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INVESTIGATING TEMPORAL RELATIONSHIPS BETWEEN RAINFALL, SOIL MOISTURE AND MODIS-DERIVED NDVI AND EVI FOR SIX SITES IN AFRICA

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Abstract - This study investigates temporal relationships between vegetation growth, rainfall, and soil moisture for six sites located in sub-Saharan and southern Africa for the period 2005-2009. Specifically, seasonal components of time series of Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) composites from the Moderate Resolution Imaging Spectroradiometer (MODIS) and half-hourly in-situ rainfall and soil moisture data at different depths (5-200 cm) during the growing season were used in a lagged correlation analysis in order to understand how vegetation growth responds to rainfall and soil moisture across different sites. Results indicate that both vegetation indices are strongly related to soil moisture (EVI slightly stronger than NDVI) for the upper 1 m reaching maximum correlations when they lag soil moisture by 0-28 days. They respond to rainfall with a 24-32 day lag at the sub-Saharan sites, EVI slightly earlier than NDVI, but their response at the southern hemisphere sites is complex.

Keywords: vegetation, soil moisture, hydrology, MODIS

1. INTRODUCTION

In arid and semi-arid regions, like sub-Saharan Africa, rainfall is the main factor controlling vegetation growth (Kong et al., 2009; Zhang et al., 2005). Soil moisture is widely recognized as the key factor that links rainfall to vegetation growth. Much work has been conducted for studying the relationships between the NDVI as an indicator of plant growth and rainfall (e.g., Pennington and Collins, 2007; Brunsell, 2006) while fewer studies have reported the relationships between vegetation indices and soil moisture (e.g., D'Odorico et al., 2007; Nandintsetseg et al., 2010). Very little work has been done on simultaneously investigating the response of vegetation (NDVI and EVI) to both rainfall and soil moisture at various soil depths from the surface to the below root zone for different vegetation types, in Africa. This multi-variable investigation can lead to a better understanding of the relationships between climate and vegetation growth, and their long-term dynamics in semi-arid Africa.

2. STUDY AREA

The data are extracted for six CarboAfrica sites. Figure 1 shows the MODIS-International Geosphere-Biosphere Programme (IGBP) land cover map of main parts of Africa

including the location of 4 study sites in sub-Saharan region and 2 sites in southern hemisphere in Africa (Table A). The southern hemisphere sites (ZA-Kru and ZN-Mon) have higher annual precipitation and slightly lower mean annual temperature than the sub-Saharan sites.

3. DATA

3.1 Rainfall and Soil Moisture

Half-hourly in-situ rainfall and soil moisture measurements (at 5, 15, 30, 60, 100, 150 and 200 cm depths) provided by the CarboAfrica project for the period 2005-2009 were used in this study (Table B). Only the SD-Dem site has complete measurements for the entire period.

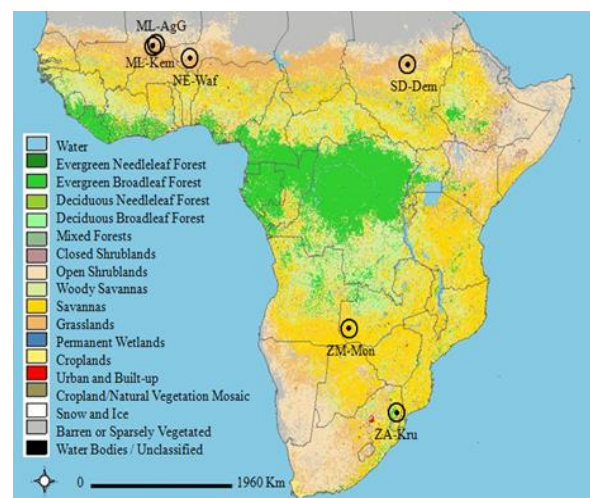


Figure 1. Location of the study sites on the MODIS-IGBP land cover map of most parts of Africa. (Source: <http://daac.ornl.gov/MODIS/modis.shtml>).

