Class Project: Relation between Ground-based Soil Moisture and Satellite Image-based NDVI

ES 6973: Remote Sensing Image Processing
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Date: May 6, 2005

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Abstract: Soil moisture is critical parameters in climatic and hydrological modeling and vegetation growth. Ground-based point measurement of soil moisture is liable but expensive and impractical for watershed measurement. Remote sensing measurement has provided thriving perspective for spatial and instantaneous measurement of soil moisture. Microwave measurement is effective and successful for surface soil moisture, but influenced by the vegetation and land roughness, and can't detect the root zone or below-root zone soil moisture. Vegetation growth is heavily dependent on the water availability in arid and semi-arid areas, and the vegetation index from satellites may respond to the change of soil moisture and reflect the soil moisture to some degree. This study analyzed the profile soil moisture characteristics in three different climate and vegetation sites from Feb 2000 through Apr 2004, compared the collocated and coincided soil moisture and MODIS NDVI, and estimated the soil moisture using NDVI by least square regression model. Results showed that the root and below-root zone soil moisture in semi-arid climate has strong correlation with simultaneous NDVI and can be estimated using NDVI during growing season; the root zone soil moisture in humid climate also has moderate correlation with simultaneous NDVI during growing season; below-root soil moisture in humid climate has weak correlation with NDVI and can't be effectively estimated using NDVI; Soil moisture has weak correlation with NDVI and can't be effectively estimated using NDVI during non-growing season (Oct-March).

Key Words: Soil Moisture, MODIS NDVI, Correlation, Regression

1. Introduction

Soil moisture is one of critical parameters in climatic and hydrological modeling, including latent heat influx, infiltration, evaporation and runoff, etc. (Western, et al., 2002). Soil moisture also plays limit factors for vegetation growth in arid and semi-arid areas, where vegetation growth is heavily dependent on the water availability, and the vegetation index from satellites may respond to the change of soil moisture and reflect the soil moisture to some degree (Sandholt, et al., 2002).

Gravimetric sampling is the only direct and exact method of determining soil moisture; however, it is time and labor consuming to undertake, and therefore impractical to use for watershed estimation (Wilson, et al., 2003). Other ground-based methods, like dielectric properties, neutron probe which are widely applied in Soil Climatic Analysis Network (SCAN) sites, are indirect and soil property-depended, and must be calibrated against gravimetric samples. Among them, time-domain reflectometry (TDR) is considerately liable and portable methods for determining soil moisture content without destructing soil moisture (Roth, et al, 2001). However, all those methods are point measurement, and only relatively limited samples and areas can be sampled (Western and Grayson, 1998).

Remote sensing methods have provided thriving perspective for spatial and instantaneous measurement of soil moisture content in a recent decade years. Thermal emissions from soils in the microwave region (passive microwave) are sensitive to the fluctuation of surface soil moisture (Jackson and Schmugge, 1989). Any soil moisture in the top 5cm of soil can influence the amount of microwave radiation that is emitted at low frequency; the more the amount of water in soil, the less the energy emitted into space; cloud cover, vegetation and roughness all can affect the amount of emission (Wang and Schmugge, 1980).

Active microwave remote sensing via Synthetic Aperture Radar (SAR) has displayed the potential to map surface soil moisture at high resolution over large areas (Verhoest et al., 1998). However, various studies indicated that the accuracy of active microwave surface soil moisture measurement depends on the content of bare soil, and the vegetation cover during summer and surface roughness of land negatively affects its accuracy (Mancini et al., 1999; Cashio et al., 2004).

Recently, microwave radiometer (PMR) has been widely and successfully used for mapping large-area surface soil moisture, such as Electronically Scanned Thinned Array Radiometer (ESTAR) in Wasita'92 (Jackson et al., 1995), Scanning Multichannel Microwave Radiometer (SMMR) in West Africa (Njoku and Li, 1999), L-band Pushbroom Microwave Radiometer (PBMR) operated by National Aeronautics and Space Administration (NASA) Langley Research Center and flown NASA Ames Research Center C-130 during FIFE (Chen et al., 1997).

Microwave radiometer only can provide the at most top 10cm soil moisture. Multispectral radiometers with high radiometric and temporal resolution, like Advanced Very High Resolution Radiometer (AVHRR), Landsat Enhanced Thematic Mapper Plus (ETM+), Moderate Resolution Image Spectroradiometer, etc., allow us to infer normalized difference of vegetation index (NDVI) based on the band-ratioing of vegetation sensitivity in near-infrared (NIR) and visible (VIS) spectral bands. NDVI may point another exciting ways to explore deeper soil moisture. Adegoke and Carleton (2002) assessed the relations between soil moisture and AVHRR-NDVI (1km by 1km), and concluded that the correlation coefficient between soil moisture and NDVI is about 0.3, stronger over forest than cropland, and their correlation coefficient increases as NDVI lags behind soil moisture up to 8 weeks. The aggregated NDVI (7km by 7km) also improved their correlation.

The target of this research is to analyze the seasonal and profile characteristics of soil moisture and assess the correlation between soil moisture and MODIS NDVI (250m by 250m) at different climatic and vegetative sites from Feb, 2000 through Apr, 2004. If there is good correlation between them, the estimation of soil moisture then can be gotten using NDVI by least square regression model.

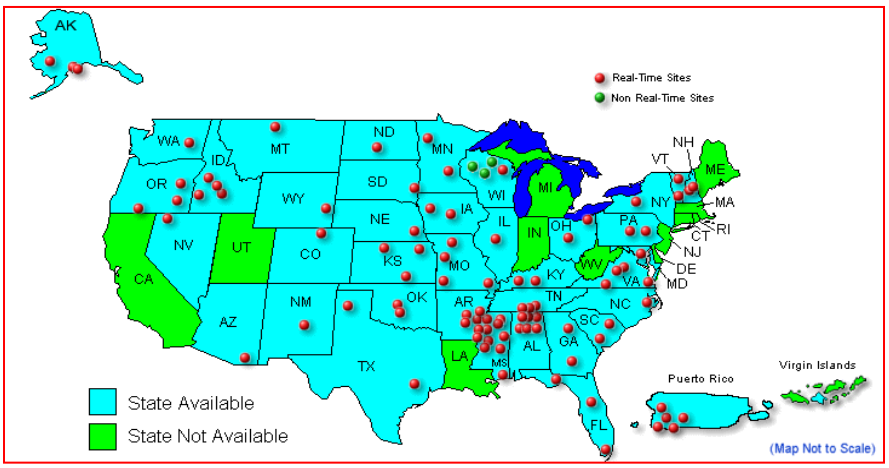
2. Research Areas and periods:

Research areas include two different climate and vegetation types. The specific data was summarized in Table 1 and displayed in Figure1.

