Part 3: Questions & Answers Session

Please type your questions in the Question Box. We will try our best to get to all your questions. If we don't, feel free to email Erika Podest (erika.podest@jpl.nasa.gov).

Question 1: Is there a direct way to measure net productivity from SIF, or does it work more like NDVI?
Answer 1: SIF only represents processes in the light reactions of photosynthesis, so it can't capture the magnitude of any respiratory process (in the leaf or from the ecosystem itself). To alleviate the problem you can use CO_2 flux measurements at the same time to disentangle net fluxes from gross fluxes. However, SIF is more than just NDVI, as it captures true green APAR (only light absorbed by chlorophyll molecules) as well as some yield effects.

Question 2: Can you estimate SIF using hyperspectral data?
Answer 2: Yes, but it depends on the spectral resolution and observing geometry. If your detector is right above the canopy, it might work by using the in-filling of dioxygen lines, which are broad and you could probably get away with a spectrometer with about 1-2 nanometer spectral resolution. You might be able to pull this off with measurements directly above the canopy but doing this from space is much harder because you also have to take into account O_2 reabsorption and scattering effects. It therefore depends on the geometry. In principle you do not need the same high signal to noise instruments that are in space if you are right above the canopy.

Question 3: What is the earliest data (in terms of years) that I can get?
Answer 3: Ironically, fluorescence data goes back further than when we started detecting it. The following website https://climatesciences.jpl.nasa.gov/sif/ contains all the fluorescence data that we have at the moment. The earliest data starts around 1995 from the GOME satellite but at much coarser spatial and temporal resolution. From 2018 onward we have TROPOMI data, which is the best instrument for fluorescence research. There is also the OCO-2 mission which started a couple of years earlier than TROPOMI.

Question 4: What are the differences between PSI and PSII?

Answer 4: This would take a long time to explain properly. Basically, PSII is the first part of the Z scheme, which is the electron transport chain and it is where the water splitting and O2 generation take place. The electrons that are transferred in the electron transport chain through PSI as well are used to produce the high energy carrier NADPH. ATP and ATPH are produced by both together and are then used to power the carbon reactions.
One thing to note is that the naming might be a bit confusing because the electron transfer occurs from PSII to PSI. The reason for this is because PSI was discovered earlier.

Question 5: I have some experience with ArcGIS Pro but I still would consider myself a beginner. Can you please recommend any particular easy reading for someone who is still taking first steps in this field on how to use SIF data?
Answer 5: We hope that the Thursday session will help. Usually, some familiarity with software (at least scripting languages) would make your life a lot easier. However, we also provide Level 3 (gridded) datasets that could be accessed via simple software tools such as the GISS panoply viewer (https://www.giss.nasa.gov/tools/panoply/).
SIF data is output as a NetCDF file, which you can read with Panoply, Python, R, or Julia. One thing to note is that there is a difference between a single sounding and gridded data. Level 1 data are the raw spectra. Level 2 data is chlorophyll fluorescence but for a single sounding. Level 3 data is Level 2 data (single soundings) aggregated spatially or temporally. There are tools available to grid the datasets. If you want to look at a world map, you would need to use Level 3 data and Panoply would be a good tool to visualize how those time steps look on a world map.

Question 6: Could you explain the K-terms again?
Answer 6: The K terms are rate constants (think of it as reaction rates in chemical reactions -basically the reaction constant). For fluorescence the Kf term is usually constant and we assume that this is an intrinsic property of the chlorophyll molecule (though there is temperature dependence in there but in principle Kf cannot be regulated). However the fluorescence yield can be regulated by changing things like the rate constant for photosynthesis, which depends on how many photosystems are open at that time and non photochemical quenching Pk and Pq, which are sometimes referred to as the pressure relief valve. When there are too many electrons flowing into the system you need to dispose of them by some reaction through the Kn term. Think of it as a bathtub analogy where the electrons are flowing into the bathtub with 2 or 3 little exit holes with one of it being Kf (which is a constant pipe diameter) and the other

ones are Kp and Kn, which can be opened and closed. Depending how much you open and close one the other ones will determine how much is flowing through the other outlets.

Question 7: Which caveats are needed to use the NDVI to calculate GPP?
Answer 7: NDVI is only a proxy for absorbed light in the PAR spectral range (so-called "greenness-index"). It is a simple band ratio based approach that provides an indication whether there is a vegetation index or not and how healthy it is because the reflectance represents the status. It might not always perfectly represent absorbed light by chlorophyll (because it includes things like branches and soil as well) and provides no indication as to how efficiently light is being used for photosynthesis. It does not sense the total light that is being absorbed by chlorophyll and you will need some other ancillary estimate for the light use efficiency to convert NDVI into a GPP product.