Table B. Data Used in Study

Study sites	Data time period			Soil moisture depth (cm)
	NDVI & EVI (year)	Rainfall (year)	Soil moisture (year)	
ML-AgG	05-09	05-07	07	5, 15
ML-Kem	05-09	05-08	07-08	15
NE-Waf	05-09	05-06	05-06	5, 15, 30, 60, 100, 150
SD-Dem	05-09	05-09	05-09	5, 15, 30, 60, 100, 150, 200
ZA-Kru	05-09	05-09	05-09	5, 15, 30, 60
ZM-Mon	05-09	07-09	07-09	5, 15, 30

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Table A. Biophysical Characteristics of the Study Sites

Study sites	Site characteristics				
	Country	Location	Land cover (MODIS-IGBP)	Mean annual temperature (°C)	Annual precipitation (mm)
ML-AgG (Agoufou G)	Mali	Lat: 15.343220, Long: -1.480670	Grassland	29.7	350
ML-Kem (Kelma)	Mali	Lat: 15.223700 Long: -1.566200	Open Shrubland	29.6	350
NE-Waf (Wankama fallow)	Niger	Lat: 13.647581 Long: 2.633689	Grassland	28.5	519
SD-Dem (Demokeya)	Sudan	Lat: 13.282900 Long: 30.478300	Grassland	26.0	320
ZA-Kru (Skukuza)	South Africa	Lat: -25.019700 Long: 31.496900	Savanna	21.9	547
ZM-Mon (Mongu)	Zambia	Lat: -15.437778 Long: 23.252777	Savanna	24.5	945

3.2 MODIS Reflectance, NDVI and EVI

The atmospherically corrected MODIS surface reflectance product (MOD09A1) was used for calculating the NDVI and EVI. These 8-day composites make up a gridded level 3 product that provides bands 1-7 at 500 m resolution in the sinusoidal projection. NDVI and EVI data were computed from Equations (1) and (2), respectively (Rouse et al., 1974; Huete et al., 1994).

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \quad (1)$$

$$EVI = G \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + C_1 \rho_{RED} - C_2 \rho_{BLUE} + L} \quad (2)$$

where ρ_{NIR} , ρ_{RED} and ρ_{BLUE} are surface reflectances of the near-infra red, red and blue bands, respectively. Coefficients for MODIS-EVI algorithms are: $L=1$, $C_1=6$, $C_2=7.5$ and $G=2.5$.

4. METHODOLOGY

4.1 Seasonal Components of Time Series

We choose to analyze the seasonal components for our data because these components can reveal general information for a time series within a year. This can be useful for comparing the general variations of two or more data series, especially for different locations for the same time period.

The seasonal component of rainfall time series for the period 2005-2009 was extracted at an 8-day time step (the seasonal component is the within-year fluctuations in a time series). To do this, sums of half-hourly rainfall measurements for every 8 days ($8 \times 24 \times 2 = 384$ measurements), starting from the first Julian day, were computed for each site and year. Then, the means of derived time series over the years 2005 to 2009 were computed. We converted half-hourly soil moisture measurements to a daily time step through simple averaging of every 48 single measurements for each site and year. The seasonal component of daily soil moisture time series for the period 2005-2009 was then computed by averaging the daily data series over the years. We also extracted the seasonal components of NDVI and EVI time series for each site at both daily and 8-day time steps to match with the time step of soil moisture and rainfall data series, respectively. Seasonal components with 8-day time steps were derived through averaging (over the years) the

already obtained vegetation indices time series (via Equations 1 and 2). But for computing the daily seasonal components, the time series of 8-day composites of vegetation indices for each site and year were firstly interpolated to a daily time step, i.e., every 8-day composite NDVI/EVI value was assigned to the exact day when that vegetation index observation was recorded for and then a linear interpolation in order to estimate the values for the remaining 7 days was performed. Finally, the seasonal component (with daily time step) was obtained by simple averaging of the interpolated time series over the years.

4.2 Correlation Analysis

Pearson correlation coefficients (R) were calculated between the seasonal components of NDVI/EVI and rainfall time series (8-day lags) during the growing season for all sites (June-November for the sub-Saharan sites and December-May for southern hemisphere sites). We also calculated correlation coefficients and time lags (in days) between the seasonal components of NDVI/EVI and soil moisture time series for all available depths at each site during the growing season.

5. RESULTS and DISCUSSION

5.1 NDVI/EVI and Rainfall

Correlation coefficients between seasonal components of NDVI/EVI and rainfall time series during the growing season against time lag (8-day) are shown in Figures 2 and 3, respectively. The highest maximum correlations between NDVI and rainfall (0.47-0.76) occur in the range of 1-4 lag intervals (8-32 days) for the sub-Saharan sites, and with 5 lag intervals (40 days) for the southern hemisphere sites with correlation coefficients of 0.47-0.50 (Figure 2). EVI responds to rainfall in the range of 3-4 lag periods (24-32 days) at the sub-Saharan sites with maximum correlations of about 0.56-0.80. At southern hemisphere sites, the maximum correlation coefficients between EVI and rainfall are lower than those at sub-Saharan sites (Figure 3).

