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Developing the Monitoring Method for Plant Water Stress Using Spectral Reflectance Measurement

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Abstract: Monitoring of the plant water stress is useful to understand the vegetation response to precipitation, temperature and studies on vegetation environment adaptability and to aid in irrigation scheduling for agriculture. Remote sensing has a powerful potential to monitor these stress signals from its spectral reflectance information without actually being at the target area. In this study, we attempted to develop an index to indicate water stress derived from plant leaf reflective information without damaging samples. *Hibiscus rosa-sinensis* was used for this study. Spectroradiometer (© EKO MS-720), which can sense reflectance in the wavelength between 350 - 1050 nm at 3.3 nm interval, was used to measure leaf surface reflectance. Two pot sets of both stressed and controlled sample plants were analyzed for plant water stress measurement by using detached leaves with pressure chamber (PMS Model 600) after their spectral measurements. Normalized Difference Indices (NDIs) were adopted to extract the signal of plant water stress from the leaf surface reflectance. NDIs can be calculated by the following equation. $NDI_{(a,b)} = (R_a - R_b) / (R_a + R_b)$, where, R_a and R_b are reflectance values in the wavelength at *a* nm and *b* nm, respectively. Every combination of 10 nm interval wavelength of NDI was examined to see if correlations with plant water stress exist. As a result, wavelength combination of 490 nm, 620 nm were found out to be the most strong correlation (r = 0.86) between NDIs and plant water stress. Difference of the reflectance in blue band and yellow-red band is indicated to be an indicator of plant water stress.

Key Words: Hibiscus, Normalized Difference Indices, Plant water stress, Spectral reflectance, Spectroradiometer

1. Introduction

Plants absorb water from the soil through their roots. When water supply is insufficient, plants may suffer water stress which could compromise their growth production, reproduction and survival (Govender *et al.*, 2009). Plant water stress can be evaluated by directly measuring its leaf water potential with pressure chamber (**Fig. 1**). However, this method is destructive and not suitable for applying to large scales. Non-destructive method to detect the plant water stress is useful for monitoring the status of vegetation cover and to aid in irrigation scheduling for agriculture. There have been a lot of efforts to detect plant water stress using remote sensing, which technique is non-destructive and suitable for a large scale monitoring. Several spectral indices from remote sensing techniques have been used for the remote assessment of plant water stress, i.e., Photochemical Reflectance Index (PRI: Gamon *et al.*, 1992), Normalized Difference Water Index (NDWI: Gao, 1995), and Water Band Index (WBI: Penuelas *et al.*, 1995). NDWI consists of the ratio of the difference between reflectance in wavelength of 860 nm and 1240 nm divided by the sum of those reflectance values. WBI can be derived from the ratio of reflectance values in 900 nm and 970 nm. PRI consists of the ratio of the difference between reflectance in wavelength of 570 and 531 nm. Another metric for detecting plant water stress is focused on red edge (maximum slope of vegetation reflectance from 690 to 740 nm). This red edge shifts toward shorter wavelength (i.e., blue-shift) (Carter, 1993; Clay *et al*., 2006; Govender *et al*., 2009).

Nevertheless, difficulties are encountered in measuring longer wavelength (viz. longer than middle infrared and short-wave infrared) with handy spectroradiometer and in deriving suitable index for the plant water stress from the red edge blue-shift. In this study, we examined all the 10 nm narrow-band combination of Normalized Difference Indices (NDIs) (e.g., Inoue *et al.*, 2008), where Normalized Difference Vegetation Index (NDVI) and PRI are included, to find the best metric to detect plant water stress by using handy spectroradiometer which covers from visible and near infrared spectral regions.

2. Materials and Methods

2.1. Measurements of leaf surface spectral reflectance and leaf water potential

Hibiscus rosa-sinensis (average 24 - 27 cm height) was selected to monitor plant water stress for this study.

