ChinaSpec: A Network for Long-Term Ground-Based Measurements of Solar-Induced Fluorescence in China

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Abstract  Remotely sensed solar-induced fluorescence (SIF) has emerged as a novel and powerful approach for terrestrial vegetation monitoring. Continuous measurements of SIF in synergy with concurrent eddy covariance (EC) flux measurements can provide a new opportunity to advance terrestrial ecosystem science. Here, we introduce a network of ground-based continuous SIF observations at flux tower sites across the mainland China referred to as ChinaSpec. The network consists of 16 tower sites until 2019 including six cropland sites, four grassland sites, four forest sites, and two wetland sites. An automated SIF system was deployed at each of these sites to collect continuous high-resolution spectra for high-frequency SIF retrievals in synergy with EC flux measurements. The goal of ChinaSpec is to provide long-term ground-based SIF measurements and promote the collaborations between optical remote sensing and EC flux observation communities in China. We present here the details of instrument specifications, data collection and processing procedures, data sharing and utilization protocols, and future plans. Furthermore, we show the examples how ground-based SIF observations can be used to track vegetation photosynthesis from diurnal to seasonal scales, and to assist in the validation of fluorescence models and satellite SIF products (e.g., from OCO-2 and TROPOMI) with the measurements from these sites since 2016. This network of SIF observations could improve our understanding of the controls on the biosphere-atmosphere carbon exchange and enable the improvement of carbon flux predictions. It will also help integrate ground-based SIF measurements with EC flux networks which will advance ecosystem and carbon cycle researches globally.

1. Introduction

To understand the impacts of climate change, it is essential to monitor the dynamics of ecosystem carbon and water fluxes and their response to environmental changes in a warming world. Eddy covariance (EC) flux measurements have been widely used to quantify carbon, water vapor, and energy exchange between biosphere and atmosphere and improve our understanding of variations in these fluxes (Baldocchi, 2008). The global EC network (FLUXNET), with >900 registered sites, has been running for >20 years since the 1990s (Baldocchi, 2019). However, the footprint of EC measurements is generally <1 km², and the sites are unevenly distributed around the world with biased spatial coverage toward flat topography and uniform ecosystem types. The insufficient spatial coverage of networks of EC flux sites makes it difficult to estimate
gross primary productivity (GPP) of terrestrial ecosystem accurately at large scales. Therefore, from the global perspective, it is necessary to upscale tower-based observations of EC flux at the ecosystem level to regional and global levels.

Remote sensing (RS) offers a unique way to parameterize explicit plant information across multiple spatial scales, and thus improves simulations of carbon fluxes of terrestrial ecosystems at regional to global scales (Hilker et al., 2008). RS techniques (e.g., MODIS sensor) have long been used for large-scale assessments of vegetation conditions, usually through the so-called vegetation indices (VIs) and other vegetation parameters derived from spectral measurements of surface reflectance (e.g., Huete et al., 2002). As a complement to reflectance-based VIs, solar-induced fluorescence (SIF) offers new possibilities to monitor vegetation function from space (Ganter et al., 2014). The recent technical advances have enabled the global SIF retrievals from satellites sensors. Remote sensing of SIF in recent years has been proven to be a novel indicator of photosynthesis or GPP. There is a growing number of spaceborne missions with SIF retrievals that has opened up new possibilities to better monitor carbon flux and upscale EC flux data (Du et al., 2018; Frankenberg et al., 2011; Guanter et al., 2014; Joiner et al., 2013; Köhler et al., 2015, 2018; Sun et al., 2018).

However, the fundamental scale mismatch in space and time remains a big challenge to upscale the EC flux data with satellite remote sensing data. Compared to high-frequency EC flux sampling, most satellite remote sensing data usually have moderate spatial resolution but limited temporal resolution (e.g., 500 m and 16 days for MODIS). This sampling mismatch between remote sensing and flux measurements hinder the direct comparison between these two types of measurements. In this respect, ground-based spectral measurements offer a unique opportunity to bridge the measurement gap between satellites and EC flux towers because they can be conducted at an appropriate scale that more closely matches the spatial and temporal scales of the EC fluxes. Numerous studies have shown the advantages of ground-based measurements of spectroscopy to connect vegetation optical properties to flux measurements (e.g., Aasen et al., 2019; Balzarolo et al., 2011; Cogliati et al., 2015; Hilker et al., 2008; Mohammed et al., 2019; Porcar-Castell et al., 2015).

The recent advances in sensor design and application have enabled the automated field optical sampling at the scale of flux tower footprints. With respect to the SIF measurements, a number of hyperspectral instruments has been deployed in the field since 2014 to support the rapid development of SIF retrievals from satellite missions (Aasen et al., 2019; Cogliati et al., 2015; Magney et al., 2019; Shan et al., 2019; Yang et al., 2015, 2018a; Zhang et al., 2019). This is benefited from the use of some commercially available spectrometers with high-spectral resolution and signal-to-noise (SNR) ratio (e.g., QEPro from Ocean Optics, Inc., Dunedin, FL, USA), which enable the direct retrievals of canopy SIF in the field. During the last few years, several novel ground-based SIF systems, including SFLUOR box (Cogliati et al., 2015), FluoSpect2 (Yang et al., 2018b), Photospec (Grossmann et al., 2018), FAME (Gu et al., 2019), FLOX (JB Hyperspectral Devices), SIFSpec (Du et al., 2019), Rotaprism (Josep A. Berry, personal communication), SIFprism (Zhang et al., 2019), and Piccolo Doppio (MacArthur et al., 2014) have been developed and operated for autonomous continuous observations of canopy SIF in the field over years covering different vegetation types around the world. These SIF measurements are generally made together with EC flux observations providing opportunities for the integration between them and also for direct comparison and validation of satellite SIF data (Parazoo et al., 2019; Yang et al., 2015). Overall, ground-based spectral instruments could be used as a “bridge” between the EC flux and satellite remote sensing data. In addition, drone-based or airborne SIF measurements could be further used to address the issue of scale mismatch (Frankenberg et al., 2018; MacArthur et al., 2014; Rascher et al., 2015).

Therefore, it is necessary to build a network with coordinated field spectral measurements concurrently with EC flux observations. Similar to the EC FLUXNET community (https://fluxnet.fluxdata.org/), several regional or global optical measurements have been established. For example, SpecNet (http://specnet.info) was founded and has been operational since 2003 for the integration of optical sampling with EC flux measurements across flux sites (Gamon et al., 2006, 2010). Although this network has stimulated an international collaboration between remote sensing and flux communities, the field sites are mainly located in North America (NA). Recently, the European remote sensing community has also started to establish its own optical network, EUROSPEC, to conduct long-term ground-based optical measurements at the representative EC towers in the European Union (EU) (Aasen et al., 2019; Cendrero-Mateo et al., 2019; Pacheco-Labrador et al., 2019; Porcar-Castell et al., 2015). EUROSPEC plays a fundamental role in supporting
European satellite missions, such as the Fluorescence Explorer (FLEX). Overall, these networks mainly cover the geographical areas of EU and NA. Recently, the Chinese remote sensing and EC flux communities have also started to conduct ground-based spectral measurements.

In China, a network of collaborating sites and investigators has been founded starting in 2016 to conduct ground-based continuous optical measurements along with EC flux for ecosystem research. The network is referred to as ChinaSpec (http://chinaspec.nju.edu.cn). The goal of ChinaSpec is to promote the integration of optical measurements, especially the novel SIF measurements, with EC flux measurements for better understanding the controls of climate and environmental factors on the biosphere-atmosphere fluxes of carbon and water vapor in China. A primary goal of ChinaSpec is to collect the long-term continuous SIF measurements in the field over different vegetation types across the country, and to fill the gap between EC flux and satellite SIF observations.