Question 8: Can we say that during day time we can not measure SIF though it is correlated with PSII yield? And at night time as the sun is out we can measure SIF clearly but it will not be correlated with PSII yield?
Answer 8: My apologies if this was misunderstood. We can only measure true SIF if the sun is out (as it is "Solar"-induced chlorophyll fluorescence). The sun is the light source to measure SIF. In the case of PAM, you are not measuring SIF because you have an artificial light source. At very low light, PSII and SIF yields may anti-correlate but at mid-day they correlate. Using the techniques outlined in the talk, we can separate the sunlight from the fluorescence signal and measure SIF directly even in the sunlight. Basically we block off the sunlight a little bit with the Fraunhofer lines.

Question 9: Please recommend a remote sensing book that contains today's material. I feel there is a lot to catch up with!
Answer 9: I referred to some overview papers at the end of the talk. See slides 45-51. Some of the papers are public access, but I am not sure if all of them are.

Question 10: Would the retrieval of SIF, especially in the far red, not be difficult from aquatic systems because it would be absorbed by the water?
Answer 10: Very good question! In fact, we have not yet managed to measure it in the far-red for this reason (and the fact that the first SIF peak at 680nm is higher if you look at the chloroplast level. It is only in the leaf where there is so much chlorophyll reabsorption that suddenly the secondary peak at 740nm appears to be stronger than the first. For phytoplankton in the ocean typically the first peak is stronger in the first

place and then the second peak around 740nm is also being reabsorbed by liquid water absorption in the ocean. In that sense the signal is being subdued. We measure SIF over the oceans with the red spectral range (around 680nm) and not in the far-red spectral range.

Question 11: Can SIF be used to monitor habitat restoration?
Answer 11: It could, but it might be an overkill. Simple vegetation indices might be better in that case as it provides better spatial resolution and can observe changes in habitats fairly well. With fluorescence, we are still working with resolutions in kilometers. MODIS and Landsat are better for higher resolutions.

Question 12: What about having an idea over phytoplankton species distribution and density via these measurements?
Answer 12: So far we have only measured the SIF signal but we do not know what kind of phytoplankton species it might be. It is a difficult problem. The photosystem should be similar to other vegetation on land however, this is an emerging field. The spectral shape could provide insight but the shape could change with depth. Ocean color might also be needed to get additional information about the phytoplankton species distribution.

Question 13: Are there other spaceborne sensors used to measure SIF?
Answer 13: Yes there are, depending on the spectrometers and their spectral range. Currently flying, we have GoSAT, OCO-2, OCO-3 and TROPOMI. We will also be covering this more in depth in the last session of this webinar series. All the sensors that can measure SIF are listed on the climatesciences.jpl.nasa.gov/sif
One aspect to highlight is that none of these missions have been designed to measure SIF. All of them are air quality missions that have been designed to measure trace gases in the atmosphere. We have taken them and used them to measure fluorescence. The only dedicated mission that will have fluorescence as its mission target will be FLEX, from the European Space Agency, but it is not yet in space.

Question 14: Can you summarise some applications for SIF?
Answer 14: Fluorescence is an excellent proxy for GPP where there is a linear or near linear correlation at coarser spatial and temporal scales. GPP is also useful for looking at seasonal cycles and can be detected earlier and in areas where it is harder to detect, especially in evergreen forests. We hope to be able to detect stress earlier using fluorescence than other vegetation measurements (e.g. NDVI). Fluorescence goes

down under stress even if the leaf does not change its pigment. There are many regions on Earth that don't have great coverage by MODIS or other imagers, such as cloudy areas of the Amazon rainforest. Fluorescence provides an insight through clouds and serves as an unbiased proxy for true APAR even under cloudy conditions and not just cloud free conditions.

Question 15: Has anyone looked at measuring SIF from aircraft or UAVs (for high-resolution measurements)?
Answer 15: Yes. Examples include CFIS (JPL Instrument), HyPlant Sensor (Julich, Germany), and others (e.g. a group from Spain). The platform needs to have good stability in order for the sensor to collect adequate measurements.