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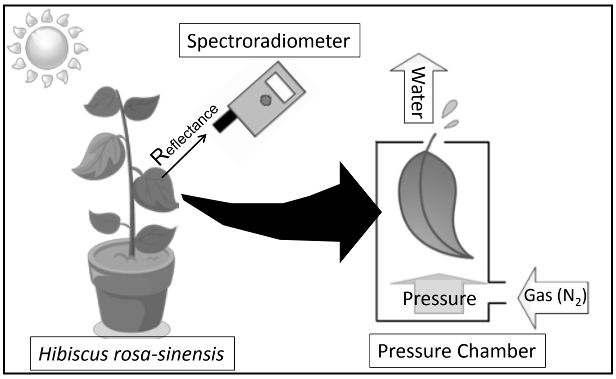

Fig. 1. Schematic image of measuring leaf surface spectral reflectance and leaf water potential using a spectroradiometer and pressure chamber.

Spectroradiometer (© EKO MS-720, FOV = 10^o), which can sense reflectance in the wavelength between 350 - 1050 nm at 3.3 nm interval, was used to measure leaf surface reflectance. Spectroradiometer was set apart in the distance of 6 cm so that the target diameter on the leaf surface would become ca. 3 cm at the spectral reflectance measurements. Reflectance data were derived from calibrating by the reflectance of white reference panel (Spectralon, ASD Inc.). Two pots of both stressed and controlled sample plants were analyzed for plant water stress measurement by using pressure chamber (PMS Model 600) with the detached leaves after their spectral measurements. Predawn leaf water potential measurement has been reported to be the reliable method to determine plant water stress (Dixon, 1914). However, in this study we measured the leaf water potential around at noon in order to make correspondence with the timing when leaf surface spectral reflectance was taken (Fig. 1).

Experiment was conducted on sunny days during Aug. 7 to Aug. 22, 2009 at outside of the campus of Tokyo University of Agriculture, Tokyo, Japan. Samples were sheltered from the rain water in the rainy days (Aug. 10, 15 and 18). Irrigation was conducted every day after the measurements so that the weight of the pods remains the same for the controlled samples, while not enough irrigation was conducted for the stressed samples. The detail of the duration of irrigation days for stressed samples was shown in **Table 1**.

Table 1 Condition of the stressed plant samples for experiment

DOY	219	220	221	222	223	224	225	226
Weather	Sun	Sun	Sun	Rain	Sun	Sun	Sun	Sun
Irrigation	No	No	No	No	No	No	Yes	Yes
Status								
DOY	**227**	**228**	**229**	**230**	**231**	**232**	**233**	**234**
Weather	Rain	Sun	Sun	Rain	Sun	Sun	Sun	Sun
Irrigation	Yes	Yes	No	No	No	No	No	No
Status						Wilt	Wilt	Wilt

DOY: 219 corresponds to Aug. 7, 2009.

2.2. Measurements of ancillary data

As ancillary information to indicate plant water stress, soil pF and the difference of temperatures between air and leaf surface were also measured during the experiment. Relationship between pF and water content were determined by centrifuge method (pF 1.0 - 2.5) and pressure plate method (pF 2.5 - 4.0).

Leaf surface temperature was measured by an infrared radiation thermometer (CEM Co., Ltd.) before spectral reflectance measurements.

2.3. Development of normalized difference index for plant water stress

We adopted narrow-band (10 nm range) combination of Normalized Difference Indices (NDIs) for the plant water stress indicator. Reflectance data interval was modified into 10 nm from 3.3 nm. NDI at the two narrow-bands in the wavelength at *a* and *b* nm ($NDI_{(a,\, b)}$) can be expressed as following equation.

$$NDI_{(a,\,b)} = \frac{R_a - R_b}{R_a + R_b} \qquad \textbf{equation (1)}$$

Where R_a and R_b are reflectance in the wavelengths at *a* nm and *b* nm. We examined all the 10 nm narrow-band combinations at *a* and *b* nm to calculate NDIs to find the best metric for detecting plant water stress. Regression analysis was conducted between every NDI and the corresponding leaf water potential. The correlation coefficient value (*r*) was used to determine the most effective NDI relate to plant water stress.