The overall aim of this paper is to present an introduction on the current status and challenges of the ChinaSpec network. A primary ChinaSpec focus is on the ground-based SIF measurements at the flux sites within ChinaFLUX network (http://www.chinaflux.org/) (Yu et al., 2006, 2010), where the EC measurements have existed for >10 years. Specifically, we emphasize on the current status of ChinaSpec and illustrate the usefulness of such network data sets for future research directions.

2. Instrumentation and Data Collection

2.1. Instrument Description

Many SIF systems have been recently developed for ground-based observations (see reviews in Aasen et al. (2019)). To have a high degree of consistency in instrumentation across the ChinaSpec network, two similar automated SIF systems are mainly used in ChinaSpec: Fluospec2 (Yang et al., 2018b) and SIFSpec (Du et al., 2019) (Figure 1a and Table 1) except for one site with FLOX. Though the controlling software is different in these systems, the core spectrometer, light path-switching approach, and spectrum sampling strategy are the same. Both systems use purpose-built microcomputers to record data. The spectrometer used for SIF observation is QEPro or QE65Pro (OceanOptics, Inc., Dunedin, FL, USA). QEPro is an improved version of QE65Pro with high saturation threshold with digital number (DN) up to 200,000 (Max. DN of 65535 for QE65Pro). These two types of spectrometer are similar in spectral resolution and SNR, and both are suitable for SIF measurements. As spectrometer with only one input optical path, a “Y-shaped” splitter fiber-optic separating one optical path into two paths, and a fiber-optic shutter TTL or two inline TTL shutters (OceanOptics, Inc., Dunedin, FL, USA) switching between two input fibers are used to enable the spectrometers to nearly simultaneously measure both solar irradiance and canopy radiance (Figure 1).

Figure 1. Schematic layout of the hyperspectral instrument used in ChinaSpec. (a) Fluospec2 or SIFSpec system. (b) SIFprism system. (c) A drawing of field configurations for ground-based spectral measurements with upwelling bare fiber or cosine corrector CC-3.
| ID | Site name | Site ID | Location | Coordinate | Height (m) | Footprint (m²) | PFT | Instrument | Spectral range and resolution | Time period |
|----|-----------|--------|----------|------------|------------|---------------|-----|------------|-------------------------------|-------------|
| 1  | Xiaotangshan | XTS    | Beijing  | 40.1786N116.4432E | 4/2.6      | 2.47/1.04     | Cropland (winter wheat and maize rotation) | SIFSpect with QE65Pro | 650–800 nm, 0.3 nm | 06/2017-   |
| 2  | Huailai    | HL     | Hebei    | 40.3489N115.7882E | 2.5        | 0.95          | Cropland (maize) | SIFSpect with QE65Pro | 650–800 nm, 0.3 nm | 0-/2017-   |
| 3  | Daman      | DM     | Gansu    | 38.8555N100.3722E | 23         | 81.68         | Cropland (maize) | SIFSpect with QE65Pro | 650–800 nm, 0.3 nm | 05/2017-   |
| 4  | Shangqiu   | SHQ    | Henan    | 34.5870N115.5753E | 12/10      | 22.23/15.44   | Cropland (winter wheat and maize rotation) | SIFSpect with QE65Pro | 650–780 nm, 0.15 nm | 07/2017-   |
| 5  | Jurong     | JR     | Jiangsu  | 31.8068N119.2173E | 8          | 9.88          | Cropland (rice and winter wheat) | SIFSpect with QE65Pro | 650–780 nm, 0.15 nm | 07/2016-   |
| 6  | QianyanZhou | QYZ    | Jiangxi  | 26.7478N115.0581E | 15         | 34.74         | Evergreen coniferous forest | FLOX with QEPro | 650–800 nm, 0.3 nm | 03-12/2017 |
| 7  | Xilinhot   | XLHT   | Inner Mongolia | 43.5513N116.6710E | 2.5       | 0.95          | Grassland | SIFSpect with QE65Pro | 650–800 nm, 0.3 nm | 06/2017-   |
| 8  | Dinghushan | DHS    | Guangdong | 23.1733N112.5361E | 18         | 50.03         | Evergreen broadleaf forest | SIFSpect with QEPro | 650–800 nm, 0.3 nm | 08/2017-   |
| 9  | Hongyuan   | HY     | Sichuan  | 32.8404N102.5775E | 3          | 1.39          | Alpine meadow | SIFSpect with QEPro | 650–800 nm, 0.3 nm | 04-07/2018 |
| 10 | A’Rou      | AR     | Qinghai  | 38.0444N100.4647E | 25         | 96.50         | Alpine meadow | SIFSpect with QE65Pro | 650–800 nm, 0.3 nm | 04/2019-   |
| 11 | Yunxiao    | YX     | Fujian   | 23.9240N117.4147E | 7          | 7.57          | Mangrove | SIFSpect with QE65Pro | 650–800 nm, 0.3 nm | 07/2017-   |
| 12 | Beibei     | BB     | Chongqing | 29.7627N106.3191E, | 10         | 15.44         | Managed Forest (Osmanthus) | FLOX with QEPro | 650–800 nm, 0.3 nm | 07/2017-   |
| 13 | Zhenglanqi | ZLQ    | Inner Mongolia | 42.9656N115.9589E | 2          | 0.62          | Sparse forest grassland | FluoSpec2 with QEPro | 730–800 nm, 0.15 nm | 01/2018-   |
| 14 | Xiaolangdi | XLD    | Henan    | 35.029N112.469E | 20         | 61.76         | Deciduous broadleaf forest (oriental oak) | SIFSpect with QEPro | 650–800 nm, 0.3 nm | 06/2019-   |
| 15 | Jiuduansha-S | JDS-S | Shanghai | 31.1881N121.9489E | 2          | 0.62          | Coastal wetland (Spartina) | SIFSpect with QEPro | 650–800 nm, 0.3 nm | 3/2019-    |
| 16 | Panjin     | PJ     | Liaoning | 40.8004N, 122.0277E | 2.5       | 0.95          | Cropland (rice) | FluoSpec2 with QEPro | 650–800 nm, 0.3 nm | 5/2020-    |

*Height above the canopy. Spectral resolution of spectrometer (FWHM). HR2000+ is used to reflectance measurements within the range of 400–1,000 nm.
One of the two input fibers is fixed upward for measuring the downwelling solar radiation equipped with cosine corrector CC-3 (OceanOptics, Inc., Dunedin, FL, USA), and another one is a bare fiber (OceanOptics, Inc., Dunedin, FL, USA) to collect the upwelling canopy radiation (Figure 1) with field of view (FOV) of 25°. The spectral range of these system is 650–800 nm (FWHM of ~0.3 nm) or 730–780 nm (FWHM of ~0.15 nm). Far-red SIF (760 nm) is measured at all the sites while red SIF (687) is only measured at some of these sites (Table 1). Recently, Zhang et al. (2019) compared the performances of these SIF systems and found that the differences in the diurnal patterns of SIF are <10% (3.7 ± 2.9% for a clear day) for the widely used SIF systems of Fluospec2 and SIFSpec in ChinaSpec when measuring the same vegetation canopy. At several sites in ChinaSpec, another spectrometer HR2000+ (OceanOptics, Inc., Dunedin, FL, USA) with spectral range from 300 to 1,000 nm (FWHM of ~3 nm) is used to measure hyperspectral reflectance (see Table 1 for the sites). For these SIF systems, a temperature-controlled waterproof enclosure with external thermoelectric cooler is generally used for housing the spectrometer and keeping the environment temperature constant at around 25 °C. This could ensure that the spectrometers work at a stable ambient temperature and stabilize the noise levels and radiometric response (Aasen et al., 2019).

