NDVI and fluorescence indicators of seasonal and structural changes in a tropical forest succession

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Declarations

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Not Applied.

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Abstract: In this research, the Sun-induced Chlorophyll Fluorescence (SIF) signal was derived from field-based spectrometers and Hyperion satellite imagery of Hong Kong's Country Parks by applying the Fraunhofer Line Difference (FLD) method. Due to high levels of atmospheric aerosols and water vapour in the study area, a modified FLD method (FLD-M) was tested for its ability to deliver improved SIF estimates by cancelling out the effects of atmospheric scattering. The SIF results were compared with the Normalised Difference Vegetation Index (NDVI), and analysed according to seasonality, five successional age groups of forest and monoculture exotic plantations. Results indicate that SIF methods are more sensitive to seasonal phenology and diurnal fluctuations than the NDVI, indicating its greater sensitivity to photosynthetic activity. The SIF responds earlier and stronger, to senescence in winter and green-up in summer. Field spectrometer data showed NDVI to be unresponsive to time of day, whereas fluorescence responds to changes in sunlight intensity from 10:15 am to 02:00 pm. Both seasonal and diurnal results indicate that SIF is better than NDVI in representing the subtle changes in vegetation conditions. Although both NDVI and SIF distinguish between the four woody structural stages of vegetation, only SIF can distinguish between forest and exotic plantations, the difference being greater in the dry season. The study provides an improved operational remote sensing methodology for investigating the health status of tropical secondary forest, where atmospheric turbidity is high.

Keywords: FLD**;** Hong Kong; Hyperspectral; NDVI; SIF; Tropical Forest.

1 Introduction

Sun-induced Chlorophyll Fluorescence (SIF) is an indirect measure of photochemical processes and carbon sequestration. However, it remains unclear how SlF and photosynthesis are linked diurnally and across the growing season, as well as how plant productivity is related to the SIF signal. Retrieval of the fluorescence signal by remote sensors can potentially provide a unique understanding of the photosynthesis cycle of vegetation, since SIF is a direct indicator of canopy photosynthesis (Mohammed et al.

2019). As different species have different fluorescence emissions (Mohammed et al. 2019), this can be useful in measuring the stress of different vegetative species, especially in dense tropical forests where the Normalised Difference Vegetation Index (NDVI) tends to saturate (Brantley et al. 2011).

The fluorescence signal is very weak compared to other emitted signals and detecting it from space is challenging, as it is only a small fraction, i.e., 0.5 – 2 % of reflected solar radiation emitted from the surface (Frankenberg et al. 2012). The SIF Spectrum is able to disentangle the reflected radiance and SIF emissions by comparing the radiance inside and outside the oxygen absorption bands. These bands cover the range 650 nm to 850 nm, and are known as the O_2-A and O_2-B bands. The O_2-A band at 760 nm is more suitable than the O_2-B band at 680 nm because at this wavelength, the original radiation is considerably reduced, allowing the sensors to detect the SIF signal (Liu et al. 2015). Therefore space based SIF retrieval is most possible within this region, and this research emphasises the O_2-A at 760 nm. However, one major drawback of using the O_2 bands for SIF retrieval is that very accurate atmospheric correction is required due to the weakness of the SIF signal (Damm et al. 2011).

A series of methods have been developed based on the FLD (Fraunhofer Line Depth) algorithm, including the standard FLD, 3 FLD, corrected FLD, improved and extended FLD, and used to extract SIF from hyperspectral remote sensing data (Ni et al. 2019), and most tend to overestimate SIF (Liu et al. 2015). Thus, there remain many drawbacks in existing models for the retrieval of fluorescence from both space and ground instruments (Mohammed et al. 2019). For monitoring of temporal growth patterns using SIF, Zhang et al (2017) used SIF to demonstrate the Net Primary Productivity (NPP) stages in young, middle age, and mature forests, which they linked to a decline in dry matter production when maximum leaf area is attained. Giardina et al (2018) showed that forest age and height are both controlling factors on photosynthesis and that younger forests are three times more sensitive than older forests to moisture deficit, due to shallow root systems. However, none of these studies linked SIF with forest successional age classes. In a recovering tropical forest such as the study area of this study (Abbas et al. 2019), age class recognition along the succession enables estimates of the carbon sequestration potential of reafforestation projects, and of forests which are recovering naturally. Also, it remains unclear how SIF and photosynthesis are linked at different spatial scales across the growing season, as well as how the Gross Primary Productivity (GPP) of plants, which depends on whole-season growth, is related to SIF (Meroni et al. 2009). Therefore, in this study, we implemented the well-established FLD method to compare the sensitivity of SIF and the NDVI to depict photosynthetic patterns of vegetation along a structural and successional gradient, as well as over the phenological cycle in a recovering tropical forest.