3. Results and Discussion

The monitoring results on soil pF, difference of air and leaf surface temperature and leaf water potential of the stressed pod plant are showed in **Figure 2**. Soil continuously increased in its pF value except during after being irrigated from DOY of 225 to 228. As soil pF gets higher, difference of air and leaf surface temperature tended to become higher, and leaf water potential tended to be lower on the stressed pod plant. Since soil pF of controlled (non-stressed) pods were maintained to be between 2.5 - 2.7 during the experiment, no tendency was seen for both in temperature difference (ranges between -3.65 - 5.55°C) and leaf water potential (ranges between -0.46 - -0.12 MPa). Leaf water potential had a strong correlation (r = 0.74) with Soil pF.

All the combination of the leaf surface reflectance in the wavelength at *a* nm and *b* nm (R_a and R_b, respectively) were assigned into **equation (1)** to calculate $NDI_{(a,\, b)}$. **Figure 3** shows the correlation efficient values between NDIs and leaf

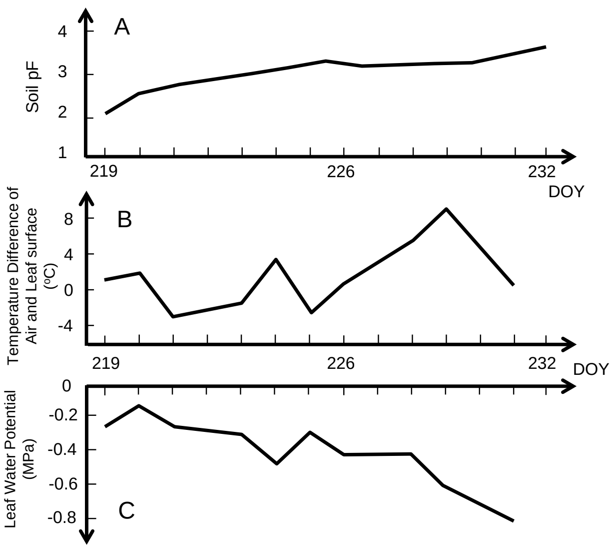

Fig. 2. Measurement results (Where, (A) Soil pF, (B) difference of air and leaf surface temperature and (C) leaf water potential of the stressed pod plant during Aug. 7 to Aug. 22, 2009).

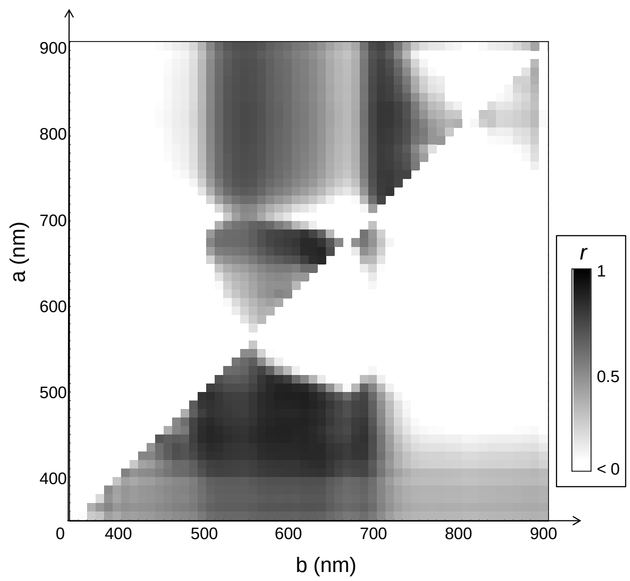

Fig. 3. Distribution of correlation efficient value between leaf water potential and normalized difference index (NDI) calculated from each combination of reflectance in the wavelength at *a* and *b* nm. NDI at (a, b) = (490, 620) shows the maximum value of *r* = 0.86.