Table 1 Research sites information

Site	Climate	Vegetation	Soil Type (%)			Location
			Clay	Silt	Sand	
Walnut Gulch (2026) Arizona	Semi-arid	Shrubland	15.2	27.8	57.0	31° 44' 1.00"N 110° 3' .00"W
Adams Ranch (2015) New Mexico	Semi-arid	Grassland	13.8	15.6	70.6	34° 15' 8.00" N 105° 25' 10.00" W
Prairie View (2016) Texas	Humid	Watermelons	22.1	24.8	53.1	30° 5' 41.00"N 95° 58' 18.00"W

Data Source: SCAN Pedon Information for Walnut Gulch (2026) Arizona, Adams Ranch (2015) New Mexico, Prairie View (2016) in Texas.



Source: **http://www.wcc.nrcs.usda.gov/scan/**

Fig.1 Soil Climate Analysis Network distribution sites

Walnut Gulch (2026) in Arizona: lies in Walnut Gulche Watershed, Lucky Hill site; yellowish red (5YR 4/6) loam, reddish brown (5YR 5/4), dry; the top 100cm average clay 15.2%, silt 27.8%, sand 57.0%; moderately alkaline, pH 8.4; slope 8.0; drainage class: well (Primary, 2005).

Adams Ranch (2015) in New Mexico: lies in Lincoln County Area, semi-rid climate, grassland. Soil is dark brown (7.5YR 3/4) sandy clay loam, brown (7.5YR 4/4), dry; the top 100cm average clay 13.8%, silt 15.6%, sand 70.6%; moderately alkaline, pH 8.0; slope 2.0; elevation 1879m; drainage class: well (Primary, 2005).

Prairie View (2016) in Texas: lies in the intersection of US Hwy 290 & Farm Rd. 1098 at Prairie View, TX, in cultivated field. Plant name: watermelons; parent material: loamy marine sediments; water table: none within 2 meters. Soil type: Wockley fine sandy loam, the top 100cm average clay 22.1%, silt 24.8%, sand 53.1%; humid climate, annual rainfall 500mm (Primary, 2005).

3. Data
3.1. Soil Moisture

Neutron probe measurements of soil moisture are made hourly at the Soil Climate Analysis Network (SCAN). All data can be downloaded free from specific SCAN web Sites. Soil moisture was measured within 5 soil layers to depth of 5cm, 10cm, 20cm, 50cm, and 100cm respectively.

3.2. MODIS NDVI

Daily MODIS reflectivity images are available from Feb 27, 2000 by ordering online (published on FFT or DVD). In order to represent the real conditions around the ground SCAN sites, this study used the 250m by 250m spatial resolution. Since the daily data can be poor quality because of atmospheric transient conditions including clouds, rainfall and aerosols (Holben, 1986), 8-day mean NDVI was used in this study. Assumed that the nine squares in figure 2 are the MODIS image pixels around the ground soil moisture monitor site (point 5), square 5 represents 250m by 250m areas. NDVI calculated from one pixel, 5 pixels and 9 pixels, has little difference among them, and the one-pixel NDVI even has better correlation with soil moisture than others, so the one pixel (Square 5) NDVI was used for further analysis.

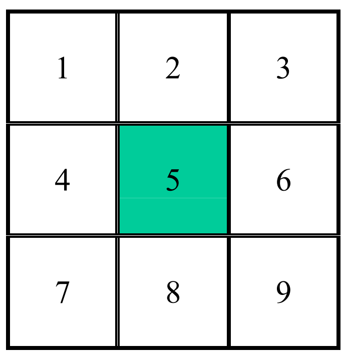


Fig.2 Collocation of the MODIS NDVI and ground soil moisture monitor site.

NDVI was calculated using the vegetation-sensitive near-infrared (NIR, band1) and visible (VIS, band2) spectral bands of MODIS reflectivity images as the following formula (1) (Agegoke and Carleton, 2002).

$$NDVI= (R_2-R_1) / (R_2+R_1) \quad (1)$$

Where: R_1 and R_2 are reflectance of band1 and band2.

4. Research Methods:
4.1. Data preparation and Q-Test

Data preparation and cleaning is extremely important step in large data mining process, where the large data sets were collected automatically and might contain out-of-range values. Analyzing data that has not been carefully screened for specific problems can produce highly misleading results, in particular in predictive data mining (Westphal and Blaxton, 1998). Since soil moisture is hourly collected automatically, it was combined into daily data for further processing. NDVI was calculated using formula (1) with raw MODIS reflectivity data for further analyzing. Then Dixon**'s** Q-Test was performed on the lowest and highest trial of all daily soil moisture and NDVI among three continuous data to screen any potential data outliers caused by all sorts of measure errors, such as the clouds, rainfall and aerosols for NDVI. The following formulas (2) are used to perform the Q-Tests (Miller, 1993).

$$Q_{\exp} = \left(\frac{|X_Q - X_N|}{w} \right) \qquad (2)$$

Where: w = Range of Data Set = Highest Value – Lowest Value; Q_{exp} = Expected Value; Q_{crit} = Critical Value; X_Q = Questionable Data Point; X_N = Nearest Neighbor Measurement to the Questionable Data Point.

If $Q_{exp} > Q_{crit}$, data point is discarded; If $Q_{exp} < Q_{crit}$, data point is retained. In order to keep the continuous data point, when $Q_{exp} > Q_{crit}$, X_Q is replaced with the mean of close two data. Table 2 contains the critical values at 95% confidence level (CL).

Table 2 Critical values for Dixon's Q-test at 95% CL (P = 0.05)

N	3	4	5	6
Q_{crit}	0.970	0.829	0.710	0.625

Source: Miller, 1993, *Statistics for Analytical Chemistry*.

After all raw data have been screened by Q-test, all data were divined by different periods, like one from April to August (growing season) and September to next March (non-growing season), to test the optimum period when the soil moisture and NDVI have the strongest correlation.

