# Spectral Characteristics of Forest Vegetation in Moderate Drought Condition Observed by Laboratory Measurements and Spaceborne Hyperspectral Data

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## Abstract

*Although there have been several studies on the spectral characteristics related to leaf water content, it remains unclear whether the spectral property of leaves can be extended to the canopy-level. In this study, we attempt to compare the spectral characteristics of forest vegetation in moderate drought condition observed by laboratory measurement and satellite hyperspectral image data. Spectral reflectance data were measured from detached pine needles and oak leaves in the laboratory with a spectroradiometer. Canopy reflectance spectra of the same species were collected from temperate forest stands with dense canopy conditions using EO-1 Hyperion imaging spectrometer data obtained during the moderate drought season in 2001, and then compared with those obtained in the normal precipitation season of 2002. The relationship between leaf-level spectral reflectance and leaf water content was the clearest at the shortwave infrared (SWIR) regions. However, the canopy-level spectral characteristics of forest stands did not quite correspond with the leaf-level reflectance spectra. Further, four water-related spectral indices (WI, NDWI, MSI, and NDII) developed mainly with leaf-level reflectance were not very effective to be used with the canopy-level reflectance in dense forest condition. Forest canopy spectra under moderate drought status may be more influenced by canopy foliage mass, rather than by canopy moisture level.*


## Introduction

Symptoms of forest canopy stress vary with the length and magnitude of a drought, here *drought* is a combination of meteorological and hydrological drought (McVicar and Jupp, 1998), resulting in a physiological response. Lack of water content in vegetation can be major limitation to primary productivity, and as it reflects a drier than normal ecosystem, environmental problems such as wild fires (Roberts *et al*., 2003; Marod *et al*., 2004) can occur at such times. Monitoring of canopy drought condition is crucial for predicting vulnerability to forest fire and diseases and for estimating changes in forest productivity as a result of climate changes (Tian *et al*., 1998). Whether remote sensing can detect vegetation drought stress in forests depends on the spectral characteristics of leaf, canopy, and stand levels. To detect such drought-stressed forest vegetation, remote sensor data should provide proper sets of spectral, spatial, and temporal resolutions.

Spectral characteristics of leaf water have attracted research attention in the remote sensing community (Thomas *et al*., 1971; Tucker, 1980; Ripple, 1986). It has been relatively well known that the leaf reflectance decreases with increasing leaf water content (Hunt and Rock, 1989; Aldakheel and Danson, 1997; Ceccato *et al*., 2001). In particular, the wavelengths between 1,400 nm and 2,500 nm (shortwave infrared: SWIR) spectrum are known to be very sensitive to leaf water content (Tucker, 1980; Danson *et al*., 1992). Several studies also found that leaf water stress affects spectral reflectance in visible and near-infrared (NIR) wavelengths, which might be related to the change of leaf pigments and internal cell structure as a result of the leaf moisture stress (Knipling, 1970; Harris *et al*., 2005). Several ratio-based spectral vegetation indices have also been developed and tested for correlating with plant water content (Cohen, 1991; Stimson *et al*., 2005).

Although forest canopy water content may be an indicator to assess drought stress, most studies have focused on the spectral characteristics at leaf-level, and few have investigated canopy-level moisture content, in particular for forests with dense canopy closure (Bowyer and Danson, 2004). Remote sensing studies of canopy moisture stress have been primarily conducted over agricultural crop and semiarid vegetation areas (e.g., Ustin and Roberts, 1998; Jackson *et al*., 2004, Van Niel *et al*., 2003). In relatively dense forest remotely sensed estimation of the seasonal drought stress may be limited by small changes in the canopy's physical structure.

In a closed canopy, the spectral resolution of multispectral data may not be sensitive enough to assess the canopy water content. Recent developments in the technology of hyperspectral sensor data have provided the capability to detect minute variation of vegetation spectra (Ustin *et al*., 2004). Hyperspectral sensing may be an alternative to overcome such limitations by providing very narrow spectral bands enabling the observation of particular spectral features

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indicative of drought condition. There have been a few studies dealing with forest canopy spectral reflectance, in particular for forests having high crown closure. Asner *et al.* (2004) reported that several vegetation indices derived from satellite hyperspectral data were sensitive to the canopy water stress in dense tropical forests.

