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[1] The evaluation of the relationship between satellite-derived vegetation indices (normalized difference vegetation index and normalized difference water index) and soil moisture improves our understanding of how these indices respond to soil moisture fluctuations. Soil moisture deficits are ultimately tied to drought stress on plants. The diverse terrain and climate of Oklahoma, the extensive soil moisture network of the Oklahoma Mesonet, and satellite-derived indices from the Moderate Resolution Imaging Spectroradiometer (MODIS) provided an opportunity to study correlations between soil moisture and vegetation indices over the 2002–2006 growing seasons. Results showed that the correlation between both indices and the fractional water index (FWI) was highly dependent on land cover heterogeneity and soil type. Sites surrounded by relatively homogeneous vegetation cover with silt loam soils had the highest correlation between the FWI and both vegetation-related indices (r∼0.73), while sites with heterogeneous vegetation cover and loam soils had the lowest correlation (r∼0.22). **Citation:** Gu, Y., E. Hunt, B. Wardlow, J. B. Basara, J. F. Brown, and J. P. Verdin (2008), Evaluation of MODIS NDVI and NDWI for vegetation drought monitoring using Oklahoma Mesonet soil moisture data, *Geophys. Res. Lett.*, *35*, L22401, doi:10.1029/2008GL035772.

1. Introduction

[2] Drought is one of the most costly natural disasters in the United States. Satellite observations potentially provide much greater spatial and temporal coverage of drought conditions than from site measurements of soil moisture and precipitation, and any relationships identified between these indicators might greatly enhance future drought monitoring efforts around the world. Currently, satellite-derived normalized difference vegetation index (NDVI) data has played an important role for vegetation drought monitoring [e.g., *Kogan*, 1995; *Gu et al.*, 2007; *Brown et al.*, 2008]. Another remote sensing measure, the normalized difference water index (NDWI) has also recently been used to monitor moisture conditions of vegetation canopies over large areas [*Jackson et al.*, 2004; *Chen et al.*, 2005]. Accurately monitoring and assessing near-real time vegetation drought conditions within the United States may provide decision makers accurate, synoptic, and timely information for effective drought planning and mitigation and should reduce economic losses. For that reason, continued evaluation of satellite-derived NDVI and NDWI for vegetation drought monitoring using ground observations (e.g., soil moisture) is required to better understand how these indices respond to soil moisture fluctuations, which are ultimately tied to drought stress on plants.

[3] NDVI, which is the normalized difference between the near infrared (NIR) and visible red reflectance [*Rouse et al.*, 1974; *Tucker*, 1979], is responsive to changes in both the chlorophyll content and the intracellular spaces in spongy mesophyll of plant leaves. Higher NDVI values reflect greater vigor and photosynthetic capacity (or greenness) of vegetation canopy, whereas lower NDVI values for the same time period are reflective of vegetative stress resulting in chlorophyll reductions and changes in the leaves' internal structure due to wilting. NDWI, derived from the NIR and shortwave infrared (SWIR) channels, responds to changes in both the water content (absorption of SWIR radiation) and spongy mesophyll (reflectance of NIR radiation) in vegetation canopies, respectively [*Gao*, 1996].

[4] Soil moisture is a critical component in land surface-atmospheric processes [*Brubaker and Entekhabi*, 1996], and prolonged soil moisture deficits often lead to drought-induced vegetation stress. Over the past decade, soil moisture observations in near-real time from the Oklahoma Mesonet have been collected and used for monitoring and assessing the spatial and temporal variability of soil moisture [*Illston et al.*, 2004] and drought conditions across Oklahoma [*Basara et al.*, 1998]. The Oklahoma Mesonet is an extensive network of over 110 environmental monitoring stations [http://www.mesonet.org/] that provide an excellent data source for thoroughly evaluating satellite-based indices in relation to soil moisture status and vegetation drought conditions. One of the most useful variables for estimating soil moisture is the fractional water index (FWI) [*Schneider et al.*, 2003; *Illston et al.*, 2004, 2008], which is a relative measure of the soil wetness and does not directly reveal the soil water content. The FWI is a calculation specific to heat dissipation sensors, such as the Campbell 229-L used by the Oklahoma Mesonet, and FWI values range from 1 (purely saturated soil) to 0 (very dry soil). Because FWI is not limited by soil texture variation, the soil water condition of each site is easily comparable across the state.