### 2.2. Field Instrumentation Setups

Ground-based SIF measurement is complicated, and needs reliable field setups and measurement protocols (Aasen et al., 2019). In order to make reliable and comparable canopy SIF measurements in ChinaSpec, we adopt the recent design of automated SIF systems as in Section 2.1 to allow a consistency in instrumentation across sites. Meanwhile, the same sampling strategy and instrument configurations are used to allow for intercomparison between sites. In the ChinaSpec network, the SIF systems used (Fluospec2, SIFSpec, and FLOX) are all using hemispherical-conical (with conical upwelling sensor) configurations for SIF measurements at all sites (Table 1). These generally use bare fibers with FOV of 25° for upwelling measurements. In ChinaSpec, the view zenith angle of the upwelling sensor is currently installed as nadir or slightly off-nadir (<10°) to constrain the effects of sun-viewer geometry variability. This uniform instrumentation setup could minimize the effects of viewing geometry across sites.

To integrate with EC flux measurements, proper instrumentation setups and protocols are needed to gain reliable and comparable SIF measurements. In ChinaSpec, the SIF systems are typically installed on the top of flux towers or close to flux towers (Figure 2). For tall canopy like forest, the systems are mounted on the platforms of flux tower as high as possible to gain a large FOV, and could cover a large part of canopy to avoid only seeing 1–2 trees. At these sites, we suggest that the bare fiber can point slightly off-nadir to avoid viewing any possible background close to the tower. Since the towers are typically high and large, it is recommended that the fiber optics should point to the south to avoid the influence of the shadow of the tower in other directions. The ends of fiber optics where the solar and canopy radiation penetrate into the system, are better far off the platform to avoid interfering the optical signal into the fiber. Therefore, the fiber optics should be extended along with horizontal-setup (or equivalent devices, such as sectional bar) about 2–4 m away from the edge of the platform. We recommend that the systems are installed at least 10 m above the canopy (>4 m in diameter of footprint) to view more trees. For short canopy (e.g., crop and grassland), a simple tripod with bracket can be used to hold the fiber optics steady (e.g., XLHT in Figure 2). The location installed should be within the footprint of the EC flux measurements. The measurement height is suggested at least 2 m above the canopy (>1 m in diameter of footprint). Considering the homogeneity in these ecosystems at the EC sites, it is assumed that the footprint of SIF system could represent the canopy as covered by EC flux footprint.

When installing the SIF systems in the field, the downwelling fiber optics with CC-3 are vertically (upward) mounted on a horizontal metal plate installation device fixed on the pipe. The upwelling bare fibers are mounted on a horizontal metal plate which is fixed nadir or slightly off-nadir at the end of the pipe. It is suggested that the irradiance (downwelling) and radiance (upwelling) channels are installed at the same height. The fiber optics should be also tightly fixed to avoid any disturbances or movements. Furthermore, the cosine diffuser (CC-3) is suggested to keep dust, insects, and birds away and a periodical check is recommended for possible degradation (Aasen et al., 2019). Additionally, a Stevenson screen or similar instrument shelter could be used to cover the enclosure of the systems against precipitation and direct heat radiation (Figure 2).
To maximize the footprint matching with EC measurements, bi-hemispherical measurements with a fore optic diffuser are also conducted to capture both downwelling and upwelling irradiance since 2019 at one site of Jurong. A newly developed system called SIFprism (Zhang et al., 2019), which is similar to Rotaprism (Joseph Berry, personal communication), was installed to conduct bi-hemispherical measurements (Figure 1b and Table 1). A rotary prism, which is rotated by an electric motor inside a sealed and adiactinic box, is used to collect both downwelling and upwelling irradiance sequentially. SIFprism collects the spectrum with less integration time than that of Fluespec2 and SIFSpec (Zhang et al., 2019), which allows for fast collection of upwelling and downwelling irradiance. With bi-hemispherical configuration (Figure 1c), SIFprism can capture a larger field of the canopy even with lower height than hemispherical-conical measurements (Figure 1c). This is more relevant to the footprint of EC flux measurements (Gu et al., 2018). SIFprism was tested in parallel with Fluospec2 in 2019 at a paddy-rice site of Jurong (Table 1). This comparison will provide a chance to investigate the pros and cons of different configurations for ground-based SIF observations, especially in synergy with EC flux measurements.

2.3. Data Collection and Processing

All systems can automatically operate and collect spectral data under various field conditions. Solar irradiance ($E$) and canopy radiance/irradiance ($L$) are sequentially acquired, or a sandwich-method ($E-L-E$), which is helpful for evaluating if changes in illumination suitable for SIF observation during this short period, is used to measure spectral data (Aasen et al., 2019; Cogliati et al., 2015; Zhang et al., 2019). Dark current (DC) is simultaneously recorded after each spectral measurement for DC correction. Integration time (IT) of spectral measurement is automatically optimized to get as high and unsaturated values as possible to improve the SNR ratio.
where $IT_{ini}$ is user-defined initial $IT$; $targetDN$ is set about 60–80% of the saturation DN value of spectrometer; and $maxDN$ is the maximum value of a spectrum acquired with $IT_{ini}$ at the beginning of each measurement.

Spectral data are recorded as DN values, which need to be radiometrically calibrated. Premounted laboratory calibration using a tungsten halogen light source (HL-2000-CAL, Ocean Optics, USA) is conducted to calibrate hemispherical sensor (CC-3) and an integrating sphere to calibrate conical sensor (bare fiber) (Aasen et al., 2019; Cogliati et al., 2015; Pacheco-Labrador et al., 2019). In the field, regular cross radiometric calibration is generally performed using a light source (HL-2000-CAL, Ocean Optics Inc., USA) to calibrate CC-3 (up-looking channel), and a well-calibrated spectrometer with a standard reference panel (Spectralon, Labsphere, NH, USA) to calibrate bare fiber (down-looking channel) under a clear-sky day around noon (Cogliati et al., 2015). The conversion of DN to radiance or irradiance can be finally expressed as (taking radiance as an example):

$$
Radiance(\lambda) = \frac{L(\lambda) \times (DN_{obs}(\lambda) - DC_{obs}(\lambda)) \times IT_{cal}}{(DN_{cal}(\lambda) - DC_{cal}(\lambda)) \times IT_{obs}}
$$

where $\lambda$ represents the wavelength, $Radiance(\lambda)$ is measured radiance by spectrometer, and $L(\lambda)$ is the radiance of standard light resource. The subscript $obs$ represents the field observation data recorded by the spectrometer and $cal$ represents the calibration data. Both $DN$ and $DC$ are normalized by the IT used in each measurement to 1 s. Since the temporal stability of the calibrations are essential for long-term field SIF measurements, we recommend a regular in-field calibration (around every 3 months) in addition to a radiometric calibration in the lab before installation. At least one calibration should be conducted before the growing season.