The drought condition in the relatively dense forests of temperate regions is very seasonal (in Korea's case during the spring), and with a short duration of only a few months may not cause any noticeable change in the forest canopy. In such a case, despite the absence of significant brownish appearance in the forest canopy, the understory herbaceous and shrub plants may undergo some degree of leaf drying. The main objective of this paper is to determine the spectral characteristics of relative dense forest canopy under such short-term drought conditions. We tried to compare the spectral characteristics of forest vegetation at both leaf- and canopy-levels, based on reflectance spectra obtained from laboratory measurement and satellite hyperspectral imagery. Our particular focus was on whether the spectral relationship obtained from laboratory measurement could be extended to the canopy level in a dense canopy forest environment.

## Materials and Methods

### Laboratory Measurements of Detached Leaf Spectra

To measure leaf-level reflectance spectra at different moisture levels, we collected sample leaves from 20-year-old pitch pine (*Pinus rigida*) and Korean oak (*Quercus mongolica*) trees in a suburban forest near Incheon, Korea. These trees are two most common species in the southern part of the Korean peninsula (Cha *et al.*, 1979). The sample leaves were stored in humid plastic zipper bags and brought to the laboratory within an hour after detachment. Reflectance spectra were continuously measured on the sample leaves as they were dried out using two 500-W halogen lamps placed at 50 cm over the sample.

Leaf reflectance spectra were measured at 1 m above the sample using a portable GER 2600 spectroradiometer with a 10-degree field of view (FOV) lens. The spectroradiometer can measure spectral reflectance over the wavelength region between 350 nm and 2,500 nm. More than double layers of sample leaves were arranged to completely cover the FOV area with a black paper background. At each measurement, the spectroradiometer actually provides percentage reflectance values for 612 continuous bands over the wavelength range from 350 nm and 2,500 nm. Reflectance measurements were performed every 10 to 20 minutes during the first two hours and continued until the sample leaves began to show noticeable symptoms of rolling and senescence. Simultaneously with the reflectance measurement, we also prepared the second set of sample leaves having the same initial condition and continuously measured the weight of the sample leaves that underwent the same drying process under halogen lamps. For the second set of leaves sample, the relative leaf water contents (RLWC) were obtained by dividing the weight by the weight of the first fresh sample.

### Preprocessing of Hyperion Data

Unlike the leaf-level reflectance, it is not easy to measure the reflectance spectra of forest canopy because of the difficulty to get above the canopy in the field, in particular for a forest with relatively dense and tall stand structure. We have chosen satellite hyperspectral image data to extract reflectance spectra at canopy-level. NASA's Earth Observing (EO-1) satellite Hyperion imaging spectrometer data provide 242 spectral bands, each approximately 10 nm wide, ranging from 356 to 2,577 nm, which enable us to obtain full reflectance spectra for every pixel. The EO-1 Hyperion data were the only available hyperspectral imagery over the study area. Among 242 spectral bands, those with high sensor noise, duplicated bands in the NIR spectrum due to the detector materials change (Pearlman *et al.*, 2003), and heavy atmospheric water absorption bands near 1,400 nm and 1,900 nm were removed to leave only 174 bands in the final analysis.

Hyperion pushbroom scanner imagery have spectral *smile* that is the cross-track wavelength shift from center wavelength for each band of all 242 bands (Goodenough *et al.*, 2003; Datt *et al.*, 2003). Across the 256 pixels per a scan line, the spectral variation of center wavelength is about 3 nm, which seems large enough to account for the 10 nm bandwidth of the sensor. Smile correction was carried out using the cross-track center wavelength calibration and full-width-at-half-maximum calibration files for the Hyperion instrument, which came with ACORN program (ImSpec, LLC, 2004). Atmospheric water vapor and aerosol are key factors in the atmospheric correction of optical remote sensor data. The atmospheric correction of hyperspectral data has a clear advantage over multispectral data, since the intensity of atmospheric water vapor at the time of data acquisition can be directly obtained from a few spectral bands of the data themselves. ACORN used two water absorption channels (940 nm and 1140 nm) in the Hyperion data to estimate the atmospheric water vapor at the time of data acquisition. Other atmospheric input data, such as atmospheric model and aerosol data, required by the program are obtained from a standard mid-latitude-summer atmospheric model and directly estimated from data themselves.

