J-1.2.2 Estimating physiological status of vegetation based on multi-scale remote sensing and biophysical modeling

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Abstract: The goal of this project is to propose new methods for remote sensing of the physiological status of vegetation based on the synergy of remote sensing and biophysical modeling. Remote sensing data in visible, near-infrared, short-wave infrared and thermal-infrared regions were obtained by ground-based and low-altitude remote sensing experiments. Major results obtained are as follows. 1) A remote sensing method was proposed for estimating physiological activity of plants such as transpiration and stomatal/canopy conductance on single-leaf and canopy scales. The method was based on the energy balance of a plant leaf or a canopy. The remote method proved promising in the estimation of canopy transpiration and conductance under a wide range of environmental conditions on both real-time and daily bases. 2) A new approach based on combined use of visible and near-infrared reflectance and thermal-infrared temperature (VITT) was proposed for estimating physiological activity of composite vegetation surfaces. The VITT index was closely correlated with the physiological plant variables such as photosynthesis. 3) An AOTF-based hyperspectral imager was developed, and shown to be useful for the field remote sensing experiments, 4) Water and nitrogen contents of plants were well correlated with spectral indices obtained by hyper-spectral measurements. The inversion of spectral simulation model using hyperspectral data proved useful for prediction of leaf water status.

Keywords Remote sensing, Plant productivity, Environmental stress, Modeling.

1. Introduction

The global information on the behavior of terrestrial ecosystem is essential in the strategy to the global environmental issues such as atmospheric CO_2 enrichment, deforestation, desertification and so forth. Especially, the wide-area and quantitative monitoring of the ecological/physiological status of terrestrial vegetation is of great importance since the above issues are closely related to the plant growth and environmental stress. Remote sensing may be the unique method that can be applied to such purposes, and the synergetic use of remote sensing and modeling is expected to be one of the most promising ways to realize the powerful potential of the remote sensing technology.

2. Research Objectives

The major objective was to propose new remote sensing methods for estimation of the physiological status of vegetation on the leaf, canopy and land surface scales. We investigated the synergy of remote sensing and bio-physical modeling based on ground-based and airborne spectral measurements. New approaches as follows were proposed and evaluated based on plant physiological measurements; 1) the combination of remotely-sensed thermal and spectral data with semi-empirical and energy balance models for estimation of transpiration and conductance on the leaf and canopy scales, 2) the use of hyperspectral data for estimation of plant physiological variables such as water, nitrogen and chlorophyll contents. Major approaches to extract the useful information from hyperspectral signature may be classified into three methods; 1) A few number of selected wavelength regions which are highly-correlated to plant variables are used in the form of simple index such as vegetation indices and position of red edge, 2) Whole spectral signature is used to estimate plant variables based on multiple-variable analysis such as multiple-regression, principal component regression and partial least square regression, and 3) Whole spectral signature is used to retrieve the plant variables incorporated in reflectance models based on inversion of such models with hyperspectral data. In the present study, we attempted these approaches to estimate the nitrogen and water status of plant based on hyperspectral measurements. We used two hyperspectral data sets; one was obtained by an AOTF-based spectral imager, and the other was by high-resolution spectral radiometer.

3. Methodology

3.1 Data acquisition

Remote sending data in visible, near-infrared, short-wave infrared, and thermal infrared regions were measured using a handheld radiometer, a spectral imager, or an airborne imager. Micrometeorological factors such as air temperature, solar radiation, and humidity were collected by an automated sensing system. Plant physiological variables such as photosynthesis, transpiration, and stomatal conductance were obtained using porometers. Canopy transpiration was estimated by the stem heat-balance method. Plant biomass, leaf area index, and water content were measured by destructive sampling. Nitrogen content was obtained using N-C analyzer.

