Int. J. Environ. Res. Public Health **2008**, *5(5)* 477-483

International Journal of
Environmental Research and Public Health
ISSN 1661-7827
www.ijerph.org

Test of Multi-spectral Vegetation Index for Floating and Canopy-forming Submerged Vegetation

Hyun Jung Cho*, Philemon Kirui, Harene Natarajan

Department of Biology, Jackson State University, Jackson, MS 39217, USA
*Correspondence to Dr. Hyun Jung Cho. Email: hyun.j.cho@jsums.edu

Received: 18 September 2008 / Accepted: 05 December 2008 / Published: 31 December 2008

Abstract: Remote sensing of terrestrial vegetation has been successful thanks to the unique spectral characteristics of green vegetation, low reflectance in red and high reflectance in Near-InfraRed (NIR). These spectral characteristics were used to develop vegetation indices, including Normalized Difference Vegetation Index (NDVI). However, the NIR absorption by water and light scattering from suspended particles reduces the practical application of such indices in aquatic vegetation studies, especially for the Submerged Aquatic Vegetation (SAV) that grows below water surface. We experimentally tested if NDVI can be used to depict canopies of aquatic plants in shallow waters. A 100-gallon-outdoor tank was lined with black pond liners, a black panel or SAV shoots were mounted on the bottom, and filled with water up to 0.5 m. We used a GER 1500 spectroradiometer to collect spectral data over floating waterhyacinth (*Eichhornia crassipes*) and also over the tanks that contain SAV and black panel at varying water depths. The measured upwelling radiance was converted to % reflectance; and we integrated the hyperspectral reflectance to match the Red and NIR bands of three satellite sensors: Landsat 7 ETM, SPOT 5 HRG, and ASTER. NDVI values ranged 0.6-0.65 when the SAV canopy was at the water level, then they decreased linearly (slope of 0.013 NDVI/meter) with water depth increases in clear water. When corrected for water attenuation using the data obtained from the black panel, the NDVI values significantly increased at all depths that we tested (0.1 – 0.5 m). Our results suggest the conventional NDVI: (1) can be used to depict SAV canopies at water surface; (2) is not a good indicator for SAV that is adapted to live underwater or other aquatic plants that are submerged during flooding even at shallow waters (0.3 m); and (3) the index values can significantly improve if information on spectral reflectance attenuation caused by water volume increases is collected simultaneously through ground-truthing and integrated.

Keywords: Vegetation Index, NDVI, hyperspectral, SAV, water depth

Introduction

Remote sensors detect electromagnetic radiation (EMR) that is reflected or emitted from an object; and users can derive information about the object by studying the EMR signals. Remote sensing of terrestrial vegetation has been successful due to the unique spectral characteristics of green plants: low reflectance in red and high reflectance in Near-InfraRed (NIR) [1]. The important plant pigments, Chlorophyll *a* and *b*, strongly absorb the energy in the blue (centered at 450 nm) and the red (centered at 670 nm) wavelengths for photosynthesis; and the internal spongy mesophyll structure of the plants' leaves is responsible for the high reflectance in the near-infrared (NIR) region (700 – 1300 nm) [2].

Spectral indices typically combine multi-dimensional spectral data into a manageable single value. Spectral indices for vegetation, including Simple Vegetation Index (SVI = NIR reflectance – Red reflectance) and Normalized Difference Vegetation Index (NDVI), have been created by utilizing the characteristics of vegetation reflectance in the red and NIR regions. NDVI, (NIR reflectance – Red reflectance) / (NIR reflectance + Red reflectance), has been extensively applied in vegetation studies using multi-spectral satellite wavebands. Use of NDVI has been a preferred method in vegetation studies due to its simplicity and versatility that enables comparison of data obtained under varying illumination conditions. The index values have been correlated with diverse plant characteristics, such as vegetation cover [3], vegetation type [4], water content [5], biomass & productivity [6], chlorophyll amount [1], PAR (Photosynthetically Active Radiation) absorbed by a crop canopy [7], and flooded biomass [8] at a broad span of scales from individual leaf areas to global vegetation dynamics.