After initial radiometric and atmospheric correction, the data were georeferenced and converted to surface reflectance. The Hyperion image were georeferenced to plane rectangular coordinates using 56 ground control points (GCP) from 1:5 000 scale topographic maps. Total root mean squared error (RMSE) of the geometric registration was 0.311 pixels, equivalent to about 10 m.

### Extraction of Canopy Spectra from EO-1 Hyperion Data

For the study, two Hyperion images were acquired over the study area in the western part of South Korea in early-June 2001 and 2002. In recent years, the frequency and magnitude of forest fires have increased during the spring drought season in the Korean peninsula. This area experienced a relatively severe drought during the spring of 2001, resulting in damage by several forest fires. Forest in this area has a diverse species composition and stand ages between 20 to 50 years old. Since the forests in this region have been relatively well protected since the 1960s, the canopy closure is mostly greater than 80 percent (KFRI, 2002). Major forest types are natural stands of mixed deciduous species and pine plantation stands (*Pinus rigida* and *Pinus koraiensis*). The study areas also include non-irrigated cropland, pasture, and irrigated rice fields.

Although the average annual precipitation in this region is about 1,400 mm, two thirds of this is concentrated during the summer monsoon period of late June to August (Cha *et al.*, 1979). Figure 1 compares the cumulative precipitation of the first six months between 2001 and 2002. In the drought year of 2001, the cumulative precipitation was 150 mm less than the average at the time of the Hyperion image acquisition on 03 June, whereas that in 2002 almost followed the average annual precipitation. Since the spring growing season in this area starts in late-March, the spring rainfall is crucial to the leaf development of trees as well as other herbaceous plants.

Initially, we tried to compare the spectral characteristics of selected forest stands between 2001 (drought year) and 2002 (normal year). While it would have been ideal to have two scenes covering the same area, this was not

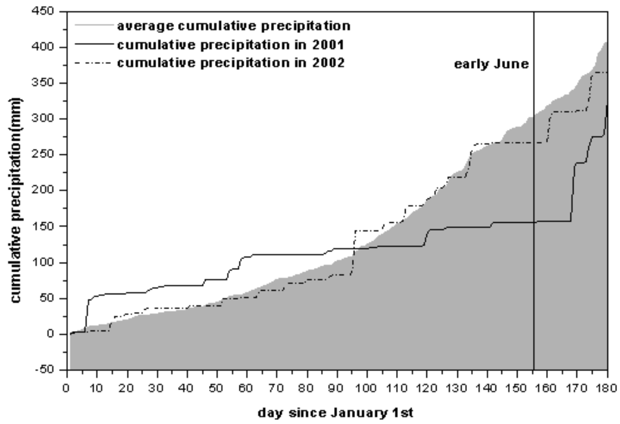


Figure 1. The cumulative precipitation of the spring drought in 2001 as compared to the normal precipitation year (2002).

Table 1. Stand Characteristics of Sample Forests to Extract Canopy Spectra from Hyperion Images

| Stands Characteristics | Pine 1 | Pine 2 | Hardwood 1 | Hardwood 2 |
|---|---|---|---|---|
| Dominant Species | *Pinus rigida* | *Pinus rigida* | *Quercus mongolica* | *Quercus mongolica* |
| Stand Age (year) | *35* | *35* | *30–40* | *40–50* |
| Canopy Closure (%) | 80 | 80 | 90 | 90 |
| Slope Aspect | north | east | south | west |

possible, and our two sites, located in the same broad ecosystem, are approximately 100 km apart (Figure 2). By the same broad ecosystem we mean that the sample forest stands selected for extracting canopy spectra have almost the same canopy structure (species, tree age, stand density), climate and topographic conditions (elevation, slope, aspect).

To locate sample forest stands for comparing canopy reflectance between 2001 and 2002, we used forest stand maps and 1:15 000 scale aerial photographs. The forest stand maps (1:25 000 scale) showed species group and average stand density, and average tree age and height. Further ground survey was conducted to verify whether each pair of sample stands has the same stand structure. We selected four pairs of forest stands from 2001 and 2002 scenes, and Table 1 shows the stand characteristics of sample forest selected for the study. Each forest stand was relatively large (at least 1 hectare) and homogenous enough to endure possible geometric error of the 30 m resolution Hyperion image data. To compare the canopy drought condition between forest and non-forest, additional sample plots were also selected from a pasture. During the ground survey, exact ground plot locations were determined using a differential global positioning system (DGPS).