It is known that wide variation in the estimated values of fluorescence emission may occur, depending on the time of year, temperature, radiation, spatial or temporal averaging and the methodology used (Ma et al. 2018). Therefore the objective of this study is to examine how diurnal and seasonal physiological changes in vegetation, as well as forest age affect the SIF signal. For comparison purposes the commonly used vegetation health indicator, the NDVI is also examined. The study compares species and forest age data with fluorescence and NDVI values computed from Hyperion satellite images and field spectrometer data in Hong Kong's forested Country Parks.

2 Materials and Methods

2.1 Study area

The study area covers approximately 3,000 ha. within the Tai Mo Shan and Shing Mun Country Parks in the New Territories of Hong Kong (Fig. 1). Topography is rugged, with convex slopes rising to Hong Kong's tallest mountain Tai Mo Shan at 957m. Upper slopes and ridgetops support fire-maintained grasses, and naturally regenerating secondary forest and plantations cover lower slopes. Forest ages are shown in Fig. 1b.

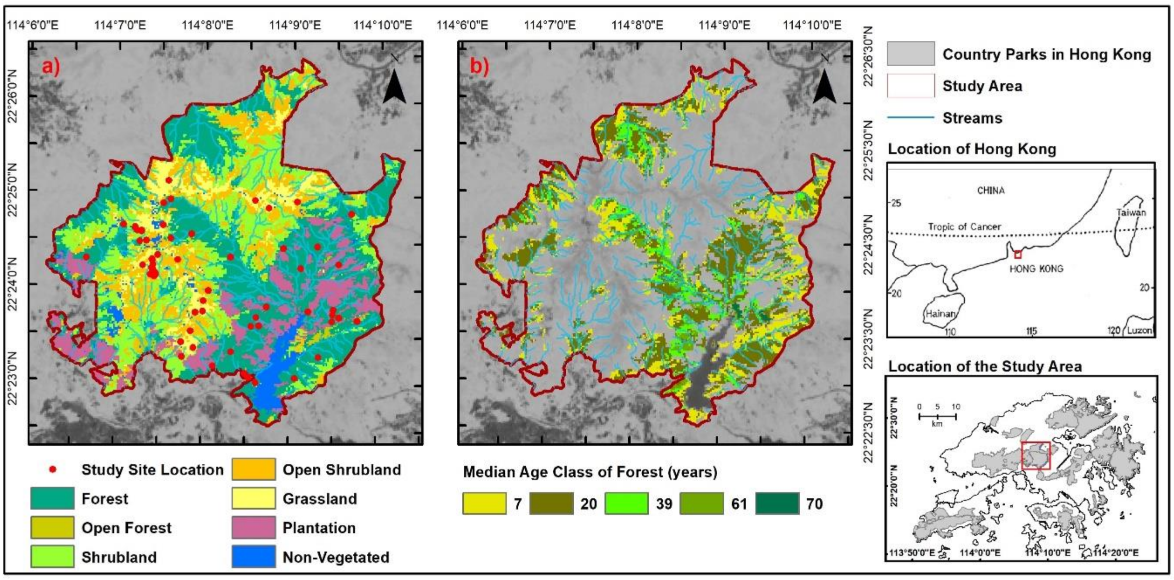

Fig. 1. Structural vegetation type (a) and age of forest (b), in Tai Mo Shan and Shing Mun Country Parks, Hong Kong (Abbas et al. 2019).

2.2 Field data collection

Field measurements were taken in different seasons from 2015 to 2018, over 26 different vegetative sample points, including grassland, and secondary forest dominated by *Machilus chekiangensis*. All readings were taken under natural sunlight and clear sky conditions to retrieve Top of Canopy (TOC) radiances. To obtain irradiance values a white reference was used with every observation. Half-hourly TOC radiances were collected from 10:15 am till 02:00 pm, to investigate whether SIF and NDVI were sensitive to diurnal changes. Data were collected at the same time of day in different months to investigate seasonal phenological changes.