Normalized Difference Vegetation Index has also been used in studies of aquatic vegetation, especially floating and emergent aquatics [9, 10]. However, Beget and Di Bella [8] showed that NDVI values calculated from satellite bands decreased with increasing flooding levels and would not be a good indicator for agricultural crops flooded with water depths of 25 cm or greater even when the water was clear and the measurements were made inside a black chamber to exclude external scattering and light diffusion. It is because of the general pattern of vegetation reflectance with increasing flooding depths, reduced red absorption and NIR peak by vegetation [11, 12]. The application of NDVI to submerged aquatic vegetation (SAV) that is adapted to the underwater life will be more difficult. SAV plants have reduced internal leaf structures and lack waxy cuticles compared to terrestrial or emergent plants, which would further affects the practical application of the common vegetation index.

In order to experimentally test if NDVI derived from satellite sensors (a multispectral index) can be used to depict SAV canopies in shallow waters, we collected reflectance data of common aquatic vegetation over controlled (outdoor tanks) experimental setting using a hand-held spectroradiometer. We analyzed the data to: (1) compare spectral reflectance characteristics of aquatic plants that are adapted to grow above water surface (emergent/floating vegetation) and below water surface (SAV); (2) document the effects of SAV in the composite upwelling energy from a water body; and (3) test if NDVI values for underwater plants can be improved if corrected for spectral attenuation caused by water.

Materials and Methods

Controlled Experimental Spectral Data Collection

Close range spectral measurements of downwelling and upwelling energy were made over outdoor tanks (0.5 m deep, 100 gallon tank) that contained the floating/emergent waterhyacinth (*Eichhornia crassipes*) (Fig. 1) or the submerged species, parrot feather (*Myriophyllum aquaticum*), fanwort (*Cabomba caroliniana*), and coontail (*Ceratophyllum demersum*) (Fig. 2). Spectral measurements were made on clear skies at near solar noon to minimize variability of solar elevation.

For the emergent plants, a GER 1500 spectroradiometer (Spectra Vista Corporation) was used to scan healthy green *E. crassipes* (waterhyacinth) leaves, brown senescing *E. crassipes* leaves, submerged healthy *E. crassipes* leaves, and purple *E. crassipes* flowers. The measurements were made 10 cm above the target plant parts in order to obtain the fine spatial resolution data to distinguish reflectance from different parts of the plants (instantaneous field of view was 8^o).

Figure 1: The floating aquatic vegetation, *Eichhornia crassipes* (waterhyacinth), with its purple flowers and other emergent plants.

Figure 2: The mixture of submerged aquatic vegetation (SAV) deployed at the bottom of the experimental tank.

To obtain the depth-induced variations in the spectral responses of SAV, a mixture of *M. aquaticum, C. demersum* and *C.caroliniana* was threaded through a black mesh sheet and fixed on the bottom of a black-lined tank. The plants were planted at a density similar to the mean natural density during the local growing season. The inside of the tanks were lined with black plastic pond liners to eliminate reflectance from the interior surface. The tank was initially filled to the top (approximately 50cm) using city tap water, then the water was continuously siphoned out with upwelling spectral measurements taken every 1.0cm in water-depth change until canopy level (10-20cm) was reached. As the water level is lowered, the sensor head was also lowered to keep a constant distance between water surface and the sensor.

The same measurements were taken over a black panel (35cm x 62cm) deployed at the bottom of the same tank to obtain data on the water depth-induced spectral variations but without the bottom reflectance effects (vegetation), assuming the black panel absorbs incoming radiation that reaches the bottom of the tank (Fig. 3).