Five pairs of sample plots (including four forest stands and a pasture) were located from each of two atmospherically corrected Hyperion data. For each sample plot, canopy reflectance spectra were obtained by averaging the reflectance values that were extracted from four pixels surrounding the sample plot.

Several spectral indices have been used to analyze drought stress in vegetation including: (a) normalized difference vegetation index (NDVI) using reflectance at 680 nm and 800 nm; (b) the water index (WI), which is a simple ratio using bands located at 900 nm and 970 nm (Penuelas *et al.*, 1997; Harris *et al.*, 2005) to enhance the spectral characteristics of water absorption features as the one band that is strongly absorbed by water and the other is not; (c) normalized difference water index (NDWI = (r860 − r1240)/(r860 + r1240)), which is a modified form of WI (Gao, 1996); (d) moisture stress index (MSI = r1650/r835, Hunt and Rock 1989); (e) normalized difference infrared index (NDII = (r835 − r1650)/(r835 + r1650); Hardisky *et al.* 1983). To compare whether these spectral indices were effective for assessing forest vegetation water status, we calculated the above five spectral indices using the reflectance data obtained from both the laboratory measurement and the Hyperion imagery.

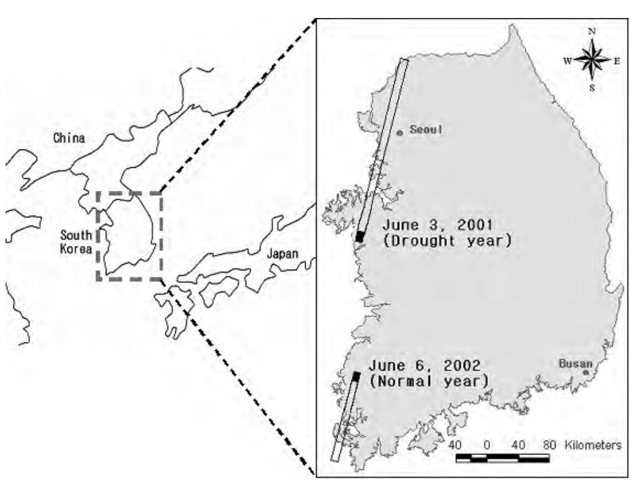


Figure 2. Location of two Hyperion images (7.5 km swath width) covering the study area.

## Results and Discussion

### Leaf Spectra of Laboratory Measurements

As time elapsed, the relative leaf water content (RLWC) change within the detached leaves began to differ between the two species (Figure 3). While the pine needles showed a gradual decrease in RLWC, the oak leaves showed a rather rapid decline within a few hours. Oak leaves lost about 50 percent of RLWC within four hours while pine needles lost only about 20 percent. Pine needles did not show any obvious visible symptoms of color change nor rolling up after 9.5 hours, although they showed partial yellowish appearance after 10 hours. However, oak leaves began to roll and brown after about 158 minutes. Although we could not determine the exact physiological limit of RLWC that may separate between *stress* and *dieback* of these two tree species, we may say that trees are under damage condition when leaves begin to roll and their color turns to yellow. In both species, a noticeable color change and rolling occurred at RLWC under 70 percent. Figure 3 indicates that pine trees may be more resistant to water deficiency than oak trees under drought condition.