2.3 Land cover and forest age classes

This study uses the habitat classification and forest age maps from Abbas et al (2019) (Fig 1a and 1b) to analyse the response of NDVI and SIF against the following parameters (i) vegetation structural classes, including forest, open forest, shrub-land, open shrub-land and grassland, (ii) stands of exotic monoculture plantations, and (iii) different successional age groups of natural forest with median ages of 7, 20, 39, 61, and 70 years. The forest age classes were derived from analysis and mapping from a time-series of three sets of aerial photographs and two satellite images. Orthorectification using detailed photogrammetric techniques was performed to obtain accurate image co-registration in the rugged terrain of the study area.

2.4 SIF retrieval from Field Spectrometer

Field measurements using a Ramses TriOS portable spectrometer, having spectral range 320 - 950 nm and spectral sampling at 3.3 nm and 190 channels were obtained. To derive the O_2-A band, bands ranging from 752 nm to 772 nm were processed. The FLD method of fluorescence retrieval (Equation 1) (Plascyk 1975) was applied to the field data to extract the fluorescence intensity of the vegetation for the oxygen absorption band at 760 nm.

$$F = \frac{L{\downarrow}\lambda out \ x \ \ L{\uparrow}\lambda in - L{\uparrow}\lambda out \ x \ L{\downarrow}\lambda in}{L{\downarrow}\lambda out \ - \ L{\downarrow}\lambda in} \qquad (1)$$

where $L\uparrow$ is the upwelling solar radiance reaching the sensor, λ_{out} and λ_{in} is the wavelength outside and inside the 760 nm, and $L\downarrow$ refers to the solar irradiance and its respective wavelength inside and outside the O_2-A band.

In addition to SIF, the NDVI was also derived using spectrometer bands at 681 nm and 752 nm, as these wavelengths are close to the bands used for fluorescence.

2.5 SIF retrieval from Hyperion images

Two Hyperion satellite images, October 12th 2015 and March 2nd 2016, with a ground resolution of 30 m, were obtained from the United States Geological Survey (USGS). The images were atmospherically corrected using the 6S model, which was found to be optimal for the study area compared to other models tested (Nazeer et al. 2014). To retrieve SIF using the O_2-A band, bands 40 to 42 (752 nm to 772 nm) were selected and the FLD method (Equation 1) was applied.

In addition to the FLD method, a modified FLD method (FLD-M) was tested for its ability to deliver improved SIF estimates by cancelling out atmospheric scattering. This is especially important over Hong Kong where high levels of AOD and water vapour are common. Although a standard atmospheric correction using 6S model was initially applied to the images, its testing over Hong Kong showed up to 10 % difference in surface reflectance from ground measurements. Thus decoupling of the weak fluorescence signal from atmospheric effects may still be difficult. FLD-M is based on Raychaudhuri (2014), where radiation in the O_2-A band is compared to its adjacent bands on either side of it, for vegetated and non-vegetated surface respectively. Thus it uses the ratio of radiation of the O_2-A band and bands outside the O_2-A bands, from both vegetated and non-vegetated surfaces. A non-vegetated surface accounts for path radiance and surface reflectance whereas a vegetated region includes, in addition, the contribution of chlorophyll fluorescence.

However, an assumption is made that the fluorescence wavelength reaching the sensor is a linear combination of incident radiance reflected from the object. Thus, by calculating F (Equation 1) for both vegetated and non-vegetated surfaces, atmospheric parameters can be neglected because at sensor, if vegetated and non-vegetated targets are close enough, atmospheric effects will cancel out. Also, the path radiance will be equal in both cases (Raychaudhuri, 2014). The final SIF formula using FLD-M method is shown in Equation 2.

$$F_m = F_v - F_{nv} \qquad (2)$$

where F_v is the SIF FLD from the vegetated surface, F_{nv} is the SIF FLD from the non-vegetated surface and F_m represents SIF FLD-M. While it is known that Hyperion images often have a low signal to noise ratio (SNR), especially at low sun angles (Kruse et al. 2003), the tropical location of the study area and avoidance of the winter season for image acquisition is deemed to have minimized this problem.

3 Results

3.1 SIF and NDVI analysis by vegetation structural class

Hyperion data of different land cover types representing green-up in March and senescence in October (Fig. 2) show NDVI values gradually decreasing with a decrease in biomass, from closed forest to open shrubland (Fig. 2a) in both seasons. However, the bar graphs of forest and plantations (Fig. 2d) show almost similar values of NDVI for forest and plantations in both senescence and green-up seasons. However, SIF (Fig. 2e-2f) shows a notable difference between plantations and forest. The differences in SIF between plantations and forest were quantified by determining the percentage difference, using $(SIF_{plantations} – SIF_{forest})/ SIF_{plantations}$. The SIF derived from the the FLD method shows plantations to be 3.5% and 8.7% higher than for forest in October and March, respectively. For the FLD-M method the SIF of plantations is 6.9 % and 9.5% higher than for forests in March and October. Both methods show that the difference is higher in March, the driest season.