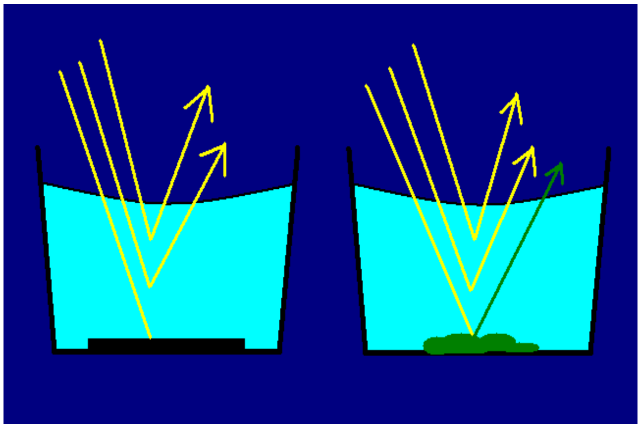

Figure 3: An illustration comparing the reflected upwelling energy from water tanks with two different bottom types, a black panel and vegetation.

Throughout the study, at least three replicate scans were taken for each depth and each setting and the mean values were used in analyses. Downwelling radiance was measured at the beginning of each set of collection using a white spectralon panel (99% reflectance) for calibration of the data collected on different days.

Calibration of Spectral Data

The spectral data were used for the computation of percent reflectance where reflectance (%) = (upwelling radiance) / (downwelling radiance) * 100. Reflectance values were calculated only between 400-900 nm to eliminate low signal-to-noise ratio of the data collected in the shorter and the longer wavelengths. The resulting data contained 315 contiguous bands.

Data Analysis

As described above, at least three replicate scans were taken for each setting (each depth) and the mean values were used in analyses. Reflectance data were plotted against the wavelengths 400-900nm. From the plot of the spectral data collected over healthy waterhyacinth, senescing waterhyacinth, submerged waterhyacinth, waterhyacinth flowers, emerged SAV, and SAV canopy just below water surface, the wavelength and the corresponding reflectance value (%) of each reflectance peaks and dips were observed and calculated. In order to see the effects of flooding on the reflectance, the spectral reflectance of flooded vegetation was subtracted from the spectral reflectance of healthy emerged vegetation for each plant type (waterhyacinth and SAV).

The spectral reflectance was averaged for the RED and NIR bands to simulate reflectance from satellites sensors of ASTER, SPOT 5, and LANDSAT 7 ETM+ (Table 1). NDVI values were then calculated for each depth using the averaged NIR and RED reflectance values. Spectral reflectance data collected over the black panel were subtracted from the SAV spectral reflectance collected at the comparable water depth to reduce the water effect (corrected for water effect) (Fig.3). NDVI values were re-calculated using the corrected data.

Table 1: Wavelength ranges for the red and the near infrared (NIR) bands of the sensors on Landsat 7, SPOT 5, and ASTER

Satellite Sensor	*Red (nm)*	*Near Infrared (nm)*
LANDSAT 7	630 – 690	760 – 900
SPOT 5	610 – 680	790 – 890
ASTER	630 – 690	780 – 860

Results

Comparison of Spectral Reflectance Characteristics of Emergent Plant and SAV

Spectral reflectance (400-900 nm) of waterhyacinth and SAV are plotted together for comparison in Fig.4. Healthy waterhyacinth and emerged SAV showed the typical vegetation spectral reflectance pattern: the green reflectance peak at around 557 nm, red absorption near 660-670 um, and the NIR peak (> 730 nm), but the reflectance values at the green and NIR peaks were significantly lower in emerged SAV (7.5% and 6.3% respectively) compared to those of waterhyacinth (23.7% and 76%). The red absorption by the plants pigments appear less in emergent SAV than waterhyacinth, resulting in the relative higher reflectance at the red wavelength for emerged SAV (6.3%) than waterhyacinth (4.6%).