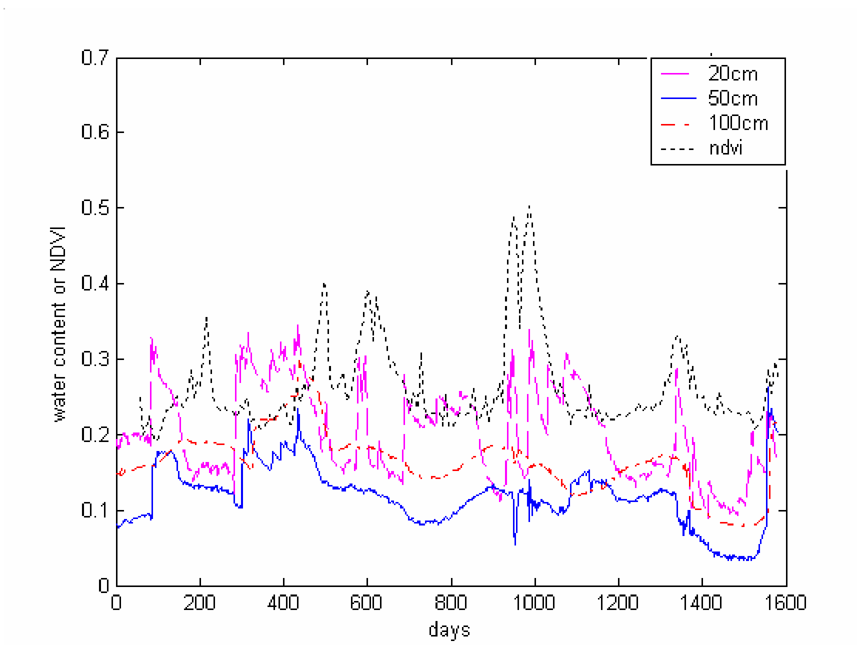


Fig.3 Plot time-series soil moisture and NDVI

The collocated and coincided NDVI and soil moisture were compared after further averaging the previous 8 daily soil moisture into one 8-day soil moisture when soil moisture and NDVI have common date. Figure 3 plots the time-series 20cm, 50cm and 100cm deep soil moisture and NDVI in New Mexico from 2000 through Apr, 2004, which shows that NDVI and soil moisture have some common change trend.

4.3. Seasonalization and Differencing Series.

Most time series patterns can be described in terms of two basic classes of components: trend and seasonality. The time series pattern of soil moisture and MODIS NDVI belongs to the latter. Seasonal pattern of time series owns serial dependencies or autocorrelation, which need to be removed in order to identify the real correlation between two variables by differencing the series, that is converting each *i*'th element of the series into its difference from the (*i-k*)"th element as shown in formula (3) (Box & Jenkins, 1976). The transformed series will be of length *N-k* (where *N* is the length of the original series) (Kendall and Ord, 1990).

$$X`(i)=X(i)-X(i-k) \qquad (3)$$

Where: X(i) is the i`th element; X(i-k) is the (i-k)`th element, k equals 8 for soil moisture and 1 for NDVI since the NDVI is 8-day average and soil moisture is daily; X`(i) is the i`th element that has been transformed or removed series dependencies.

Time-series average also called seasonalization, which displays the seasonality of variable, in the formula (4). This process mainly identifies the seasonal and profile characteristics of soil moisture at three different conditions.

$$SM(d) = \frac{\sum_{i=1}^{n} SM(d,i)}{n} \qquad (4)$$

Where: SM(d, i) is raw soil moisture on dth day, ith year.
d: the specific day in a year;
i: year (2000, 2001…2004)
n: 4 or 5 years depending on different days.
SM(d) is the time-series mean (or seasonal) soil moisture

4.4. Cross Correlation analysis

The most common measurement of correlation is the Pearson Product Moment Correlation as shows in formula (5). Pearson's correlation reflects the extent of linear relationship between two variables, which ranges from +1 to -1. Correlation of +1 or -1 means that there is a perfect positive or negative linear relationship between variables. Agegoke and Carleton's research (2002) showed that there was better correlation when

NDVI lagged soil moisture up to 8 weeks, so this study also concerned the effect of time-lagged NDVI.

$$R^2 = \frac{C(i,j)}{SQRT(C(i,j)*C(i,j))} \qquad (5)$$

R2 is a matrix of correlation coefficients from matrix X.
C is the covariance matrix of Matrix X.
SQRT(X) is the square root of the elements of Matrix X.
X is a matrix composed of soil moisture and NDVI

4.5. Regression Analysis:

Regression analysis is a traditional exploratory data analysis (EDA) technique and the final step of data mining to some degree, which is oriented towards number applications other than the basic nature of the underlying phenomena, just like a "black box". NDVI is affected by all sorts of factors, such as soil moisture, soil type, soil fertilization, air temperature, rainfall, etc. It's difficult to specify the relation between NDVI and other factors. In particular situations, one of the factors will be the primary factor, and this factor may have strong correlation with NDVI and can be estimated through regression analysis using NDVI. In arid and semi-arid regions, soil moisture becomes the major factor affecting NDVI; therefore, it can be estimated using NDVI as formula (6)-(9).

$$Y = X\beta + \varepsilon \qquad (6)$$

$$\beta = (X`X)^{-1}X`Y \qquad (7)$$

$$\check{Y} = X\beta \qquad (8)$$

$$r = Y-\check{Y} \qquad (9)$$

Where:

- Y is an n×1 vector of observed soil moisture.
- X is an n×2 matrix composed of 1 and NDVI.
- β is a p×1 constant vector calculated from X and Y
- ε is the random error component.
- ^Y is an estimated n×1 vector.
- r is an n×1 vector error between observed and estimated soil moisture.

R^2 is correlation coefficient between regressed value and observed value. Correlation and Regression model was run at Matlab6.0 software.

5. Results and Discussion:

5.1. Profile and seasonal characteristics of soil moisture.

Figure 3a below displays the soil moisture at New Mexico from Jan 1, 2000 through Apr 31, 2004. Some high frequency signals can be seen in the soil moisture of 5cm, 10cm and 20cm depth, and low frequency signals in the 50cm and 100cm depth. This is reasonable because the high frequency signals were filtered by the soil (low-pass-filter). Thus, the below root-zone soil moisture conserves some long-term (or seasonal) signal of the root-zone soil moisture. Physically, NDVI is related to root-zone soil moisture via vegetation biophysics, especially in the arid and semi-arid regions, where water availability is the growth limit factor (Sandholt, et al., 2002). It is also reasonable to assume some correlation between NDVI and the below-root-zone soil moisture, which is the water pool of root zone soil moisture, especially under high temperatures in summer when the transpiration by the vegetation is very large.

Furthermore, the soil moisture increases from 5cm, 10cm till 20cm deep, then decreases and reaches lowest at 50cm deep, finally increase again from 50cm to 100cm deep. Seasonal 5cm-deep soil moisture always less the 0.15; seasonal 10cm-deep soil moisture has the biggest changing amplitude (0.02-0.25), 20cm-deep 0.15-0.25, 50cm-deep 0.1-0.17, 100cm-ddep 0.14-0.2 (Fig. 3b). According to the profile soil moisture change, it can be reasonably assumed that the top 40cm soil responds to the root zone for grassland and soil below 40cm is the below-root zone (Heathman, et al., 2003). The seasonal change of soil moisture in figure 3b clearly displays this trend. Soil moisture has the lowest value during April through June and relative higher value during other period.