Regarding the differences in vegetation response between the March greening and October browning seasons (Fig. 2a-2c), the NDVI shows some differences between the vegetation classes in the March green-up season, but hardly distinguishable differences in the October browning season. However, the SIF response shows considerable differences between classes in both seasons. The SIF FLD-M method (Fig. 2c) also shows significant differences between the seasons for all classes, whereas only the Open Forest class shows differences for the SIF FLD method (Fig. 2b).

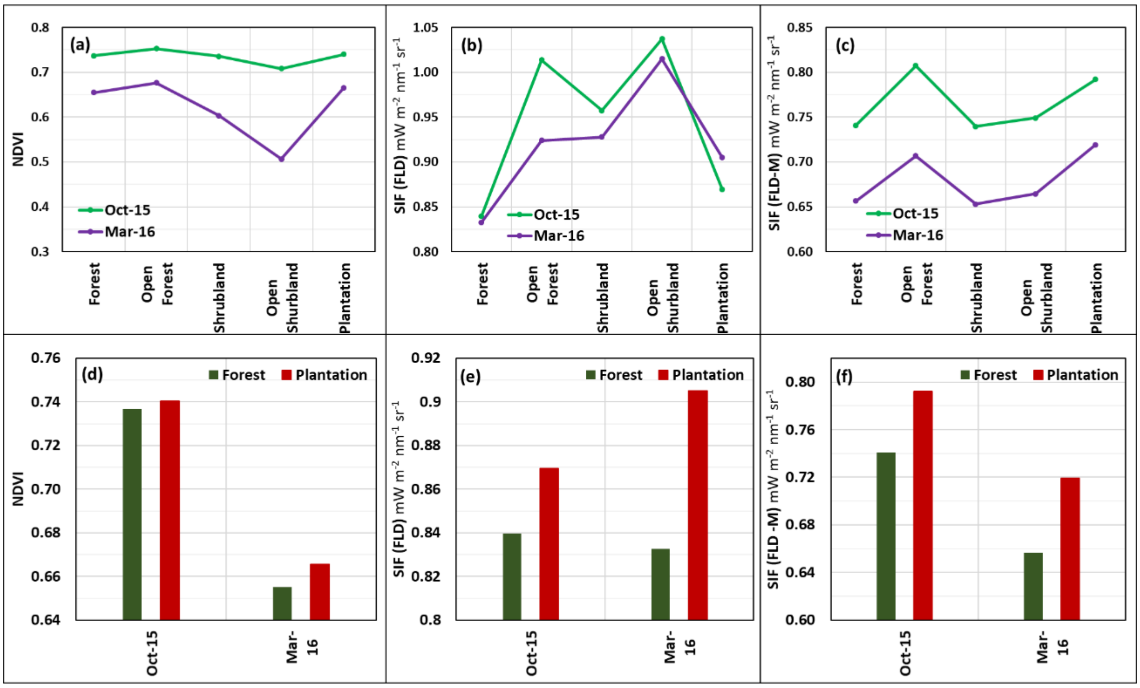

Fig. 2. Hyperion NDVI and SIF response for March and October by (a-c) Land cover type, and (d-f) Forest and Plantation.

