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An AOTF-based hyperspectral imaging system for field use in ecophysiological and agricultural applications

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Abstract. An AOTF (Acousto-Optic Tunable Filter)-based spectral imager was developed for hyperspectral measurement of plant reflectance in the field. A hyperspectral image cube for the spectral region between 450–900 nm could be acquired at 3 to 5 nm resolution intervals within a few seconds. The system was light and compact, and both the spectral wavelengths and intervals were programmable with PC control. Wavelengths could be tuned rapidly, either sequentially or randomly. The hyperspectral image cube for rice canopies obtained by the system showed its potential in the estimation of leaf nitrogen and chlorophyll concentrations. The AOTF-based hyperspectral system would have great potential for further investigations in remote sensing of biochemical and ecophysiological plant variables.

1. Introduction

Both in agricultural and ecological issues such as precision agriculture and carbon cycle assessment, physiological and bio-chemical plant information is needed for diagnosis of a wide range of plant disease and nutrient stress (Moran *et al.* 1997), as well as for estimation of net primary productivity (Ruimy *et al.* 1996). It has been suggested that hyperspectral reflectance signatures from plant leaves and/or canopies contain a wide range of physiological and bio-chemical information (Yoder and Pettigrew-Crosby 1995, Penuelas and Filella 1998, Blackburn 1998, Kokaly and Clark 1999).

Recent advances in sensor technology may allow to detect weak signals in a narrow spectral wavelength even from space such as by Hyperion (Perlman *et al.* 1999). However, as yet only a few airborne-based and no satellite-based, hyperspectral sensors are available for such purposes. Therefore, basic investigations must be conducted with ground-based or airborne hyperspectral image measurements. Some airborne systems such as CASI and AVIRIS may be employed for large-scale

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campaigns; nevertheless, there are few hyperspectral-imaging systems that can be utilised in the field. Thus, we have developed a new hyperspectral imaging system, for field use, which is based on an acousto-optic tunable filter (AOTF) and a CCD camera. Hyperspectral images of rice canopies were obtained using the system and a preliminary analysis was conducted to estimate several physiological plant variables based on the measurements.

2. Materials and methods

2.1. *An AOTF-based imaging system for hyperspectral observation of plant canopies*

We designed a spectral imaging system to obtain hyperspectral imagery of plant canopies in the field, which was manufactured at Opto-research Inc. (Tokyo, Japan). The system consists of an AOTF, an AOTF controller (radio-frequency drive unit), monochromatic Si-CCD camera, a palmtop computer, and a small video recorder (figure 1). An AOTF is an electronically tunable phase grating that is set up in an anisotropic crystal by the propagation of an acoustic wave. The acoustic wave is generated by radio-frequency signals, which are applied to the crystal via an attached piezoelectric transducer (Gupta 1997). The entire system is solid state (no moving parts), robust, and can be operated easily in the field. The spectral range of this particular system is between 450 nm and 900 nm considering the range of the Si-CCD sensitivity and specification of the AOTF. The spectral resolution is 3 nm and 5 nm for the visible and near-infrared spectral regions, respectively. The field of view was about 10°. Measurement configurations, such as the number of wavelength bands

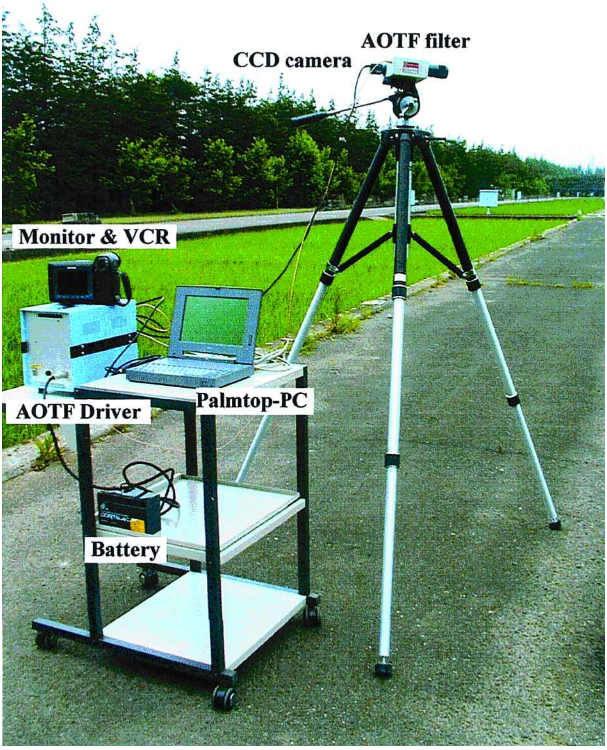

Figure 1. The AOTF-based spectral imaging system for field use.

and the interval of measurements can be programmed on the palmtop computer. A simple Hi-8 video recorder is used to monitor and record the successive spectral images.