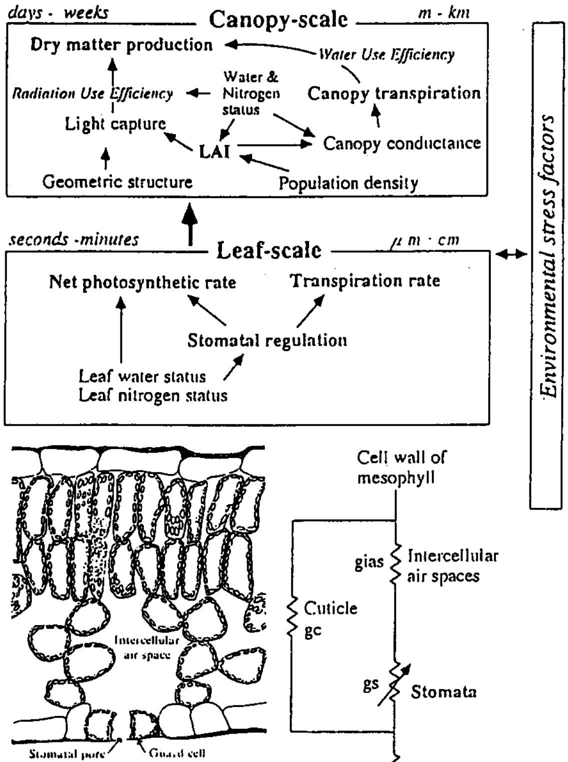
3.2 AOTF-based imaging system for hyperspectral observation of plant canopies

A spectral imaging system was developed to obtain hyperspectral image of plant canopies in the field. The system utilized an acousto-optic tunable filter (AOTF), and a simple monochromatic CCD camera (Fig.13). The spectral range of the system was between 450 nm and 900 nm, and the spectral resolution was 3 nm and 5 nm for visible and near-infrared spectral regions, respectively. Since the system required no-mechanical movement to scan the wavelength, any desired band could be selected in milliseconds. The setting of measurement configuration such as the number of wavelength bands and position of them to be measured was programmable on the PC.

4. Results and Discussion

4.1 Remote sensing of transpiration and conductance on the leaf and canopy scales

Plant productivity or physiological vigor may be considered as an aspect of dynamic change of the plant and environmental system (Fig. 1). The water and CO_2 exchange between sub-stomatal cell and ambient atmosphere can be expressed by the energy-balance and mass-transfer models. The photosynthetic rate is intimately related to the transpiration rate since they are both regulated by stomata (Fig.2). Thus, the leaf transpiration and conductance/photosynthesis can be estimated using remotely sensed leaf temperature and other micrometeorological data. The method was tested using the data set obtained by porometry (Fig.3). The similar method was constructed for the canopy scale that utilizes the



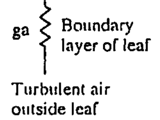


Fig.1 Schematic presentation of gas-exchange via stomata - factors and parameters in the estimation of plant productivity

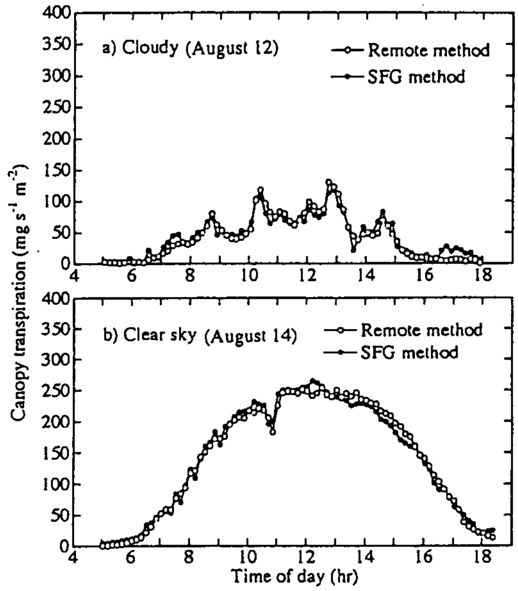


Fig. 4 Diurnal comparison of canopy transpiration rates of soybean plant estimated by remote and direct (SFG) methods. Examples under a) cloudy, and b) clear sky conditions.

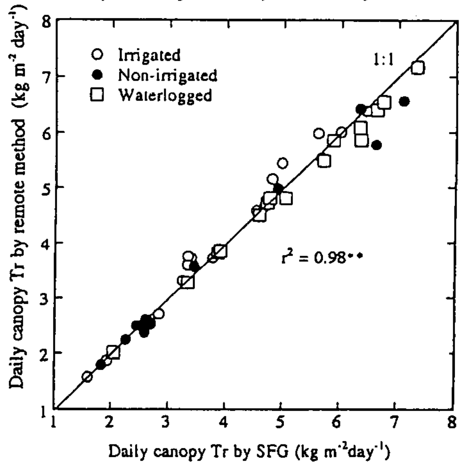


Fig. 5 Comparison of daily canopy transpiration rates estimated by remote and direct (SFG) methods.

