Space-borne sun-induced fluorescence: an advanced probe to monitor seasonality of dry and moist tropical forest sites

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Space-borne sun-induced fluorescence (SIF) is the latest breakthrough in remote sensing of physiological response of plants. We studied the seasonality of sal (*Shorea robusta*) forest canopies analysing space-borne SIF and reflectance data collected over moist and dry sites in central India. Results indicate that the monthly response of OCO-2 SIF, MODIS NDVI and GPP differs significantly across the wet and dry forest sites. SIF explained higher seasonal variations and was also better correlated to rainfall across sites compared to NDVI.

Keywords: Fluorescence, remote sensing, seasonal variations, tropical forests, vegetation index.

REMOTE sensing has been used widely for monitoring photosynthetic activity of the vegetation[1,2]. However, reflectance-based vegetation indices such as normalized difference vegetation index (NDVI) are less sensitive to vegetation under stress. Vegetation under seasonal stress shows little changes in leaf colour and that has a minimal effect on reflectance of solar radiation[3]. Chlorophyll fluorescence is a promising alternative to traditional measures of physiological response of plants[4]. The chlorophyll fluorescence (re-emission of light at a longer wavelength than for excitation) is dissipated as by-product of the light reactions during photosynthesis[3,5,6]. Previous studies carried out using *in situ* instruments have reported that chlorophyll fluorescence is a strong indicator of photosynthesis[4,7].

Recent developments in satellite-based sensor technology offer a more direct and instantaneous measure of photosynthetic status of vegetation through the mapping of sun-induced fluorescence (SIF)[3,8]. It can be derived directly from satellite radiance data and is considered as a potential indicator of light use efficiency, vegetation stress and global primary productivity[8,9]. Lee *et al.*[10] found that SIF is a better predictor of forest productivity compared to NDVI across evergreen and deciduous forest sites in the Amazon Basin, using coarse spatial scale SIF signal from Greenhouse Gases Observing Satellite (GOSAT) satellite.

Previous studies have used SIF data from satellite available at coarser scale, e.g. GOSAT at 10 km diameter and Gome-2 at 80×40 km^2 spatial resolutions. These datasets are suitable for global and national-scale studies. However, they are not suitable for capturing species-specific SIF responses as photosynthesis rate is governed by local environmental conditions and abiotic factors (soil, water, nutrients).

Now, NASA's Orbiting Carbon Observatory-2 (OCO-2) offers unprecedentedly high spatial resolution (1.29 km × 2.25 km), space-based SIF measurements. It facilitates the evaluation of sensitivity of SIF measurements with respect to reflectance-based vegetation indices for studying forest seasonality at local scale. Sal (*Shorea robusta*) forests cover approximately 13.30% of the total forest area of India[11]. They show characteristic phenological trajectories ranging from evergreen to deciduous across moist to dry sites[12,13]. We studied seasonal variations in sal forest canopies across the two moisture regimes, based on space-borne SIF and reflectance data collected across moist and dry sites in central India.

The sal distribution areas in central India in the states of Madhya Pradesh, Odisha, Chhattisgarh and Maharashtra were selected for the study (Figure 1). The study area lies between 26°18′3.03″–16°52′39.26″N and 79°32′13.81″–88°47′57.24″E. Moist sal forests are mostly distributed in Tropical Savanna (A_W) climatic zone and dry sal forests lie in temperate dry winter hot summer (Cwa) climatic zone[14]. In sal, leaf fall usually starts in late winter (February) and is completed by the end of April[15]. Maximum

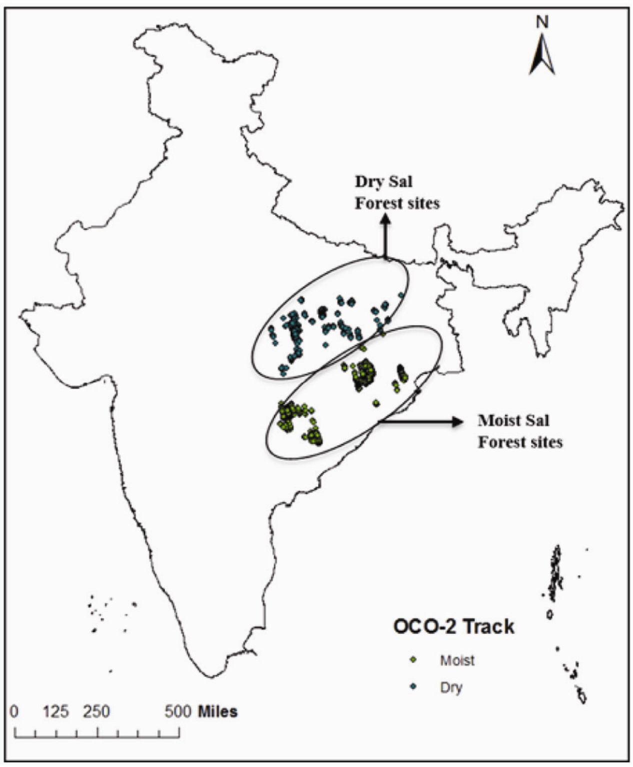

Figure 1. OCO-2 track passing through the study sites.

