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HYPERSPECTRAL MANIPULATION FOR THE WATER STRESS EVALUATION OF PLANTS

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Abstract: There are high demands for water content estimation in vegetation, e.g. water-stress control for sweet crops, forest disease monitoring and drought monitoring. In this paper, normalized difference-based and ratio-based water stress indices by means of hyperspectral information from NIR to SWIR, spectral ranges of InGaAs sensor, are introduced to facilitate realizing simple measurement system at reasonable cost. Regardless of the simple definition, sufficient estimation accuracies are realized in the proposed indices under the condition of laboratory observation. The experimental results based on airborne hyperspectral forest images showed that the water-stress indices are useful to detect oak wilt areas.

Keyword: Hyperspectral data, water stress, vegetation, normalized difference index, ratio-base index.

1. INTRODUCTION

There is a high demand for vegetation monitoring by remote sensing. Environmental monitoring is one of the principal motives of the demand. The estimation of global distribution of biomass as CO_2 storage occupies an indispensable position in the prevention of global warming. Disaster damage map caused by natural disaster, e.g. forest fire and forest mortality by tree disease, is an important information source for disaster management. From the viewpoint of farm management, the acquisition of the growth state of farm products is required for precision farming. Global crop forecasting based on remote sensing is a valid measure for the stabilization of the food supply and distribution.

Hyperspectral remote sensing provides a reliable source for qualitative and quantitative estimation of the activity in vegetation. In regions from visible-infrared (VNIR) to shortwave infrared (SWIR), spectral profiles of leaves are well-approximated by a model defined by dry matter contents and pigments, e.g. chlorophyll, carotenoid, and water [1], [2]. Pigments with strong absorption peaks at corresponding narrow spectral bands are estimated by the comparison between absorption peak bands and pigment-independent reference bands. Normalized difference vegetation index (NDVI) [3] is a well-known measure of vegetation activity. Reflectance at near- infrared, i.e. 700-1300nm, is significantly correlated with the thickness of leaf in leaf scale [4], as well as with leaf area index (LAI) in canopy scale [5]. Reflectance at the red band indicates chlorophyll concentration level because chlorophyll contains narrow peaks at 662nm (chlorophyll a) and 642nm (chlorophyll b). Therefore, vegetation with large quantity of biomass and high chlorophyll concentration shows high value in NDVI, which is an index defined by a normalized difference between near-infrared and red bands.

The neighboring region around the absorption peak is also affected by the change in pigments due to the continuity in hyperspectral profile. Therefore, the reflectance not at pigment's absorption peak could be a clue for pigment estimation. The bands at non-absorption peaks are utilized in some indices. In [6], ratio-base indices of chlorophyll content are defined by means of green/red edge bands instead of red band to avoid the saturation of NDVI in case of high concentration of chlorophyll.

In spectral region from NIR to SWIR, water contains a feature as a pigment with narrow absorption peaks, i.e. it is possible to estimate water content based on normalized difference-base and ratio-

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base indices defined by water absorption-related bands and the reference bands. There are potential demands for water content estimation in vegetation. Water stress has a positive effect on the sugar contents in some crops, i.e. fruit, green soybeans, and sweet potatoes. However, an appropriate control of water stress is required because there is a decline in the fruit size and the total crop in case of overly water-stressed vegetation. Tree fungal disease, e.g. oak wilt, causes massive mortality in forests. Since the stoppage of sap flow by fungi results in wilt, it is possible to detect an early stage of affected trees before the outbreak of the disease by estimating water stress distribution in forest. Drought monitoring is an important technology from agricultural and environmental view points.

In this paper, normalized difference-based and ratio-based water stress indices by means of hyperspectral information from NIR to SWIR are introduced. New water stress indices based on spectral ranges of InGaAs sensor are proposed. Regardless of the simple definition, sufficient estimation accuracies are realized in the proposed indices under the condition of laboratory observation. Water stress indices are applied to airborne hyperspectral forest images to detect oak wilt trees.