Data quality control is operated before SIF retrieval following the protocol presented by (Cogliati et al., 2015) to exclude abnormal data caused by changing illumination conditions and other unpredictable reasons. At the present, we propose that the approaches used for SIF retrieval are Spectral Fitting Methods (SFM, Meroni & Colombo, 2006) and three-band Fraunhofer Line Depth (3FLD, Maier et al., 2003) in ChinaSpec. The 3FLD algorithm stems from the FLD principle, which requires spectral measurements at two bands, one inside and one outside a Fraunhofer line (Theisen, 2002). The FLD method assumes that reflectance and SIF maintain constant at the two bands. However, in fact, the two variables are far from being constant, especially for reflectance at 687 nm and SIF at 760 nm. Therefore, the FLD assumption has been questioned by several authors (Alonso et al., 2008; Gómez-Chova et al., 2006; Meroni & Colombo, 2006; Meroni et al., 2009; Moya et al., 2006). The 3FLD method is based on an advanced assumption compared with FLD, namely reflectance and SIF vary linearly in the spectral domain considered, which overcomes the limitations given by FLD assumptions (Cendrero-Mateo et al., 2019; Meroni et al., 2009). The 3FLD-based SIF at 760 nm can be derived as

$$
SIF_{760} = \frac{(E_{left} \times w_{left} + E_{right} \times w_{right}) \times L_{760} - (E_{left} \times w_{left} + E_{right} \times w_{right}) \times E_{760}}{(E_{left} \times w_{left} + E_{right} \times w_{right}) - E_{760}}
$$

where $w_{left}$ and $w_{right}$ denote the weight of the band, which is proportion to the length between the right/left band and the inner band. The subscripts “left” and “right” represent the band at the left and the right sides of the absorption domain.

Differently, SFM employs two mathematical functions to describe $r$ and SIF, which relaxes the assumptions of some FLD-based methods (Cendrero-Mateo et al., 2019; Meroni et al., 2009). Here, we use two linear functions to determine $r$ and SIF in a restricted spectral domain around the $O_2$ absorption bands. Therefore, $L\lambda$ can be expressed as

$$
L(\lambda) = \frac{r_{mod}(\lambda)E(\lambda)}{\pi} + SIF_{mod}(\lambda) + \kappa(\lambda)
$$
where $r_{\text{mod}}(\lambda)$ and $SIF_{\text{mod}}(\lambda)$ are linear functions describing $r$ and SIF, respectively. $\epsilon(\lambda)$ represents the error between the simulated and observed $L(\lambda)$. With a large number of spectrum observations with high resolution <0.3 nm pledged by spectrometers and continuous measurements, Equation 4 can been over-determined. Least square method is applied to solve the parameters (i.e., the respective gain and offset of $r_{\text{mod}}(\lambda)$ and $SIF_{\text{mod}}(\lambda)$) in the two functions. Then, SIF at 760 nm can been determined as $SIF_{\text{mod}}(760)$.

3. Current Status of ChinaSpec

3.1. Current SIF Field Sites in ChinaSpec

Sixteen sites have registered with ChinaSpec network, including six cropland, four grassland, four forest, and two wetland sites across from subtropical to cold temperate zones and also covered from humid to semiarid regions (Figure 3 and Table 1). Locations of these sites are shown in Figure 3, and detailed information of each site can be found in Table 1. The spectral range of all SIF system covers the range for far-red SIF (760 nm) and some of them cover both red SIF (687 nm) and far-red SIF (Table 1). Details on climate, soil, and vegetation can be found in the ChinaSpec website. Here, we briefly present some basic information for these sites.

Figure 3. Summary of current field SIF sites in the network of ChinaSpec. Site names are defined in Table 1. The subplots are the vegetation type at each site (blue star). The base map is land cover map based on the MODIS Land Cover Type product (MCD12C1) at 500 m. SIF, solar-induced fluorescence.
The cropland sites are distributed on the Zhangye oasis in northwest China (DM, 2011), the North China Plain (SQ), the Yangtze Plain (JR), the Northeast Plain (PJ), and North China Plain (HL and XTS) that monitor maize, rice, and winter wheat (2013). Among these cropland sites, HL, PJ, and DM have only one growing season in a year with a maize or rice crop in the summer, while the other three have a rotation of two crops every year. Among the four forest sites, DHS is an evergreen broadleaf forest and QYZ is an evergreen needle forest. Both sites are located in a subtropical area with abundant rainfall and solar radiation. The BB site consists of managed pure sweet Osmanthus (Yang et al., 2009). The XLD site is located in Jiyuan county, Henan province (410 m asl), and is dominated by Chinese cork oak. The area of the 32-years mixed plantation is ~7,210 ha, with a stand density of 1,905 trees ha⁻¹ (Tong et al., 2019).

The four grassland sites include two alpine meadow (HY and AR), one semiarid grassland (XLHT) and one sparse forest grassland (ZLQ). HY is located in an alpine meadow of the eastern Qinghai-Tibetan Plateau (3,500 m asl) (Quan et al., 2019). The XLHT site (1,250 m asl) is located in the Xilin River Basin, Inner Mongolia. This site has been fenced since 1999 and no grazing or other disturbance occurred thereafter (Zhang et al., 2016). Vegetation in this site is a typical steppe and dominated by perennial grasses. The ZLQ site is Elm Sparse Forest Grassland Ecosystem (1,300 m asl), and is located in the northeast of Otingdag Sandland, Inner Mongolia. The typical vegetation is natural sparse elm and grass (Wang et al., 2019). The AR site is located in the Heihe River Basin (3,000 m asl) with a typical temperate continental climate. The dominant vegetation is alpine meadow. In addition, two wetland sites (JDS-S and YX) are also included in ChinaSpec, which are very unique ecosystems for SIF measurements. JDS-S is a coastal salt marsh site located in the Jiuduansha Shoal of the Yangtze estuary to the East China Sea. It is dominated by saltmarsh cordgrass with 2-m height during the growing season. The YX site is located in the area of the Zhanjiang estuary to the South China Sea. It is a subtropical intertidal wetland vegetated with mangrove forests. The biggest challenge of observation for these two sites is the protection of the observation systems from humid and salty air to avoid corrosion of metal components. At present, the spectrometers are kept in a sealed box and routine maintenances have to be done in the field to protect the systems from humid and salty air. To make stable measurements in such environment, it is necessary to seal the spectrometers and electronic components in a waterproof box to avoid the exchange of air between inside and outside of the box. The fibers also need to be covered by stainless tube. Meanwhile, collaborations with the manufacturer are needed to develop new tools/instruments in the future.

3.2. Data Policy

ChinaSpec collaborates with the network of ChinaFLUX and other communities, and shares ground-based spectral and SIF data acquired from the sites of the network. The intent of sharing this data set is to provide ground-based continuous SIF and reflectance measurements across multiple ecosystems in China to the broad community of scientists. The website (Figure 4, http://chinaspec.nju.edu.cn) is the platform for releasing the related information and sharing data sets of the sites registered in the ChinaSpec network since 2016 when the first data set was collected. A few sites could also share EC flux data, but most sites are shared through ChinaFLUX network (Yu et al., 2006, 2010) or National Tibetan Plateau Environment Data Center (2018; 2020).

The data usage polices for ChinaSpec is similar to that for FLUXNET data set (especially the FLUXNET2015 data set). The use of spectral data in ChinaSpec will follow “the fair use policy” (https://fluxnet.fluxdata.org/). In other words, the ChinaSpec data sets are open and freely available for scientific and educational purposes by any registered user after acceptance of a proposal submitted to the steering committee. That is, data users submit a proposal on the intended use of the data before they download the data; this intended-use statement will be emailed to the data producer(s) of the sites. This policy means that “(1) data producers are informed of who uses the data and for what purpose and (2) that proper acknowledgment and citations are given to all data used in a peer-reviewed publication, via the following protocols: providing a coauthorship to the site PIs or at least a citation of a publication for each site.” It is requested that every publication specifies each site used with the data-years used and brief acknowledgment for funding (if provided by the PI) in the text. We recommended the users to contact the site PIs before publishing to avoid potential misuse or misinterpretation of the data. In particular, if a work is based on the SIF data from only
a few sites, it is strongly recommended to contact the site PI about coauthorship or proper acknowledgment for their contribution.