Question 16: How do you know NPQ = 0 for stressed vegetation?
Answer 16: NPQ is not equal to 0 for stressed vegetation, but it is for the dark adapted leaf. If you take a leaf that has been outside in the sun and put it into a dark chamber so that it does not see any light, slowly but steadily all the non-photochemical quenching mechanisms will relax and go to 0 (if there is no sustained quenching as in winter evergreens). This is the reason why in the PAM measurements mentioned, we first looked at a dark adapted leaf and then we put it in the light. That is the only way to perform measurements where Kn is at its lowest. It is not sustained photochemical quenching. In evergreen overwintering plants there might still be NPQ going on at night and it might not go to 0 because there is sustained long term quenching but the dynamic one typically goes down to 0 so that Kn goes to 0 in dark conditions. It might take 15 minutes or up to 1 hour to fully relax and reduce NPQ to its minimum.

Question 17: Why does the plant re-emit parts of the absorbed light by fluorescence?
Answer 17: It can't help it. It is a natural process, related to the lifetime of the excited state of the chlorophyll molecule. Plants have other mechanisms to quench the excited state of a chlorophyll molecule even past fluorescence. This happens through photosynthesis or non photochemical quenching.
In principle plants cannot do anything about it because it happens with the chlorophyll molecule. It is just a small percent, around 1%, of the energy is getting lost that way. It is not a huge energy loss term for the plant and the fluorescence rate constant is something that the plant cannot control.

Question 18: Can you comment on how large scale SIF is closely related to APAR, so GPP?

Answer 18: If a measurement is taken over an entire continent, you would integrate the signal over a long time period over the entire area. In such a case, you would just be measuring the integrated fluorescence emission over that entire continent, which is an unbiased product. In principle, the signal measured with a very bad spectrometer with the spatial resolution of a continent would be exactly the same ***integrated signal*** *compared to the perfect instrument that had a 30 meter resolution with all the pixels added. This is very different from an imaging system. The NDVI of an entire continent would be meaningless and not the same as NDVI at 30 meters and averaging everything together. SIF is an unbiased estimator that is irrespective of scale for APAR, because SIF is blind to snow, streets and everything else.*

Question 19: Do you think that SIF products could replace existing FAPAR products?

Answer 19: I am not sure about "replacing", but complement is a better term since FAPAR will always be useful. Every product has its place. By the nature of the fluorescence measurement, we would not be able to get it in the same noise free and spatial resolution as imaging spectrometers that just look at color. Ideally we would use a combination of products to try to tease out changes in light use efficiency from changes that are purely related to FAPAR. When you start combining data you get much more information out of it. It will certainly not replace high resolution information measurements like MODIS, Landsat or other satellites.

Question 20: How much of the correlation between coarse SIF/GPP is about the APAR variation vs. the changing yield ratios? Is the dynamic range of the yield ratio particularly large?

Answer 20: This is a difficult question to answer for several reasons. Once we look at SIF to GPP we often do not have a perfect proxy for APAR. People try to use something for APAR but then you divide both SIF and GPP by some number that might be wrong, yet they are correlated with each other. This correlation does not mean anything because you are using a common APAR that is wrong. In that sense it is still very tricky to disentangle these effects. Changing leaf orientation might change APAR and you might confuse it with yield changes. The only thing that we can tackle is at the leaf scale when you stress a leaf with the same light conditions, which changes the absorption. There are other effects even more insidious. You might have chloroplast movements within the leaf (they stack on top of each other) to minimize light absorption

conditions under stress or high blue light conditions. You might also have leaves wilting (changing their shape) or moving away from the sun.
There are two different ways to cope with stress. One is to turn on non photochemical quenching but an even easier method for the plant is to avoid light absorption in the first place. Some can do that by changing their leaf position. There are tricky things that are happening, making it hard to disentangle them. Overall, APAR has a much higher dynamic range and SIF/GPP changes due to yields for fluorescence are on the order of +/- 20%.

Question 21: Is SIF more linked to FAPAR or for LUE?
Answer 21: SIF is more linked to APAR. The absolute value of SIF is always closely linked to FAPAR times PAR. At the global scale there is the complication that we don't know PAR above the canopy directly. SIF captures this uncertainty to a degree as well. The fraction of absorbed light is captured well because we are only sensitive to the fraction that has been absorbed by the antenna system of the plant. This is a fundamental difference to vegetation indices. To the first order, most of the global drivers are related to changes in APAR across the globe. The light use efficiency part is always a second order effect that might modulate the yields and fluorescence plus/minus 20% roughly. If you take a look at a canopy - not all the leaves are the same. The ones on the top might experience much more light stress than leaves in shaded conditions. This mixture is one we have to deal with as well because stress is not evenly distributed across the canopy in the vertical domain.