When submerged below water surface, the spectral reflectance for both waterhyacinth and SAV decreased at the green, red, and NIR regions (Figs.4 and 5). The reflectance was reduced to 5% (green), 3.6% (red), and 10% (NIR) for waterhyacinth when submerged; and the corresponding reflectance for SAV was 1.5%, 0.9%, and 3.5%. The magnitudes of reflectance reduction caused by submergence were comparable between waterhyacinth and SAV at green (79% reduction) and NIR (87% and 91% reduction), but the red reflectance was more significantly reduced in SAV (85% reduction) than in waterhyacinth (22% reduction) (Fig. 5). The maximum peak and the minimum dip wavelengths in the green and red reflectance were shifted to somewhat lower ranges (557nm → 553 nm and 677nm → 640 nm) in waterhyacinth.

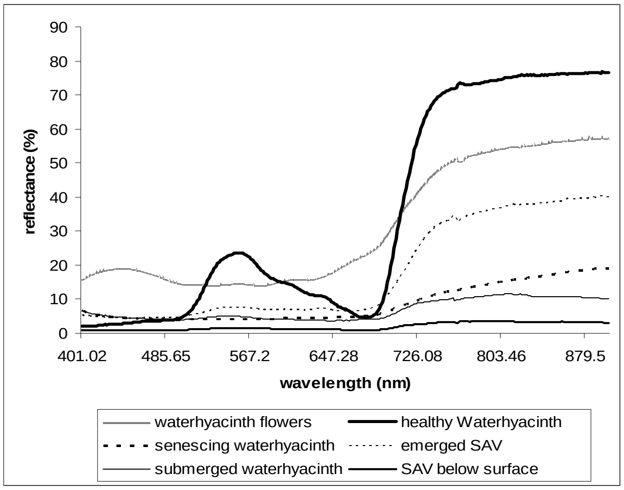

Figure 4: Spectral reflectance (%) of the floating waterhyacinth and submerged aquatic vegetation (SAV).

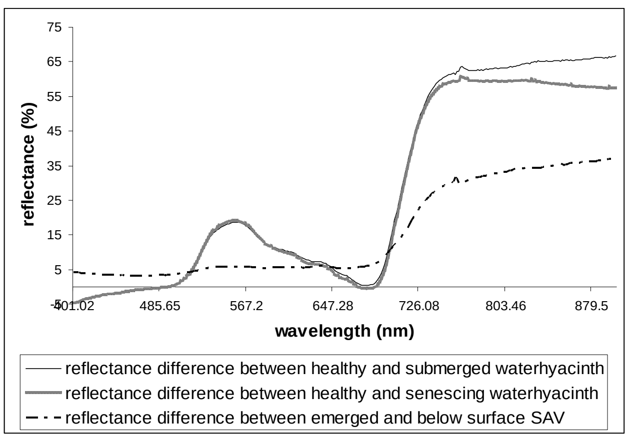

Figure 5: Difference in the spectral reflectance (1) between floating and submerged waterhyacinth, (2) between healthy and senescing waterhyacinth, and (3) between emerged and below surface submerged aquatic vegetation (SAV).

The reflectance of the brown-colored senescing waterhyacinth at green (4.3%) and NIR (18%) was also significantly lower than those of healthy waterhyacinth (Fig. 4). The violet-colored flowers of healthy waterhyacinth show very distinct spectral reflectance pattern (relatively higher reflectance at blue and red compared to green) in the visible light region (400-700 nm), and the NIR reflectance (56-57%) was comparatively lower than that of green waterhyacinth leaves, but higher than that of submerged or senescing water hyacinth.

NDVI values were calculated by averaging of the measured reflectance values at the red and NIR bands of the three satellite sensors (Table 2). The difference in the NDVI values among the sensor types was not significant at 5% confidence level. As expected, NDVI values were greatest for healthy emerged waterhyacinth. Emerged SAV had the higher NDVI values than those of senescing or submerged waterhyacinth. Waterhyacinth flowers, despite the higher NIR reflectance compared to emerged SAV or senescing waterhyacinth, had lower NDVI values due to the relatively higher red reflectance that is responsible for the purple/violet color of the petals along with the increased blue reflectance (Figs. 1 and 4). Higher NDVI values were observed from the SAV below water surface compared to submerged waterhyacinth at the same depth.