The distribution of the data for each site will be shared after the first publication or 2–3 years later after data collections. At this stage, the data set consists of metadata of each site, vegetation indices (e.g., NDVI, EVI, and PRI depending on sites), retrieved far-red SIF (760 nm) with two methods (3FLD and SFM) after data quality control. The temporal scale of the data set is half hourly, which is processed from high-frequency raw data (∼1 min for spectral data). Error/uncertainty estimations on retrieved SIF will also be included in the data set in the future. Since the year of 2019, we have distributed the spectral data set including reflectance and SIF for 1–2 years from six sites. The rest of the spectral data set will be regularly updated with data from new site years.

4. The Usefulness of Networking SIF Observations

Field spectral and SIF measurements collected in ChinaSpec are not only essential for the integration of optical remote sensing and EC flux data across space and time, but also for investigating the dynamics of canopy SIF and its link to GPP across multiple spatial and temporal scales. These continuous ground-based measurements of SIF will also benefit validation of fluorescence models and satellite SIF retrievals.

4.1. Characteristics of Canopy SIF and its Link to GPP Across Multiple Ecosystems

There are growing interests on how SIF changes with radiations and GPP across different ecosystems. Among the 16 sites in the ChinaSpec network, eight sites were selected as an example to investigate the relationships of SIF with photosynthetically active radiation (PAR) and GPP at diurnal scale (Figure 5). SIF
generally varied with both PAR and GPP across these sites at diurnal scale, which indicates that SIF and GPP were both driven by PAR under the clear-sky conditions. For the broadleaf forest, SIF mostly varied with GPP though SIF and GPP obviously decreased in the afternoon even PAR level was higher than that in the morning. At seasonal scale, the results from four sites also show that the seasonal dynamics of SIF and GPP were generally consistent during the growing season, while normalized difference vegetation index (NDVI) was generally stable (Figure B1 in Appendix). In particular, SIF captured the increase of GPP at the start of the growing season (DM) and decreased at the end of the growing season (SQ), when PAR remained at a high level. On the other hand, NDVI increased with GPP and SIF at the beginning of the growing season, but maintained high values after SIF and GPP decreased after day 240. It then started to decline until SIF and GPP approached zero, possibly contributing to the fact that plant LAI remained stable until the very end of the growing season. These results demonstrate the potential of continuous SIF measurements for understanding diurnal and seasonal canopy SIF variations across different vegetation types, and also highlight the importance of networking on SIF measurements.

Different relationships between SIF and GPP have been reported in different ecosystems at the seasonal scale (e.g., Damm et al., 2015; Li et al., 2020; Nichol et al., 2019; Wieneke et al., 2018; Yang et al., 2015, 2018a). At the diurnal scale, however, it is not clear how this relationship varies across different vegetation types. With the observations from ChinaSpec, we further analyzed the relationship between SIF and GPP at diurnal scale across different vegetation types. Figure 6 shows that there are also significant diverse
slopes of relationships between SIF and GPP but comparable relationships between SIF and PAR at diurnal scale across different vegetation types. The inconsistent relationships between SIF and GPP across different ecosystems may be attributed to different canopy structures. The regression slopes of SIF with PAR from different sites have less variations. Additionally, SIF is also affected by escaping probability due to multiple scattering in far-red region. This indicates the necessity to expand SIF observations covering a variety of ecosystems to investigate and improve the ability of SIF for monitoring photosynthesis. With the growing SIF observations in ChinaSpec over multiple ecosystems, further synthesis work could be done for better understanding the link between SIF and GPP at different temporal and spatial scales by combining with satellite and drone-based SIF measurements.

4.2. Validation of Fluorescence Models with Ground-Based SIF Observations

Development and validation of fluorescence models are reliant on observational data. Here, we refer to examples of the utility of ChinaSpec data for validating these models. During recent years, several fluorescence models have been developed for the purpose of canopy radiative transfer of SIF. A widely used model is the Soil-Canopy Observation Photosynthesis and Energy fluxes (SCOPE), which is typically used to simulate SIF at the site level (Van der Tol et al., 2009). To conduct global SIF simulations, several terrestrial biosphere models have been also coupled with fluorescence model (e.g., Lee et al., 2015; Qiu et al., 2019). For example, an efficient scheme accounting for the canopy scattering of SIF has been developed and implemented into the Boreal Ecosystem Productivity Simulator (BEPS-SIF) (Qiu et al., 2019).

We use continuous ground-based SIF observations from three sites (JR-rice, SQ-maize, and XLHT-grassland) in ChinaSpec to compare with SIF simulations by SCOPE and BEPS-SIF model (see details in the Appendix A for model setup). Figure 7 shows the scatter plots between observed SIF and simulated SIF from SCOPE and BEPS-SIF at both hourly and daily scales for one year’s data. For all the three sites, SIF simulations from two models are significantly correlated with ground-based observations, though the relationship between BEPS-SIF simulation and observation is slightly scattered. This result demonstrates that these two models are effective in simulating SIF for different vegetation types at both hourly and daily scales. The equally good performance of BEPS-SIF with SCOPE also illustrates its effectiveness for regional and global SIF simulations. This comparison between observations and simulations demonstrates the potential of continuous ground-based SIF observations to validate fluorescence models at multiple temporal scales.

Ground-based SIF measurements could also feature in the development of new model components. For example, SIF measurements at a subalpine forest in Colorado are used to account for sustained NPQ in the SIF model, which largely improves the seasonal variations of SIF simulations for evergreen conifer forest (Raczka et al., 2018). With more data available in ChinaSpec, the synergy of ground-based SIF data and

Figure 6. Diurnal relationship between SIF and GPP across multiple sites from 1-day measurements under clear-sky conditions. Site names are defined in Table 1. SIF, solar-induced fluorescence; GPP, gross primary productivity.
fluorescence models will help to improve mechanistic understanding of photosynthetic activity and SIF at different temporal scales (i.e., diurnal to seasonal), which is important for constraining large-scale simulations of terrestrial carbon cycles from satellite SIF data.

4.3. Validation of Satellite SIF Observations at the Site Scale

Validation against ground-based SIF observations is necessary for satellite SIF products. Continuous ground-based SIF measurements in ChinaSpec over multiple vegetation types provide opportunities for direct comparison and evaluation of satellite products. In particular, the fine spatial resolution of OCO-2 and TROPOMI SIF have facilitated the comparison with ground-based measurements, though it is still challenging due to spatial mismatch. Here, five relatively homogeneous sites in ChinaSpec, including four croplands (JR, HL, DM, and SQ) and one grassland (XLHT), are chosen to compare with SIF retrievals from TROPOMI and OCO-2. They have overlap with the swath from both OCO-2 and TROPOMI. Land cover around each site is shown in Figure 8, which also shows the available observations from OCO-2 from 2014 to 2018. To compare with ground-based observations, both TROPOMI and OCO-2 SIF observations were averaged from all available data within a 50-km buffer around each site (red circle in Figure 8).

Figure 9 displays seasonal variations of SIF retrievals from ground-based observations and two satellite products. Note that ground-based SIF values of each day are averaged at the overpass local time of ~1:30 p.m. of OCO-2 and TROPOMI. As for OCO-2 SIF with a coarse temporal resolution (16 days), multiyear (2014–2018) mean data are used as the climatic mean SIF. Overall, both OCO-2 and TROPOMI SIF show seasonal consistency with ground-based SIF measurements, capturing the timing and amplitude of seasonal
features over a variety of vegetation types. This is further confirmed by the correlation between TROPOMI and ground-based SIF (Figure 9). Significant relationships (p < 0.001) were observed for all sites except for HL during the growing season of wheat. The correlation ($R^2$) varied across different sites, ranging from the minimal of 0.34 at XLHT to the maximal of 0.75 at JR. Considering that there are still mismatch of the footprint between satellite and ground-based measurements, such direct comparison demonstrates the potential of ground-based SIF measurements in ChinaSpec for validation of satellite SIF data.