2. WATER STRESS INDICES

In the spectral region from infrared to shortwave infrared, there are some narrow absorption peaks contained in water, i.e. strong absorbance around 1450nm and 1950nm, and weak absorption around 970nm and 1200nm [7], [8]. Fig. 1 shows spectral reflectance profiles of a fresh and dry Japanese oak leaf from 350nm to 2500nm, in which significant changes around 1450 and 1950 are confirmed. Because of the continuity in hyperspectral profile, neighboring regions around the absorption peaks are affected by a change in water content as well.

In hyperspectral remote sensing field, water stress is estimated by comparison between water absorption-related bands and the reference bands. Water index (WI) [9] and Moisture Stress Index (MSI) [10] are ratio-based indices as shown in Equation (1) and (2).

$$WI = \frac{R_{900}}{R_{970}}, \tag{1}$$

$$MSI = \frac{R_{1599}}{R_{819}}, \tag{2}$$

where R_λ is a reflectance at λ nm. 900nm and 819nm are water independent reference bands. 970nm is a water absorption peak. Although 1599nm in Equation (2) is not a water absorption peak, the reflectance around 1599nm is affected by absorption peak at 1450nm. The increase of water content causes the high value in WI, whereas MSI value is reduced in accordance with the growth in moisture level.

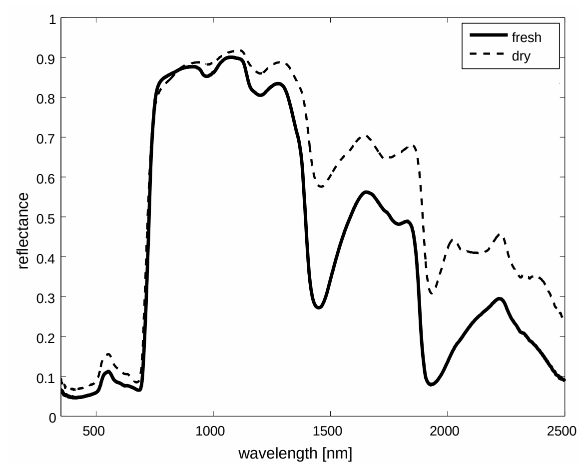

Figure 1: Reflectance of a fresh and dry oak leaf

Table I: R^2 values between water content and water related index

index	$NDWI_{1240}$	$NDWI_{1640}$	$NDWI_{2130}$	*NDII*	*WI*	*MSI*	Red edge
R^2	0.8294	0.8797	0.6874	0.8911	0.9173	0.8984	0.4578

Normalized difference water index ($NDWI_{1240}$, $NDWI_{1640}$, $NDWI_{2130}$) [11], [12], [13], and Normalized difference Infrared Index (NDII) [14] are normalized difference-based indices as shown in Equation (3), (4), (5), and (6).

$$NDWI_{1241} = \frac{R_{860} - R_{1240}}{R_{860} + R_{1240}}, \tag{3}$$

$$NDWI_{1640} = \frac{R_{860} - R_{1640}}{R_{860} + R_{1640}}, \tag{4}$$

$$NDWI_{2130} = \frac{R_{860} - R_{2130}}{R_{860} + R_{2130}}, \tag{5}$$

$$NDII = \frac{R_{819} - R_{1649}}{R_{819} + R_{1649}}, \tag{6}$$

where 860nm and 819nm are water independent reference bands. 1240nm is a water absorption peak. The reflectance around 1640nm, 1649nm and 2130nm are affected by water absorption peaks (Fig. 1). NDWI and NDII are positively correlated with water content. In those indices, strong absorption bands around 1450nm and 1950nm are eliminated in order to avoid the effect of water vapor.