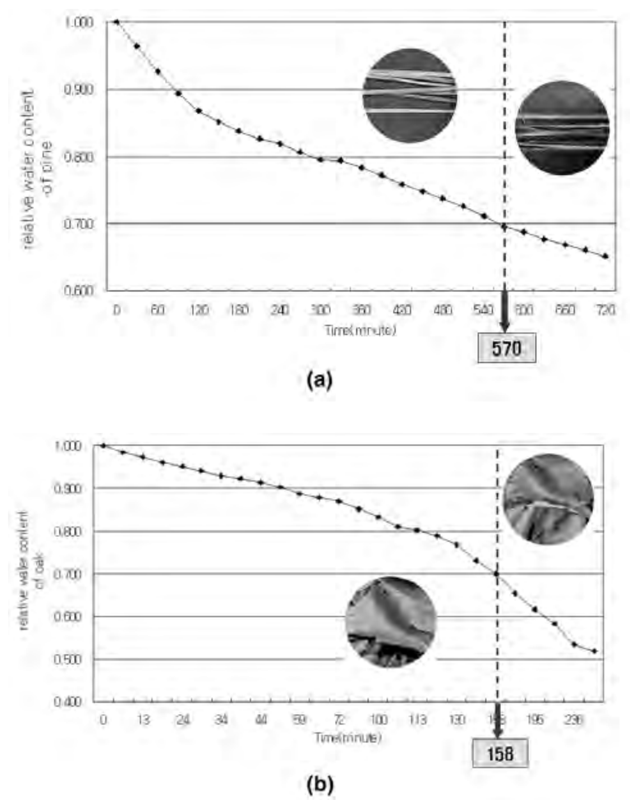


Figure 3. Change of relative leaf water content (RLWC) of sample leaves of (a) pine and (b) oak during the laboratory measurement. Dashed line indicates the time of rolling and yellowish of leaves.

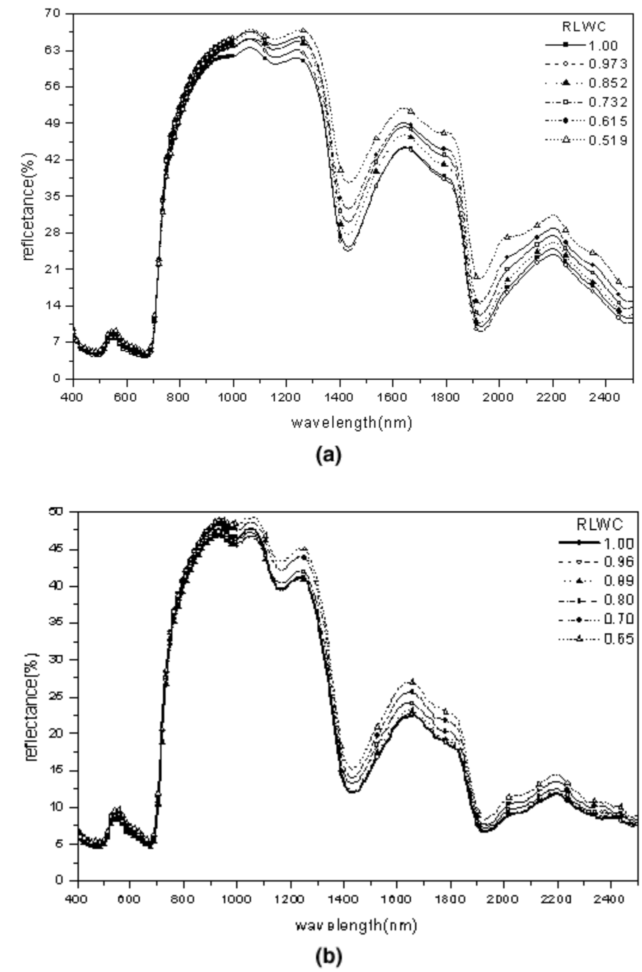


Figure 4. Leaf reflectance spectra obtained by laboratory measurements using a spectroradiometer: (a) pine needles, and (b) oak leaves.

Figure 4 shows laboratory measured reflectance spectra of pine needles and oak leaves with decreasing RLWC. As expected, the leaf spectra of both species showed only very minimal changes in visible wavelengths since pine needles and oak leaves did not reveal any evident color change until the last measurements. Leaf spectra in the SWIR region were highly sensitive to RLWC with the leaf reflectance increasing with decreasing RLWC.

Unlike the SWIR region, however, the range of NIR reflectance changes between the fresh and the 65 percent RLWC condition was very small for the pine needles. In this NIR portion of the spectrum, it has been known that internal leaf structure is a key factor influencing spectral reflectance (Gates *et al.*, 1965). Although internal leaf structure might be changed during dehydration, it did not have much effect on leaf reflectance. The NIR reflectance of oak leaves showed a fluctuation pattern similar to that of pine needles except that they increased from the first measurement. The gradual increase of oak reflectance in this wavelength range may also be explained by the changes of internal leaf structure during the drying out. Unlike the pine needles that did not show any morphological changes until 10 hours after the detachment, oak leaves showed gradual rolling about one hour after the first measurement. Morphological changes due to the rolling might affect the viewing surface (such as shadow) of leaves within the FOV of the spectroradiometer. Since double layers of leaves were completely covered within the FOV area, there would not be any significant effect from background. The reflectance values beyond the 1,100 nm followed the same pattern as the SWIR reflectance.