Spectral Reflectance of SAV at Varying Water Depth

Depth-varying spectral reflectance over SAV and the black panel is shown in Figs. 6 and 7, respectively. The general flooding effects on the vegetation signals were similar to those observed in previous studies [8, 5, 12]: reduced red absorption and NIR peak by vegetation. The near infrared reflectance shown as a reflectance plateau in terrestrial or in emergent plants (Fig. 4) became two peaks near at approximately 710-715nm and 810-815nm in the submerged plants (Fig. 6) due to the water absorption of the energy in between those two NIR peaks.

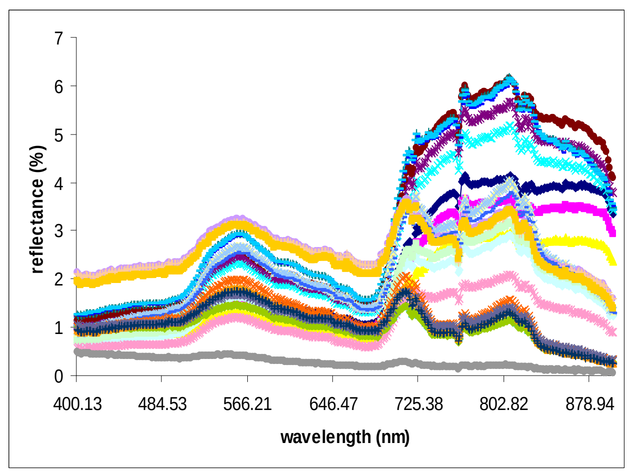

Figure 6: Spectral reflectance of submerged aquatic vegetation (SAV) at varying depths. The depth ranged from 0 cm and 30 cm above the SAV canopy; the line for the highest reflectance is at 0 cm and the reflectance continuously decreases with water depth increases.

The upwelling signals over the black panel (Fig. 7), as described earlier, contain information on changes in the water column volume without the bottom reflectance. The magnitude of the upwelling energy along the spectra is mainly related to the wavelength, with the highest reflectance at the shortest wavelength due to increased scattering in the blue region. As expected, the reflectance was reduced at all wavelengths similarly with increasing depths.

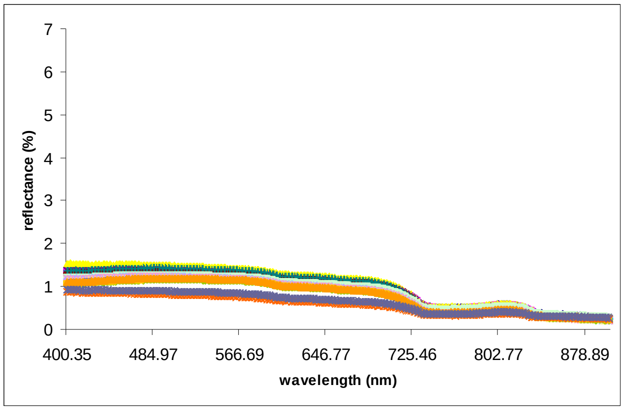

Figure 7: Spectral reflectance from the water tank with black panel at varying depths. The depth ranged from 0 cm and 30 cm above the black panel deployed at the bottom of the tank; the line for the highest reflectance is at 0 cm and the reflectance continuously decreases with water depth increases.

In order to test if the SAV signal can be extracted better if the water volume reflectance is removed; the spectral reflectance of the black panel was subtracted from the spectral reflectance of the SAV at each comparable depth. An example of the correction with the data from black panel is shown in Fig. 8.