[5] A limited number of investigations examining the relationships between NDVI and soil moisture have been done over the U.S. Corn Belt [*Adegoke and Carleton*, 2001], semiarid New Mexico and Arizona regions, and

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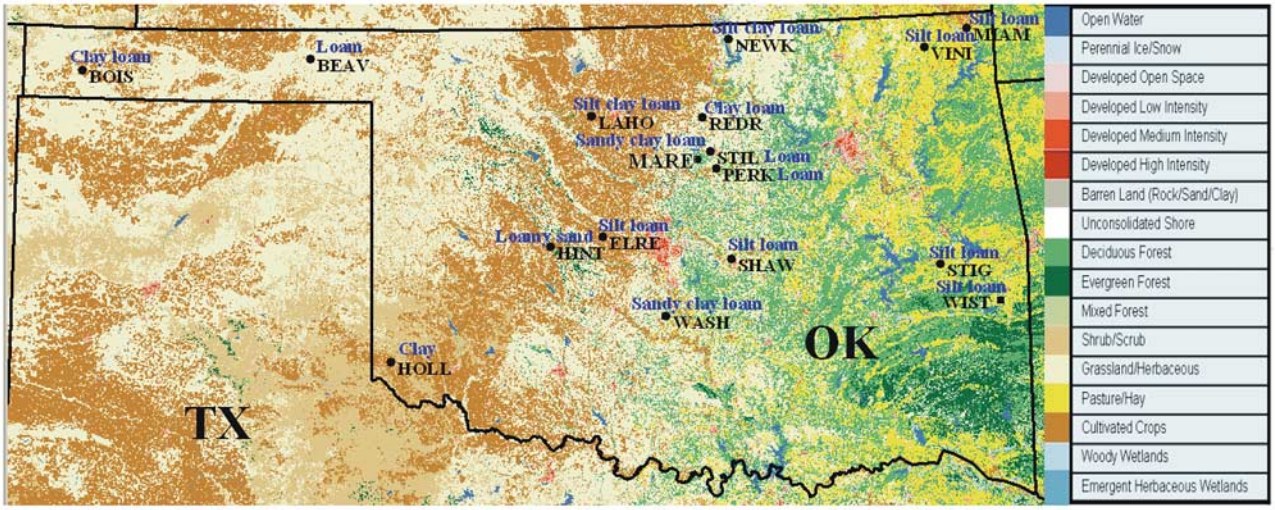

Figure 1. Locations and names of the 17 Oklahoma Mesonet sites (text in black), soil type of each site (text in blue), and the land cover types as identified in the National Land Cover Dataset (NLCD) [*Homer et al.*, 2004].

the humid Texas Gulf Coast region [*Wang et al.*, 2007]. However, the validation of using both NDVI and NDWI for monitoring drought stress on vegetation under different vegetation types, soil types, and climatic regimes has been limited and warrants investigation. The extensive soil moisture network of the Oklahoma Mesonet combined with the diversity of soil type, land cover, and rainfall gradient across the state of Oklahoma provided a unique study to determine that relationship. Thus, the objective of this study was to evaluate satellite-derived indices (NDVI and NDWI) for vegetation drought monitoring using Oklahoma Mesonet soil moisture observations. Results from this study will fill these gaps and will improve the capability of satellite remote sensing vegetation drought monitoring.

2. Strategy of Soil Moisture Site Selection

[6] Seventeen Oklahoma Mesonet sites were selected as representative locations of the different vegetation cover types, soil types, and climate zones found across Oklahoma. The Campbell 229-L heat dissipation sensors that are used in the Oklahoma Mesonet and in the ARM network do not perform well in highly sandy soils (sand > 40% of the total soil volume) [*Schneider et al.*, 2003], and such sites were eliminated during the selection process. The method for determining the percentage of silt, sand, and clay in a soil was described by *Illston et al.* [2008]. The geographic location, soil characteristics, and land cover type (as identified in the 2001 National Land Cover Dataset (NLCD) [*Homer et al.*, 2004]) of each study site are shown in Figure 1. The primary land cover types across the Oklahoma study locations were grass and crops (Table 1). A visual assessment of land cover patterns from high-resolution imagery from Google Earth was used to determine the spatial variability of general vegetation types within 500 m of each study site. Eleven sites (Table 1) were located in homogeneous vegetation conditions (single vegetation cover) within the surrounding 500 m from the site (in all directions), and the vegetation type was consistent with the site's vegetation (to ensure the vegetation type does not change within the MODIS 500-m pixel). Six heterogeneous sites (Table 1) contained more than one vegetation type within 500 m of the site.

3. Data and Methodology

[7] The Moderate Resolution Imaging Spectroradiometer (MODIS) data used in this study are the 8-day composite (the best quality daily reflectance data of the 8-day period), 500-meter surface reflectance data (MOD09A1, Collection 4) obtained from the Land Processes Distributed Active Archive Center (LP DAAC) and accessed from the Earth Observing System (EOS) Data Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/). The 500-meter spatial resolution of MODIS makes it a natural tool to monitor soil moisture conditions. A data quality control process was applied to screen the "cloud" and "fill value" pixels obtained from the associated MODIS quality assurance (QA) data product. NDVI and NDWI were calculated according to equations (1) and (2):

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

$$NDWI = \frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}} \quad (2)$$

where ρ_{Red}, ρ_{NIR}, and ρ_{SWIR} are the reflectances for MODIS bands 1 (620–670 nm), 2 (841–876 nm), and 7 (2,105–2,155 nm), respectively.

[8] The 8-day NDVI and NDWI composites were sequentially stacked to generate a 5-year (2002–2006) time series. Both NDVI and NDWI time-series data were then smoothed using a weighted least-squares approach to reduce additional atmospheric noise. The time-series NDVI and NDWI data were extracted for the 500-m pixel that geographically corresponded to each study site.