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leaf fall is reported during mid-February to mid-May[16,17]. Sal shows dual phenological character; so it has always some leaf and is governed by the availability of soil moisture[11]. Sal forests growing across moist and dry sites also show significant variation in stand structure and diversity across the sites[18].

We extracted spatial distribution of sal forests in central India from the vegetation-type map of India prepared by Roy *et al.*[19]. WorldClim (http://www.worldclim.org) mean annual precipitation data (1961–90) were used to differentiate dry (<1500 mm) and wet (>1500 mm) zones in sal distribution areas. District-wise monthly rainfall data (2015) were compiled from the annual reports of the Indian Institute of Tropical Meteorology (IITM), Pune. OCO-2 SIF (OCO-2 7 LITE) tracks falling over dry and moist sal forests were extracted from global datasets (https://co2.jpl.nasa.gov//download/). OCO-2 SIF uses mainly O_2 absorption band around 757.5 nm to retrieve fluorescence using Fraunhofer lines present at 758.81 nm (ref. 8). Monthly averaged SIF was derived from the OCO-2 SIF sample points available for the sites. MODIS monthly NDVI (MYD13A3, Aqua) and gross primary product (GPP) (MOD17) (at 1 km spatial resolution) were downloaded from reverb-echo database of NASA (https://reverb.echo.nasa.gov/reverb). MODIS-derived GPP as well as NDVI were used because they have been widely used as a proxy for GPP[20]. Finally, we analysed trends in SIF, NDVI, GPP and rainfall for both dry and moist sites.

It was observed that greenness (as indicated by NDVI values) decreased from February to April at both dry and moist sites, but with lesser magnitude for the latter (Figure 2). This indicates that the moist sites retain more foliage in comparison to the dry sites. Similar to NDVI, SIF also showed continuous decline during winter season. However, SIF response was markedly different from NDVI during April, where it showed a sharp increase and attained a peak. This impulsive rise in SIF was found related to scanty showering and leaf flushing in the study

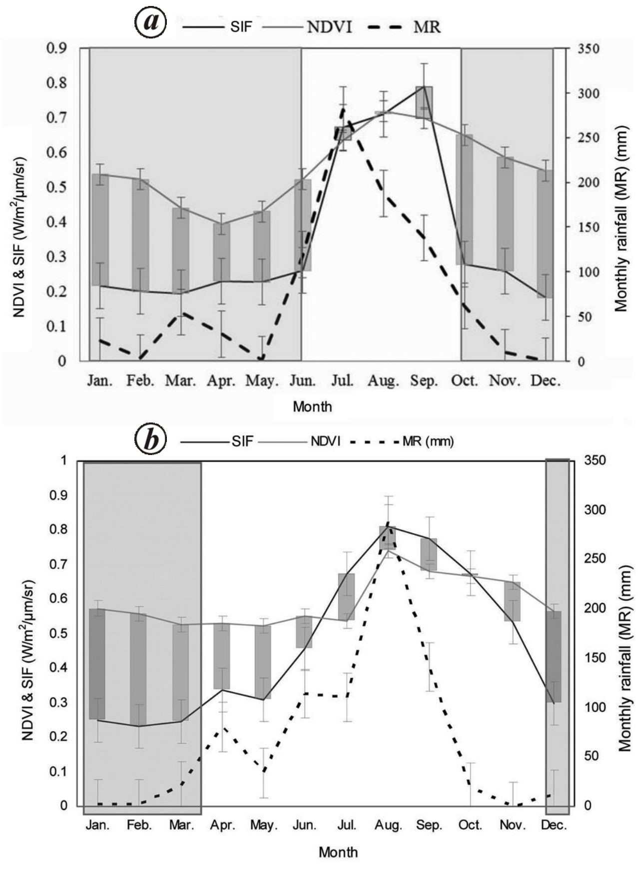

Figure 2. Intra-annual distribution of SIF, NDVI and rainfall at (***a***) Dry site and (***b***) Moist site. Shaded area represents the average SIF value lower than 0.3 W/m^2/µm/sr.