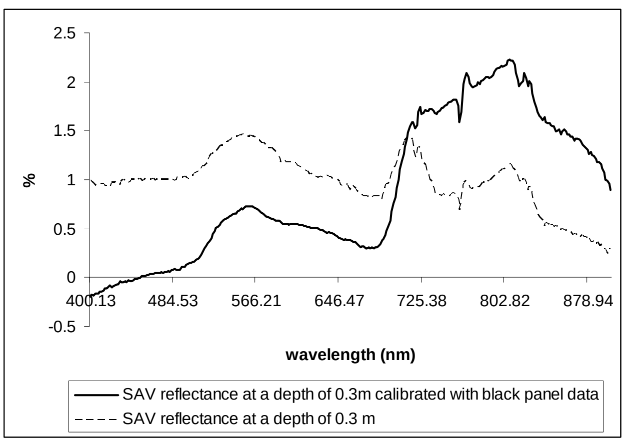

Figure 8: An example of the original reflectance of SAV compared the same data corrected with the black panel data at the same depth.

The NDVI values for SAV at each water depth calculated using the original spectral reflectance at the corresponding red and NIR regions are presented in Fig. 9 and they are compared with the NDVI calculated using the corrected spectral reflectance (SAV reflectance – black panel reflectance) are presented in Fig. 10. The NDVI values calculated with the original reflectance ranged 0.6-0.65 when the SAV canopy was at the water level (Figs. 9 and 10), then they decreased linearly (slope of 0.013 NDVI/meter) with water depth increases in clear water. When corrected for water attenuation using the data obtained from the black panel, the NDVI values significantly increased at all depths that we tested (0.1 – 0.5 m) (Fig. 10; p<0.001).

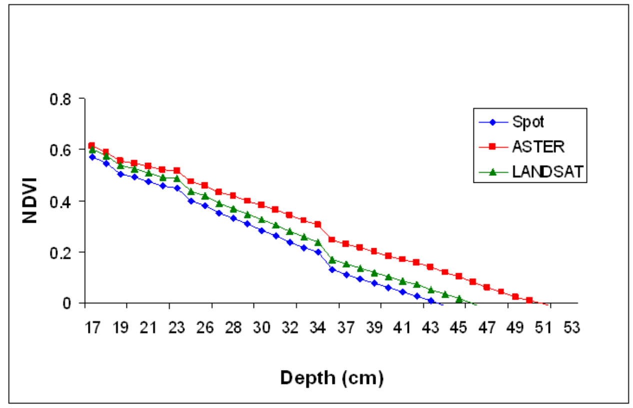

Figure 9: Water depth-induced changes in the Normalized Difference Vegetation Index (NDVI) values calculated with the reflectance values integrated to match the red and NIR (near infrared) bands of the sensors of the three satellite (Landsat7, ASTER, and SPOT5).

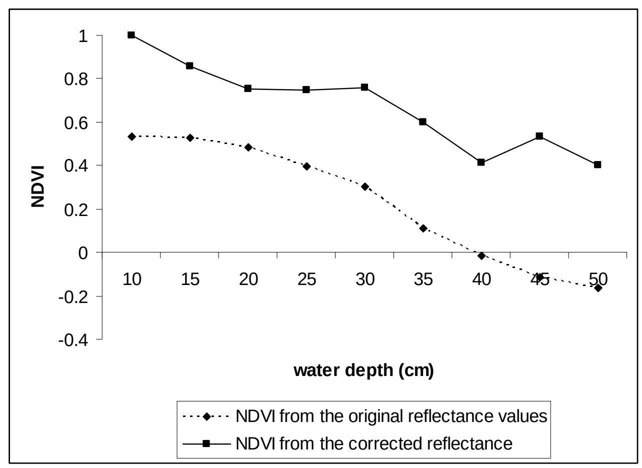

Figure 10: Water depth-induced changes in the Normalized Difference Vegetation Index (NDVI) values compared with the NDVI values calculated from the corrected reflectance (SAV reflectance – black panel reflectance) at the corresponding depths.

