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Evaluating the Invasion Strategic of Mesquite (*Prosopis juliflora*) in Eastern Sudan Using Remotely Sensed Technique

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Abstract: In the Red Sea coastal area, the problems of desertification, land degradation and dust storm are still serious. Because, the invasive species Mesquite **(***Prosopis juliflora*) has a high capacity to fix sand dunes, mesquite trees were introduced into Sudan and planted in Khartoum and eastern Sudan. However, the tree was invaded both natural and managed habitats, including watercourses, floodplains, highways, degraded abandoned land and irrigated areas. The weed is more of a problem within central, northern and eastern Sudan. In this study a remote sensing approach for the mesquite tree control is proposed. To monitor mesquite water use efficiency the concept of a Normalized Difference Infrared Index (NDII), which is defined as the ratio of actual to foliar water content, have been applied and compared with the ground measurements of stomatal conductance (mmol. m^{-2}. s^{-1}), field spectral, volumetric soil water content. As results, on the base of the PALSAR L-band microwave polarimetric backscatter coefficient, the soil moisture and surface roughness could be estimated with a good accuracy for bare-soil surfaces.

Key Words: Africa, Backscatter coefficient, Mesquite *(Prosopis juliflora)* control, NDII

1. Introduction

The mesquite tree is native to South and North America and was introduced into Sudan in 1917. The tree is well known for its high adaptability to arid and semi-arid conditions and characterized by very high water use efficiency. Introduction of the mesquite has caused several environmental problems in Sudan.

Mesquite can detect even very tiny soil moisture and grow to various conditions. Some of the many adaptive abilities that allow mesquite to thrive under such conditions involve ability of roots to adapt to a wide variety of soil conditions. Its roots can grow upwards towards the soil surface to capitalize on little rainfall, and can also grow to depths down to 80 m and extend laterally more than 30 m. This is the most extensive root system of any plant in the world (Thorp *et al.*, 2001).

Remote sensing methods for mesquite control in eastern Sudan come within a project of Human Subsistence Ecosystem in Arab countries to combat livelihood degradation for the post-oil Era. The project is implemented with the co-ordination and partnership between the Research Institute for Humanity and Nature (RIHN) in Japan and the College of Agricultural Studies at Sudan University of Science and Technology (SUST). The work is conducted in the Red Sea coastal and Kassala irrigated agriculture area in eastern Sudan using different methods of remote sensing, aiming at setting a practical methodology that could effectively help in assessing mesquite distribution and its spreading patterns.

Studies on the plants adaptation to environment are very important for evaluation of the vegetation response to global climate changes. Vegetation water content is important ecophysiological parameter that provides information on the vegetation's environmental adaptation and used to determine the plants water stress. An accurate estimate of the plant water content is significant key in evaluating the strategic expansion of the invasive mesquite in semi-arid area of Africa. The mesquite has a problematic spreading that threatens agriculture in vast areas of eastern Sudan, including Tokar Delta, Gash Delta, numerous sites along Red Sea coast area and irrigated farmland of Kassala plain. According to Brown *et al.* (1929), in 1917 the mesquite tree were introduced into Sudan from South Africa and Egypt and planted in Khartoum. This tree has characteristics of high drought tolerance, sand dunes fixing, and could also be used as fodder for animals. The mesquite usage, beside sand dune fixation is limited to firewood and charcoal production. More than 90% of mesquite is thought to be spreaded in eastern Sudan, where livestock keeping and subsistence cultivation constitute the main source of income. Invasive mesquite tends to form dense and impenetrable thickets. Its highly competitive

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nature leads to reduce grass cover, stocking density, and threatens the livelihood of traditional herders. Its invasion into agricultural land, along irrigation channels and water courses is also a major problem. The high water tables, which contribute to the menacing of mesquite spread in addition to the fertile soil, at the downstreams of Tokar, Gash Delta and Kassala plain seasonal river (see Fig. 3) are expected. Previous studies (Babiker *et al.*, 2006) in other part of the world clearly showed that eradication of mesquite is neither desirable nor tenable. In this study a remote sensing approach for evaluating the invasion strategy of mesquite tree (*Prosopis juliflora*) was proposed.

