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Normalized difference spectral indices for estimating photosynthetic efficiency and capacity at a canopy scale derived from hyperspectral and CO_2 flux measurements in rice

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Abstract

We explored simple and useful spectral indices for estimating photosynthetic variables (radiation use efficiency and photosynthetic capacity) at a canopy scale based on seasonal measurements of hyperspectral reflectance, ecosystem CO_2 flux, and plant and micro-meteorological variables. An experimental study was conducted over the simple and homogenous ecosystem of an irrigated rice field. Photosynthetically active radiation absorbed by the canopy (APAR), the canopy absorptivity of APAR (fAPAR), net ecosystem exchange of CO_2 (NEE_{CO_2}) gross primary productivity (GPP), photosynthetic capacity at the saturating APAR (P_{max}), and three parameters of radiation use efficiency (ε_N: NEE_{CO_2}/APAR; ε_G: GPP/APAR; φ: quantum efficiency) were derived from the data set. Based on the statistical analysis of relationships between these ecophysiological variables and reflectance indicators such as normalized difference spectral indices (NDSI[*i*,*j*]) using all combinations of two wavelengths (*i* and *j* nm), we found several new indices that would were more effective than conventional spectral indices such as photochemical reflectance index (PRI) and normalized difference vegetation index (NDVI = NDSI[near-infrared, red]). ε_G was correlated well with NDSI[710, 410], NDSI[710, 520], and NDSI[530, 550] derived from nadir measurements. φ was best correlated with NDSI[450, 1330]. NDSI[550, 410] and NDSI[720, 420] had a consistent linear relationships with fAPAR throughout the growing season, whereas conventional indices such as NDVI showed very different relationships before and after heading. Off-nadir measurements were more closely related to the efficiency parameters than nadir measurements. Our results provide useful insights for assessing plant productivity and ecosystem CO_2 exchange, using a wide range of available spectral data as well as useful information for designing future sensors for ecosystem observations.

Keywords: CO_2 flux; Eddy covariance; fAPAR; GPP; Hyperspectra; Radiation use efficiency; Spectral index

1. Introduction

Assessment of photosynthetic functioning is one of the most important bases for the diagnosis and prediction of plant growth, as well as carbon exchange between ecosystems and the atmosphere. A great deal of research effort has been directed towards the assessment of crop yield and ecophysiological variables using remote sensing in optical, thermal, and microwave wavelength domains together with modeling approaches (e.g., reviews by Moran et al., 1997; Inoue, 2003; Olioso et al., 2005). Remotely sensed optical signatures have proved useful for estimating ecological variables such as leaf area index (LAI) and the absorptivity of photosynthetically active radiation (fAPAR; Asrar et al., 1984; Daughtry et al., 1983; Huete, 1988) that affect photosynthetic capacity. The relationship between fAPAR and spectral indices such as normalized difference vegetation index (NDVI) have been examined in detail with theoretical and experimental analyses (Asrar et al., 1989; Baret & Guyot, 1991; Myneni & Williams, 1994). Several important physiological variables, such as chlorophyll and nitrogen concentration, that affect

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photosynthetic efficiency are also related to reflectance signatures (e.g., Inada, 1985; Inoue et al., 1998; Gitelson & Merzlyak, 1997; Yoder & Pettigrew-Crosby, 1995). It is obvious that efficiency and capacity are related to each other during long growth periods. However, in the context of ecosystem monitoring at high temporal resolution, we use the term "photosynthetic-efficiency variable" to indicate photosynthetic rates per unit of absorbed radiation and the term "photosynthetic-capacity variable" for potential photosynthesis at canopy scales, such as fAPAR and the canopy photosynthesis at the saturating APAR (P_{max}). In other words, the former is related to "rate", whereas the latter is related mainly to "size". Furthermore, stomatal or canopy conductance and canopy transpiration are also estimated using remotely sensed canopy temperatures with energy balance models (e.g., Inoue et al., 1990, 1994; Olioso et al., 1999; Taconet et al., 1995). These variables strongly control photosynthetic efficiency. Nevertheless, direct estimation of photosynthetic efficiency and capacity is an important research target for remote sensing.

In the past few decades, remote sensing has become more and more crucial in the study of biogeochemical cycles such as carbon, water, and energy exchange between ecosystems and the atmosphere in the context of global climate change (e.g., Grace, 2005; Roy & Saugier, 2001). One recent effort for systematic data acquisition and analysis is the Spectral Network (SpecNet) proposed by Gamon et al. (2006). Advanced concepts, methodologies, or achievements in agricultural remote sensing have been applied to various types of natural and managed ecosystems. For example, the use of fAPAR in a simple mechanistic model (e.g., Monteith, 1977) has been employed in a range of applications for rough assessment of net primary productivity (NPP) at various scales using remote sensing (e.g., Goetz et al., 1999; Maisongrande et al., 1995; Potter et al., 1993; Ruimy et al., 1994; Turner et al., 2002; Veroustraete et al., 1996).