3.2 SIF and NDVI analysis by forest age class

Figure 3 shows the responses of five different forest age classes at greening and browning seasons. Both NDVI and SIF FLD-M indicate a significant and consistent difference between the seasons across all age classes (Fig. 3), which is expected due to March being the end of the dry season. The SIF FLD method does not represent these differences. However, the SIF FLD method show more difference between the age classes than do the NDVI and SIF FLD-M, with a continuous and large increase in fluorescence emission with age up to 61 years, after which the 70-year forest shows a dramatic fall in response (Fig. 3b). The relative differences of SIF among the successional age classes were determined as percentage differences from the youngest forest (i.e., 7-year old forest), using ($SIF_{7\text{-year}}$ – $SIF_{(20,\ 39,\ 61,\ 70\ \text{years})}$) / $SIF_{7\text{-year}}$, for both seasons. In March the percentage difference for SIF FLD-M gradually increases by 3.8%, 9.2%, 15% from 20 to 61 year old forest, but falling to 10.3 % for the 70-year old forest. Similar patterns were observed for October SIF FLD-M but with less marked differences (3.2%, 6.2%, 10.3%, and 6.8 %, respectively) along the successional gradient. The SIF FLD method indicated high percentage differences among the successional age classes in March, which increases gradually from 20 to 61 year old forest (11.2 %, 45.8 %, and 66%, respectively), but a negative difference of 23.6% for the 70-year old forest (i.e., the SIF of the oldest forest, 70-year old, was 23.6% lower than the youngest forest, 7-year old). The October SIF FLD follows a similar pattern along the successional sequence but with less difference (6.8%, 28%, 36.8%), except for the oldest forest (-27.4 %).

This large drop in photosynthetic response between 61-year and 70-year old forest appears unrealistic given the small age difference, as well as the stability of the forest species composition and structure over these age classes (Abbas et al. 2019). The SIF FLD-M method appears to be the overall best index for representing both the distinction between seasons, as well as among different forest age classes. The age classes represent potentially different levels of carbon sequestration, especially marking a distinct reduction after 60 years of age. Most notably, the SIF FLD method shows less ability to distinguish between seasons for the 5 forest age classes, than either NDVI or SIF FLD-M.

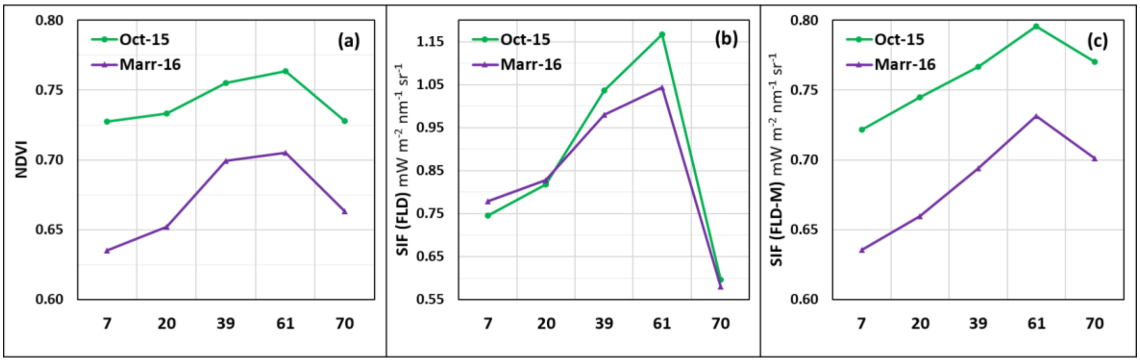

Fig. 3. Hyperion NDVI and SIF response for forest age classes.

3.3 Seasonal variation in grassland and shrubland, from field spectrometer data

A year-long field experiment was undertaken over grassland (Fig. 4a) and shrubland (Fig. 4b), with all readings around midday. As the SIF FLD-M method was adopted to cancel out atmospheric scattering effects, it was not included in this field experiment. For grassland (Fig. 4a) a strong phenological pattern over a year is indicated by both NDVI and SIF. Both NDVI and SIF FLD have minimum values in November to March and the highest values from May to August (Fig. 4a). This pattern was also observable in the field. However, the evergreen shrub species *Machilus chekiangensis*, the NDVI shows no significant phenological changes (Fig. 4b). As an evergreen, leaves remain green and are able to photosynthesise year-round, albeit at a lower level in winter. However, very strong phenology is indicated by SIF, with a steep decline in December, the cool dry season.

3.4 Diurnal variation in grassland from field spectrometer data

The diurnal experiment during late growing season in October, showed the NDVI response varying little over a day, whereas fluorescence responded more strongly (Fig. 4c). The SIF FLD method reaches maximum values before noon and then decreases afterwards, whereas NDVI values remain similar throughout the day. This would make the NDVI a better general indicator for studies of vegetation condition, as readings from any time of day could be used for multi-temporal comparisons. The diurnal sensitivity of fluorescence may not be a response to increasing daily temperatures, as these peak towards 02:00 pm, and is thus more likely due to sunlight intensity, initiating photochemical reactions at cellular level. As fluoresence appears sensitive to time of day, this may result in significant uncertainty when studying seasonal phenological, or inter-annual changes.