However, this rough and direct comparison also exemplifies the challenges for the validation of different satellite SIF observations with ground-based SIF measurements. Lesser agreement (i.e., HL and XLHT) might be due to the mismatch of footprints between satellite SIF and ground-based measurements of SIF. It is important to filter out uniform vegetation, even for mostly homogeneous areas. It would also be worthwhile to explore the synergy of UAV-based and ground-based SIF systems to validate/evaluate satellite data across sensors over multiple sites in the network. The advances in UAV-based SIF systems (Bendig et al., 2018; MacArthur et al., 2014) offer unique opportunities for upscaling ground-based SIF measurements to satellite level observations.

5. Outlook and Challenges

5.1. Implications for Linking SIF With EC Flux Measurements

Recent advances in remote sensing of SIF has stimulated the research in monitoring terrestrial photosynthesis at large scale. However, a direct comparison is difficult between satellite and ground measurements due to the differences in sampling scales in space and time. An opportunity to investigate the ability of SIF to monitor biosphere-atmosphere carbon exchange benefits from the development of high-resolution spectroscopy technique (Porcar-Castell et al., 2015). In this context, the development of the ChinaSpec network within the framework in ChinaFLUX network (Yu et al., 2006, 2010) will help bridge the integration of EC flux measurements and remote sensing.

A primary goal of ChinaSpec is to improve the understanding of links between SIF and GPP across different vegetation types and scales. Understanding the linkage of SIF-GPP is fundamental to monitoring global
Figure 9. Comparison of seasonal variations of ground-based and satellite (TROPOMI and OCO-2) SIF observations at five SIF sites. The correlation coefficient ($R^2$) in each subplot is between TROPOMI and ground-based SIF measurements. Site names are identified in Table 1. SIF, solar-induced fluorescence.
photosynthesis from satellite SIF data. Over the last decade, most efforts to investigate the relationship between SIF and GPP derive from the satellite SIF data (e.g., Guanter et al., 2014; Sun et al., 2018). Ground-based SIF measurements have also recently emerged as a useful tool to study the temporal and spatial variability of SIF and its link to GPP at the site scale (e.g., Damm et al., 2015; Li et al., 2020; Nichol et al., 2019; Yang et al., 2015). Strong linkages between SIF and GPP have been found, but the form of the relationships varies (nonlinear or linear) depending on vegetation types and spatiotemporal scales (Mohammed et al., 2019). However, such analyses mostly focus on single site in different ecosystems. Thus, establishing a network of ground-based SIF observations is important to fully characterize the relationship between SIF and GPP across different terrestrial ecosystems and to understand photosynthetic activities of terrestrial ecosystems. A synergy of SIF and EC flux measurements in a network such as ChinaSpec could benefit the analysis of SIF and flux data for a cross-site synthesis because relative standardized instrumentations and field setups (see Sections 2.1 and 2.2) are employed in ChinaSpec. As shown in Figure 6, a cross-site synthesis sheds light on the controls of SIF-GPP linkages at diurnal scale in different vegetation types. With continuation of SIF observations from different sites in ChinaSpec, it is possible to study not only the short-term (diurnal and seasonal) but also interannual variability of SIF and its linkage to GPP. Importantly, the temporal match between ground-based SIF measurements and flux data benefits the modeling and validation of the linkages of SIF and GPP from the satellite data. By integrating SIF and EC measurements over space and time, we could also assess ecosystem function to climate extreme events in China. Extreme climatic events (e.g., drought, heat wave) have significant impacts on the function of terrestrial ecosystem and thus carbon cycle. In China, drought and heat wave has become more frequent during the past decades, especially since the late 1990s (Yu & Zhai, 2020). Questions pertinent to ChinaSpec include when and where SIF observations can provide a better monitoring for stress detection than the widely used remote-sensed data. It is also interesting to investigate whether useful information of functional response of ecosystem to extreme climatic events can be derived from canopy SIF measurements at multiple sites. In this regard, the continuous measurements of SIF stations in ChinaSpec could provide unique opportunity to study how sensitive are different ecosystems to the emerging compound drought and heat event.

The regional network of ChinaSpec could also contribute to the validation of satellite SIF products, and help to resolve issues that derive estimates of large-scale GPP directly from satellite data. Currently, there are a number of spaceborne sensors with high-spectral resolution which enable the global retrievals of SIF at regional and global scales, including GOME-2, OCO-2, and TROPOMI (Joiner et al., 2013; Köhler et al., 2018; Sun et al., 2018). Airborne high-resolution imaging sensors are also available for retrievals of SIF at landscape scale (e.g., HyPlant and CFIS) (Frankenberg et al., 2018; Rascher et al., 2015). Therefore, it is urgent to develop ground-based measurements of SIF in parallel to validate the accuracy of SIF retrievals from satellite or airborne platforms. Most current satellite SIF is measured at a certain time of a day (e.g., GOME-2 local overpass time is around 9:30 a.m.). Therefore, the validation of satellite-based SIF can provide robust information on regional to global-scale plant photosynthetic function and provide important information for ecosystem photosynthesis monitoring from satellite remote sensing. In addition, the information of red SIF retrieval has been investigated from ground-based SIF measurement but is not available for most current satellite SIF observations. Since red SIF contains more information of the photosystem II, the knowledge obtained from ground-based measurements will help the use of red SIF from satellite mission (e.g., FLEX) to achieve a combination of red SIF and far-red SIF, which is important to understanding the mechanisms of SIF emission by vegetation.

### 5.2. Standardization of Instrumentation and Data Process

The main challenge to the establishment of an optical measurement network, as in any other network, is the standardization and comparability of measurements across sites. The standardization is especially important and challenging for the ground-based SIF measurements across different vegetation types since optical measurements are more complicated. Lack of standardization of optical sensors and sampling methods will make it difficult to directly compare measurements across sites (Gamon, 2010; Forcar-Castell et al., 2015). Continuous automatic canopy SIF observation in the field is not as straightforward as are EC flux measurements. During the last decade, a number of SIF instruments have been developed for ground-based measurements. However, the standardization of SIF observations systems is still in its early stage compared to EC flux instruments. In the ChinaSpec network, we propose the use of the relatively
uniform instrumentation (at least the same sensor) to produce comparable spectral data. Though different SIF systems are used at different sites, the custom designed spectrometers, light path, and spectrum sampling methods are very similar for ground-based continuous spectral measurements (see Section 2.1). This could reduce the uncertainties in making cross-site comparisons. However, there are still discrepancies in the spectral range and resolution among the SIF systems at different sites. In the future, we suggest a more standardized systems with a spectral range of 650–800 nm to be used to improve data quality, and benefit the comparison of SIF data across sites. Furthermore, we suggest a complementary VNIR spectrometer (∼400–1,000 nm) in these systems to collect broadband reflectance for deriving VIs.

