Temporal and Spatial Changes in Grassland Transpiration Detected using Landsat Imagery

C.D. Holifield, S. McElroy, M.S. Moran, R. Bryant, T. Miura, X. Gao and A. Huete
USDA-ARS Southwest Watershed Research Center, Tucson, Arizona 85719 USA
Department of Soil, Water and Environmental Science, University of Arizona 85721 USA

moran@tucson.ars.ag.gov

Abstract – The Water Deficit Index (WDI) derived from Landsat imagery was used to detect temporal and spatial changes in grassland transpiration. The WDI approach to estimating evapotranspiration is based on the relation between surface reflectance and temperature and driven by meteorological data, and has been successfully applied over heterogeneous terrain with little apriori information. The WDI information was derived from a 10-year, Landsat-4, -5, -7 data series taken of the Walnut Gulch Experimental Watershed in Arizona during the summer monsoon period. Transpiration estimated by the WDI was compared with precipitation data obtained from rain gauge instrumentation located in the watershed. Results from this study showed that the WDI was able to detect temporal and spatial changes in transpiration, as well as differences in transpiration caused by topography. Ultimately, the WDI approach may be used as a viable tool to measure plant health over heterogeneous regions.

I. INTRODUCTION

Grasslands compose a substantial portion of the world's rangeland ecosystem and are a significant food source for wild and domestic animals. The ultimate goal of rangeland sustainability may be attained through the monitoring of grassland health. The National Research Council (1994) defines an organism as being healthy when it is "functioning properly and normally in its vital functions." One such vital function of grasslands is photosynthesis. Photosynthesis has been used to monitor health at fine scales using various closed, open, and isotopic systems. Unfortunately, photosynthesis is very difficult to estimate at the regional scale.

However, a number of methods using satellite data have been developed to estimate regional evapotranspiration (ET), or transpiration in cases when evaporation is zero (Granger, 2000). As plants open their stomates to take up carbon dioxide for photosynthesis, water is lost through transpiration. Reductions in transpiration can cause a cessation in plant growth, and excessive transpiration causes growth retardation and even death. Due to its link with photosynthesis, transpiration can be used as an indicator of plant health and activity.

Images from satellite-based sensors can be used to monitor plant and soil conditions over extensive regions. For this reason, a great deal of attention has been given to estimation of ET in rangelands using satellite imagery. Most methods for estimation of rangeland ET from satellite imagery require a great deal of information about plant cover, plant height, and soil moisture, which is difficult to compute over a heterogeneous region (e.g., Henebry, 1993). One approach, based on the relation between surface reflectance and temperature and driven by meteorological data, has been successfully applied over heterogeneous terrain with little apriori information. This approach, termed the Water Deficit Index (WDI) (Moran et al., 1996), was used in this study to give a relative estimate of ET over a considerable area. In the Southwest United States, where evaporation from soil is generally small, estimates of ET are generally dominated by transpiration from plants. Thus, regional estimates of ET from satellites are related directly to transpiration, and consequently to plant health.

In the past, a study like this one would have involved the use of imagery from one or a combination of satellite types (Landsat TM, SPOT, NOAA, etc). However, the 1999 launch of Landsat-7 now provides the opportunity to utilize the imagery of three consecutive Landsat satellites. Therefore, the objectives of this study were to 1) use the WDI derived from Landsat-4, -5, and -7 imagery to detect temporal and spatial changes in grassland transpiration in Southeast Arizona; 2) determine whether WDI can detect changes in transpiration caused by changes in topography; and 3) investigate the relationship between WDI and an Antecedent Retention Index (ARI) used to estimate plant available soil moisture.

II. METHODS

The WDI is based on a Vegetation Index/Temperature (VIT) Trapezoid (Fig. 1) which combines a spectral vegetation index with surface (combination of soil and vegetation) temperature measurements to determine water deficit conditions (see Moran et al., 1996 for computation details). The WDI = $(1 - ET/ET_p)$, where ET is the actual evapotranspiration rate and ET_p is the potential evapotranspiration rate. The WDI ranges from 0 (high transpiration) to 1 (no transpiration).