Discussion

As demonstrated in previous studies [13, 14], our results support that NDVI can serve as a good indicator to delineate healthy waterhyacinth (Table 2) and other emergent/floating water plants because of the high reflectance in the NIR regions and low red reflectance (Fig. 4), the spectral responses that resemble the terrestrial vegetation spectral signals. Our results also indicate NDVI can be used to distinguish and classify floating plants by their health status (Fig. 4 and Table 2), but confusing classification results may occur as the NDVI values for senescing waterhyacinth, submerged waterhyacinth, and SAV canopy at water surface appear similar (Table 2). Particularly, the effects of senescence and submergence on the vegetation reflectance were very similar even at the hyperspectral resolution (Figs. 4 and 5). The purple/violet-colors of waterhyacinth flowers (Fig. 1) can also affect classification of the plants using NDVI during the peak flowering season because the relatively increased reflectance at red (Fig. 4) for the flowers results in lower NDVI values (Table 2). These aspects should be considered when taking ground-truth measurements in order to reduce errors in image classification and delineation.

Table 2: Mean NDVI (Normalized Difference Vegetation Index) values calculated from the reflectance values integrated to match the red and near infrared bands of the three satellite sensors.

	LANDSAT 7	*ASTER*	*SPOT5*
Healthy Waterhyacinth	0.82	0.82	0.79
Emerged SAV	0.69	0.69	0.70
Senescing Waterhyacinth	0.54	0.53	0.57
Waterhyacinth flowers	0.50	0.50	0.54
Submerged Waterhyacinth	0.47	0.48	0.48
SAV below water surface	0.54	0.54	0.52

Submerged aquatic vegetation (SAV) plants that are adapted to underwater life had lower NDVI values than those of floating plants even when emerged above water surface (Table 2, Fig. 4). The red reflectance for the emerged SAV was higher than healthy waterhyacinth, which indicates lower red absorption by the plant pigments in SAV; and the NIR reflectance was also significantly lower than that of waterhyacinth. This is probably due to the SAV's lower chlorophyll content of the leaves per unit of tissue and weight [15] and the higher water contents in and on SAV leaves. One interesting factor is that SAV below water surface had the higher NDVI values than submerged waterhyacinth at the same depth, which probably explains the red absorption by waterhyacinth is more significantly affected by submergence compared to SAV that is adapted to utilize the red color more efficiently in submerged conditions.

NDVI appears to be useful in delineating SAV canopy at the water surface (NDVI values close to 0.6), but the values decreased linearly with water depth increases, becoming ineffective for underwater vegetation detection even at the depth of 0.3 m (Fig. 9). However, the NDVI values significantly increased at all depths that we tested (0.1 – 0.5 m) when corrected for water attenuation using the data obtained from the black panel, indicating the index values can be used for studies of SAV that from canopies near water surface if information on spectral reflectance attenuation caused by water volume increases is collected in the field and used to correct the original spectral reflectance data.

The importance of this research is linked to the need for mapping the distribution, composition, and abundance of aquatic vegetation in shallow inland and coastal waters using satellite images. Aquatic plants provide food to aquatic organisms, serve as nursery habitats, help reduce shoreline erosion, and influence the supply of oxygen in water. However, fast growing aquatic plants especially free-floating or floating-leaved plants of inland water bodies can become invasive by outcompeting native species. Therefore, information on aquatic vegetation distribution, composition, and abundance is widely used as an indicator of aquatic environmental quality; and the improved mapping capability for those plants will enhance the ability to assess underwater habitat changes.

Our study suggest that the conventional NDVI: (1) can be used to depict SAV canopies at water surface; (2) is not a good indicator for SAV that is adapted to live underwater or other aquatic plants that are submerged from less common events such as flooding even at shallow waters (0.3 m); and (3) the index values can significantly improve if information on spectral reflectance attenuation caused by water volume increases is collected simultaneously through ground-truthing.