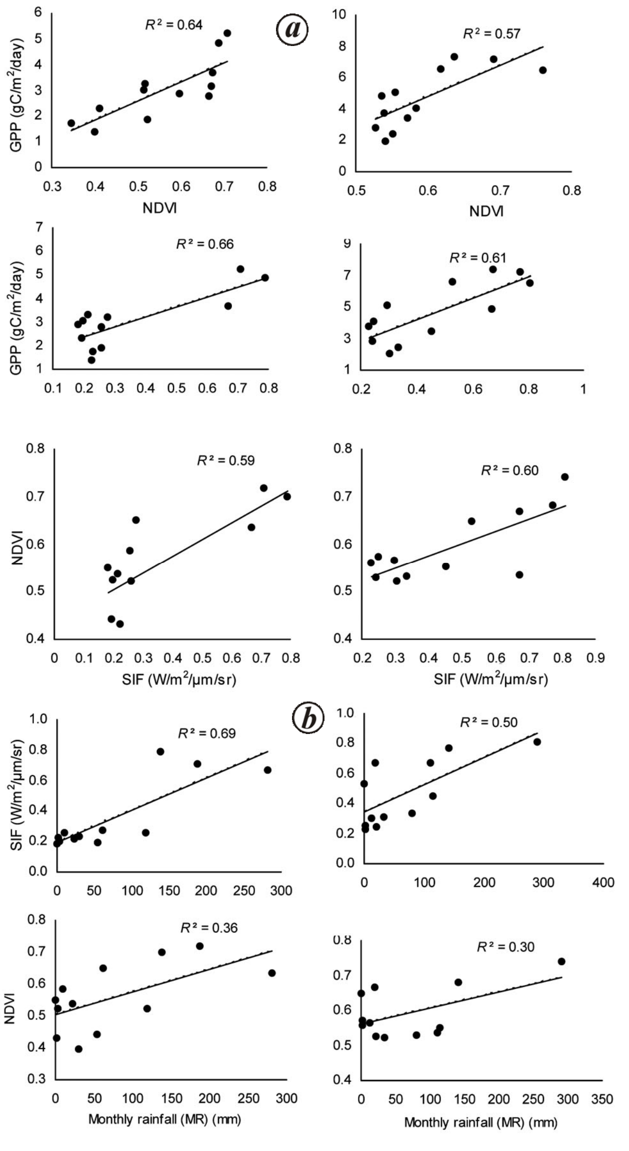

Figure 3. Relationship between (***a***) GPP, SIF and NDVI at dry site (left) and moist (right); (***b***) SIF and NDVI with monthly rainfall at dry site (left) and moist (right).

Table 1. OCO-2 SIF vis-à-vis NDVI/GPP relationship in different seasons

	Dry sal forest site			Moist sal forest		
Season*	MODIS GPP versus SIF (R^2)$^{\#}$	MODIS GPP versus MODIS NDVI (R^2)$^{\#}$	MODIS NDVI versus SIF(R^2)$^{\#}$	MODIS GPP versus SIF(R^2)$^{\#}$	MODIS GPP versus MODIS NDVI (R^2)$^{\#}$	MODIS NDVI versus SIF(R^2)$^{\#}$
JJA	0.84	0.95	0.87	0.97	0.81	0.56
SON	0.98	0.99	0.71	0.72	0.52	0.99
DJF	0.98	–0.78	0.23	0.94	0.06	0.91
MAM	0.79	0.28	0.55	0.70	–0.5	0.21
Annual	0.66	0.64	0.59	0.62	0.57	0.61

$^{\#}R^2$ = Coefficient of determination at $P < 0.05$.
*JJA, June–July–August; SON, September–October–November; DJF, December–January–February, MAM, March–April–May.

area. SIF showed rapid rise after the first showers of monsoon, i.e. from May (moist site) and June (dry site), and reached its maximum value during August and September respectively. SIF response during April is well correlated to similar rise in above-ground biomass, as reported by Rana and Rikhari[13]. SIF starts declining rapidly after monsoon at the dry sites in comparison to the moist sites. The sudden decline in SIF signals is the dry sites is mainly linked to low water retention capacity. Dry sites lose canopy moisture more rapidly compared to moist sites.

Statistical analysis showed that SIF has a higher correlation with GPP ($R^2 = 0.66$ and 0.62, $P < 0.05$) compared to NDVI ($R^2 = 0.64$ and 0.57, $P < 0.05$) (Figure 3 *a*). NDVI showed a lower correlation with SIF ($R^2 = 0.23$, $P < 0.05$) during December–January–February (DJF) in the dry sites and March–April–May (MAM) ($R^2 = 0.21$, $P < 0.05$) in the moist sites. NDVI showed negative correlation with GPP ($R^2 = –0.78$, $P < 0.05$) during DJF in the dry sites and during MAM ($R^2 = –0.50$, $P < 0.05$) in the moist sites. Whereas GPP correlated well with SIF during the same periods ($R^2 = 0.98$ and 0.70, $P < 0.05$ respectively) (Table 1). This indicates that SIF is a better indicator of seasonality and productivity than NDVI across moist and dry sal forests.