Proc. Internat'l. Soc. Rem. Sens. Environ. Conf., April 8-12, 2002, Buenos Aires, Argentina

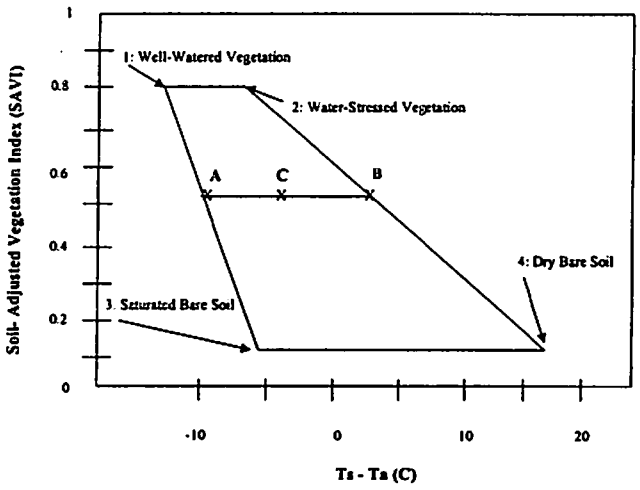

Fig.1 The hypothetical trapezoid shape that would result from the relation between temperature and the soil adjusted vegetation index (ranging from ~ 0.1 for bare soil and ~ 0.8 for full-cover vegetation). The Water Deficit Index (WDI) is equal to the ratio of AC/AB.

WDI was computed for a study area within the Walnut Gulch Experimental Watershed (WGEW) in SE Arizona. An area of approximately 9 square kilometers, located in the northeastern section of the watershed was examined for this study. This section of the watershed is dominated by black grama (*Bouteloua eriopoda*), blue grama (*B. gracilis*), sideoats grama (*B. curtipendula*), bush muhly (*Muhlenbergia porteri*), and Lehmann lovegrass (*Eragrostis lehmanniana*). In terms of topography, the primary drainage runs from the northeast to the southwest. Typical ridge to valley height ranges from 15-20 m and spacing between ridge tops is around 500 m. To obtain a realistic estimate of available soil moisture and rainfall, the study area was divided into seven sections using Thiessen polygons based on the locations of rain gauges.

Stations designed to measure runoff from rainfall events are also located in the watershed. One such station was located near the study area. Precipitation and runoff data obtained from the rain gauges and the nearby watershed station were used to estimate plant available soil moisture using an Antecedent Retention Index (ARI) (Saxton and Lenz, 1967). The ARI is an index based on previous precipitation minus runoff. To account for soil water loss over time, a decay constant is also used. Thus, the equation used to calculate the ARI was

$$ARI_i = (ARI_{i-1} + R_{i-1})K, \qquad (1)$$

where R = precipitation – runoff, K = 0.85 and $_i$ = the selected day.

The soil moisture information obtained from the ARI was compared with the transpiration estimated by the WDI. Analysis of the relation between WDI and soil moisture (or ARI) was defined by Moran et al. (1997), where

$$WDI = (1 - E/E_p) = 1.17e^{[-12.91 h_v]}, \qquad (2)$$

and h_v is the volumetric soil moisture content.

Regional changes in grassland transpiration were estimated using a ten year (1990-2000) series of Landsat-4, -5, and -7 images of the WGEW in southeastern Arizona during the summer monsoon period. Each image was geocorrected to sub-pixel accuracy using the nearest neighbor resampling method. Surface reflectance was derived from Landsat digital number (*dn*) using the Refined Empirical Line (REL) method (Moran et al., 2001). Temperature was retrieved from the Landsat thermal *dn* using the technique outlined by Moran (1990). Meteorological data taken at 10:00 a.m. or 10:30 a.m. on image days was used to compute the WDI according to Moran et al. (1996).

III. RESULTS AND DISCUSSION

There were no distinguishable differences in WDI values derived from Landsat-4, -5, or -7 satellite images, thus indicating continuity among all three satellites. The WDI was able to detect both temporal and spatial changes in grassland transpiration. For example, Fig. 2 shows the plant available soil moisture for the 1995 summer monsoon season, and the WDI data for three images taken within that period (DOY 218, 266, and 282). The increase in transpiration from DOY 218 to DOY 266 was due to precipitation within that 48-day period. Following this interval, a decrease in transpiration was detected between DOY 266 and DOY 282 due to the soil drying out over a 16-day period. Thus, the 1995 data illustrated the changes in transpiration caused by an increase and subsequent decrease in soil moisture.