2. Methodology and Result

2.1. Measurement of mesquite water use efficiency

In the eastern Sudan's semi-arid land, adaptation of the mesquite to a variety of habitats may be related to a plasticity of root system distribution. Mesquite tree uses deep ground water with a taproot in the dry season and the soil water with a lateral roots in wet season. When available, mesquite will exploit sources of deep water by growing a taproot. Mesquite can also persist on sites that have little or no ground water by growing lengthy shallow lateral roots. Therefore, most of the native plants growing around a mesquite tree become withered and died.

Moreover the mesquite can control the leaf water evaporation and survive even in the driest season, because the mesquite water use efficiency is higher than those of native species. **Figure 1** shows the parameters of the stomatal conductance (mmol m^{-2} s^{-1}) in native plants and mesquite. Beginning from 11:00 am, most of the native plants goes into midday depression of photosynthesis and reduce evapotranspiration (ET) when air temperatures are near 40^{o}C.

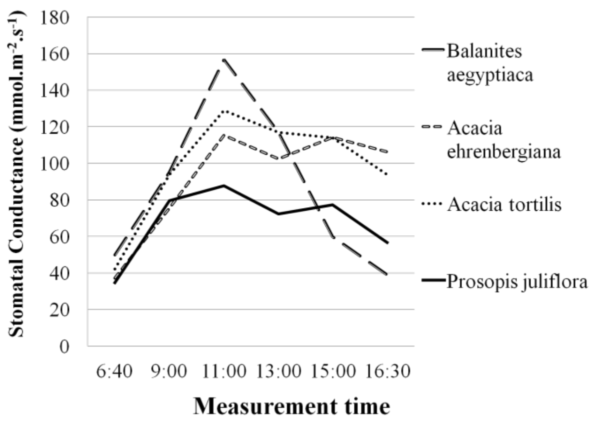

Fig. 1. Comparison of the stomatal conductance (mmol m^{-2} s^{-1}) in native plants and invasive species (mesquite) at semi-arid area of Kassala, Sudan (Nov. 7th, 2010).

However, mesquite is gradually reducing ET from 9:00 am, and remained low evapotranspiration during the whole day.

2.2. Detecting the invasion route of mesquite trees

Mesquite tree invasions are expanded along the riverside in Atbara River basin in eastern Sudan. However, the native plants and farm land products retreat by the expansion of invasion species of mesquite. The remote sensing method is very useful to detect the invasion route of mesquite tress in wide area. Since plants leaf absorbs red light energy, and reflect near-infrared (NIR) light energy of sunlight. Therefore, vigorously growing healthy vegetation has low red-light reflectance (due to its chlorophyll) and high near-infrared reflectance (due to its total biomass). **Figure 2** shows parameters of the spectral reflectance of mesquite trees and the surrounding native plants. Mesquite has low red-light reflectance and high near-infrared reflectance. Moreover, comparison of the mesquite's absorption of red light and the reflection of NIR light with those of other native plants, showed that the mesquite was more healthy and vigorously growing. To quantify water stress level in aboriginal and invasive species we are followed. Moran *et al.* (1989) investigated the effect of water stress on canopy architecture in alfalfa (*Medicago sativa* L.) and the sequential effect on canopy reflectance. They found water-stressed canopies to have a lower spectral reflectance in the NIR wavelength and lower spectral absorption in the red wavelength when compared with unstressed canopies. A ratio of the two wavelengths was most successful in estimating the onset of stress. In our study, as shown in Figure 2, the native plants in the same habitat of mesquite have more water-stressed growing situation than the mesquite. The ratio of NIR to red wavelength for the mesquite was 4.5 while those of a native plant was only 1.9.

We investigated the concept of a Normalized Difference Infrared Index (NDII), which is defined as the ratio of actual to foliar water content. The foliar water content is often divided by the density of liquid water to derive the equivalent water

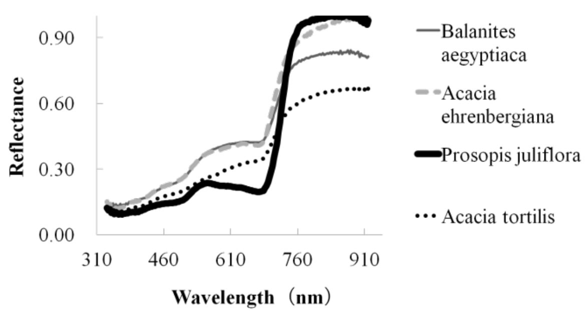

Fig. 2. The measurement field spectral reflectance (FieldSpec® HandHeld) of native plants and invasive species (mesquite) in semi-arid area of Kassala, Sudan (Nov. 7th, 2010).