We found a positive correlation (dry sites: $R^2 = 0.69$, $P < 0.05$; moist sites: $R^2 = 0.50$, $P < 0.05$) between monthly rainfall and SIF (Figure 3 *b*). An earlier study has also reported that rainfall is directly related to sal growth (0.65–0.81; $P < 0.05–0.01$)[14]. Though NDVI is the commonly used indicator of vegetation growth, it exhibited a lower correlation with rainfall (dry sites: $R^2 = 0.36$, $P < 0.05$; moist sites: $R^2 = 0.30$, $P < 0.05$). Plant growth in the dry sites highly depends on water availability, and hence has a higher impact on seasonality than the moist sites.

The present study highlights the potential of satellite-derived SIF in capturing the seasonal variability in forest canopies across variable moisture gradient. We observed significant intra-annual differences in satellite-derived SIF signal vis-à-vis NDVI/GPP at a finer scale. Use of SIF information may give more robust and precise estimation of forest seasonal variability.

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Sustainable livelihood options for women in the coastal ecosystem: a participatory assessment

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The present study aimed at identifying the need-based and sustainable livelihood options suitable for members of the coastal women self-help groups (SHGs). The study was conducted on a sample of 240 women representing 24 SHGs in Kerala, India. Out of the 30 potential and sustainable livelihood options assessed through participatory tools, aqua tourism (index: 83.33) was found to be the most potential option for women in the coastal ecosystem, especially as a group activity for the women SHGs. Fish drying units (80.42), preparation of value-added fish products (77.08), catering units (77.08), fish/prawn feed manufacture (69.17), fish/prawn seed collection (64.17) and collection of bivalves such as oyster, clam, etc. (61.67) were also found to have high potential as sustainable livelihood options. Lack of access to institutional finance was reported as a major constraint, which traps women microentrepreneurs in the clutches of private moneylenders. Policy development to support women in the coastal ecosystem requires appropriate institutional arrangements and effective organizations and structures, which extend assistance in the areas of training, credit, technology and marketing through SHGs.

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Keywords: Coastal ecosystem, participatory methods, self-help groups, sustainable livelihoods, women empowerment.

WOMEN in the coastal communities play a major role in household management. This includes food, childcare, education, health and even financial management of getting and repaying the loans. While these factors add to impasse among women, realization that active fishing alone cannot support the family due to highly fluctuating earnings owing to uncertainty in marine fisheries, necessitated mainstreaming of women to adopt profitable and sustainable enterprises. Even though microenterprises are a viable option for women entrepreneurs, they often fail due to very small investments, inadequate training, lack of quality concern, irregular production and supply to the market, and lack of managerial skills. As a result, either they close their business after a while, or become subjects of exploitation by middlemen[1]. Involvement of women in productive activities is an important strategy for poverty alleviation in the society and for overall women empowerment. Any initiative related to microenterprises with women, designed with a right frame and implemented using a right approach can prove to be an important tool for social and political empowerment along with economic empowerment[2,3].

Against this background, the present study aimed at identifying and documenting the need-based and sustainable livelihood options suitable for self-help groups (SHGs) among coastal women. Resource availability, perceived needs of the respondents, marketing scope and sustainability issues related to the identified livelihood options were assessed in a participatory mode.

The study was conducted on 240 women members of 24 SHGs from eight fishing villages in four coastal districts of Kerala, India, viz. Kollam, Ernakulam, Thrissur and Kannur (Figure 1). The respondents were selected using multi-stage stratified random sampling procedure.

The need-based and sustainable livelihood interventions required for the coastal women SHGs were assessed using a participatory tool, namely the ‘H form’ method. The original H-form method was particularly designed for monitoring and evaluation of programmes. The method can be used for developing indicators, evaluating activities, and to facilitate and record interviews with individuals or group discussions[4]. For the present study, a modified H form method was used. A large sheet of paper was taken and folded in the form of a ‘H’. The paper was unfolded and the ‘H’ lines were darkened with a pen. The indicator/livelihood need to be assessed was written at the top centre of the H form. On the left of the horizontal line of ‘H’, the score of ‘0’ representing ‘poor’ and on the right side, the score of ‘10’ representing ‘extremely good’ were written (Figure 2). The groups were asked to discuss and place their group consensus score along the line between 0 and 10. They were also asked to justify their