Time-series and seasonal soil moisture at Arizonan Walnut Gutch is displayed in figure 4a and 4b. Since the soil moisture data during the first 270days (Jan-Sep, 2000) is unavailable, this figure just plots the data after that day. Compared to New Mexico, soil moisture has obvious wet and dry season (Fig. 4a), and soil moisture is lower than that in New Mexico. Similar as in New Mexico, soil moisture has the lowest value during April through June and relative higher value during other period (Fig.4b). Soil moisture increases from 5cm, 10cm, 20cm till 50cm deep, then decreases till 100cm deep. As the soil moisture profile characteristics were concerned for shrubland, the top 80cm soil can be classified into root zone, other as below-root zone.

Time-series and seasonal soil moisture at Texas Prairie View is displayed in figure 5a and 5b. Soil moisture is much higher than that in New Mexico and Arizona. Seasonal 5cm and 10cm deep soil moisture ranges 0.05 through 0.30, 20cm depth 0.10 through 0.30, 50cm depth 0.15 through 0.35, 100cm depth 0.30 through 0.40 (Fig.5b). Different from New Mexico and Arizona, soil moisture has the lowest value during June through August and relative higher value during other period (Fig.5b). Soil moisture increases from 5cm, 10cm, till 100cm deep, and 100cm deep soil moisture has much higher value than that in other layers. As the soil moisture profile characteristics were concerned for farmland (Watermelon), the top 50cm soil can be classified into root zone, other as below-root zone.