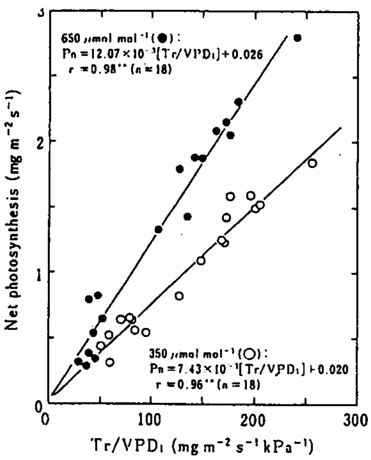


Fig. 2 Relationship between leaf photosynthesis and transpiration under ambient and doubled CO2 concentrations.

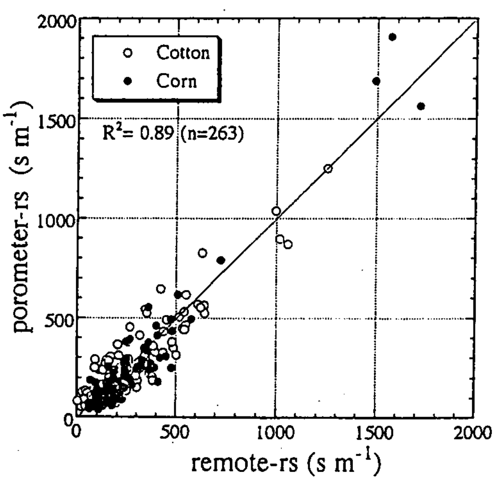


Fig. 3 A comparison between "remotely" estimated and directly measured stomatal resistance on a single leaf basis - an example for cotton and corn plants.

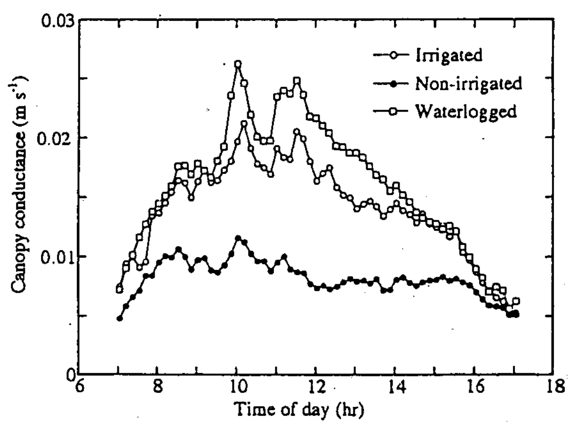


Fig. 6 Diurnal comparison of canopy conductance values estimated by remote methods in three differentially-irrigated soybean canopies.

canopy temperature instead of leaf temperature. The remotely estimated canopy-transpiration was well correlated with the directly measured values both on instantaneous and daily basis (Figs. 4 and 5). Further, it was possible to estimate the canopy conductance (Fig.6). This synergetic method between remote sensing and physical process model requires extra information such as micrometeorological data, but provides robust and quantitative estimates of the plant physiological status.

4.2 Remote sensing of water availability of vegetated surfaces based on VITT concept

The approach proposed here, termed the vegetation index – temperature trapezoid (VITT), is an attempt to combine spectral vegetation indices with composite surface temperature measurements to allow application of Crop Water Stress Index theory to partially vegetated fields without *a priori* knowledge of the percent vegetation cover. The VITT concept is based on the hypothesis that a trapezoid shape would result from a plot of measured surface minus air temperatures ($t_s - t_a$) versus vegetation cover (Fig. 7). The vertices of the trapezoid would correspond to 1) well-watered full-cover vegetation, 2) water-stressed full-cover vegetation, 3) saturated bare soil, and 4) dry bare soil. They can be calculated theoretically by the following equations:

$$(t_s - t_a)_1 = [r_a(Rn-G)/Cv][\gamma(1+r_{cm}/r_a)/\{\Delta+\gamma(1+r_{cm}/r_a)\}] - [VPD/\{\Delta+\gamma(1+r_{cm}/r_a)\}]$$