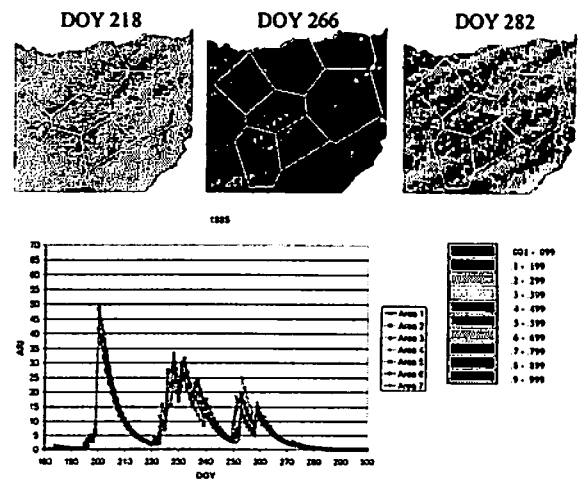

Fig. 2 Water Deficit Index images with color ramp for 8/6/95 (DOY 218), 9/23/95 (DOY 266), and 10/9/95 (DOY 282). Antecedent Retention Index for the summer monsoon period in 1995 for the seven study areas.

A relation between WDI and ARI,

$$WDI = 0.62e^{[-0.095(ARI)]} , \qquad (3)$$

was determined based on estimates from all images over all years (Fig. 3). This relation was significant but weak (R^2=0.43). There were several factors that could account for this discrepancy. The first being that WDI was based on numerous variables (Moran et al., 1996) and there may have been some error associated with one or more of the variables used as an input. For example, it was discovered that a change of one degree in air temperature made a 13 to 17% difference in the WDI calculation. A second factor was the error associated with the inputs used in the generation of the ARI, particularly the K coefficient. A third factor was the data for 1994 and 1995. The majority of the data fit the exponential curve, but these two years did not. We were unsuccessful in determining the cause of their deviation from the trend. Finally, it should be noted that though WDI and ARI are similar, they are not measuring the same information. The data showed that a WDI value of approximately 0.6 was equivalent to a soil moisture measurement of zero (Fig. 3). After this point, WDI continued to be responsive to changing conditions while ARI did not, implying that WDI was the more sensitive indicator of vegetation health.

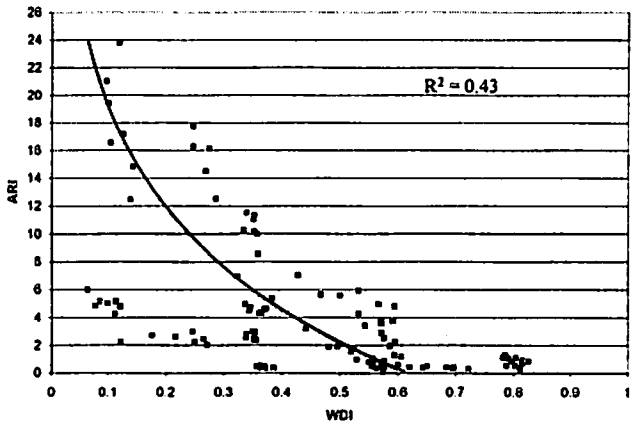

Fig. 3 Comparison of Antecedent Retention Index and Water Deficit Index for 10 years of data for the seven study areas.

IV. CONCLUSIONS

The Water Deficit Index (WDI) derived from continuous Landsat-4, -5, and -7 imagery was able to detect temporal and spatial changes in grassland transpiration, as well as changes caused by topographic effects. The WDI shows great promise as a viable tool for estimating plant health over heterogeneous regions, and any future work aimed at reducing the error associated with inputs used for its calculation can only serve to strengthen this prospective land management tool.

ACKNOWLEDGEMENTS

This work was supported by the NASA EO-1 grant (M.S. Moran). The authors wish to express sincere thanks to Carl Unkrich, Scott Miller, Dave Goodrich, Mary Nichols, Tim Keefer, Sharon Biedenbender, and the personnel at the USDA ARS Southwest Watershed Research Center, Tucson, and the USDA ARS Tombstone facility for all of their cooperation and assistance.

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