Stress in plant causes a "blue-shift" of the peak of the first derivative around red edge region from 680nm to 750nm [15], [16]. Water deprivation is one of the stress factors, so that the water stress is estimated by the peak position $\lambda_{rededge}$.

$$\lambda_{rededge} = \underset{\lambda\in[670 \quad 720]}{\arg mah} \frac{dR_\lambda}{d\lambda}, \tag{7}$$

R^2 values between water contents in camellia leaves and water-related indices are shown in table I. Leaf water contents in leaves are controlled from 52% to 17% by hot dry air. The leaf water contents are measured by the comparison between the leaf weight and the dry leaf weight. Hyperspectral reflectance data of targets and backgrounds are collected by ASD FieldSpec 3. The spectral range is from 350nm to 2500nm. The spectral resolution is 3nm at 700nm, 8.5nm at 1400nm, and 6.5nm at 2100nm. Data are recorded at wavelength interval of 1nm. The R^2 values in table I are based on 30 measurements.

It is shown that the water absorption-related indices are considerably correlated with water content, by contrast with lower correlation between red edge and water content. The poor estimation performance of red edge is caused by relatively rough spectral resolution, 3mm at red edge region, of the spectrometer compared with the small quantity of blue shift.

Table 2: R^2 values between water content and water related index

index	NDW_{1450}^{1100}	NDW_{1450}^{1280}	WI_{1450}	WI_{1450}^{1100}	WI_{1450}^{1280}	WI_{1401}	WI_{1160}^{1100}	WI_{1384}^{1280}
R^2	0.8323	0.8259	0.6600	0.7364	0.7345	0.7473	0.9087	0.8848

Each of most water stress indices, i.e. MSI, NDWIλ and NDII, is defined by a reference band at near infrared region, e.g. 819nm and 900nm, and an absorption related band at shortwave infrared region, e.g. 1240nm and 1640nm. Because of the spectral range restriction in spectral imagers, i.e. Charge Coupled Device (CCD) sensor has the sensitivity range from 400nm to 1000nm whereas the spectral sensitivity of Indium Gallium Arsenide (InGaAs) sensor ranges from 1000-1700nm, it is impossible to acquire the two bands by a single imager. Although the WI is defined by two bands covered by CCD sensor, the spectral information is not reliable because the bands are placed around the limit of the sensitivity, near 1000nm. Therefore, it is preferable to propose a new water index defined by bands within a spectral range covered by a single sensor, especially spectral range of InGaAs sensor containing water absorption peaks, with sufficient sensitivity response. On the other hand, in laboratory observation, spectral information at strong water absorption bands is accessible because the effect of water vapor is minute [17]. In this section, some of water stress indices defined by bands in the spectral range of InGaAs sensor are proposed. Reflectance at near-infrared, i.e. 700-1300nm, is significantly correlated with the cell structure and biomass [4], [5]. The spectral bands at 1100nm and 1240nm are local minima points in water absorption [7], so that it is expected that 1100nm and 1240nm are candidates for water-independent reference bands representing the structural information. New normalized difference water stress indices are defined by Equation (8) and (9).

$$NDWI_{1450}^{1100} = \frac{R_{1100} - R_{1450}}{R_{1000} + R_{1450}}, \tag{8}$$

$$NDWI_{1450}^{11280} = \frac{R_{1280} - R_{1450}}{R_{1280} + R_{1450}}, \tag{9}$$

In [6], it is shown that the absorption coefficient is highly correlated with an inverse of the measured reflectance. The estimation accuracy is improved by the product of the inverse and reflectance at a structure-related reference band. New ratio-base water stress indices are defined by Equation (10), (11) and (12).

$$WI = \frac{1}{R_{1450}}, \tag{10}$$

$$WI_{1450}^{1100} = \frac{R_{1100}}{R_{1450}}, \tag{11}$$

$$WI_{1450}^{1280} = \frac{R_{1280}}{R_{1450}}, \tag{12}$$

Besides, water absorption-related bands are optimized by maximizing the correlation coefficient between water contents and ratio-base indices defined in Equation (13) and (14).