$$(t_s - t_a)_2 = [r_a(Rn-G)/Cv][\gamma(1+r_{cx}/r_a)/\{\Delta+\gamma(1+r_{cx}/r_a)\}] - [VPD/\{\Delta+\gamma(1+r_{cx}/r_a)\}]$$

$$(t_s - t_a)_3 = [r_a(Rn-G)/Cv][\gamma/(\Delta+\gamma)] - [VPD/(\Delta+\gamma)]$$

$$(t_s - t_a)_4 = [r_a(Rn-G)/Cv]$$

$$CB/AB = \text{WAVI (Water Availability Index)} = (t_s - t_a)_x - (t_s - t_a)_r] / (t_s - t_a)_x - (t_s - t_a)_m] \fallingdotseq ETa/ETp$$

where, t_a: air temperature, t_s: composite surface temperature, t_c: plant temperature, t_0: soil temperature, r_a: aerodynamic resistance, r_c: canopy resistance, Rn: net radiation, G: soil heat flux, γ: psychrometric constant, Cv: volumetric heat capacity of air, Δ: slope of the saturated vapor pressure-temperature curve, VPD: vapor pressure deficit of the air, ETa and ETp: actual and potential evapotranspiration, and the subscripts m, x, and r refer to the minimum, maximum, and measured values, respectively.

The concept has been well supported by the experimental data sets obtained by the ground-based and airborne sensors (Figs. 8 and 9). The index WAVI was closely correlated with the photosynthetic rate of plant canopies (Fig.10). Another data set for wheat also showed the close relationship between the WAVI and stomatal conductance (Fig.11). The time course change of measurement in the coordinates of VITT corresponded well to the growth change of a soybean canopy (Fig.12).

This VITT approach is based on the sound physical and biological foundations, and may be useful in the combined use of spectral and thermal remote sensing information.

4.3 Estimation of nitrogen status from reflectance images using AOTF-based hyperspectral imager

The reflectance spectra of canopies changed greatly in accordance with their biomass and nitrogen status (Fig. 14). However, results of regression between reflectance of single wavelength and canopy variables did not show high correlation. Neither the principal

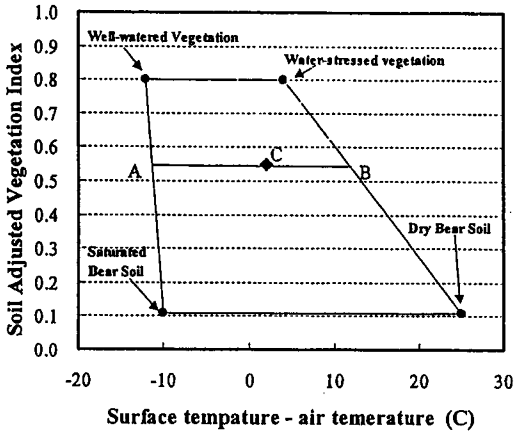


Fig. 7 Vegetation index – Temperature Trapezoid (VITT) concept for estimating vegetation vigor from remotely-sensed optical and thermal information. The ratio CB/AB can be an indicator for water availability for the vegetated surface.

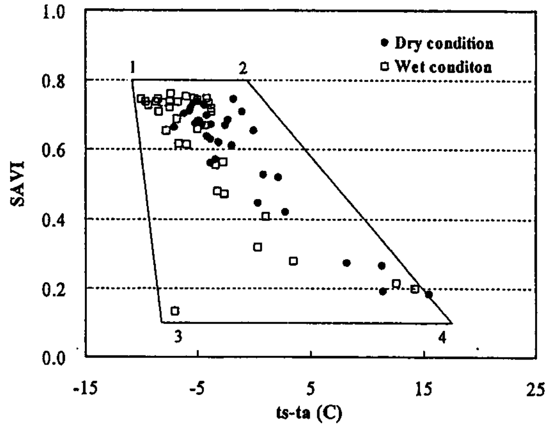


Fig. 8 Some actual data points under different environmental conditions within the VITT trapezoid.