2.2. *Measurement of plant canopies using the AOTF imaging system*

Hyperspectral images were taken over thirty seedling canopies of rice (*Oryza sativa* L.), which were managed differently to produce a wide range of biomass and nitrogen concentration. Rice seedlings were grown at three levels of seeding density and nitrogen fertilization, respectively. Further, after germination, a half of the plots experienced relatively lower temperature under outdoor conditions while the other half was under greenhouse conditions.

Fifty bands were selected at a spectral resolution of 10 nm. Since we used an inexpensive, non-cooled Si-CCD camera as the image detector, multiple images were recorded for each wavelength (which corresponded to a few seconds) so that we could apply image-enhancement in the post-processing. All images were recorded on Hi-8 tapes in analogue format and later converted to digital images. Image processing such as A/D conversion and enhancement was conducted using commercial image-processing systems (Hamamatsu Photonics Inc., DVS3000, and ERDAS Inc., Imagine 8.2). The image-enhancement was done simply by averaging twenty consecutive images and by subtracting the background noise-image from the averaged image. The background noise-images were taken automatically just before the observation of target at each wavelength by using an inner shutter. The solar zenith and viewing angles were 40° and 0° (nadir), respectively. The distance between the target and the sensor was about 30 m; thus, the spatial resolution at the target was approximately 0.8 cm while the length and width of the leaves were approximately 10–15 cm and 0.5–1 cm, respectively. The range of biomass (fresh weight), and nitrogen concentration (dry weight basis) were 83–1433 $\mathrm{g\,m^{-2}}$, and 2.1–5.4%, respectively. The soil used was classified to Grey Lowland-Soil, for which the surface was partly observed at the sparse plots. Reflectance images were generated from the CCD-count images, based on the calibrated relationship between the CCD-count and the reflectance of reference greyscales (Japan Colour Research Institute) at each wavelength. The reflectance of greyscales was calibrated against a white reference panel (SPECTRALON, Labsphere Inc.). The reflectance spectrum was rather flat in the visible and near-infrared wavelength regions approximately at the level of 4.8, 5.1, 6.7, 10.0, 13.0, 16.7, 24.9, 35.1, 49.5, and 75.5%, respectively.

The biomass (fresh and dry phytomass) of the canopies was determined through destructive sampling. Chlorophyll and nitrogen concentrations were determined using an optical chlorophyll-metre (Minolta, SPAD502) and an N-C analyser (Sumigraph), respectively.

3. Results and discussion

The system has numerous advantages over conventional hyperspectral imaging systems for use in the field. The use of an AOTF allows our system to be small, compact, robust and programmable. Wavelengths can be tuned rapidly, either sequentially or randomly. Thus, the system can provide an efficient collection of hyperspectral image cubes that do not require separate image registration. That, in turn, facilitates easier image processing and analysis. Hyperspectral images of rice canopies were obtained successfully using our system in the field. Image processing and analysis was performed using the spectral image cubes. Figure 2 shows the

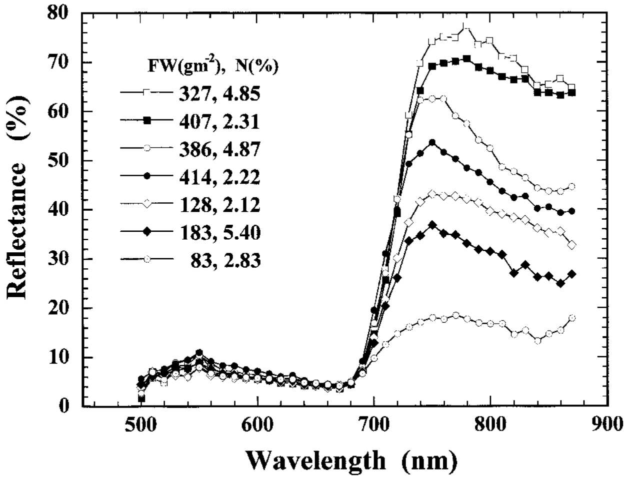

Figure 2. Reflectance spectra of differently-managed rice canopies obtained by the AOTF imaging system. Some typical data were plotted among thirty lines. FW and N indicate biomass and nitrogen concentration for each canopy, respectively.

spectral patterns of selected canopies, whose biomass and nitrogen content differed. The reflectance spectra of these canopies varied highly, according to their biomass and nitrogen status.