Water-related spectral indices were better than raw reflectance spectra for showing leaf water stress. As shown in Figure 5, the relationship of five spectral indices with RLWC using all of the laboratory measured reflectance data is apparent. Although the scale of each spectral index varies, the strength of the relationship with RLWC is slightly different each other. Among the spectral indices, MSI and NDII, which are based on both NIR (835 nm) and SWIR (1,650 nm) spectrum, show stronger relationship as compared with other indices (WI and NDWI) of using only NIR spectrum. Leaf-level spectral reflectance in the SWIR region seems to be mostly sensitive to RLWC. Our next concern is whether the spectral relationship observed from the leaf-level measurement can be extended to the canopy level.

### Canopy Spectra Obtained from Hyperion Image

Forest canopy spectra obtained from the satellite hyperspectral data were very different from the laboratory leaf measurements. Canopy reflectance of pine and mixed deciduous stands between the drought (2001) and normal (2002) seasons showed an inverse relationship with possible canopy water condition. Hyperion canopy spectra extracted

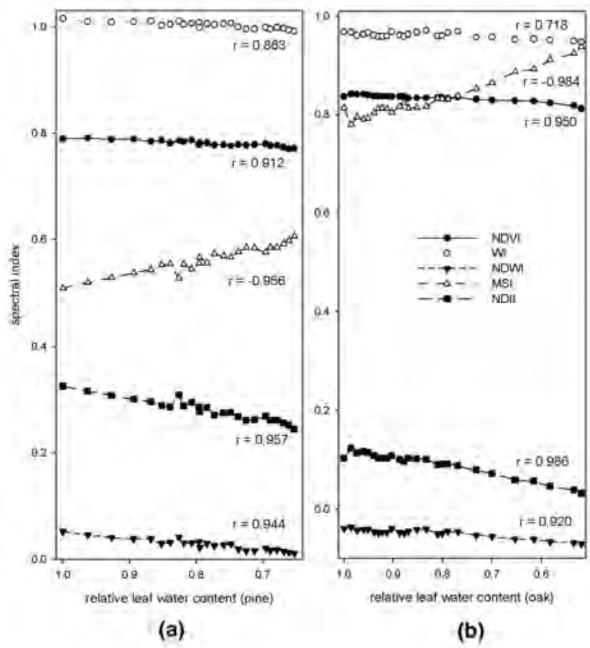


Figure 5. Relationship between five spectral indices with the relative water content of sample leaves for the laboratory measurement of (a) pine, and (b) oak.