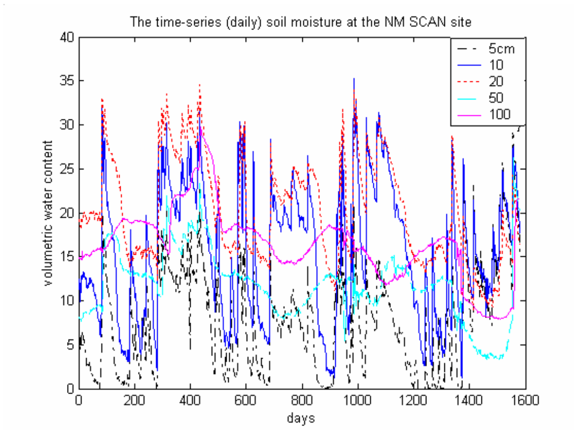


Fig. 3a Time-series daily soil moisture at NM

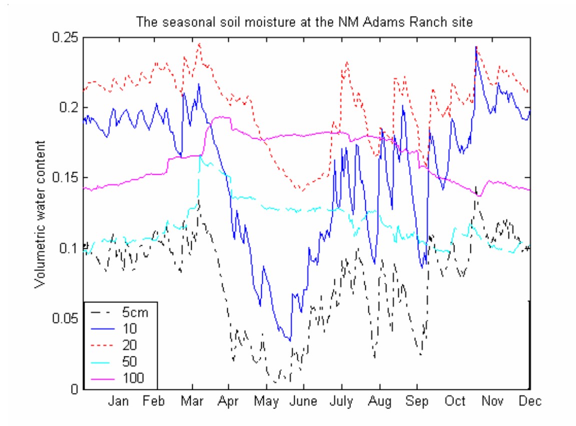


Fig. 3b Seasonal soil moisture at NM

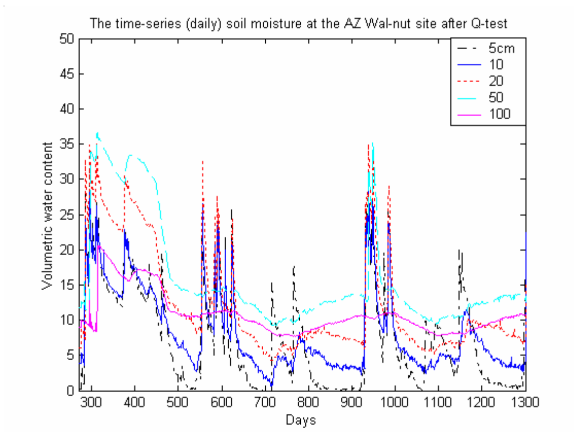


Fig. 4a Time-series daily soil moisture at AZ

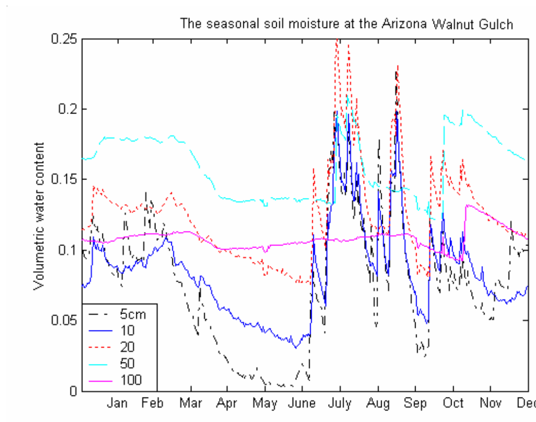


Fig. 4b Seasonal soil moisture at AZ

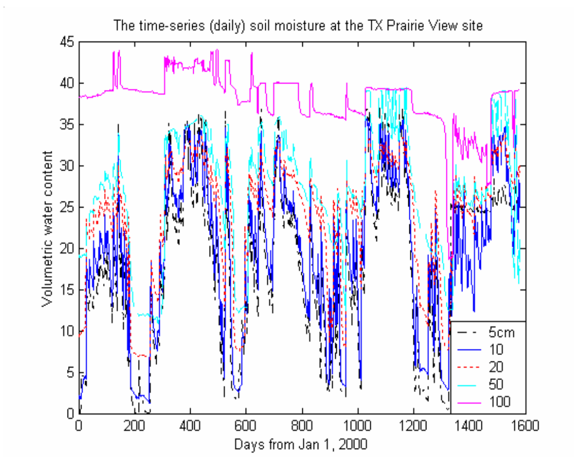


Fig. 5a Time-series daily soil moisture at TX

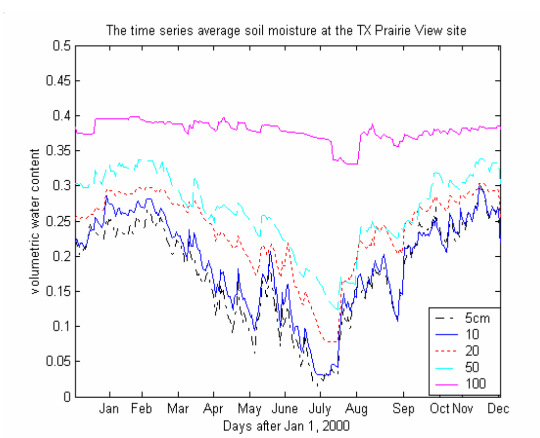


Fig. 5b Seasonal soil moisture at TX

5.2 Cross-correlation between soil moisture and NDVI
5.2.1 New Mexico Adams Ranch (2015)

The Pearson Product Moment Correlation of soil moisture and NDVI was calculated using Matlab 6.0 software. Since during non-growing season, like in winter, the leaves of most vegetation become yellow and fall, NDVI accessed from Satellite image can not represent the real situations of vegetation. Therefore soil moisture and NDVI were divided into growing season and non-growing season by trials. After trial for different periods, top 10cm and 20cm deep soil moisture has strongest correlation, respectively 0.54 and 0.65, with NDVI from April through July at Adams Ranch in New Mexico (See Fig.6a). As NDVI lags behind soil moisture, their correlation decreases. This is different from Carleton’s research (2002) that there was better correlation when NDVI lagged root zone soil moisture (top 30cm) up to 8 weeks, Scatter-plot of NDVI VS 10cm soil moisture from April through July displays their obvious linear correlation pattern (See Fig.6b).

Interestingly, during April to July, only one month ahead, the 100cm deep soil moisture demonstrates its strongest correlation (0.7) with NDVI, and linear correlation pattern is displayed in the Fig.6b. Of course, this correlation contains the series correlation or seasonal patterns of two variables, which can’t really reflect the physical meaning and relation except removing their seasonal autocorrelation/dependency. Meanwhile, 10cm and 20cm soil moisture has weaker correlation than that during May to August. 50cm deep soil moisture has very weak correlation with NDVI in both periods.

During Non-growing season (Sep-March), all layer’s soil moisture has not obvious correlation with NDVI (See Fig.7a and 7b). When NDVI lags soil moisture, their correlation gently increase.

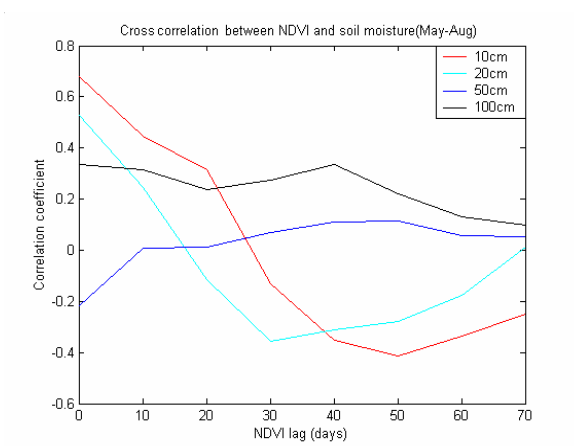


Fig.6a Correlation between soil moisture and NDVI during May to Aug at NM.

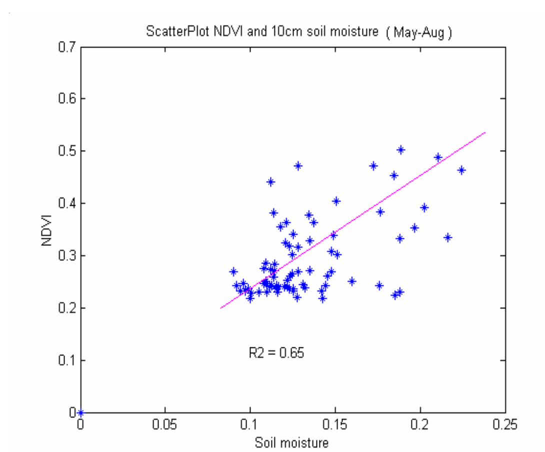


Fig.6b Scatter-plot 10cm soil moisture and NDVI during growing season (May-Aug).

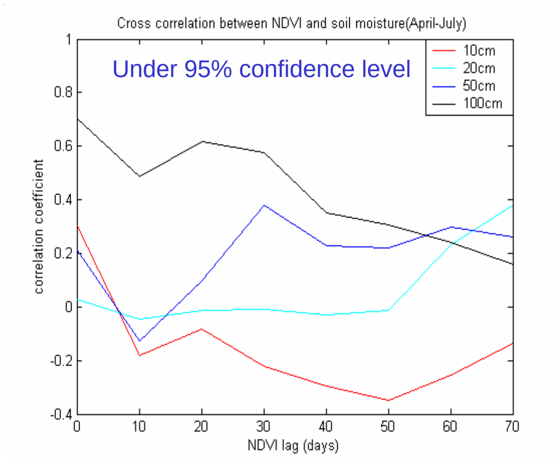


Fig.7a Correlation between soil moisture and NDVI during May to Aug at NM.

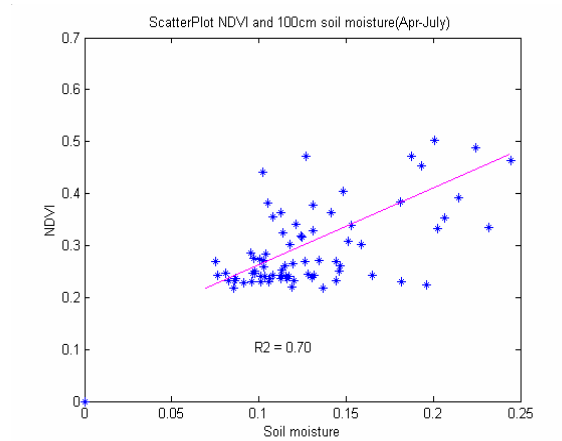


Fig.7b Scatterplot 100cm soil moisture and NDVI during growing season (May-Aug).

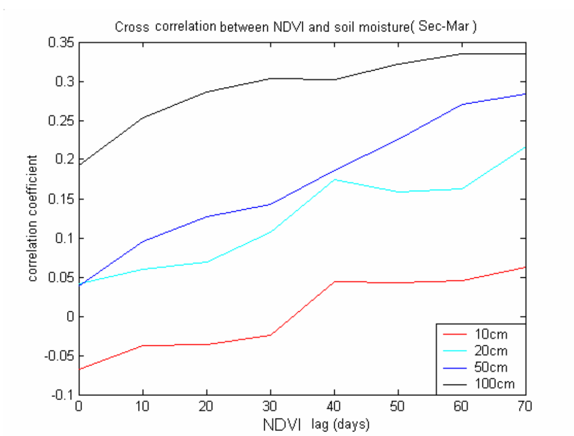


Fig.8a Correlation between soil moisture and NDVI during Sep to March at NM.

