sampling and sensitivities to clouds of these satellites varied from one another (Table 1). As discussed, due to the 16-day revisiting schedule, the sparse spatial resampling strategies and the masks of cloudy measurements, OCO-2 data that can be used for comparison and validation for most EC sites are limited. On the contrary, one of the exciting futures of TROPOMI would be the daily global coverage of its measurements. The footprints of Tropospheric Monitoring Instrument, around 7 km by 7 km, are comparable to that of OCO-2, but may not match well with those of most EC towers that are typically around 0.5 to 1 km[27]. Selected as the 8^{th} earth explorer mission of the European Space Agency, Flex will fly in tandem formation with Sentinel-3 that will be launched around 2022 and could help provide remotely sensed SIF at a spatial resolution of 300 m.

Despite challenges, the emerging new, high-spatial-resolution remotely sensed SIF data provide unprecedented opportunities to estimate GPP over time and space and its underlying mechanism for variations. We recommend that to fully use the remotely sensed SIF data, a research agenda is critically needed to improve our understanding of the relationship between SIF and GPP across biomes, ecosystems, and even species. Field-based observation and experiments for mechanistic research is a key to understand this relationship. We also recommend maintaining and upgrading the current EC sites would be very useful in matching with current and future satellite SIF data. If possible, adding ground-based SIF measurements to provide another scale of SIF observation[14,15]. We also recommend any constructions of new EC sites should consider to be within the belts of the observations of OCO-2 or other remotely sensed SIF products to fully use the satellite information. The paradox of spatial, temporal, and spectral resolutions requires us to design and retrieve remotely sensed SIF strategically, to advance our understanding of GPP and ecosystem functions.

Acknowledgments

This work was partially supported by the Fundamental Research Funds for the Central Universities in China. This work was also supported by the Chinese Arctic and Antarctic Administration, National Natural Science Foundation of China (Grant Nos. 41676176 and 41676182), the Chinese Polar Environment Comprehensive Investigation, Assessment Program. The study of US-PFa is funded by Department of Energy Office of Science, Ameriflux Network Management Project Support for UW ChEAS Cluster (2012-present). These data were produced by the OCO-2 project at the Jet Propulsion Laboratory, California Institute of Technology, and obtained from the OCO-2 data archive maintained at the NASA Goddard Earth Science Data and Information Services Center.

References

1 Beer, C. *et al.* Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate. *Science* **329**, 834-838 (2010).

2 Yuan, W. *et al.* Global estimates of evapotranspiration and gross primary production based on MODIS and global meteorology data. *Remote Sensing of Environment* **114**, 1416-1431, doi:10.1016/j.rse.2010.01.022 (2010).

3 Piao, S. *et al.* Evaluation of terrestrial carbon cycle models for their response to climate variability and to CO2 trends. *Global change biology* **19**, 2117-2132 (2013).

4 Richardson, A. D. *et al.* Terrestrial biosphere models need better representation of vegetation phenology: results from the North American Carbon Program Site Synthesis. *Global change biology* **18**, 566–584 (2012).

5 Turner, D. P. *et al.* Evaluation of MODIS NPP and GPP products across multiple biomes. *Remote Sensing of Environment* **102**, 282–292 (2006).

6 Gamon, J. A., Kovalchuck, O., Wong, C. Y. S., Harris, A. & Garrity, S. R. Monitoring seasonal and diurnal changes in photosynthetic pigments with automated PRI and NDVI sensors. *Biogeosciences* **12**, 2947-2978 (2015).

7 Guanter, L. *et al.* Global and time-resolved monitoring of crop photosynthesis with chlorophyll fluorescence. *Proceedings of the National Academy of Sciences of the United States of America* **111**, E1327-1333, doi:10.1073/pnas.1320008111 (2014).

8 Guan, K. *et al.* Improving the monitoring of crop productivity using spaceborne solar-induced fluorescence. *Global change biology* **22**, 716-726, doi:10.1111/gcb.13136 (2016).

9 Joiner, J. *et al.* The seasonal cycle of satellite chlorophyll fluorescence observations and its relationship to vegetation phenology and ecosystem atmosphere carbon exchange. *Remote Sensing of Environment* **152**, 375-391, doi:10.1016/j.rse.2014.06.022 (2014).

10 Zhang, Y. *et al.* Model-based analysis of the relationship between sun-induced chlorophyll fluorescence and gross primary production for remote sensing applications. *Remote Sensing of Environment* **187**, 145-155, doi:10.1016/j.rse.2016.10.016 (2016).