In general, the major approaches for extracting useful information from hyperspectral signatures may be classified into three methods: (1) A selected number of wavelength regions (which are highly-correlated to the plant variables) are used to form a simple index, such as vegetation indices or the position of the red edge (Chappelle *et al.* 1992, Asner 1998, Blackburn 1998, Penuelas and Filella 1998). (2) The entire spectral signature is used to estimate plant variables, based on a multiple-variate analyses such as multiple-regression, principal component regression and partial least-squares regression (Cloutis 1996, Grossman *et al.* 1996). (3) The entire spectral signature is used to estimate plant variables incorporated into reflectance models, based on inversion of such models with hyperspectral data (Jacquemoud and Baret 1990). In this study, we used the first and second approaches to estimate the nitrogen and chlorophyll contents of plants. However, the results of regression between the reflectance of a single wavelength and canopy variables did not show high correlation. The principal component analysis, using all wavelengths, also showed no highly significant correlation. The most significant relationship was obtained through multiple regression analysis using all available spectral reflectance data. The coefficients of determination were 0.72 and 0.86 for the nitrogen concentration (%DW) and chlorophyll index (counts of SPAD502), respectively (figure 3). Reflectance in the spectral regions of 520–570 nm, 610–680 nm and 720–800 nm contributed highly in the multiple regression models. Neither spectral derivative analysis nor red-edge analysis (based on finer spectral resolution measurements) yielded any clearer relationships in this experiment. Results in the present study support previous work that suggests that hyperspectral information is useful for estimating plant physiological variables (Chappelle *et al.* 1992, Yoder and Pettigrew-Crosby 1995, Blackburn 1998, Penuelas and Filella 1998).

Our field-deployable hyperspectral imaging system proved to be a powerful tool

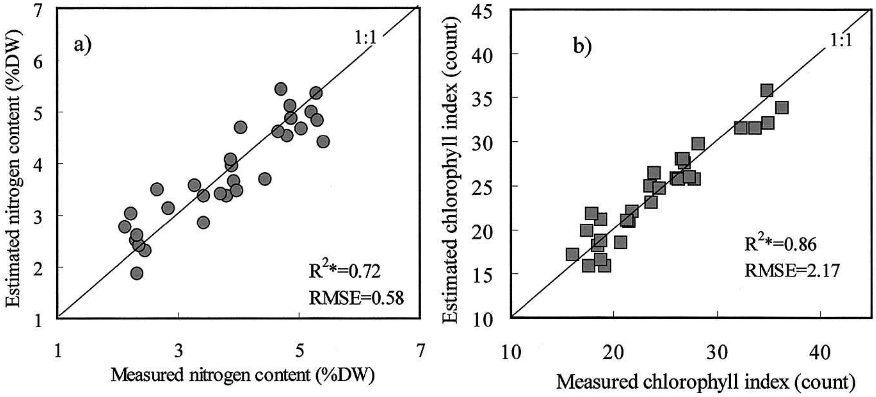

Figure 3. Results of multiple linear regression using hyperspectral measurements to estimate (*a*) plant nitrogen concentration, and (*b*) chlorophyll index. R^2* indicates the value of R^2 is corrected for degrees of freedom.

for basic research in the remote sensing of plant physiological variables. It should be noted that the narrow field of view (about 10°), and a slight shift of focusing due to an aberration might be inherent restrictions to existing AOTF systems although the latter effect was not problematic in this spectral region. AOTF tuners can be designed to cover a wider spectral range, from the ultraviolet to short-wave infrared wavelength regions (Gupta 1997). Therefore, it will be possible to develop systems that cover a wide spectral range by combining such AOTF tuners and image sensors that have enough signal-to-noise ratio to detect the weak energy at narrow spectral width.

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