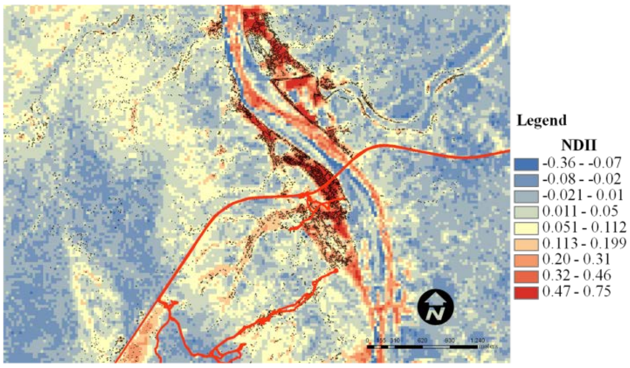

Fig. 3. NDII map calculated from Landsat5-TM data (where, red-colors shows the satellite extraction of mesquite tree pixels. Mesquite was expanded along the bank of a river; and the polygons shows the mesquite distribution area. Dec. 11th, 2009**).**

thickness (EWT). EWT is useful because the canopy EWT is equal to the leaf EWT multiplied by the leaf area index (LAI). Leaf reflectance at short wave infrared (SWIR) wavelength increases linearly with respect to leaf reflectance at NIR for a decrease in leaf EWT. The measurement can be calculated from remotely sensed data (NIR and SWIR). Hardisky *et al.* (1983) defined the Normalized Difference Infrared Index (NDII) as:

$$NDII = \frac{NIR - SWIR}{NIR + SWIR} \qquad (1)$$

Where, NIR is reflectance of near Infrared and SWIR is reflectance of short wave infrared.

This can be calculated from the Landsat 5 Thematic Mapper (TM) bands 4 (as NIR) and 7 (as SWIR). **Figure 3** shows the NDII image calculated from Landsat 5 spectral band 4 and band 7. This index exhibits the ability to evaluate the invasion strategic of alien species mesquite. As shown in Figure 3, the field measurement and result of NDII (NDII value > 0.1) shows that the mesquite trees expansion followed a high soil moisture area along the banks of a river.

2.3. Measurement of polarimetric backscattering

The field measures using a hand-held soil moisture measurement system (©Hydrosense) showed that the volumetric soil water content ranged between 3-5% in the area within the circle of 10 meter-radius from mesquite tree centers including under the mesquite canopies.

As the amount of water contained in soil becomes greater, specific inductive capacity of the whole soil increases in proportion, and as a result, backscatter strength increases. In this way, analysis of backscatter strength leads to estimate the amount of water content in target land area. Based on the accurate scattering model (Oh *et al.*, 2002) both the soil moisture and surface roughness can be retrieved from the measurements of polarimetric backscattering with a good accuracy for bare-soil surfaces. It is well known that the retrieval of soil moisture in vegetated surface from the microwave backscatter coefficient is affected by surface roughness. In bare soil area of Atbara River basin (in Kassala plain, Sudan), we found good relationship between field measure soil moisture (Mv) and ALOS/PALSAR L-band backscatter coefficient ($M_v = 4.24\sigma^0_{baresoil} + 126.4$, R^2=*0.985*) (Hoshino *et al.*, 2011). However, for surfaces with vegetation cover, the soil moisture retrieval is a challenging problem because of complicated scattering mechanisms in the vegetation canopy. Except for the case of dense forest canopies, backscatter from vegetation (σ^0_{dB}) can be divided into surface (σ^0_s), volume (σ^0_{dv}) and multiple (both) scattering (σ^0_{int}) (Oh *et al.*, 2002):

$$\sigma^0_{dB} = \tau^2\sigma^0_s + \sigma^0_{dv} + \sigma^0_{\mathrm{int}} \qquad (2)$$

