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Airborne based spectroscopy of red and far-red sun-induced chlorophyll fluorescence: Implications for improved estimates of gross primary productivity

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ABSTRACT

Remote sensing (RS) approaches commonly applied to constrain estimates of gross primary production (GPP) employ greenness-based vegetation indices derived from surface reflectance data. Such approaches cannot capture dynamic changes of photosynthesis rates as caused by environmental stress. Further, applied vegetation indices are often affected by background reflectance or saturation effects. Sun. induced chlorophyll fluorescence (F) provides the most direct measure of photosynthesis and has been recently proposed as a new RS approach to improve estimates of GPP and tracing plant stress reactions. This work aims to provide further evidence on the complementary information content of F and its relation to changes in photosynthetic activity compared to traditional RS approaches. We use the airborne imaging spectrometer *HyPlant* to obtain several F products including red fluorescence (F_{687}), far-red fluorescence (F_{760}), F_{760} yield ($F_{760yield}$) and the ration between F_{687} and F_{760} (F_{ratio}). We calculate several vegetation indices indicative for vegetation greenness. We apply a recently proposed F-based semi-mechanistic approach to improve the forward modeling of GPP using F_{760} and compare this approach with a traditional one based on vegetation greenness and ground measurements of GPP derived from chamber measurements. In addition, we assess the sensitivity of $F_{760yield}$ and F_{ratio} for environmental stress. Our results show an improved predictive capability of GPP when using F_{760} compared to greenness-based vegetation indices. $F_{760yield}$ and F_{ratio} show a strong variability in time and between different crop types suffering from different levels of water shortage, indicating a strong sensitivity of F products for plant stress reactions. We conclude that the new RS approach of F provides complements to the set of commonly applies RS: The use of F_{760} improves constraining estimates of GPP while the ratio of red and far-red F shows large potential for tracking spatio-temporal plant adaptation in response to environmental stress conditions.

1. Introduction

Photosynthesis is a complex physiological ecosystem process that determines plant CO_2 uptake. On ecosystem scale photosynthesis is often referred as gross primary production (GPP). It is regulated by various biophysical processes and chemical reactions, which dynamically adapt to changing environmental conditions (Farquhar et al., 2001). As a consequence, spatial and temporal patterns of GPP are determined by environmental factors and the plant's ability to adapt to them.

Although accurate observations of temporal and spatial GPP patterns are important, making these observations at the landscape scale is still challenging. One possibility is to use eddy covariance (EC) flux towers, which measure the net carbon dioxide (CO_2) exchange of vegetated ecosystems with the atmosphere, and to partition the resulting fluxes into GPP and ecosystem respiration. EC flux towers, however, only represent small areas in pre-selected ecosystem (Drolet et al., 2008). Process modeling (Sitch et al., 2003) or combinations of in-situ EC observations and statistical modeling (Jung et al., 2011) provide estimates of GPP at across-spatial scales but are challenged by the complexity of natural systems and do not sufficiently account for actual photosynthetic rates. Recently, Schimel et al. (2015) even showed how model results are biased since their parameterization depends on

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observations that are not spatially distributed according to carbon stocks.

Space- and airborne-based spectroscopy can be considered the only technology that measures important information about vegetation status and functions at broad scale, thus providing regional and global GPP information. Typically, vegetation indices (VIs) derived from optical measurements are employed in estimating GPP, under the assumption that physiological plant processes and the biochemical composition of vegetation canopies determine the optical properties of vegetation canopies (Hilker et al., 2008). The foundation of most remote sensing (RS) approaches used to estimate GPP is the resource balancing paradigm (Field et al., 1995), which hypothesizes that the plant's investment in the various resource-harvesting complexes is balanced and that plant growth can be sufficiently estimated by measuring only one growth-limiting factor. This idea – aligned to the measurement of light – is conceptualized in Monteith's light use efficiency (LUE) model (Monteith, 1972; Monteith and Moss, 1977); a model used in all RS-based GPP approaches (see Eq. 1):

$$GPP = PAR * fAPAR * LUE \tag{1}$$

The model sets GPP in a proportional relationship with the incident of photosynthetically active radiation (PAR), the fraction of PAR absorbed by the vegetation (fAPAR), and the photosynthetic light use efficiency (LUE; defined as the amount of μmol CO_2 absorbed per μmol photons). The challenge in RS is to parameterize the three terms of Monteith's equation.

According to Hilker et al. (2008), fAPAR can be estimated through various methods, some of them based on its empirical non-linear relationship to VIs e.g., to the normalized difference vegetation index (NDVI). However, the saturation of VIs in dense canopies and their sensitivity to the background contributions of soil or non-photosynthetic vegetation components often lead to GPP being overestimated for sparse and less productive canopies and underestimated for dense and high productive canopies (Huete et al., 2002; Turner et al., 2003; Running et al., 2004; Xiao et al., 2008). Quantifying LUE is challenging and direct measurements are not yet possible. Besides unrealistically assuming a constant LUE, more sophisticated approaches adjust biome-specific potential LUE values by using meteorological variables derived from in-situ measurements and geo-statistical modeling (Jung et al., 2011; Running et al., 2004; Ryu et al., 2011; Xiao et al., 2004). Described approaches are based on vegetation greenness and do not show a direct mechanistic connection to actual photosynthesis, which is characterized by rapid and short-term adaptations to changing environmental conditions (e.g., fluctuating light, short term drought). Consequently, greenness-based approaches tend to be more related to potential than to actual photosynthetic rates (Meroni et al., 2009).