This simple approach using fAPAR and radiation (or light) use efficiency (ε) has been widely used to estimate crop biomass, yield, or NPP (e.g., Choudhury, 2000). fAPAR is estimated from spectral indices such as NDVI ($=[R_{NIR}-R_{red}]/[R_{NIR}+R_{red}]$) or a simple ratio ($SR=R_{NIR}/R_{red}$]; e.g., Asrar et al., 1984; Baret & Guyot, 1991; Kumar & Monteith, 1982) and applied to a model (e.g., Nouvellon et al., 2000; Ruimy et al., 1994), where R_{NIR} and R_{red} are reflectance at near-infrared and red wavelength regions, respectively (hereafter, the term Rx indicates spectral reflectance at a wavelength x nm). The relationship is little affected by pixel heterogeneity, LAI, or variation in leaf orientation and optical properties (e.g., Pinter et al., 1985), but is affected by background, atmospheric, and bidirectional effects (Myneni & Williams, 1994) and by phenological stages and senescence. For instance, the NDVI-fAPAR relationship is largely different between before and after heading (anthesis) in most crops (e.g., Asrar et al., 1989; Choudhury, 2000; Daughtry et al., 1983; Inoue & Iwasaki, 1991; Inoue et al., 1998). In this approach, ε is first defined as the ratio of dry matter production (dDM) to APAR for season-long periods (e.g., Shibles & Weber, 1966). ε may be assumed to be constant under non-stressed conditions, but it is affected by stresses, phenological stages, and the physical environment (Choudhury, 2000; Kiniry et al., 1989; Sinclair, 1994). Hence, it may be inappropriate to assume that ε is constant and that the fAPAR-NDVI relationship is consistent for entire growth periods, especially when the model is applied to the assessment of canopy carbon exchange at a short (e.g., daily) time resolution over different phenological stages.

The photochemical reflectance index ($PRI=[R531-R570]/[R531+R570]$) is closely related to photosynthetic radiation use efficiency of plant leaves (Gamon et al., 1992; Peñuelas et al., 1995). R531 is presumed to detect the photochemical reaction in the xanthophyll cycle that dissipates excess light to protect the photosynthetic apparatus, while R570 is used as a reference assumed not to be affected by changes in short-term stress events (Peñuelas & Filella, 1998). Its simplicity, using only two wavelengths, is an attractive feature since it may meet the specifications for a range of available airborne and satellite sensors; thus a number of studies have examined the usefulness of PRI using various datasets and approaches (Barton & North, 2001; Drolet et al., 2005; Filella et al., 1996; Gamon et al., 1997; Inoue & Peñuelas, 2006; Rahman et al., 2001; Thenot et al., 2002; Trotter et al., 2002). Nevertheless, its applicability at canopy or ecosystem scales is not well known, and the use of remotely sensed signatures in the assessment of primary productivity (NPP or gross primary productivity, GPP) and net ecosystem CO_2 flux (NEE_{CO_2}) awaits further methodological innovations. Synergy of remote sensing signatures in ecosystem functioning models that include photosynthetic processes is promising (e.g., Inoue & Olioso, 2006), but simple and direct means are still a very attractive approach. Nevertheless, canopy-scale investigations of PRI and other spectral indices based on *in situ* measurements of CO_2 flux and hyperspectral measurements over homogenous ecosystems are still lacking (e.g., Peñuelas & Inoue, 2000), so that useful indices may yet be undiscovered.

Therefore, the objective of this study was to explore the significant and/or consistent relationships for remote sensing of photosynthetic-efficiency and-capacity variables such as å and fAPAR. We made seasonal measurements of hyperspectral reflectance, ecosystem CO_2 flux, and plant and micrometeorological variables over an irrigated rice field. The dataset from this simple and homogenous ecosystem facilitates efficient extraction of more significant relationships. In general, hyperspectral measurements allow various analyses such as multiple linear regression, principal component regression, partial least squares regression, and derivatives (e.g., Adams et al., 1999; Grossman et al., 1996; Takahashi et al., 2000), or assimilation techniques using a radiative transfer model such as PROSPECT+SAIL (e.g., Jacquemoud, 1993). Nevertheless, here we focus mainly on the comparative usefulness of the simple normalized difference spectral indices (NDSIs) using narrow band reflectance, instead of the whole spectrum for wider applications.