Question 22: In your fluorometer experiment, why is Kp=0 when there is no light at the beginning dark stage? I mean Kp max at the beginning of the dark stage?
Answer 22: It means that if it is dark then no photo system is closed and theoretically the maximum rate of Kp is highest. Basically, the modulating light beam is quenched through Kp directly and no photo system closes at that time, meaning there is a maximum Kp yield. Whereas if a flash is applied (around 8000 micromole per square meters per seconds), the high brightness will not allow the plants to quench the energy fast enough, forcing their photo centers to close so that no light can be funneled through. This is how you set Kp to 0 once you flash it. It is a saturating light beam. If you fly something like this on a spaceborne system, it is not going to work.

Question 23: Could it be possible to differentiate between "healthy" and "diseased" vegetation using SIF data?

Answer 23: Typically under normal conditions, healthy vegetation emits a lot more fluorescence than unhealthy vegetation. Quite often they also show quite a difference in their vegetation indices.
A forest system that might have an FAPAR of 1 or near 1 emits much less fluorescence than a healthy corn canopy, which also has an FAPAR close to 1. In that sense, fluorescence over agricultural areas is always highest across the globe. The corn belt in the US glows up in the summertime and has the highest peak fluorescence values across the globe.

Question 24: Can we open SIF data in any GIS Software? a) How does it differ from NDVI? b) SIF accuracy in %? c) Can we find water stressed areas?
Answer 24: It differs from NDVI based on spatial resolution. SIF cannot be measured at fine spatial scales.
NDVI captures a band ratio approach or the greenness of the plant, which is generally referring to capacity while fluorescence is referring to activity. NDVI might give you a theoretical upper limit on what the canopy can do but what it actually does might not be fully captured.
SIF accuracy - must first distinguish between precision (standard deviation) and accuracy (bias). SIF is typically very accurate (unbiased) but imprecise (high standard deviation). A single measurement of fluorescence can have errors of 50% easily related to its absolute value. If you measure fluorescence over non-vegetated areas then the SIF precision percentage over background is infinity. A single measurement is often noisy and for that reason we have to average data in space and time to look at coarser temporal and spatial averages. It is important to keep the precision in mind. What we always do for each and every individual point that we get from space is calculate the fluorescence value and estimate the 1 sigma precision error, which is purely noise related (it translates to noise on the detectors). This is something that we compute during the retrieval process from first principles. It is a very accurate error estimate. Once you start to aggregate or average soundings over one area you scale your uncertainty by the square root of the number of observations. E.g. you have 9 observations and you decrease your uncertainty by ⅓. In our case all the precision errors are perfectly uncorrelated, it means that we can use error propagation and reduce the error in the mean (divide it by the square root of the number of measurements that you averaged).

Question 25: Which case on a sunny day vs cloudy day shows a better relationship between GPP and SIF?

Answer 25: On a cloudy day (you have a lower dynamic range), GPP and SIF will be in the linear range of each other. On a sunny day, there is more non-linearity. Typically on a cloudy day if you have a lower dynamic range of the total sunlight that hits the canopy, fluorescence and GPP should be linearly related because the light level where GPP levels off has not been reached and hence the light saturation point of photosynthesis is reached, which is more in the linear range where GPP and fluorescence are almost perfectly correlated. Under fully bright sunny skys plants need to dissipate more energy and there is often a slight non-linearity between fluorescence and GPP because under very high light the PSII yield is fractionally more reduced than the fluorescence unit.

Question 26: Is it possible to combine SIF with other remote sensing data (e.g. Landsat data)? And can it be used to monitor multitemporal AGB changes/modelling?

Answer 26: First part - yes it is possible to combine SIF with other remote sensing data. Landsat is higher resolution so there might be higher discrepancies because you will have to aggregate lots of Landsat data to represent a fluorescence footprint. MODIS might be better suited in terms of spatial resolution, on the order of 250 to 500 meter resolution. There are lots of studies that combine fluorescence and for instance MODIS data to downsample the fluorescence product from its coarse spatial scales to finer spatial scales. Alex Turner has done wonderful work in the US and over California. Such combinations can be used to monitor multi temporal above ground biomass changes. In principle if the ABG changes change APAR or some of the other efficiencies, you should be able to see changes in there as well. In some cases it might be better to combine SIF with other measurements such as multi-temporal LIDAR measurements, which are much better to detect changes in the structure than fluorescence plus LANDSAT and MODIS would also help in that case. If you can, it would be good to combine with other remote sensing data.