Recently, sun-induced chlorophyll fluorescence (F) was proposed as a means of overcoming these limitations when estimating GPP. Light energy absorbed by the plant is being channeled to three competitive pathways: (1) photosynthesis, (2) heat dissipation (non-photochemical quenching (NPQ)), and (3) F emission. Consequently, F is theoretically related to both APAR and LUE and opens up new perspectives for making GPP estimates more accurate.

Emitted F light has a well-defined spectral shape with two major peaks at 685 nm ($maxF_{<685>}$; red) and 740 nm ($maxF_{<740>}$; far-red) (Franck et al., 2002). The radiance signal received at an RS sensor comprises two radiance fluxes: sunlight reflected by the surface and the emitted F. The F radiation signal weakly adds to the reflected surface radiance (1–5% in the far-red), making the detection of F from RS data challenging. Analytical and technical developments nowadays allow F to be reliably measured using ground (Burkart et al., 2015; Cogliati et al., 2015; Damm et al., 2010a), airborne (Damm et al., 2010b, 2011, 2014; Rossini et al., 2015; Rascher et al., 2015), and satellite sensors (Frankenberg et al., 2014; Guanter et al., 2012; Joiner et al., 2011, 2012, 2013; Frankenberg et al., 2011a, 2011b; Frankenberg et al., 2011a, 2011b; Frankenberg et al., 2012). These developments make it possible to study the mechanistic link between F and GPP in time and space (Damm et al., 2010a; Guanter et al., 2014; Zarco-Tejada et al., 2013; Rossini et al., 2015; Yang et al., 2015; Zhang et al., 2014).

The complexity of F-GPP relationships, recently discussed in Damm et al. (2015), requires further understanding and experimental evaluation of the robustness of this link as well potentially confounding factors (Porcar-Castell et al., 2014). Aim of this study is to elaborate on the mechanistic link between F and changes in photosynthetic activity as well on confounding factors. Maps of F_{760} and F_{687} (fluorescence at the wavelengths of 687 nm and 760 nm respectively) as well as several VIs were derived from the novel airborne image spectrometer *HyPlant* during three overflights around solar noon in August 2012 (Rascher et al., 2015). We use the semi-mechanistic approach by Guanter et al. (2014) to calculate GPP maps in high spatio-temporal resolution using resulting F_{760} maps. We compare F_{760} based GPP (GPP_{F760}) estimates with GPP based on common greenness-based approaches (GPP_{VI}) and validate them with ground measurements of GPP derived from parallel gas-exchange chamber measurements. Furthermore we analyzed the spatio-temporal changes of F products, particularly F_{687}, F_{760}, their ratio, and F_{yield}.

2. Material and methods

2.1. Study area

The study area close to the village of Selhausen (50.864 N, 6.452 E, altitude 103 m above sea level) is located in the Rur catchment in the central western part of North Rhine-Westphalia, Germany (Fig. 1 A&B). The Rur catchment is an intensive study area of the Transregional Collaborative Research Centre 32 (TR32, http://tr32new.uni-koeln.de/), founded by the German Research Foundation. Within the study area, one sugar beet field was selected as an experimental site for ground measurements. The experimental site covers 1.4 ha (200 m × 70 m) with a gentle slope of 4° in east-west direction. The upper part of the field is more gravelly than the lower part, resulting in a lower water-holding capacity in that area (Rudolph et al., 2015; Stadler et al., 2015). The climate is characterized by an annual mean temperature of 11 °C and an annual mean precipitation of around 700 mm/year (Lanuv, 2014). The region is dominated by agriculture. The dominant crop type is sugar beet followed by maize, rapeseed, and potatoes.

This study focuses on sugar beet, which grew in 2012 from March (day of year (DOY): 87) to September (DOY: 254). Ground measurements were carried out in sugar beet field G (Fig. 1C) with fully developed leaves and a fractional cover of 90% (BBCH-Code: 39 – the Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie (BBCH) code describes the phenological status of a plant. BBCH-Code: 39 indicate that the Rosette growth is completed and that leaves cover 90% of the ground). Imaging spectroscopy data were acquired with the *HyPlant* sensor on August 23, 2012 (DOY: 236). The observation took place under clear sky conditions. A rain event with a precipitation sum of 0.12 mm was recorded one day before the airborne data acquisition, and the maximum air temperature was 23 °C. Sunrise was at 4:32 a.m., solar noon at 11:35 a.m. and sunset at 6:36 p.m. UTC (Coordinated Universal Time).

2.2. Ground measurements

2.2.1. Field spectroscopy to estimate F_{760}, $APAR_{MSS}$ and $F_{760yield}$

During the flight campaign, the custom-made measurement setup Manual Spectrometric System (MSS) was used to continuously measure irradiance and surface-leaving radiance to eventually derive F emissions at 760 nm (F_{760}) as well as the absorbed photosynthetic active radiation ($APAR_{MSS}$). The spectrometer system was designed for high-temporal frequency sampling of radiometric measurements. Briefly, top of canopy radiances were measured using two portable spectrometers