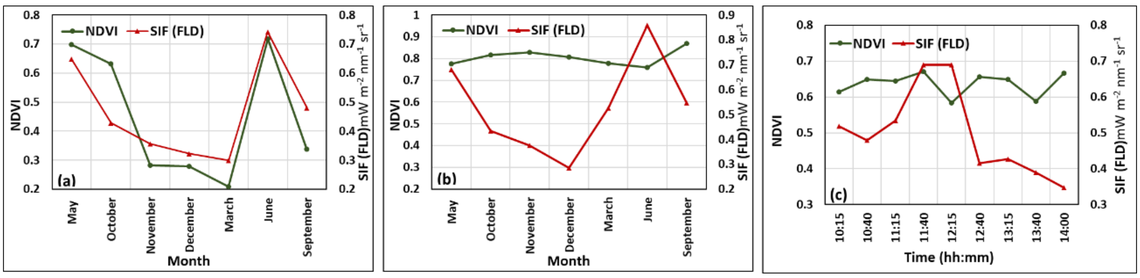

Fig. 4. Field spectrometer NDVI and SIF response throughout the year for (a) Grassland, and (b) Shrub, and (c) Diurnal variation in grassland in October (10:15 am to 02:00 pm).

4 Discussion

The results indicated that SIF may be a better overall indicator of photosynthetic processes than NDVI, as it generally outperformed NDVI when considering vegetation structural type, age and phenology. Although both NDVI and SIF indices showed differences between the structural vegetation types, with an expected increase according to biomass levels, from grassland to closed forest, no significant NDVI differences were observed between exotic plantations and forest. Conversely, both SIF retrievals showed very marked differences between plantations and forest. The difference was significant in both greening and senescence seasons, but greater for the end of dry season in March, when exotic plantations may be under moisture stress compared to the better adapted natural forest pioneers. Indeed Ni et al (2015) observed a negative relationship between fluorescence and moisture content. Of the two SIF methods, the SIF FLD-M method showed significant differences between the seasons for all structural classes, whereas, for the SIF FLD method, only the Open Forest class showed inter-seasonal differences.

All three methods observed a continuous and significant increase in response with forest age till 61 years, with decline thereafter, thus supporting carbon sequestration studies which have observed reduced photosynthetic activity in older forests (Colombo et al. 2018). However, the SIF FLD-M method appears to be the overall best index for representing both the distinction between forest structural classes as well as between seasons.

In terms of phenology, SIF showed very marked seasonal changes compared to almost no change from the NDVI. This is remarkable as the shrub species measured, *Machilus chekiangensis,* is evergreen, and thus does not go through noticeable senescence at any time of year. Thus, although the grassland sites showed strong phenology for both NDVI and SIF, woody species might not be expected to show much seasonal change. Thus again SIF appears able to measure subtle changes which the NDVI does not show, and these changes may be unrelated to the degree of greenness of the plant leaves. This is supported by Merrick et al (2019) who found that in Amazon forests, fluorescence was more sensitive to photosynthetic activity than to canopy biomass.

The retrieved NDVI index showed little diurnal change whereas SIF showed considerable variability, with values peaking around noon, the time with maximum solar radiation. Since maximum temperature is usually reached around 3 pm, the increased SIF values appear to be a physiological response to sunlight rather than temperature. This explanation is supported by two previous research papers. Firstly Ni et al (2015) reported that under slight moisture stress warmer leaf temperatures may be associated with decreased fluorescence. Secondly, Meroni et al (2009) observed that chlorophyll fluorescence and photosynthesis processes are negatively correlated in two situations, (i) in low light conditions when plants are healthy, and (ii) in plant stress conditions in full sunlight. This explains why we observed very great differences in SIF response as light conditions changed over a day, whereas the NDVI showed little change as it is more dependent on plant leaf structure which does not change diurnally.

4 Conclusion

Although our results indicate that SIF may be a better measure of vegetation physiological processes in real-time, and under some conditions is superior to NDVI, they also suggest that care should be taken when using SIF values at different times of day or in different seasons, with different solar inclinations. This is especially true in estimating vegetation structural condition or biomass, for which diurnal changes in cell response would be irrelevant. Of the two SIF methodologies tested with the Hyperion image data, SIF FLD-M gave more consistent and useful indications of plant health and condition, than the SIF FLD method, which is likely due to its additional compensation for high atmospheric turbidity in the study area. Results also suggest that further research on how vegetation moisture status affects the SIF signal may be useful, especially in view of forest dieback due to climate change reported in many regions.

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