$$WI_{\lambda_{opt}} = \frac{1}{R_{\lambda_{opt}}}, \tag{13}$$

$$WI_{\lambda_{opt}}^{\lambda_{ref}} = \frac{R_{\lambda_{ref}}}{R_{\lambda_{opt}}}, \tag{14}$$

where λ_{ref} is 1100 and 1280nm. The optimal bands for $WI_{\lambda_{opt}}$, $WI_{\lambda_{opt}}^{1100}$ and $WI_{\lambda_{opt}}^{1280}$ are 1401, 1160 and 1384nm, respectively.

R^2 values between water contents in camellia leaves and new water-related indices are shown in table II. The estimation accuracies of the proposed indices are approximately equivalent to that of conventional water indices (Table I). In addition, some of optimal bands, i.e. 1160nm and 1384nm, are applicable to airborne hyperspectral data affected by water vapor.

Hyperspectral images for evaluation are acquired by a CCD and InGaAS hyperspectral array sensors. The CCD image contains visible to near-infrared, 400-1000nm, spectral information with 5nm spectral resolution. The spectral range of the InGaAs image is from near-infrared to shortwave infrared, 1000-1700nm, with spectral resolution of 5 nm. Camellia leaves of a fresh, one-day air dried, five-day air dried, oak leaves of one-month air dried, and artificial leaves are arranged on paper in the range of image (Fig. 2a).

It is shown that all of water stress indices indicate the highest value in fresh leaves. Red edge, Fig. 2b, and inverse indices, Fig. 2e and 2h, suffer from shading effect. Ratio-based indices based on non-absorption peaks, i.e. Fig. 2i and 2j, show superior estimation accuracy at high water content area in leaf veins. The improvement of estimation accuracy at high water content is expected to be caused by defining the indices based on bands with relatively low absorption coefficient, i.e. 1160nm and 1384nm, as mentioned in [6].

3. OAK WILT DETECTION BASED ON AIRBORNE HYPERSPECTRAL DATA

On August 12th, 2008, June 12th, 2009, August 26th, 2009, a forest affected by mass mortality of oak wilt was observed by AISA airborne hyperspectral imaging system in Sakata, Yamagata, Japan. The image data contain visible to short wave infrared, 400-2500nm. The number of spectral bands is 195, and the spatial resolution is 1.5 meters/pixel. Reflectance images are calculated based on solar irradiance data observed by a hyperspectral irradiance sensor mounted on the airplane. Although the reflectance is affected by water absorption by atmospheric vapor, it is possible to evaluate the water stress distribution in local area by assuming the local uniformity of atmosphere.

Oak wilt is an infectious tree disease affected by fungi, i.e. Caratocystis fagacearum, which obstruct the upward flow of sap [18]. The expansion process is an annual cycle. After the dispersion of Platypus quercivorus, i.e. a vector of the fungi, around June, the outbreak of mortality continues from summer to winter. The water stress indices are promising measures for the prevention and extermination of mortality through early detection of affected trees before the outbreak. In color images Fig. 3a and 3c, oak wilt regions are colored in red. Because Fig. 3b was acquired before the outbreak of wilt, remarkable mortality is not recognized.