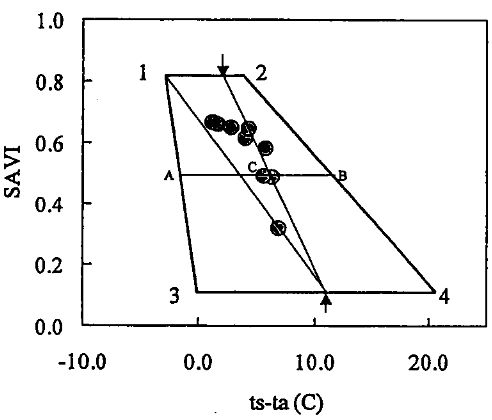


Fig .9 Some actual data points in the VITT – data measured for soybean canopies by an airborne sensor -.

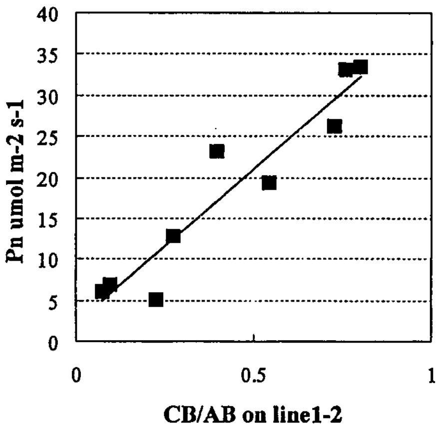


Fig. 10 Relationship between photosynthetic rate and WAVI=CB/AB.

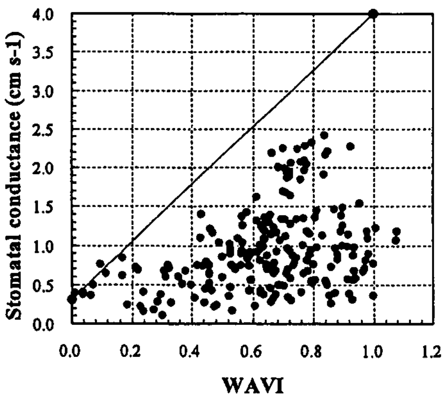


Fig. 11 Relationship between stomatal conductance and WAVI in differentially irrigated wheat canopies.

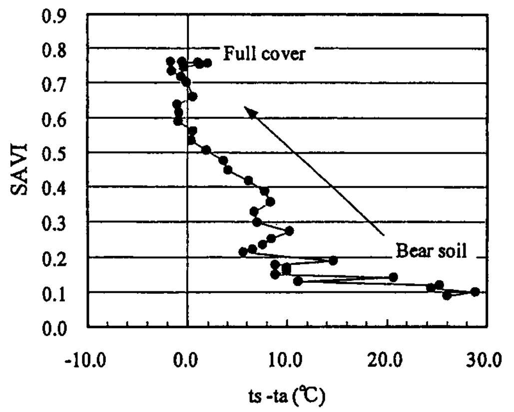


Fig. 12 The time course change of observed points for a soybean canopy within the VITT.

component analysis using all wavelengths showed highly significant correlation. The most significant relationship was obtained by multiple regression analysis using all spectral reflectance data. The correlation coefficient (corrected for degree of freedom) was 0.72, 0.86 and 0.85 for nitrogen content, chlorophyll index (count of SPAD501), and amount of nitrogen, respectively (Fig. 15). Reflectance at spectral regions of 520-570 nm, 610-680 nm and 720-800 nm showed high contribution in the all multiple regression models. Neither spectral derivative analysis nor red-edge analysis based on finer spectral resolution measurements yielded any clearer relationship in this experiment.

4.4 Hyperspectral estimation of water status of plant leaf

The leaf reflectance increased in all wavelengths with decreasing leaf water content from the fully turgid to dry conditions (Fig.16). The driest condition in the experiment seemed to occur in natural conditions since those leaves could recover the initial status after re-watering. There were strong reflectance troughs, due to strong absorption by water at 1430 and 1950 nm that tended to disappear with progressive desiccation. The trough at 970 nm in the reflectance spectra is instead measurable in natural field conditions, and it also disappeared with progressive desiccation. Thus, we examined the following radiometric indices:

1. Water Index (WI) = R900/R970
2. Normalized Difference Vegetation Index (NDVI)= (R900-R680)/(R900+R680)
3. WI/NDVI
4. Structural Independent Pigment Index (SIPI)= (R800-R445)/(R800-R680), where R indicates reflectance and numbers indicate nanometers.