Question 27: Please discuss any possible relationship of SIF to or with water stress or excessive wetness. Or perhaps no relationship?

Answer 27: This is a more complicated question than it seems. To first order, it depends on how water stress or excess wetness actually changed the canopy structure (or planting date). These effects can be easily seen in SIF but equally well in vegetation indices. The 2nd order effect is when stress suppresses photosynthesis but keeps its absorbed PAR the same. If the plant has enough capacity to perform NPQ, it should result in a reduction of both PSII yield as well as SIF yield, i.e. it should be partially

reflected in SIF. However, the reductions in SIF are more muted compared to reductions in GPP. See He, L., Wood, J.D., Sun, Y., Magney, T., Dutta, D., Köhler, P., Zhang, Y., Yin, Y. and Frankenberg, C., 2020. Tracking seasonal and interannual variability in photosynthetic downregulation in response to water stress at a temperate deciduous forest. Journal of Geophysical Research: Biogeosciences, 125(8), p.e2018JG005002.
And Magney, T.S., Barnes, M.L. and Yang, X., 2020. On the covariation of chlorophyll fluorescence and photosynthesis across scales. Geophysical Research Letters, 47(23), p.e2020GL091098.

Question 28: Why does SIF measure GPP in conifer forests than deciduous forests?
Answer 28: I am not sure I fully understand the question. In principle, the SIF to GPP relationship in both forest systems is similar. In evergreen forests that shut down photosynthesis in winter, we found that SIF tracks GPP variations well, as sustained NPQ largely reduced both SIF as well as photosynthesis yields.
See Magney, Troy S., David R. Bowling, Barry A. Logan, Katja Grossmann, Jochen Stutz, Peter D. Blanken, Sean P. Burns et al. "Mechanistic evidence for tracking the seasonality of photosynthesis with solar-induced fluorescence." Proceedings of the National Academy of Sciences 116, no. 24 (2019): 11640-11645.

Question 29: How much does the spatial resolution influence the relationship between SIF and GPP.., in other words can you get similar linear relationships if we were to use "high" spatial resolution data e.g. at 30m or 20m.
Answer 29: The nice thing about SIF is that it is scale invariant, so in principle the integral of SIF over the ground pixel is closely related to the integral of GPP over the same area. For instance, if half the pixel is just a parking lot, both SIF and GPP will be reduced by half. If you go to finer spatial resolution, you will have the advantage of better interpreting the signal though, as the cover type will be more homogenous.

Question 30: Flux tower GPP has smaller footprint and much finer timescale (half-hourly) compared to the satellite SIF. How can you compare these two? Can this be a good study?
Answer 30: Good question! This is the reason we started working with ground-based spectrometers on towers as well. From space, it only works if the large-scale area around the tower is homogenous, so that the large satellite footprint is representative of the cover around the tower. You might be able to apply down-sampling methods to

improve this representativeness. Another challenge is to compare continuous (throughout the day and night) tower measurements to instantaneous satellite measurements (only once a day). We convert satellite measurements to a daily average by applying a so-called daily correction factor to be able to compare the measurements.

Question 31: Can you comment again on what cases (i.e. stressed vegetation) SIF and GPP have the anti-correlationship?
Answer 31: Under stress, when NPQ is working, the SIF and PSII yields should be correlated. One always has to distinguish between yields and absolute fluxes (both for GPP and SIF). Even though the yields are not always perfectly coupled, the absolute fluxes are typically correlated as they are mostly driven by light. If there are cases when vegetation is stressed beyond its limits (i.e. more than it has been acclimated to), the SIF yield might indeed go up. There are also experiments where herbicides have been used to suppress the CO2 fixation and to block the electron transport chain in which case a lot of the absorbed energy is dissipated as SIF (no GPP, high SIF).

Question 32: At what time of the day we can say SIF from plants is maximum? Does it depend on the amount of sunlight? Or is there a specific time window when SIF is at maximum?
Answer 32: Typically when light is at its maximum, i.e. mid day, so absolute SIF largely follows absorbed radiation

Question 33: Thank you for an excellent talk on a very intriguing line of research! I was wondering, how do you account for possible noise in the form of anthropogenic light when looking at SIF in urban ecosystems?
Answer 33: This is an excellent question, in principle SIF can be confused with any other additional light source in the 750nm range. Incandescent light bulbs should also emit light in this spectral range but LEDs likely not as they are meant to optimize emissions in just the visible spectral range. In addition, anthropogenic light sources are negligible at the time of the satellite overpass (which is in the daytime).