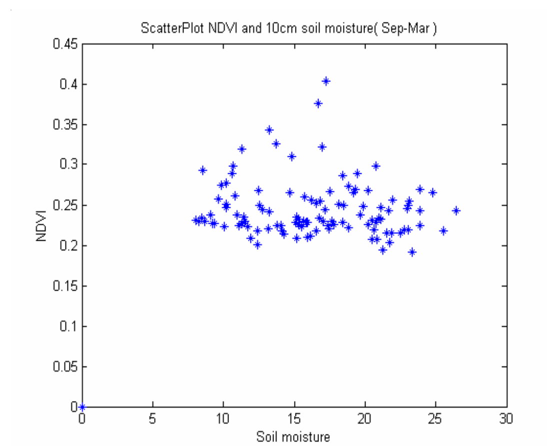


Fig.8b Scatter-plot 10cm soil moisture and NDVI during growing season (Sep-Mar).

5.2.2 Arizona Walnut Gulch (2026)

The soil moisture is lower in Arizona than that in New Mexico, meaning that the climate in Arizona is drier than that in New Mexico. Therefore water availability plays more important role for vegetation, and NDVI can more effectively reflect the soil moisture. Among different growing period trials, 10cm and 20cm deep soil moisture shows strongest correlation (0.78) with NDVI during May to August (See Fig.9a and 9b). As NDVI lags behind soil moisture, their correlation decreases. 100cm deep soil moisture has strongest correlation with NDVI during April to September(See fig.10a and 10b), while 10cm, 20cm and 50cm deep soil moisture also has strong correlation with NDVI, which identify the assume that the top 80cm soil in Arizona belong to the root soil. During the non-growing season (Oct-Mar), soil moisture shows very weak correlation with NDVI; as NDVI lags behind soil moisture, their correlation increase lightly (See fig. 11a and 11b).

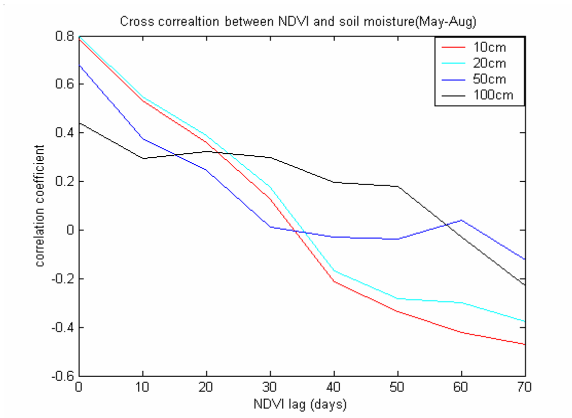


Fig.9a Correlation between soil moisture and NDVI during Sep to March at AZ.

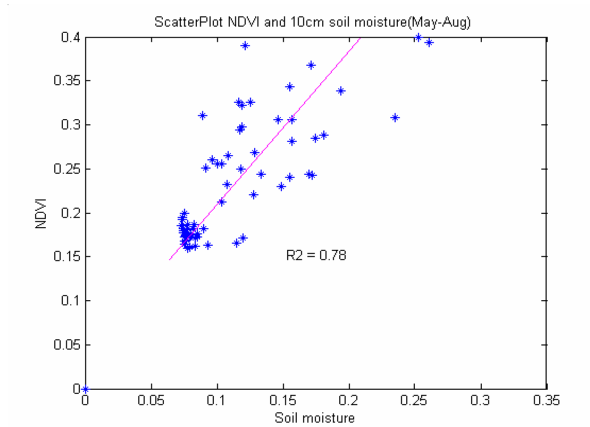


Fig.9b Scatter-plot 10cm soil moisture and NDVI during growing season (Sep-Mar).

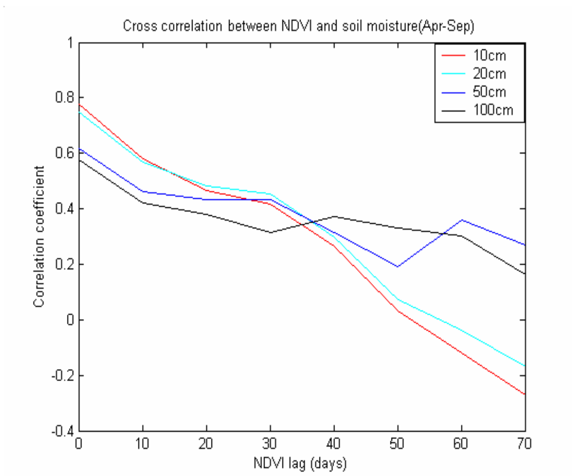


Fig.10a Correlation between soil moisture and NDVI during Apr to Sep at AZ.

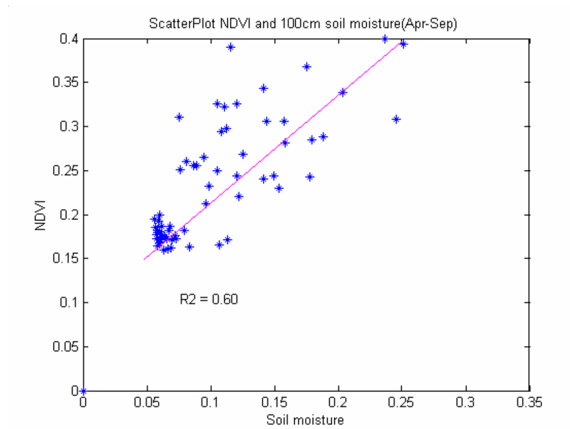


Fig.10b Scatter-plot 10cm soil moisture and NDVI during growing season (Apr-Sep).

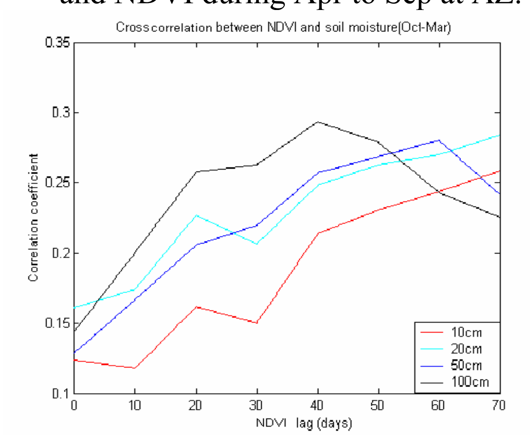


Fig.11a Correlation between soil moisture and NDVI during Oct to Mar at AZ.