The relative water content (RWC) was well correlated with WI (R900/R970) ($r=0.92$ for peanut and $r=0.6$ for wheat, $p<0.001$). However, whereas WI started to decrease with first water losses in wheat, it did not start to decrease until 60% RWC in peanut leaves, which had about twice as much water content than wheat leaves (Fig.17). No common regression for both species was thus obtained. The difference in equations must be due to the structural and water content differences of their leaves. WI has been reported to also change with structural leaf characteristics such as cell wall elasticity. As the NDVI follows structural and color changes (loss of pigments) in the drying leaves, the rationing of WI by NDVI performed as better indicator of RWC than the water index itself in both species (Fig.18). These results at the leaf level are in agreement with similar results reported at plant and canopy levels for other many species. Interestingly, the pigment index SIPI was also very strongly correlated with RWC (Fig.19) indicating a possible progressive increase in the ratio between carotenoids and chlorophyll, likely because of chlorophyll degradation under desiccation. It adds new possibilities of indirectly assessing progressive leaf water stress. These reflectance indices should be effective for estimating leaf RWC or WC in the respective crops by using reflectance simple techniques. It is thus feasible to develop a compact portable instrument for field measurement of leaf water content. For example, a simple radiometer that only measures reflectance at 680, 900 and 970 nm can instantaneously calculate the NDVI and the WI, and by using appropriate calibration functions give the instantaneous and *in situ* estimation of plant water content.

4.5 Estimation of leaf water status by model inversion based on hyperspectral reflectance measurement

The above regression approaches and index approaches have great merits because of their

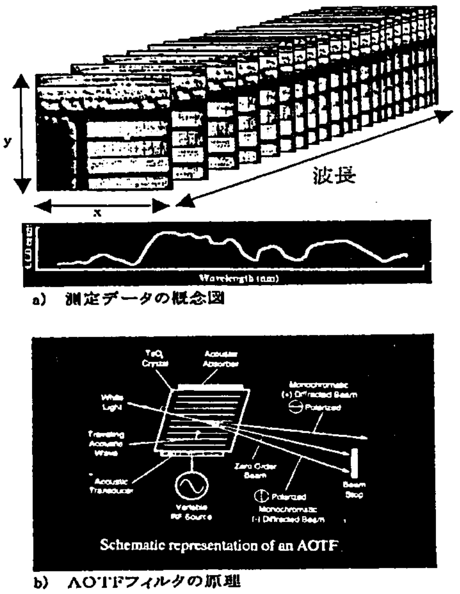


Fig 13. Schematic presentation of the AOTF-based spectral imager.

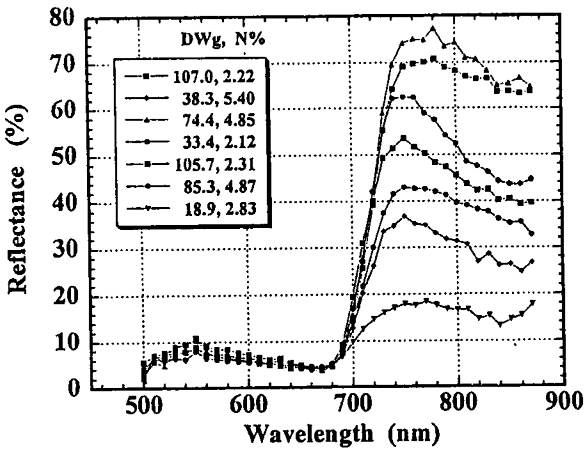


Fig. 14 Spectral reflectance patterns of rice-seedling canopies obtained by the AOTF imager.