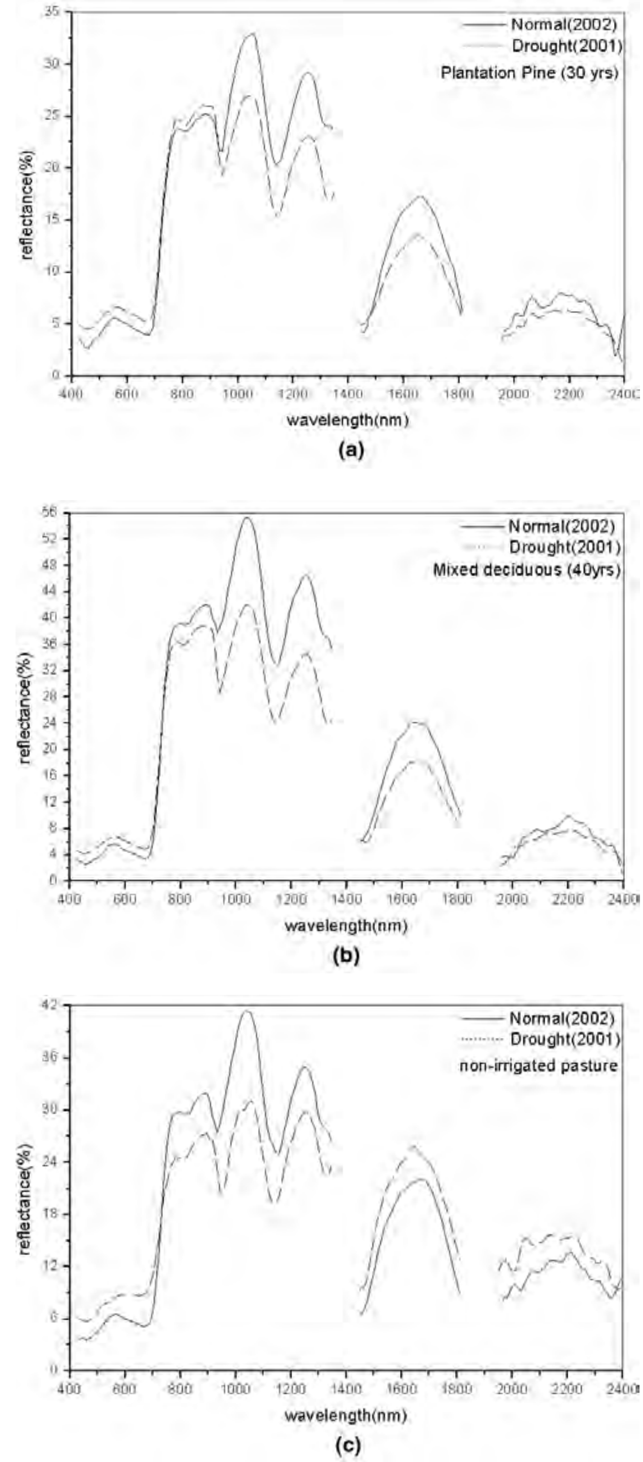


Figure 6. Canopy spectra obtained from the Hyperion data of drought year (2001) and normal condition (2002), which were extracted from (a) plantation pine stands, (b) mixed deciduous stands, and (c) non-irrigated pasture.

from the actual forest stands varied by wavelength and forest types (Figure 6). Although we selected two pairs for each of pine and deciduous forest stands, the canopy spectra extracted were almost identical within each forest type.

In the visible wavelength, canopy reflectance of the drought year was higher than that of the normal year, which corresponded to the typical pattern of leaf-level reflectance. The reflectance pattern in NIR wavelength could be separated at 940 nm, which is recognized as one of several water absorption features. Canopy reflectance of the drought year was slightly higher in the plantation pine stands but somewhat lower in the hardwood stands. The slightly higher NIR reflectance of the evergreen pine canopy under the drought condition may be explained by the minor differences in ground condition and, possibly, in canopy closure between two different sites. The 50-day long spring drought may not have a great effect on the physiology and morphology of the pine stand canopy.

Beyond 940 nm, the canopy reflectance of the drought year was lower than that of the normal year in both plantation pine and mixed hardwood forests, which was opposite to the trend of the leaf-level reflectance. The lack of precipitation during the early growing season influenced the leaf growth and, consequently, the canopy coverage and leaf area index (LAI). Several hardwood species, including oaks, in temperate mixed forests in Korea begin their growing season in March. Leaf growth commences in April and reaches the maximum stage in July and August. A lack of almost any precipitation from early-March in 2001 surely affected the leaf growth and canopy foliage mass in the mixed deciduous canopy. The lower amount of green foliage in the mixed deciduous forest canopy in 2001 contributed to the lower reflectance in the NIR and SWIR wavelength regions.

While the leaf-level reflectance is determined by biochemical properties of leaves such as pigmentation, cell structure, and water content, the canopy-level reflectance is affected by several factors including leaf optical properties, crown morphology, and canopy structure. In this experiment, we were not able to analyze the effects of canopy structure and the actual amount of foliage mass between the drought

TABLE 2. FIVE SPECTRAL INDICES OBTAINED FROM THE HYPERION REFLECTANCE OVER THE SAMPLE FORESTS IN 2002 (NORMAL YEAR) AND 2001 (DROUGHT YEAR)

| Spectral Index | Pine 1 | | Pine 2 | | Hardwood 1 | | Hardwood 2 | | Pasture | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2002 | 2001 | 2002 | 2001 | 2002 | 2001 | 2002 | 2001 | 2002 | 2001 |
| NDVI | 0.711 | 0.639 | 0.696 | 0.621 | 0.838 | 0.756 | 0.824 | 0.708 | 0.705 | 0.455 |
| WI | 0.935 | 1.150 | 0.954 | 1.118 | 0.941 | 1.146 | 0.976 | 1.145 | 0.920 | 1.117 |
| NDWI | −0.081 | 0.060 | −0.074 | 0.041 | −0.059 | 0.052 | −0.032 | 0.058 | −0.051 | −0.051 |
| MSI | 0.712 | 0.543 | 0.729 | 0.565 | 0.617 | 0.488 | 0.573 | 0.507 | 0.737 | 1.027 |
| NDII | 0.168 | 0.296 | 0.157 | 0.278 | 0.237 | 0.344 | 0.272 | 0.327 | 0.151 | −0.013 |

and normal years. Including such factors (i.e., LAI and canopy coverage) would have provided us with a better insight on the spectral characteristics of canopy drought stress.