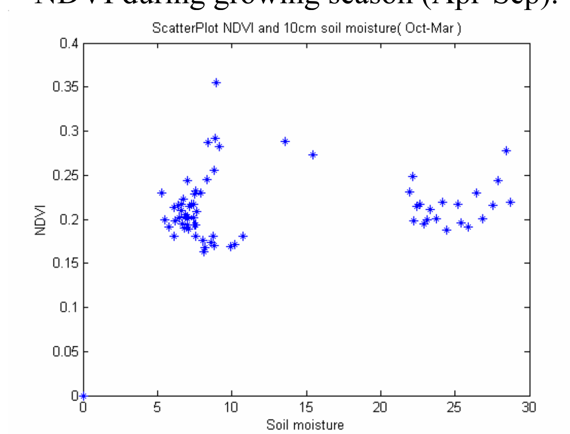


Fig.9b Scatter-plot 10cm soil moisture and NDVI during Oct to Mar.

5.2.3. Texas Prairie View (2016)

Prairie View at TX lies around Mexico Gulf and belongs to sub-tropic climate. Soil and air are very humid. Soil moisture is always above 0.15 in the root zone, and below-root zone, where soil moisture is always over 0.35, can provide much enough water pool for the root zone. Water availability is not a major factor for vegetation growth except during high-temperature period (July and August), when high temperature leads to high transpiration and water demand for vegetation. Consequently, the root zone (20cm and 50cm deep) soil moisture has a moderate correlation (0.44) with simultaneous NDVI during May through September, and 100cm deep soil moisture shows negatively weak correlation with NDVI (See Fig.12a and 12b). During the non-growing season, the correlation between soil moisture and NDVI is weak and decreases as NDVI lags soil moisture (See Fig.13a and 13b).

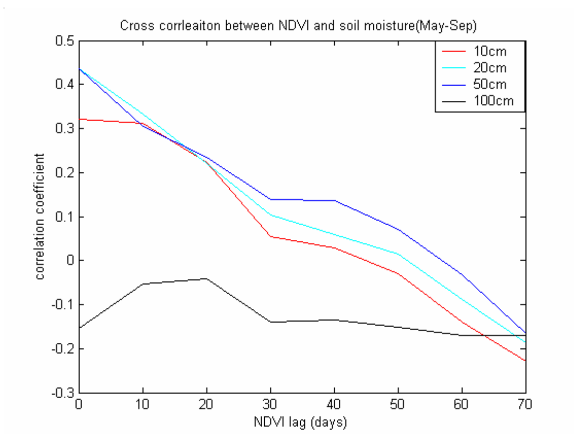


Fig.12a Correlation between soil moisture and NDVI during May to Sep TX.

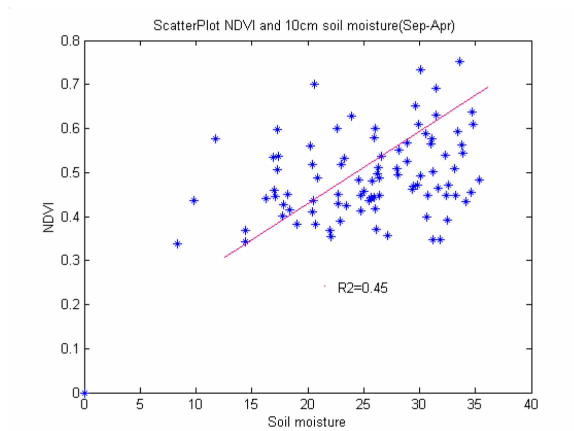


Fig.12b Scatter-plot 10cm soil moisture and NDVI during growing season (May-Sep).

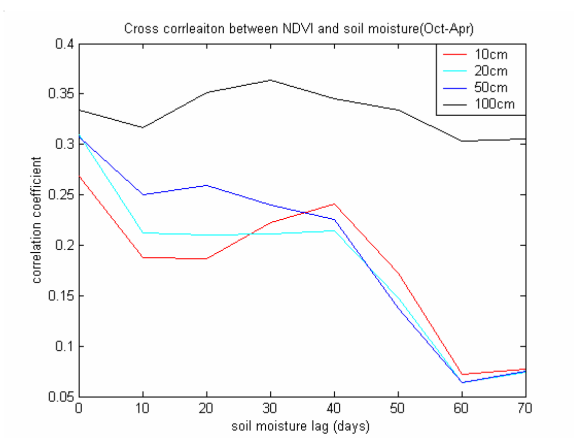


Fig.13a Correlation between soil moisture and NDVI during Oct to Apr at TX.

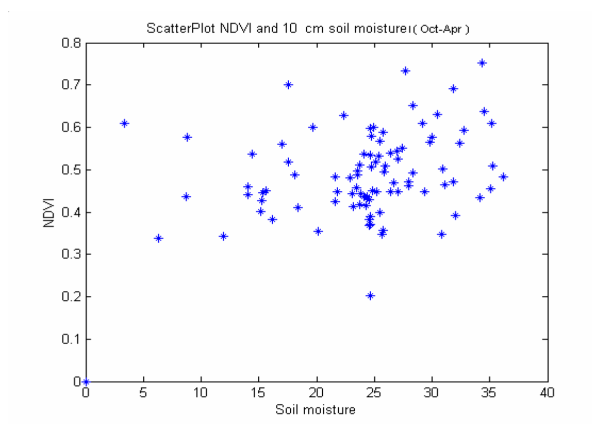


Fig.13b Scatter-plot 10cm soil moisture and NDVI during non-growing season (Oct-Apr).

5.3 Estimation of soil moisture using NDVI

Climatic and hydrological modeling requires soil moisture as input parameters. Getting exact watershed soil moisture over a long period is a big problem (Western, et al., 2002). Lots of ways have been developed to determine or estimate soil moisture based on different principles. According to cross-correlation analysis results above, the root zone soil moisture and NDVI displays strong correlation in arid and semi-arid regions during growing season. This correlation between two time-series variables may contain some autocorrelation or seasonal dependency, which is widely used for predicting time-series' future value only based on this seasonal pattern in economy, and can't really reflect the physical meaning of two variables; however it allows to estimate the soil moisture based on combining their seasonal dependency and real correlation using satellite image-based NDVI over large areas and long period (Kendall and Ord, 1990).

The least-square regression model was used to estimate soil moisture using simultaneous NDVI. All regression was analyzed under 95% confidence level. Regression coefficient R^2 represents the correlation coefficient between estimated value and observed value. Fig.14a and 14b displays the regressed 10cm deep soil moisture versus observed 10cm deep soil moisture at Walnut Gulch in Arizona and at Adams Ranch in New Mexico during a growing season, and their R^2 is 0.60 and 0.46 respectively. Since the soil moisture is lower and correlation between soil moisture and NDVI is stronger in Walnut Gulch than that in Adams Ranch, similarly, the estimated result is better in Walnut Gulch. This means that soil moisture in root zone can be effectively estimated using NDVI in arid and semi-arid region during growing season.