water potential. NDI$_{(490,\ 620)}$ showed strong correlation with leaf water potential and the highest value in correlation coefficient (r = 0.86, P < 0.001). This result revealed that this NDI was the best metric to detect plant water stress among all the combinations of NDIs. The other NDIs showed very strong correlation (r > 0.85, P < 0.001) with leaf water potential were found out to be around the NDI$_{(490,\ 620)}$ in the correlation efficient distribution space of Figure 3, viz., NDI$_{(480,\ 620)}$, NDI$_{(490,\ 610)}$, NDI$_{(490,\ 600)}$ and NDI$_{(490,\ 590)}$. NDVI, which can also be expressed as NDI$_{(850,\ 650)}$, had no significant correlation with leaf water potential (r = 0.35, P = 0.12). PRI, i.e., NDI$_{(570,\ 530)}$, had a slight correlation with leaf water

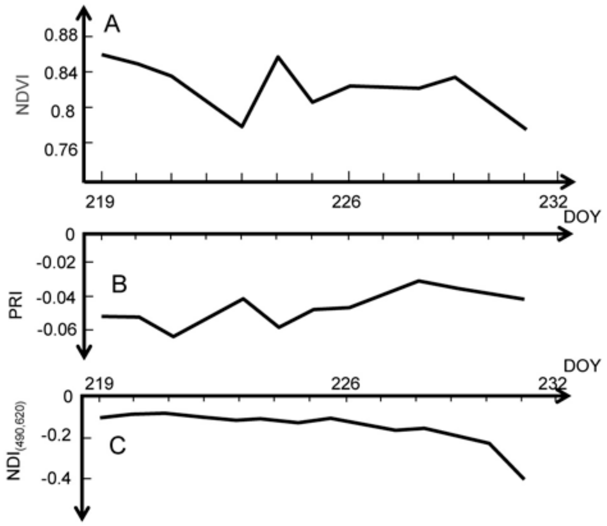

Fig. 4. Calculated result (Where, (A) NDVI, i.e., NDI$_{(850,\ 650)}$, (B) PRI, i.e., NDI$_{(570.\ 530)}$, (C) NDI$_{(490,\ 620)}$ of the stressed pod plant during Aug. 7 to Aug. 22, 2009.

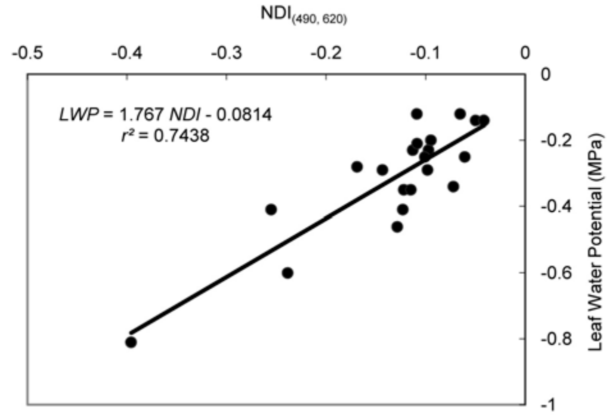

Fig. 5. Correlation between Leaf water potential (LWP) and normalized difference index of 490 and 620 nm (NDI$_{(490,\ 620)}$), which had the highest correlation coefficient value (0.86) among all (a, b) combinations (cf. Fig. 3).

potential (r = -0.45, P = 0.04) (see NDI$_{(530,\ 570)}$, r = 0.45 in Figure 3).