Fig. 3d, 3e and 3f show oak wilt distribution estimated by Normalized Wilt Index (NWI) [19]. The green, blue and red regions in Fig. 4 correspond to oak wilt trees in Fig. 3d, 3e, 3f, respectively. It is confirmed that i) affected trees in 2009 (red) are distributed around the neighborhood of wilt trees in 2008 (green), and ii) before the outbreak, detected trees before the outbreak are minor (blue). Water stress maps based on $NDWI_{2130} < 0.5$ and MSI < 1 are shown in Fig. 3g to 3l. Fig. 5 shows color composite images based on Fig. 3g to 3l. The red and green regions are oak wilt area in August, 2008 and August, 2009, respectively. The blue regions in Fig. 5a, 5b, 5e and 5f correspond to water stressed region in June, 2009. Blue regions in Fig. 5c, 5g are water stressed regions in August, 2008, and Blue regions in 5d, 5g are water stressed regions in August, 2009. The cyan regions are the intersection regions of blue and green regions, and the magenta regions are the intersection regions of blue and red regions. The water stress maps in Fig. 5c, 5d, 5g, and 5h show that water stress maps approximately coincide with oak wilt maps, although some small false detection fragments are scattered. Therefore, water stress indices are feasible for alternative indicators of oak wilt. In Fig. 5a and 5e, water-stressed regions approximately overlap with oak wilt region in August, 2008, whereas water-stressed regions in Fig. 5b and 5f disagree with oak wilt region in August, 2009. It is inferred that the reason why the detected water-stressed regions are related with the affected regions in 2008 rather than in 2009 is in the fact that the affected regions in 2008 are not fully recovered. During the observation on the ground in the concerned region on June 9th in 2009, it was confirmed that some trunks of oak trees were slightly attacked. But there was no sign of wilt because the perspiration level was low and the absence of grass denied the occurrence of mass attack. Therefore, it is expected that the affected trees on August 26th in 2009 are not water-stressed because fungi had not been sufficiently propagated to stop the sap flow.