A semi-empirical polarimetric backscattering model for bare soil surfaces is inverted directly to retrieve both the volumetric soil moisture content and the surface roughness height from multipolarized radar observations (Wang *et al.*, 1980; and Pathe *et al.*, 2009). However, we found that the PALSAR L-band has had difficulties to penetrate the high dense mesquite trees. Fig. 4 shows the backscatter coefficient subtraction value ($\Delta\sigma^0_{(Sep-15-2009)-(Sep-10-2007)}$) calculated from total backscatter coefficient $\sigma^0[dB] = 10\log\sigma^0[m^2m^{-2}]$ of PALSAR L-band HH/HV polarimetric data on September 10th, 2007 and September 15th, 2009 and computed as follows:

$$\Delta VSM = f(R, m_s) \approx \Delta\sigma^0_t = (\sigma^0_{t2} - \sigma^0_{t1}) \qquad (3)$$

Where, $\triangle VSM$ is seasonal or annual change of volumetric soil moisture; *R* is surface roughness and m_s in soil moisture.

To reduce the effect of roughness on a retrieval of soil moisture, a ratio of backscatter coefficient for wet and dry soil has been calculated. The backscatter coefficient subtraction values (September 10th, 2007 and September 15th, 2009) showed that changes in the soil moisture at the bare soil areas were greater than that in mesquite tree ground (**Fig. 4**).

It has been suggested that the mesquite trees had grown up a little during two years period (from 2007 to 2009), because the value of $\Delta\sigma^0_t$ was slightly positive (0 to + 4) at the mesquite tree areas. Contrarily, the soil moisture of bare soil in the Atbara River basin showed a great change ($\Delta\sigma^0$ was (+ 4 < $\Delta\sigma^0$) or (0 > $\Delta\sigma^0$)).

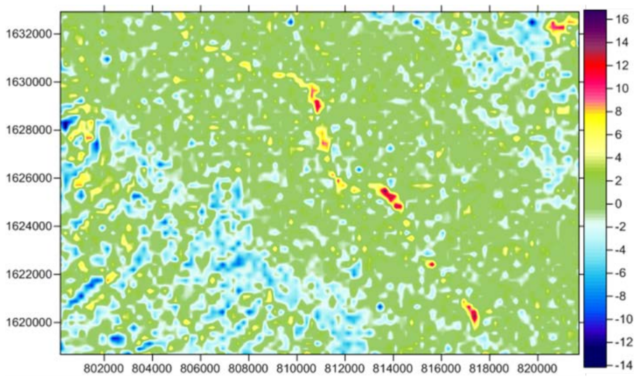

Fig. 4. The distribution map of PALSAR backscatter coefficient subtraction value ($\Delta\sigma_t^0$) between September 15th, 2009 and September 10th, 2007 of Kassala area (where, the changes of surface roughness (mesquite tress pixels) ranged the values of ($0 \leq \Delta\sigma_t^0 \leq +4$) and the changes of soil moisture (bare soil or river channel pixels)) are ($+4 < \Delta\sigma_t^0$) or ($0 > \Delta\sigma_t^0$)).

3. Discussion

The mesquite trees (*Prosopis juliflora*) grow in arrays of habitats, and characterized by very high water use efficiency. In this study we applied ground measurement of the plants stomatal conductance and satellite based Normalized Difference Infrared Index (NDII) to detect the foliar water content, and tried to retrieve the mesquite tree distribution area.

If vegetation water content can be estimated independently using reflectance in the SWIR, then the retrievals of soil moisture content would be more accurate. The problem is that SWIR reflectances are dominated by foliar water content and are not affected by stem water content. However, plants often have allometric relationships between foliar and stem mass, so estimation of foliar water content from SWIR reflectance would allow predicting of vegetation water content. We found that the high dense mesquite trees make it difficult to detect by using PALSAR L-band because of the penetration difficulties. Based on the accurate scattering model, both the soil moisture and surface roughness can be retrieved from the measurements of the polarimetric backscatter with a good accuracy for bare-soil surfaces. However, for areas covered with dense mesquite trees, the soil moisture retrieval is a challenging problem because of complicated scattering mechanisms in the mesquite canopy. So far, additional studies on the estimation of the mesquite biomass using PALSAR L-band microwave data are needed. In this study, the backscatter coefficient subtraction values ($\Delta\sigma_t^0 = (\sigma_{t2}^0 - \sigma_{t1}^0)$, where, *t1* and *t2* are September 10th, 2007 and September 15th, 2009, respectively) showed that changes in the soil moisture in the bare soil area were greater than that in vegetated ground in semi-arid region.

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