5.1.1 Dry vs. Wet Sites

The quicker response of NDVI to rainfall at drier sites (sub-Saharan) is in agreement with findings by Wang et al., (2003, 2007) for the central Great Plains, USA and also consistent with occurrence of more sandy soils at these sites, leading to high evaporation, quick infiltration, and shorter response times. Note that the southern hemisphere sites have many more trees with deeper roots and less sandy soil than the sub-Saharan sites. This means it would take a longer amount of time for water to infiltrate to the root zone and therefore become available for

plant growth. This explains the larger lags between rainfall and NDVI at southern hemisphere sites.

At the wetter southern hemisphere sites, the correlation coefficients are lower than those for the sub-Saharan sites. According to Nicholson and Farrar (1994), saturation occurs in the NDVI response to rainfall in semi-arid Botswana with rainfall > 500 mm per year (like the southern hemisphere sites in this study). NDVI saturation for these dense vegetation canopies might reduce the correlation coefficients values at the southern hemisphere sites. Additionally, for wetter sites, vegetation growth may be more sensitive to other factors like solar radiation, nutrients, etc. According to Zhang et al. (2005) relations between rainfall and vegetation indices at the southern Africa is complex.

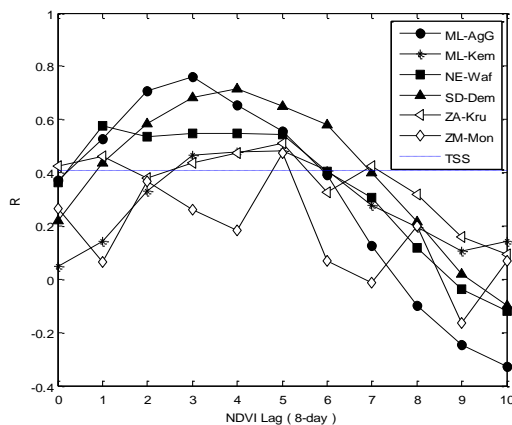


Figure 2. NDVI-rainfall correlation coefficient vs. time lag (8-day) of NDVI at the study sites during the growing season. The TSS line (0.41) indicates the threshold of 95% statistical significance.

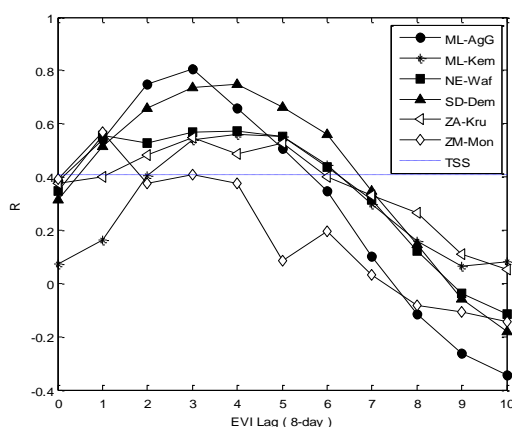


Figure 3. EVI-rainfall correlation coefficient vs. time lag (8-day) of EVI at the study sites during the growing season. The TSS line (0.41) indicates the threshold of 95% statistical significance.

5.1.2 NDVI vs. EVI Responses

EVI shows slightly higher correlations with rainfall than NDVI by about 0.04-0.09 at all sites during the growing season. In addition, EVI responds to rainfall changes earlier than NDVI by about 0-8 days at the sub-Saharan sites where rainfall is a controlling factor.

5.2 NDVI/EVI and Soil Moisture

Maximum correlation coefficient values (R_{max}) and their corresponding time lags (in days) between seasonal NDVI/EVI and soil moisture time series during the growing season for all sites are shown in Table C. In general, NDVI/EVI shows slightly stronger correlations with soil moisture than rainfall.

5.2.1 Grassland vs. Savanna Sites

The majority of grass roots are generally located at shallow depths (up to 50 cm) and in some cases depending on the climate, soil and vegetation characteristics they can be present at soil depths up to 1 m (Kurc and Small 2007; Schnur et al., 2010). For the SD-Dem site, the vegetation indices lag soil moisture by 10-22 days with maximum significant correlation values (> 0.73) at 5-100 cm depths. At the NE-Waf site, there is a 28-day lag between both vegetation indices and soil moisture at 5 cm depth and 8-11 day lag at a 60 cm depth. Correlation coefficients at 30 cm and 150 cm depths at this site did not show a strong relationship between vegetation indices and soil moisture.

For the southern hemisphere savanna sites (ZA-Kru and ZM-Mon) with lower correlations than the sub-Saharan grassland sites, both vegetation indices lag soil moisture by 0-24 days for the upper 1 m depth. At the ML-Kem site (open shrubland), time lags between NDVI/ EVI and soil moisture are longer than those at the ML-AgG site but with lower correlation coefficient values. The longer lags can likely be explained by the time it takes for water to infiltrate from the surface to deeper shrub roots at the ML-Kem site compared to the grass roots at the ML-AgG site.