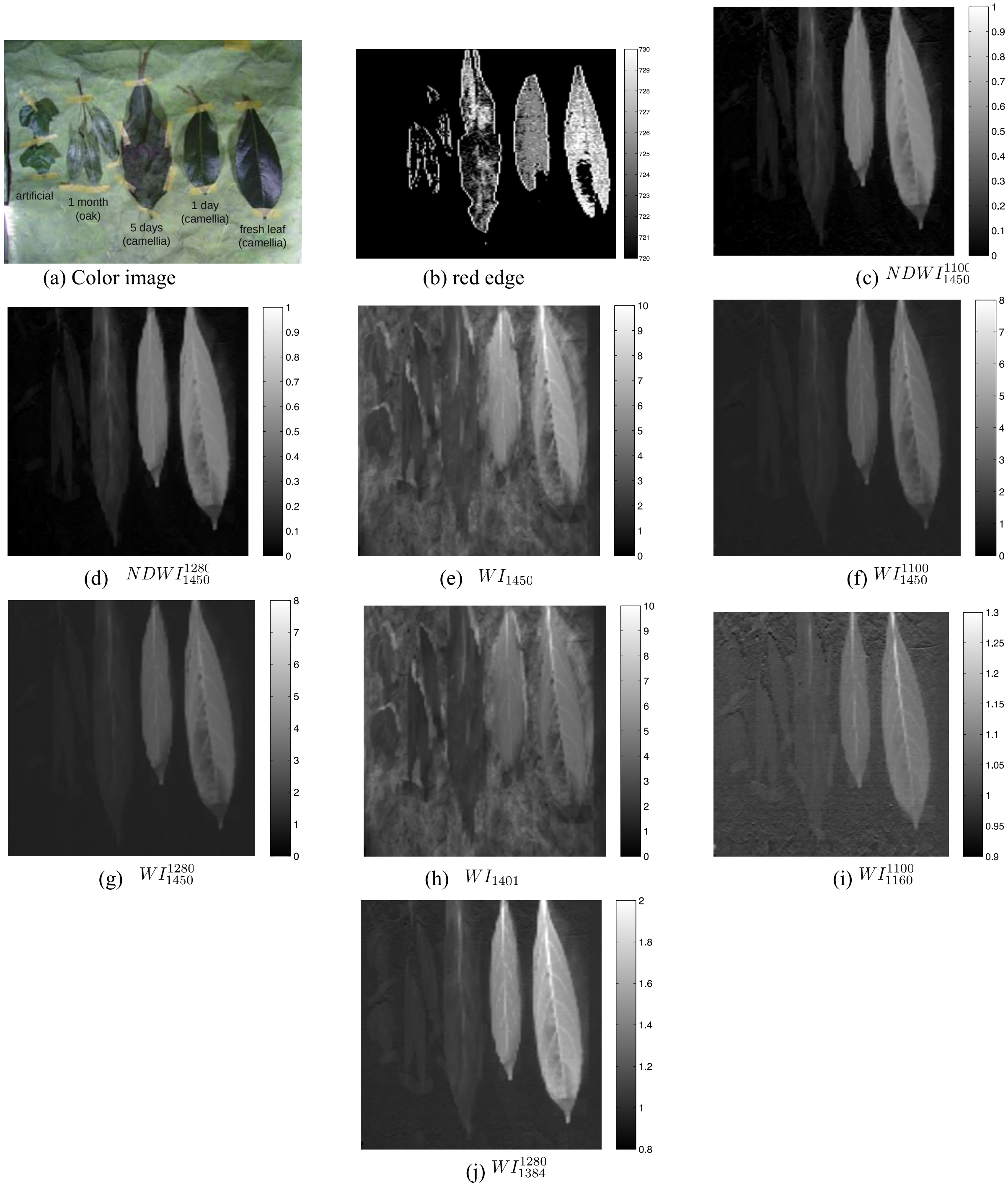

Figure 2: A color image and proposed water stress indices

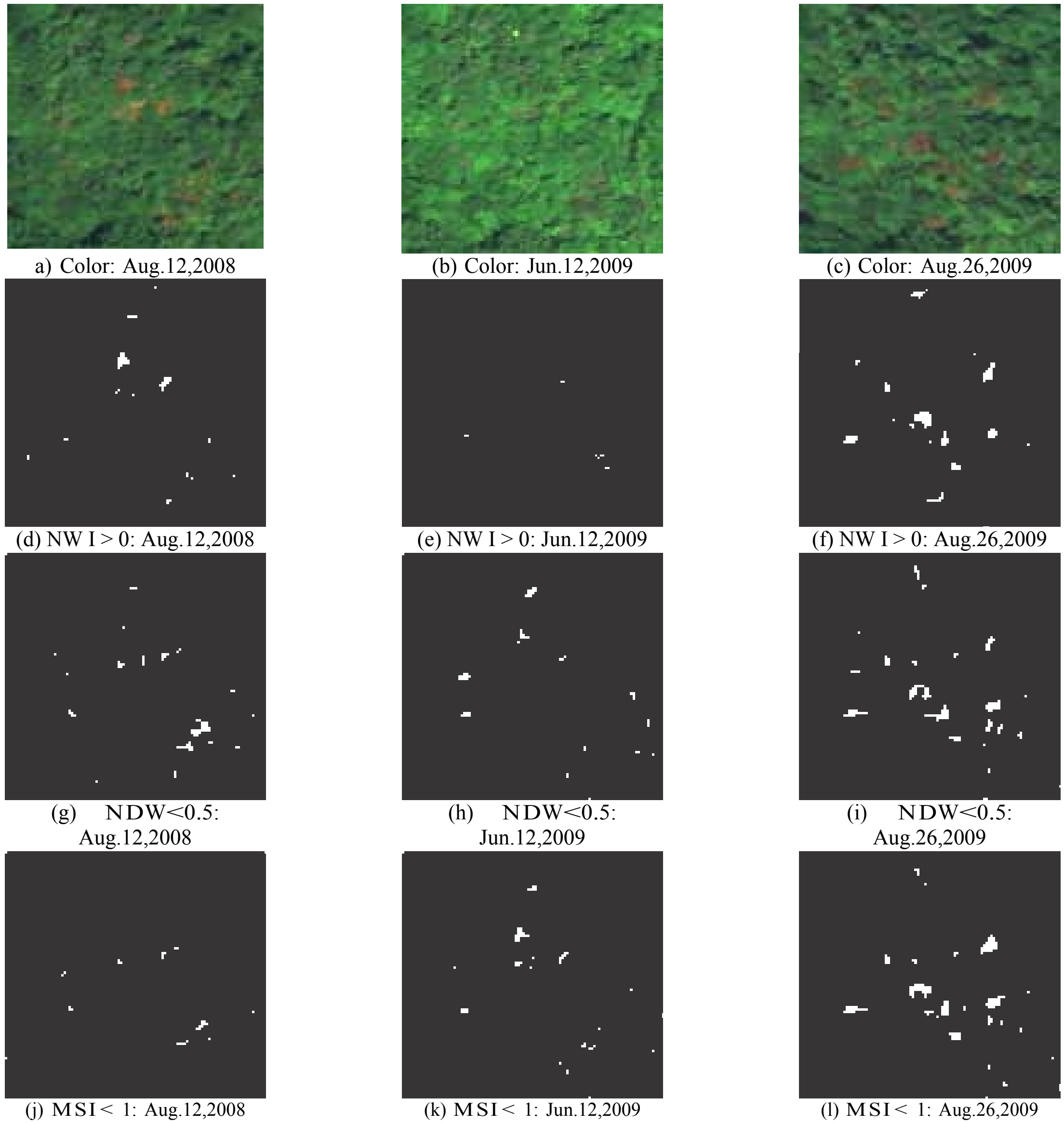

Figure 3: Color images and proposed water stress indices

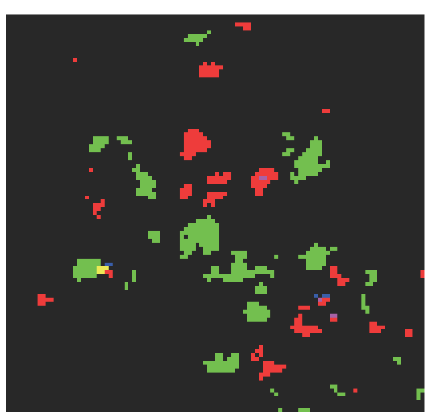

Figure 4: Oak wilt distribution: Green (Aug.12,2008), Blue (Jun.12,2009), Red (Aug.26,2009)