Time series on three NDIs, viz., NDVI, PRI, and NDI$_{(490,\ 620)}$ for stressed pod are shown in **Figure 4**. A slight tendency can be seen as the degree of water stress increases, i.e., decrease in NDVI and NDI$_{(490,\ 620)}$, and increase in PRI. Since each target leaf sample was removed and changed after the surface temperature and spectral reflectance measurements before leaf water potential measurement, slight fluctuation corresponding to leaf water potential fluctuation (cf. Figure 2C) can be seen for each NDI (e.g., DOY=224). However, the decreasing trend corresponding to leaf water potential was the most significant at NDI$_{(490,\ 620)}$ and this resulted the strong positive correlation of the two metrics (**Fig. 5**).

Figure 6 shows the succession of spectral reflectances of stressed plant leaf surfaces in time-series focusing on the wavelength region where NDI$_{(490,\ 620)}$ is involved. Reflectance in the wavelength region between ca. 550 - 650

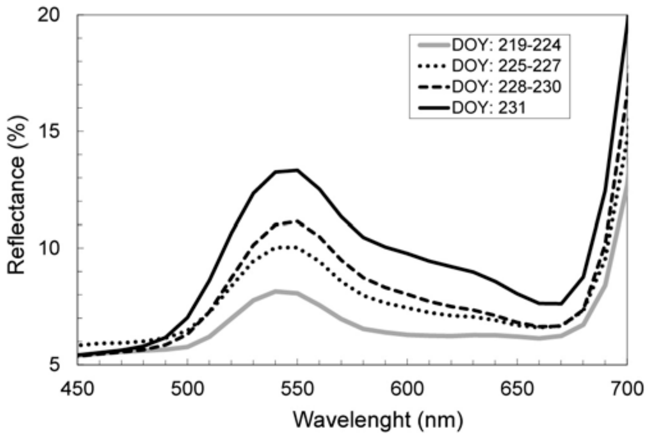

Fig. 6. Spectral reflectance curves of stressed plant leaf surfaces between 450 - 700 nm wavelength region. The averaged spectra in DOY of 219 - 224, 225 - 227, 228 - 230 and 231 are plotted in the space.

nm increases as the water stress increases, while relatively invariant in ca. 480 - 490 nm. This result is responsible for the high correlation coefficient value ($r > 0.85$, $P < 0.001$) between leaf water potential and NDI narrow-band combination at ca. 480 - 490 nm versus ca. 600 - 620 nm. Another feature which can be seen in this figure is the blue-shift of red edge (wavelength at 680 - 690 nm).

The increase of the reflectance in the wavelength at ca. 550 - 650 nm might be explained by the interaction of leaf pigment composition. Relatively very low reflectances in the wavelength at 480 - 490 nm in all the stages of water stress are assumed to be the results of high absorption of chlorophylls and carotenoids, and this result indicate that chlorophylls should still have high absorption in the 650 - 680 nm region. However, the result of blue-shift of red edge indicates a decrease in chlorophyll absorption (Curran *et al.*, 1991). Important information about response and adaptation of plants to environmental stresses are considered to be indicated from anthocyanin content in leaf (Gitelson *et al.*, 2001; Gitelson *et al.*, 2009). Increase in anthocyanins contains the possibility of the consequence of spectrum succession. However, according to the results of Gitelson *et al.* (2001, 2009), anthocyanin absorption maxima in vivo were found between 537 and 542 nm, where reflectance increased contrarily in this study. Satisfactory explanation of the results that absorption in wavelength of 620 nm (yellow-red band) of the leaf decrease as plant water stress proceeds is not yet provided. However, the change in combination of the leaf pigments can be pointed out for the one possibility of this spectrum change.

4. Conclusion

We tested all the narrow-band combinations in normalized difference index (NDI) which variables consist from two narrow-band reflectances of leaf surface to have relation with leaf water potential. As a result, we found that normalized difference index of the reflectance in blue band (490 nm) and yellow-red band (620 nm) is an indicator for plant water stress. Much work remains to be done to identify the change in composition of leaf pigments under the condition of water stress.

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