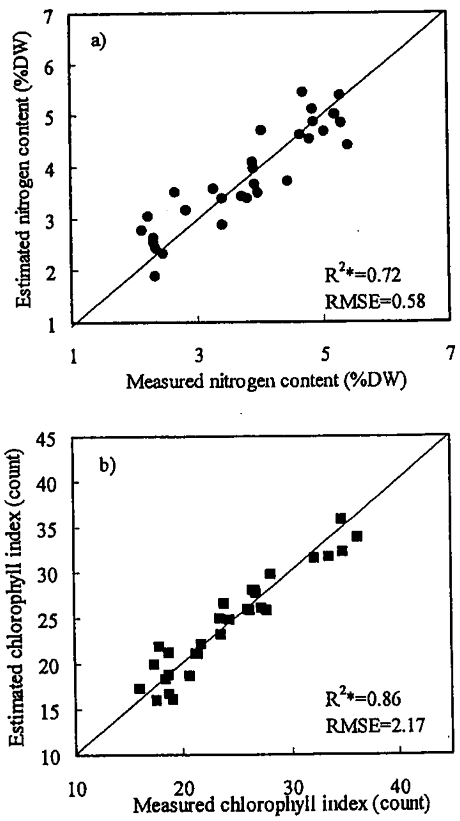


Fig. 15 Regression trials using hyperspectral measurements for estimating a) plant nitrogen content, and b) chlorophyll index.

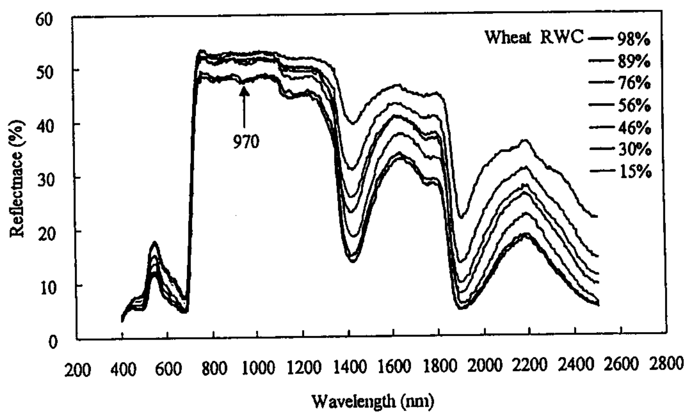


Fig. 16 Changes in reflectance spectra of plant leaves during progressive desiccation.

simplicity especially when reflectance measurements are available at some limited number of wavelengths. Nevertheless, when spectral values at a large number of consecutive wavelengths, it may be the best way to utilize the whole spectra as input to radiative transfer model. It has been shown that an iterative inversion of reflectance model, making the most of abundant data by hyperspectral measurement, would yield sound parameterization for the model. In the present study, we examined the feasibility of this approach using a reflectance model with hyperspectral measurements. The model has three unknown parameters, i.e., water and chlorophyll contents and structural index that can be estimated by iterative inversion of the model using hyperspectral data. We used whole spectral data in the region from 400 nm to 2500 nm. Figure 20 shows the comparison between the directly measured water content and that obtained by model inversion. There is a highly linear relationship between the two independently derived water contents. The relationship for wheat, corn and soybean was very close to each other and to the 1:1 line as well. The simulated spectra by the model with the optimized parameters agreed well to the measured spectra (Fig.21). Results suggest that this inversion approach based on hyper-spectral measurements has potential in the estimation of plant physio-chemical variables of plant. Nevertheless, there is a good example (i.e., results for peanut leaves) that indicates the importance of model tuning. In this particular model, the structural parameter N was expressed as a function of specific leaf area, but the discrepancy found for peanut leaves suggests that the model does not account for the structural property of some species. It would be needed to further refine the model tuning in physiologically meaningful manner.

5. Conclusions

1) It was confirmed there is a close correlation between photosynthesis and transpiration rates based on experimental study. Photosynthetic productivity can be estimated via transpiration by remote sensing method.
2) Transpiration and conductance on the leaf and canopy scales could be inferred by combination of remotely sensed thermal data and biophysical modeling.
3) The Vegetation Index – Temperature Trapezoid (VITT) concept has been proposed to estimate the physiological vigor by remote sensing. The relative position in the VITT coordinates can be indicative of water availability of any terrestrial surface. The WAVI (Water Availability Index) was closely correlated with the photosynthetic rate of plant leaves. On the basis of airborne and ground data set, the VITT approach proved to have potential in estimation of plant productivity and stress detection.
4) An AOTF-based hyperspectral imager for field use has been developed. The nitrogen and chlorophyll contents were estimated by multiple-regression using hyperspectral data.
5) Several hyperspectral indices such as R900/R970 were found to be useful in the estimation of leaf water content. The inversion of reflectance model using hyperspectral measurements proved useful in the estimation of water and pigment concentrations.