Field setups and protocols are also critical for ground-based optical measurements, especially for hyperspectral measurements needed to retrieve SIF. Due to the very dynamic nature of SIF, it needs particular and careful consideration in the measurement setups and protocols. Retrieving SIF at the canopy level in the field requires synchronously measured incoming and outgoing solar irradiance. In general, incoming solar and outgoing canopy radiation should be acquired as simultaneously as possible using the same sensor to avoid spectral shifting from two sensors. Several instrument configurations can be applied to ground-based SIF measurements to collect incoming and outgoing solar radiation: hemispherical-conical and bi-hemispherical configurations (e.g., Gu et al., 2019; Porcar-Castell et al., 2015; Yang et al., 2015). At the current stage of ChinaSpec, we utilized the hemispherical-conical configurations with a nadir view at a single fixed point for continuous measurements at all the sites. We suggest in ChinaSpec that solar irradiance measurements use a cosine diffuser for continuous observations. For canopy radiance, a conical foreoptic (bare fiber) is used to measure upwelling radiance from canopy.

The last important aspect in a network is the standardization of data postprocess and SIF retrieval. Reliable retrievals of SIF need careful quality checks of the spectral data before analysis. This is particular important for the automated field SIF systems measurements under diverse environmental conditions. Though data collection and storage are conducted in different ways in ChinaSpec, the spectral information, including raw DN, IT, and DC, are all recorded for postprocessing. The same data processing and analysis techniques are also needed to better standardize the SIF measurements across sites. At the current stage of ChinaSpec, we adopt the data postprocess chain introduced by Cogliati et al. (2015). As mentioned in Section 2.3, the raw data should be corrected (dark current), calibrated (radiometric and wavelength calibration), and nonlinearity corrected, as well as data quality check following a standard procedure for reflectance calculation and SIF retrievals. This is necessary for processing such large amounts of spectra from unattended automated systems to exclude low-quality data due to illumination changes (cloud overpass), high solar zenith angle, and instrument saturation. As for the methods of SIF retrieval, we propose the use of SFM as the main retrieval algorithms with 3FLD as a backup in the current stage of ChinaSpec. The SFM approach is one of the most reliable SIF retrieval algorithms for ground-based SIF measurements (Cendrero-Mateo et al., 2019). Thus, we suggest that the output data for sharing at least consists of solar and canopy radiation, PAR, reflectance, and SIF retrievals using 3FLD or SFM in ChinaSpec.

5.3. Ongoing Challenges and Future Prospects
5.3.1. Issues in Measurement Protocols at EC Sites

The SIF community still lacks a consensus on the standardization of SIF measurement protocols. Though we suggest the use of more consistent instruments and field setups in ChinaSpec, independent PIs may still adopt different solutions for SIF measurements without following a set of general guidelines. There are still some open questions that link to standardization of SIF instrumentation and protocols. Of particular concern is the radiometric and spectral calibration of SIF systems. This is a new challenge to calibrating the automated SIF sensors on a continuous basis at the flux sites. Since SIF retrievals need measurements of absolute solar irradiance and vegetation radiance, the absolute radiometric calibration becomes especially critical to derive reliable and reproducible SIF retrievals. Due to its continuous measurements over months to years, a regular onsite calibration is definitely needed for the sensors to avoid drift over time. We find that some of the SIF instruments in ChinaSpec were rarely calibrated over a year even though we suggest an onsite calibration at approximately every 3 months. In addition, wavelength calibration of spectrometers is also important to ensure that SIF retrievals are using the correct wavelength regions. Spectrometers are initially calibrated by the manufacture and should be periodically recalibrated to correct bias from true variations by
sensing them back to the suppliers. We suggest that the QEPro used in the SIF instruments is recalibrated after 1 year of purchase by the manufacture. This regular recalibration was rarely done in ChinaSpec. Thus, the stability of such sensors over time in the field needs further investigation. We recommend routinely both spectral and radiometric calibration of the instruments at least once per year at the beginning of the growing season. Apparently, there is an urgent need for more close collaboration between SIF scientists and industry to foster the technological improvements.

There is also a need to develop more stable SIF retrieval methods and data quality control standards. The retrieval methods used in ChinaSpec, SFM and 3FLD, are based on the FLD principle using O$_2$ A and O$_2$ B absorption features which are easily affected by atmospheric scattering, surface pressure, and temperature conditions. The atmospheric effects between the SIF sensors and the observed canopy needs more attention. A few studies have suggested the necessity of atmospheric correction on SIF retrievals even though there are only a few meters between canopy and sensor (Aasen et al., 2019; Sabater et al., 2018). Considering that some SIF systems are mounted on flux towers at greater than 10 m above the canopy, we recommend the use of an atmospheric correction routine before SIF retrievals (Liu et al., 2019). Otherwise, an SIF retrieval algorithm based on Fraunhofer line such as singular vector decomposition (SVD) could be used to provide tolerance for atmospheric scattering effects. At the present, however, we still do not have a guaranteed method for SIF retrievals which can be used for all sky conditions. In addition, the retrieval of red SIF at the O$_2$ B band is more challenging, and a systematic assessment of the SIF method is needed to ensure a stable approach for red SIF.

5.3.2. Footprint Match of SIF and EC Fluxes

There is still debate on how to deal with the effect of SIF vs. flux footprint mismatch from a point of view of ground-based measurements. The current continuous SIF measurements can temporally match well with EC flux data. However, the issue of footprint mismatch is critical between SIF and EC flux measurements. It is well known that the EC flux footprints vary with wind direction, atmospheric stability, measurement height, and canopy structure (Baldocchi, 2008). On the contrary, the SIF systems are usually deployed in a fixed direction (a bare fiber with nadir) on top of a flux tower, which generally have a footprint of a few to a tenth of a meter squared. This will obviously result in footprint mismatch with flux observations, and miss the peak contribution area of the flux. At sites with homogenous canopy (e.g., crop, grassland), the spatial representativeness of SIF data may not be a critical issue. In places with heterogeneous vegetation like savanna, however, characterization of the footprint match could be critical for the joint use of SIF and flux data.

This footprint mismatch between optical and flux observations clearly points out the need for better SIF observations or postprocessing to create representative SIF signal of flux footprints. The influence of view-geometry and canopy structure are also needed to account for the interpretation of SIF, especially at diurnal scale. This is due to the distribution of light throughout the canopy (i.e., the classic surface BRDF problem). A few studies have reported the strong angular dependence of SIF emissions on sun-canopy geometry and canopy structure from ground-based measurements (Pinto et al., 2017; Zhang et al., 2020). Thus, new tools/protocols are needed to address these issues. One option is the use of a multiangle SIF system. For example, Zhang et al. (2020) recently presented an automated multiangle SIF system (Multi-Fluo) capable of measuring the angular dependencies in measurements of canopy SIF. The Multi-Fluo system uses QEPro to automatically acquire spectra with different viewing angles of the canopy that cover different areas around a flux tower. Photospec with a narrow FOV could also be used to collect multiangle spectrum (Grossmann et al., 2018). In addition, correction of the directional SIF observation could be done to derive total canopy SIF emission by combining canopy reflectance data (Yang & van der Tol, 2018; Zeng et al., 2019; Zhang et al., 2019).

The other option is to use the bi-hemispherical measurements with a cosine corrector with FOV of 180° (Gu et al., 2019; Zhang et al., 2019). The bi-hemispherical configurations could enlarge the field of view to represent the average condition of the canopy and also reduce the signal from nonvegetation factors. The systems could measure a large area around the flux towers, which make them a valuable solution to address footprint variability. In the future, we recommend conical measurement of radiance for homoge-
neous canopy (e.g., crop and grassland), and hemispherical measurement for heterogeneous canopy (e.g., forest, savanna) in ChinaSpec (Balzarolo et al., 2011; Gu et al., 2019; Porcar-Castell et al., 2015). In addition, cost-affordable UAV-based SIF instruments (e.g., Piccolo, MacArthur et al., 2014) are also unique systems available to quantify the footprint variability, since they have more flexibility and capacity to measure the same canopy from different heights. This will be especially valuable in investigating the different sources of error to upscale from ground-based SIF measurements to satellite pixel level. However, further considerable work is still needed on this subject and our understanding of how to address this scale issue at the flux sites requires more attention.