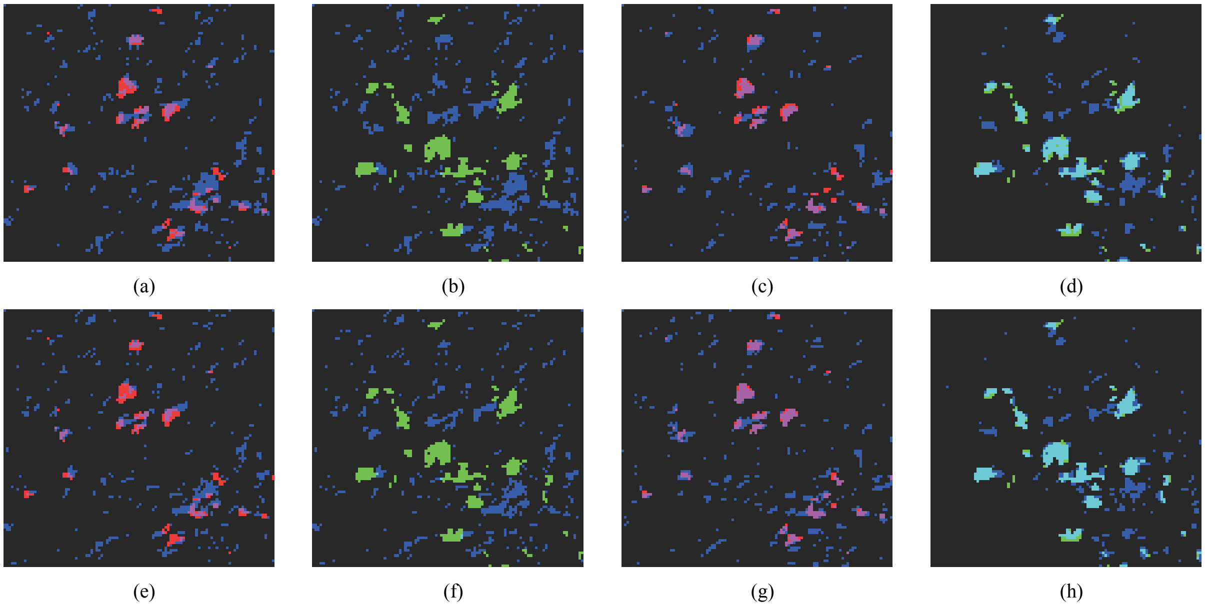

Figure 5: Oak wilt distribution and water stress indices, (a) Red (Oak wilt, Aug. 12, 2008), kBlue ($NDWI^{860}_{2130} \prec 0.5$,Jun.12, 2009), (b) Green (Oak wilt, Aug. 26, 2009), Blue ($NDWI^{860}_{2130} \prec 0.5$, Jun. 12, 2009), (c) Red (Oak wilt, Aug.12, 2008), Blue ($NDWI^{860}_{2130} \prec 0.5$, Aug.12, 2008), (d) Green (Oak wilt, Aug. 26, 2009), Blue ($NDWI^{860}_{2130} \prec 0.5$, Aug. 26, 2009), (e) Red (Oak wilt, Aug. 12, 2008), Blue ($NDWI^{860}_{2130} \prec 0.5$, Jun. 12, 2009), (f) Green (Oak wilt, Aug. 26, 2009), blue ($NDWI^{860}_{2130} \prec 0.5$, Jun. 12, 2009), (g) Red (Oak wilt, Aug. 12, 2008), Blue ($NDWI^{860}_{2130} \prec 0.5$, Aug. 12, 2008), (h) Green (Oak wilt, Aug. 26, 2009), Blue ($NDWI^{860}_{2130} \prec 0.5$, Aug. 26, 2009).

4. CONCLUSION

In this paper, we proposed new water-stress indices based on spectral ranges of InGaAs sensors, to facilitate realizing simple measurement system at reasonable cost. We also confirmed that the newly proposed indices show quite consistent results when compared with conventionally proposed ones under the condition of laboratory observation. The experimental results based on airborne hyperspectral forest images showed that the water-stress indices were useful to detect oak wilt areas. It is expected that water stress maps estimated by the water stress indices will be a promising means for the prevention against the vanishing of forests caused by forest fire and tree disease when hyperspectral satellite images are accessible by the launching of hyperspectral satellites in the near future.

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ПРИМЈЕНА ХИПЕРСПЕКТРАЛНЕ АНАЛИЗЕ ЗА ПРОЦЈЕНУ ВОДЕНОГ СТРЕСА КОД БИЉАКА

Сажетак: Постоје велики захтјеви у погледу процјене воденог садржаја у вегетацији, нпр. контрола воденог стреса код слатких житарица, праћења болести шума и праћења суше. У овом раду уведени су нормализовани индикатори воденог стреса заснованог на разлици односно коефицијенту, уз помоћ хиперспектралних података од NIR-а до SWIR-а, спектралних опсега InGaAs сензора, у циљу омогућавања постизања једноставног и економичног система мјерења. Без обзира на једноставну дефиницију, постигнуте су довољно прецизне процјене код предложених показатеља у условима лабораторијског посматрања. Експериментални резултати засновани на хиперспектралним снимцима шума из ваздуха показују да су индикатори водног стреса корисни при проналажењу подручја са увенулим храстом.

Кључне ријечи: хиперспектрални подаци, водени стрес, вегетација, нормализована разлика индекса, индекс заснован на односу коефицијента.