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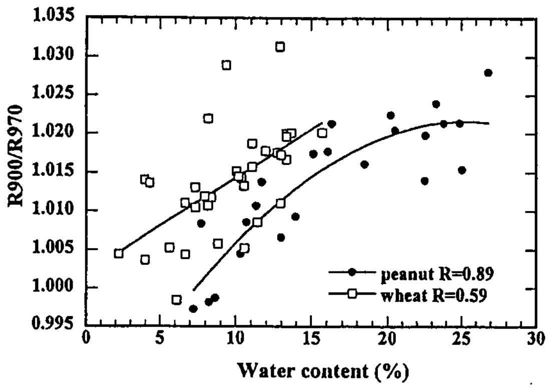

Fig.17. Relationship between spectral index R900/R970 and water content.

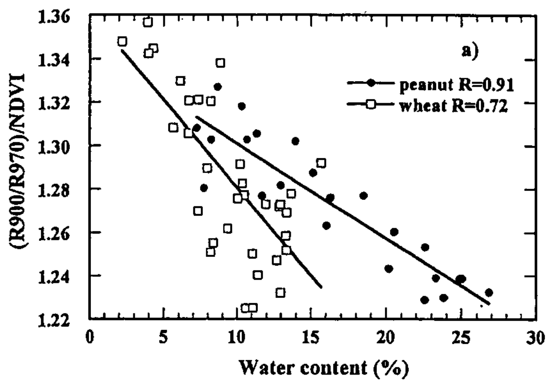

Fig. 18 Relationship of spectral index (R900/R970)/NDVI with water content.

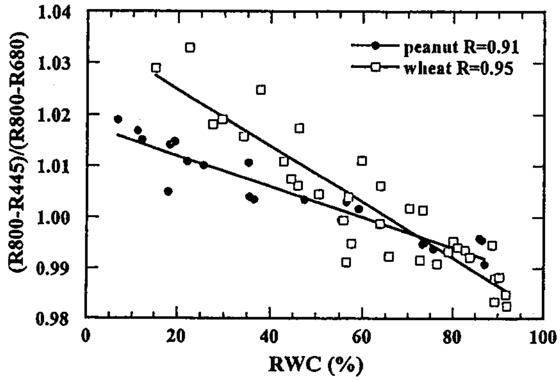

Fig. 19 Relationship between spectral pigment index and relative water content.

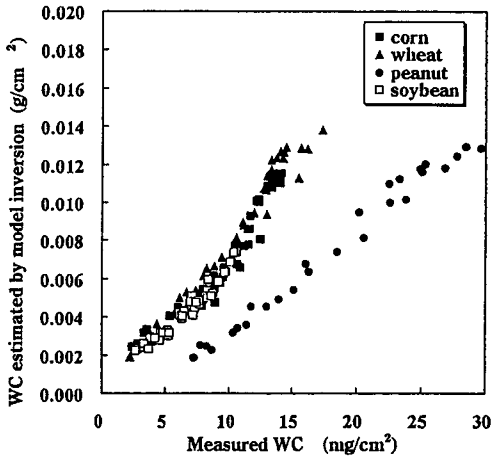

Fig. 20 Relationship between measured leaf water content and those estimated by model inversion

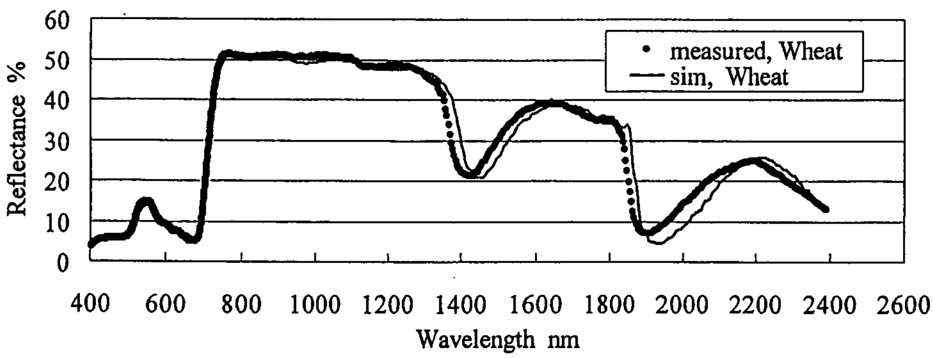

Fig. 21. Comparison of reflectance spectra measured and simulated by the leaf reflectance model.

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