5.3.3. Toward a Global SIF Network

Through the integration of ground-based SIF and EC observations in a network, we are able to deepen our understanding of the controlling mechanisms of the biosphere-atmosphere carbon exchange. In the next few years, we anticipate a continuing expansion of ChinaSpec to more vegetation types/sites. Two more sites, Naqu site in Tibet (31.64N, 92.01E) and Shihzei in Xinjiang (44.91N, 86.16E), are starting the SIF measurements in 2020. In particular, the Naqu site is located in Northern Tibetan Plateau with an altitude of 4,600 m and a vegetation of typical alpine meadow (Li et al., 2020; Zhu et al., 2020). These sites make ChinaSpec very unique in SIF measurements in the highest landscape. Some future projects have already been discussing for deploying automatic SIF systems over more forest, wetland and alpine meadow sites in ChinaFLUX. As the network is growing with more sites in ChinaSpec and other regional network (Aasen et al., 2019; Parazoo et al., 2019; Yang et al., 2018a), we could expect a global ground-based SIF network similar to the global network of FLUXNET in the near future. Yet, there is still tremendous work needed to accomplish this coordinated goal. The effort could benefit from communication and collaboration between the SIF community and EC flux scientists. A relevant platform for communication among different communities would help to promote the development of such a global SIF network. Apparently, SIF observations alone cannot fully show the advantage of SIF for photosynthesis and carbon cycle research (Gu et al., 2019). Further work should investigate how different approaches in different regional networks can be consolidated/synthesized in a meaningful way to gain the full SIF picture. It can be foreseen that a regional/global joint long-term measurement of SIF and EC flux are very useful for improving our understanding of biosphere-atmosphere interactions. Collaboration from data scientists is also needed for studies that can fully utilize the rich information contained in the large amount of ground-based SIF data that are and will be available.

6. Summary

An automatic spectral observation system has been used to continuously measure ground-based canopy reflectance at several sites in China, especially SIF, which is an efficient approach for monitoring the carbon budget of terrestrial ecosystems. The network of ChinaSpec was established to conduct ground-based SIF measurements using automated instruments across various vegetation types in China. The network currently consists of 16 sites including six cropland sites, four grassland sites, four forest sites, and two wetland sites. Here, we specifically describe the details of instrument configurations, data collection and processing procedures, data sharing, and utilization protocols. Based on data acquired from sites in last 2 years, we show examples how the SIF observations can be used to track vegetation photosynthesis from diurnal to seasonal scale, to validate the fluorescence models and satellite SIF products (e.g., from OCO-2 and TROPOMI). ChinaSpec is dedicated to facilitate integration of spectral and flux measurements for better monitoring and prediction of carbon exchange between the atmosphere and biosphere, and benefits both remote sensing and ecology research communities. Still, there are many challenges in expanding the network and in reaching a standard protocol from data acquisition, processing to utilization. This necessarily requires broader collaborations from interested researchers or groups to advance this research area.

Appendix A: Information on the Model Setups

SCOPE is a vertical (1-D) integrated radiative transfer and energy balance model and has been widely used for simulating both photosynthesis and chlorophyll fluorescence processes (van der Tol et al., 2009). In this model, the canopy is divided into many elementary layers and the leaf angle is treated as 36 leaf azimuth
classes and 13 discrete leaf zenith inclinations. SCOPE can simulate the fluorescence emitted from all the leaves and canopy-leaving fluorescence by considering the reabsorption and scattering processes within the canopy. The latest version of SCOPE (v1.73) is used for the simulation of SIF observed at the top of the canopy. The meteorology forcing data for SCOPE simulations include incoming shortwave and longwave radiation, air temperature, surface atmosphere pressure, atmospheric vapor pressure, and wind speed which are from field measurements at the EC flux sites.

The BEPS model is an enzyme kinetic two-leaf model, which has been used to simulate water and carbon fluxes for different vegetation types at both site and global levels (Chen et al., 1999). An efficient scheme to account for the canopy scattering in an SIF model has been developed and this mechanistic representation of SIF is coupled to the BEPS model. The BEPS model demonstrated the ability to reproduce global patterns of SIF observed by a satellite sensor and to capture the seasonality of SIF reasonably well over different regions (Qiu et al., 2019). The forcing data for BEPS-SIF simulations include relative humidity, wind speed, air temperature, surface atmosphere pressure, incoming solar shortwave flux, and total precipitation. At the three sites, LAI is obtained from the field measurements and used for SIF simulations for the SCOPE and BEPS models (Qiu et al., 2019). The other main input parameters for the SCOPE and BEPS simulations are shown in Tables A1 and A2 which are from field measurements.

### Table A1
Main Input Parameters of Three Sites for the SCOPE Simulations

| Parameter | Description | Unit | Shangqiu | Xilinhot | Jurong |
|-----------|-------------|------|----------|----------|--------|
| C_{ab}    | Leaf chlorophyll a + b content | μg/cm² | 80 | 20 | 60 |
| Rdparam   | Respiration | — | 0.015 | 0.025 | 0.015 |
| Slope (m) | Ball-Berry stomatal conductance parameter | — | 9 | 4 | 9 |
| LIDFₐ     | Leaf inclination parameter | — | -0.35 | -1 | -1 |
| LIDFₐ     | Bimodality parameter | — | -0.15 | 0 | 0 |
| V_{cmax}  | Maximum carboxylation capacity | μmol/m²/s | 100 | 20 | 80 |
| FQE       | Fluorescence quantum yield efficiency | — | 0.01 | 0.01 | 0.01 |
| VZA       | View zenith angle | Degree | 0 | 0 | 0 |
| RAA       | Relative azimuth angle | Degree | 0 | 0 | 0 |

### Table A2
Main Input Parameters of Three Sites for the BEPS Simulations

| Parameters | Description | Unit | Shangqiu | Xinlinhot | Jurong |
|------------|-------------|------|----------|-----------|--------|
| V_{cmax}   | Maximum carboxylation capacity | μmol/m²/s | 100 | 20 | 80 |
| J_{na}     | Maximum electron transport rate | μmol/m²/s | 200 | 193 | 200 |
| N          | Leaf nitrogen content | g/m² | 1.69 | 1.62 | 1.69 |
| Xₙ         | Slope of V_{cmax} variation with N | m²/g | 0.60 | 0.62 | 0.60 |
| Slope (m)  | Slope in the Ball-Berry equation | — | 9 | 4 | 9 |
| Intercept (b) | Intercept in the Ball-Berry equation | μmol/m²/s | 0.0011 | 0.0011 | 0.0011 |
| Rdparam    | Respiration | — | 0.015 | 0.025 | 0.015 |
| Ω          | Clumping index | — | 0.85 | 0.8 | 0.85 |
Figure B1. Seasonal variations of daily mean SIF, PAR, GPP, and NDVI at four SIF sites. The names are identified in Table 1.
Appendix C: Calibration Coefficients From Different Times

![CC-3 calibration factors](image)

Figure C1. Three calibration coefficients acquired from two different times and before-after-cleaning dust, as well as fractions of change on the basis of coefficient obtained on August 12, 2018.

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Data Availability Statement

The TROPOMI SIF data providers, Prof. Philipp Koehler and Prof. Christian Frankenberg, were also acknowledged. The TROPOMI SIF data used here can be accessed in https://doi.org/10.6084/m9.figshare.13277810. We also greatly appreciate the ChinaFLUX for providing EC flux data (http://www.cnern.org.cn/data/meta?id=141840).

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