The root zone soil moisture reaches the lowest value during April through July, when air temperature gets its peak value among a whole year and transpiration by vegetation also corresponds to the maximum, while below-root zone plays a water pool, which saves water when root zone soil accepts too much water because of rainfall and supplies water as high water demand for root zone soil because of high evaporation of surface soil and transpiration of vegetation. The below-root zone soil moisture also shows a strong correlation with simultaneous NDVI although much of the correlation is the seasonal pattern and can be estimated with NDVI. Fig.15a and 16b gives the regressed 100cm deep soil moisture and observed 100cm deep soil moisture at Walnut Gulch in Arizona and at Adams Ranch in New Mexico during a growing season, and their R^2 is 0.33 and 0.46 respectively.

For humid regions, like at Prairie View in Texas, water availability is not a critical factor for vegetation growth. NDVI has not strong correlation with soil moisture and can't be used to effectively soil moisture.

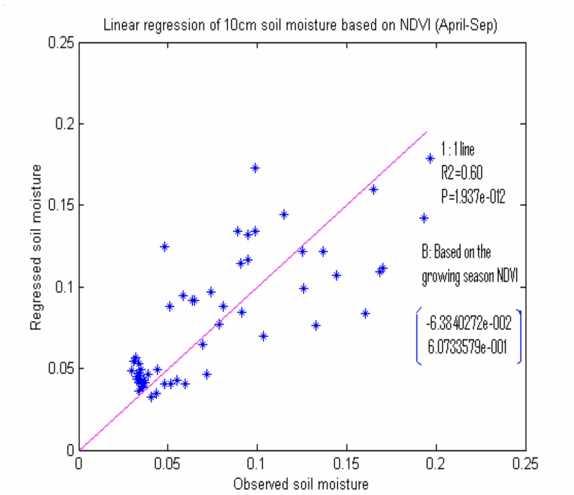


Fig.14a Regressed 10cm-deep soil moisture versus observed 10cm-deep soil moisture during April to Sep at Arizona.

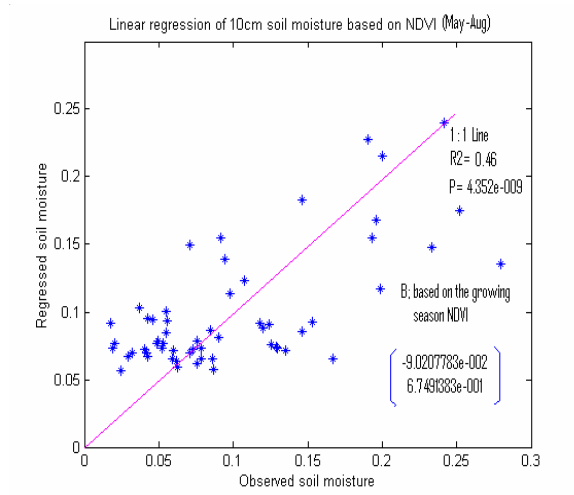


Fig.14b Regressed 10cm-deep soil moisture versus observed 10cm-deep soil moisture during April to July at New Mexico.

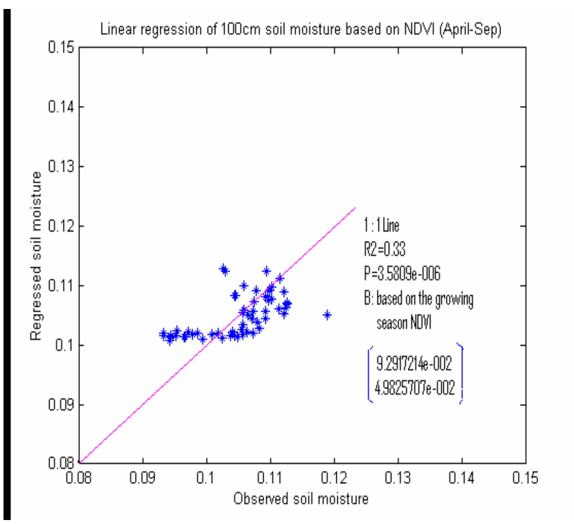


Fig.15a Regressed 100cm-deep soil moisture versus observed 10cm-deep soil moisture during April to Sep at Arizona.

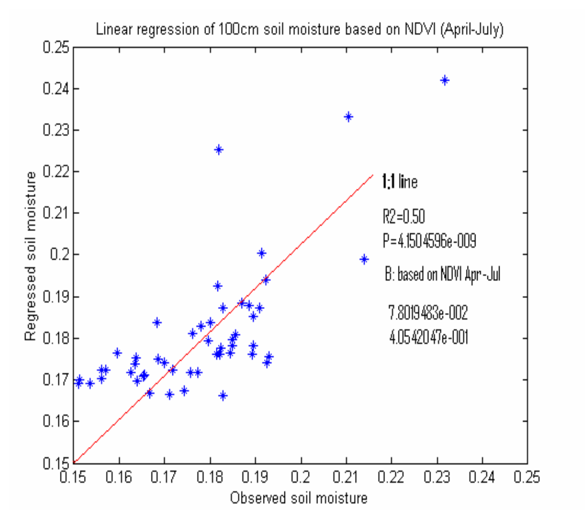


Fig.15b Regressed 100cm-deep soil moisture versus observed 10cm-deep soil moisture during April to July at New Mexico.

6. Conclusion

Water availability is a critical parameter for vegetation growth in arid and semi-arid regions. The influence of soil moisture on vegetation can be evaluated through the satellite (MODI) image-based NDVI during the growing season. After a series analysis and comparison, this study shows that root and below-root zone soil moisture in semi-arid regions has strong correlation with simultaneous NDVI during growing season, the lower the root zone soil moisture, the stronger the correlation; the root zone soil moisture in humid climate also has moderate correlation with simultaneous NDVI during growing season; below-root soil moisture in humid climate has weak correlation with NDVI.

Those correlations between two time-series variables may contain some autocorrelation or seasonal dependency and can't really reflect the physical relation of two variables; however, the root zone and below-root zone soil moisture over large areas and long period in semi-arid regions can be effectively estimated using simultaneous satellite image-based NDVI during growing season. Soil moisture can't be effectively estimated using NDVI during non-growing season (Oct-March). Soil moisture in humid regions can't be estimated using NDVI.

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