Under moderate drought condition, actual leaf water content does not change much because the plant struggles to maintain its basic functioning (Ceccato *et al.*, 2001). The precipitation of less than 150 mm during the 50 days in the early growing season may not have changed the canopy water content in the study area. Although it did not change the canopy water level, the lower precipitation must have been influential in reducing the amount of leaf mass, in particular for the deciduous trees. The reflectance spectra obtained from the non-irrigated pasture clearly showed the effects of reduced foliage mass due to the lack of precipitation.

Although several spectral indices are designed to be sensitive to vegetation water contents, they are mostly based on the spectral absorption features that can be observed in the leaf-level reflectance spectra. When we applied five spectral indices to the canopy reflectance obtained from the two sets of Hyperion imagery, the results were not very compatible with the ones applied with the leaf-level reflectance (Table 2). If leaf-level responses scaled to canopy-level, we would expect that the five spectral should have corresponded with the pattern seen in Figure 5. Except for the NDVI, all four water-related indices showed the opposite results.

Three water-related indices (WI, NDWI, and NDII) should have been lower during the drought season if the canopy moisture level was low. The moisture stress index (MSI), which is like a reciprocal number to NDII and should have been higher in the drought year, was also higher in the normal year. The water absorption features observed in the leaf spectra may not be corresponded to the canopy spectra. Otherwise, there was no actual change in canopy water content for the forest stands between the drought and normal years. Perhaps, the discrepancy observed with the canopy-level spectral indices might be explained by other than canopy water content.

Possible explanations for the discrepancy can be found from the NDVI that follows the same pattern with the leaf-level measurement. The differences in NDVI between the drought and normal years may account for the change of the foliage mass and canopy coverage in the forest. The non-irrigated pasture clearly showed the largest increase in NDVI, which was not very surprising considering the leaf development at the time of data acquisition (early-June) between the drought and normal years. The lack of precipitation during the early growing season definitely influenced the low leaf growth and, consequently, the low canopy coverage and LAI. This explanation can be further expanded to the NDVI difference observed between the two hardwood forest stands. A lack of almost any precipitation from early-March 2001 surely affected the leaf growth and foliage mass in the deciduous oak canopy. Plantation pine stands showed minimal difference in NDVI between the drought and normal years. As in the oak stands, the pine forests may also have suffered foliage loss during the drought season. However, NDVI was not very sensitive in very dense and close canopy forests (Chen and Cihlar, 1996; Cohen *et al.*, 2003). The very dense canopy closure and relatively high LAI of the plantation pine stands were probably the cause of the small change in NDVI. Better canopy-level spectral indices may be necessary to provide greater sensitivity to canopy moisture content regardless of other parameters such as species, canopy structure, and amount of foliage biomass (Penuelas *et al.*, 1997; Hunt and Rock, 1989).

## Conclusions

Remote sensing of forest canopy drought condition can be very important for various applications ranging from forest fire hazard monitoring to assessment of forest productivity. The comparison between reflectance spectra obtained from the laboratory measurements and the observation of satellite hyperspectral data showed no consistent relationship between leaf- and canopy-levels. Reflectance spectra from laboratory measurements may not be directly applied at canopy level for analyzing drought condition in a relatively dense and close canopy forest environment. Under moderate drought condition, the forest canopy water content may not change significantly. Therefore, application of the spectral indices obtained from leaf-level measurements needs careful attention. Spectral characteristics of forest canopy in a moderate drought condition may be more closely related to the changes in forest canopy structure, such as canopy closure and LAI, rather than canopy moisture content.

Although several water-related spectral indices have been developed to monitor vegetation drought stress, they are mostly based on leaf-level reflectance spectra and are not particularly applicable to canopy-level reflectance in the relatively dense temperate forest. The four water-related spectral indices (WI, NDWI, MSI, and NDII) that we tested did not showed the consistency between the leaf-level and canopy-level. Considering the potential for obtaining complete spectral characteristics at a canopy-level from hyperspectral data, other spectral indices that are more sensitive to canopy moisture stress are expected in the near future.

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