11 Yang, H. *et al.* Chlorophyll fluorescence tracks seasonal variations of photosynthesis from leaf to canopy in a temperate forest. *Global change biology* (2016).

12 Verma, M. *et al.* Effect of environmental conditions on the relationship between solar-induced fluorescence and gross primary productivity at an OzFlux grassland site. *Journal of Geophysical Research Biogeosciences* **122** (2017).

13 van der Tol, C. *et al.* A model and measurement comparison of diurnal cycles of sun-induced chlorophyll fluorescence of crops. *Remote Sensing of Environment* **186**, 663-677, doi:10.1016/j.rse.2016.09.021 (2016).

14 Yang, H. *et al.* Chlorophyll fluorescence tracks seasonal variations of photosynthesis from leaf to canopy in a temperate forest. *Global Change Biol* **In press** (2017).

15 Yang, X. *et al.* Solar-induced chlorophyll fluorescence that correlates with canopy photosynthesis on diurnal and seasonal scales in a temperate deciduous forest. *Geophys Res Lett* **42**, 2977-2987, doi:Doi 10.1002/2015gl063201 (2015).

16 Frankenberg, C. *et al.* New global observations of the terrestrial carbon cycle from GOSAT: Patterns of plant fluorescence with gross primary productivity. *Geophysical Research Letters* **38**, n/a-n/a, doi:10.1029/2011gl048738 (2011).

17 Joiner, J., Yoshida, Y., Guanter, L. & Middleton, E. M. New methods for retrieval of chlorophyll red fluorescence from hyper-spectral satellite instruments: simulations and application to GOME-2 and SCIAMACHY. *Atmospheric Measurement Techniques Discussions*, 1-41, doi:10.5194/amt-2015-387 (2016).

18 Frankenberg, C. *et al.* Prospects for chlorophyll fluorescence remote sensing from the Orbiting Carbon Observatory-2. *Remote Sensing of Environment* **147**, 1-12, doi:10.1016/j.rse.2014.02.007 (2014).

19 Eldering, A. *et al.* The Orbiting Carbon Observatory-2: First 18 months of Science Data Products. *Atmospheric Measurement Techniques Discussions*, 1-30, doi:10.5194/amt-2016-247 (2016).

20 Joiner, J. *et al.* Global monitoring of terrestrial chlorophyll fluorescence from moderate-spectral-resolution near-infrared satellite measurements: methodology, simulations, and application to GOME-2. *Atmos Meas Tech* **6**, 2803-2823, doi:DOI 10.5194/amt-6-2803-2013 (2013).

21 Frankenberg, C., Butz, A. & Toon, G. C. Disentangling chlorophyll fluorescence from atmospheric scattering effects in O2A-band spectra of reflected sun-light. *Geophysical Research Letters* **38**, n/a-n/a, doi:10.1029/2010gl045896 (2011).

22 Luus, K. A. *et al.* Tundra photosynthesis captured by satellite-observed solar-induced chlorophyll fluorescence. *Geophysical Research Letters* **44**, 1564-1573, doi:10.1002/2016gl070842 (2017).

23 Kohler, P., Guanter, L. & Joiner, J. A linear method for the retrieval of sun-induced chlorophyll fluorescence from GOME-2 and SCIAMACHY data. *Atmos Meas Tech* **8**, 2589-2608, doi:10.5194/amt-8-2589-2015 (2015).

24 Guanter, L. *et al.* Potential of the TROPOspheric Monitoring Instrument (TROPOMI) onboard the Sentinel-5 Precursor for the monitoring of terrestrial chlorophyll fluorescence. *Atmospheric Measurement Techniques* **8**, 1337-1352 (2015).

25 Rascher, U., Gioli, B. & Miglietta, F. *FLEX — Fluorescence Explorer: A Remote Sensing Approach to Quantify Spatio-Temporal Variations of Photosynthetic Efficiency from Space*. (Springer Netherlands, 2008).

26 Drusch, M. *et al.* The FLuorescence EXplorer Mission Concept-ESA's Earth Explorer 8. *IEEE Transactions on Geoscience & Remote Sensing* **PP**, 1-12 (2016).

27 Chen, B. *et al.* Characterizing spatial representativeness of flux tower eddy-covariance measurements across the Canadian Carbon Program Network using remote sensing and footprint analysis. *Remote Sensing of Environment* **124**, 742-755 (2012).