Acknowledgments: This research is supported by grants from the National Geospatial-Intelligence Agency (NGA), NOAA-ECSC (Grant No.NA17AE1626, Subcontract # 27-0629-017 to Jackson State University), and NASA (Grant No. NNG05GJ72H/07-11-052, Agreement No. NNG05GJ72H). We sincerely thank Melissa Larmer and Jonathan Jones who assisted with the data collection.

References

1. Graets, D.: Remote sensing of terrestrial ecosystem structure: an ecologist's pragmatic view. *Ecological Studies* **1990**, *79*, 5-30
2. Lillesand, T. M.; Kiefer, R.W.; Chipman, J. W.: *Remote Sensing and Image Interpretation. 6th Edition*. Wiley, **2008**, pp 768.
3. du Plessis W. P.: Linear regression relationships between NDVI, vegetation and rainfall in Etosha National Park, Namibia. *J. of Arid Environments* **1999**, *42*, 235-260.
4. Geerken, R.; Zaitchick, B.; Evans, J. P.: Classifying rangeland vegetation type and coverage from NDVI time series using Fourier Filtered Cycle Similarity. *Int. J. of Remote Sensing,* **2005**, *26,* 5535-5554.
5. Jackson, T.; Chen, D.; Cosh, M.; Li, F.; Anderson, M.; Walthall, C.; Doraiswamy, P.; Hunt, E. R.:

Vegetation water content mapping using Landsat data normalized difference water index (NDWI) for corn and soybean. *Remote Sensing of Environment,* **2004**, *92(4),* 475-482.

6. Fang, J.; Piao, S.; Tang, Z.: Interannual variability in net primary production and precipitation. *Science* **2001**, *293*, 1723.
7. Goward, S. N.; Huemmrich, K. F.: Vegetation canopy PAR absorptance and the normalized difference vegetation index: an assessment using the SAIL model. *Remote sensing of environment*, **1992**, *39*, 119-140.
8. Beget, M. E.; Di Bella, C. M.: Flooding: The effect of water depth on the spectral response of grass canopies. *J. of Hydrology*, **2007**, *335*, 285-294.
9. Kiage, L. M.; Walker, N. D.: Using NDVI from MODIS to monitor Duckweed bloom in Lake Maracaibo, Venezuela. *Water Resource Manage* DOI 10.1007/s11269-008-9318-9. **2008**.
10. Penuelas, J.; Gamon, J. A.; Griffin, K. L.; Field, C. B.: Assessing community type, plant biomass, pigment composition, and photosynthetic efficiency of aquatic vegetation from spectral reflectance. *Remote Sensing of Environment*, **1993**, *46*, 110-118.
11. Han, L.: Spectral reflectance of Thalassia testudinum with varying depths. *Proceedings of Geoscience and Remote Sensing Symposium*, **2002**, *4,* 2123- 2125.
12. Han, L.: Rundquist, D. C.: The spectral responses of *Ceratophyllum demersum* at varying depths in an experimental tank. *International Journal of Remote Sensing*, **2003**, *24(4)*, 859-864.
13. Shekede, M. D.; Kusangaya, S.; Schmidt K.: Spatio-temporal variations of aquatic weeds abundance and coverage in Lake Chivero, Zimbabwe. *Physics and Chemistry of the Earth,* **2008**, *33,* 714-721.
14. Venugopal, G.: Monitoring the Effects of Biological Control of Water Hyacinths Using Remotely Sensed Data: A Case Study of Bangalore, India *Singapore Journal of Tropical Geography* **2002**, *19,* 91-105.
15. Hemminga, M. A.; Duarte, C. M.: Seagrass Ecology. Cambridge University Press. The Edinburgh Building, Cambridge CV2 8RU, UK. **2000**.