5.2.2 Time Lags vs. Depths at Grassland Sites

For the sub-Saharan grassland sites, both vegetation indices have shorter time lags with soil moisture at larger depths. Plants begin the process of growth as water infiltrates from surface depth to the root zone. When water reaches the deeper layers, plants have already started to grow. Therefore, the shorter time lags at greater depths at the grassland sites may be explained by the longer time it takes for water to infiltrate, as well as earlier vegetation growth. However, the relatively high correlation coefficients between vegetation indices and soil moisture at > 1 m depths at the NE-Waf and SD-Dem grassland sites (the only sites with soil moisture data for depths > 1 m), might not be due to a direct correlation between growth and soil moisture but rather to the inter-correlation between soil moisture at different levels.

5.2.3 NDVI vs. EVI Responses

In general, both NDVI and EVI are highly correlated with soil moisture at all sites up to a 1 m depth implying strong relationships between vegetation growth and soil moisture at these depths, where most of the root biomass is located. Furthermore, EVI shows slightly higher correlations with soil moisture than NDVI at all sites during the growing season. In addition, EVI responds to soil moisture changes earlier than NDVI by about 0-4 days at the sub-Saharan sites where rainfall is a controlling factor. These slightly stronger relationships with EVI might occur because of improved corrections for variations in atmosphere, soil, and canopy background which make it sufficient for monitoring open canopy areas such as grasslands and savannas (Huete et al., 1997). However, a more physically-based investigation using the equal-length data series is needed for demonstrating the differences between temporal responses of NDVI and EVI to rainfall and soil moisture variations at the study sites.

Table C. Maximum Correlation Coefficient Value (R_{\max}) and Time Lag (day) between the Seasonal Components of NDVI/EVI and Soil Moisture Time Series during the Growing Season. The Threshold of 95% Statistical Significance for R is 0.15.

		ML-AgG		ML-Kem		NE-Waf		SD-Dem		ZA-Kru		ZM-Mon	
		R_{\max}	Lag	R_{\max}	Lag	R_{\max}	Lag	R_{\max}	Lag	R_{\max}	Lag	R_{\max}	Lag
NDVI	5 cm	0.58	21	-	-	0.61	28	0.73	22	0.48	5	0.58	0
	15 cm	0.68	11	0.45	24	0.79	0	0.83	19	0.57	5	0.56	8
	30 cm	-	-	-	-	0.18	0	0.86	16	0.66	22	0.57	8
	60 cm	-	-	-	-	0.79	8	0.81	20	0.71	22	-	-
	100 cm	-	-	-	-	0.66	0	0.87	11	-	-	-	-
	150 cm	-	-	-	-	0.36	0	0.90	5	-	-	-	-
	200 cm	-	-	-	-	-	-	0.83	4	-	-	-	-
EVI	5 cm	0.61	18	-	-	0.63	28	0.77	21	0.55	10	0.76	0
	15 cm	0.71	12	0.40	22	0.81	0	0.87	18	0.64	24	0.82	0
	30 cm	-	-	-	-	0.19	0	0.88	12	0.75	22	0.80	0
	60 cm	-	-	-	-	0.81	11	0.84	18	0.82	21	-	-
	100 cm	-	-	-	-	0.68	0	0.89	10	-	-	-	-
	150 cm	-	-	-	-	0.39	0	0.91	4	-	-	-	-
	200 cm	-	-	-	-	-	-	0.83	3	-	-	-	-

6. CONCLUSIONS

For the period 2005-2009, we conclude that NDVI/EVI demonstrate strong correlations (0.47-0.80) with rainfall (EVI slightly higher than NDVI) at the sub-Saharan sites. Vegetation indices respond to rainfall changes during 24-32 days at these sites with, stronger correlation than that at the southern hemisphere sites where relationships are complex. Further, results show that vegetation growth indicators (NDVI and EVI) are highly correlated with soil moisture at the upper 1 m (0.40-0.89) at all sites during the growing season for the same period. But, the temporal response of vegetation to soil moisture is different between the sites with decreasing lags with depth at the sub-Saharan sites while the south African sites showed increasing lags with depth.

This study helps us to better understand how vegetation growth is temporally affected by rainfall and soil moisture variations in semi-arid Africa. The next phase of this study will focus on a more process-oriented understanding of the interactions between vegetation growth, soil moisture and rainfall for each site, including the role of soil texture, soil composition and within-growing season rainfall distributions.

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