[9] Daily FWI data from 2002–2006 for the 17 Mesonet sites were obtained. A 23-point moving average method adapted by Wang et al. [*Wang et al.*, 2007] was applied to the daily FWI to remove high-frequency noise and to be

Table 1. Correlation Coefficient (r) Between NDVI and FWI, NDWI and FWI for May 25 – September 30 period[a]

			NDVI/NDWI and FWI for the Same Time Period							NDVI/NDWI One Period (8-Days) Later Than FWI						
	Vegetation Cover Type	Soil Type	NDVI FWI 5-cm	NDVI FWI 25-cm	NDVI FWI 60-cm	NDWI FWI 5-cm	NDWI FWI 25-cm	NDWI FWI 60-cm	Average	NDVI FWI 5-cm	NDVI FWI 25-cm	NDVI FWI 60-cm	NDWI FWI 5-cm	NDWI FWI 25-cm	NDWI FWI 60-cm	Average
Homogeneous Site																
Stigler (STIG)	*Pasture/hay*	*Silt loam*	*0.73*	*0.76*	*0.84*	*0.73*	*0.75*	*0.80*	*0.77*	*0.83*	*0.85*	*0.82*	*0.81*	*0.82*	*0.80*	*0.82*
Vinita (VINI)	*Pasture/hay*	*Silt loam*	*0.66*	*0.69*	*0.78*	*0.71*	*0.76*	*0.80*	*0.73*	*0.76*	*0.78*	*0.85*	*0.80*	*0.84*	*0.86*	*0.82*
Wister (WIST)	*Pasture/hay*	*Silt loam*	*0.67*	*0.77*	*0.64*	*0.64*	*0.75*	*0.63*	*0.68*	*0.78*	*0.81*	*0.68*	*0.77*	*0.81*	*0.69*	*0.76*
Red Rock (REDR)	*Grassland*	*Clay loam*	*0.62*	*0.68*	*0.76*	*0.58*	*0.63*	*0.79*	*0.68*	*0.69*	*0.72*	*0.74*	*0.68*	*0.71*	*0.79*	*0.72*
Washington (WASH)	Grassland	Sandy clay loam	0.74	0.66	0.75	0.72	0.62	0.72	0.70	0.74	0.66	0.68	0.74	0.62	0.67	0.69
Miami (MIAM)	*Pasture/hay*	*Silt loam*	*0.59*	*0.55*	*0.61*	*0.59*	*0.54*	*0.57*	*0.57*	*0.66*	*0.62*	*0.69*	*0.69*	*0.63*	*0.66*	*0.66*
Hollis (HOLL)	*Crops*	*Clay*	*0.66*	*0.53*	*0.60*	*0.60*	*0.54*	*0.60*	*0.59*	*0.72*	*0.66*	*0.60*	*0.68*	*0.66*	*0.58*	*0.65*
Newkirk (NEWK)	Grassland	Silt clay loam	0.79	0.57	0.59	0.73	0.62	0.66	0.66	0.72	0.58	0.56	0.69	0.64	0.63	0.64
El Reno (ELRE)	*Grassland*	*Silt loam*	*0.51*	*0.57*	*0.55*	*0.45*	*0.46*	*0.48*	*0.50*	*0.62*	*0.64*	*0.56*	*0.60*	*0.55*	*0.48*	*0.57*
Marena (MARE)	*Grassland*	*Sandy clay loam*	*0.30*	*0.47*	*0.69*	*0.35*	*0.45*	*0.62*	*0.48*	*0.37*	*0.57*	*0.70*	*0.41*	*0.54*	*0.62*	*0.53*
Beaver (BEAV)	Grassland	Loam	0.45	0.57	0.49	0.30	0.31	0.23	0.39	0.45	0.49	0.41	0.28	0.24	0.20	0.34
Heterogeneous Site																
Boise City (BOIS)	*Grassland*	*Clay loam*	*0.62*	*0.59*	*0.41*	*0.44*	*0.48*	*0.49*	*0.50*	*0.68*	*0.72*	*0.33*	*0.53*	*0.62*	*0.40*	*0.55*
Hinton (HINT)	*Grassland*	*Loamy sand*	*0.39*	*0.38*	*0.12*	*0.58*	*0.63*	*0.33*	*0.40*	*0.45*	*0.42*	*0.18*	*0.58*	*0.55*	*0.37*	*0.43*
Shawnee (SHAW)	Crops	Silt loam	0.45	0.52	0.44	0.39	0.51	0.39	0.45	0.34	0.38	0.35	0.35	0.47	0.39	0.38
Lahoma (LAHO)	Crops	Silt clay loam	0.45	0.43	0.21	0.35	0.48	0.18	0.35	0.43	0.45	0.11	0.25	0.47	0.08	0.30
Perkins (PERK)	*Crops*	*Loam*	*0.26*	*0.54*	*0.37*	*−0.02*	*0.15*	*0.08*	*0.23*	*0.41*	*0.58*	*0.27*	*0.08*	*0.14*	*0.03*	*0.25*
Stillwater (STIL)	Grassland	Loam	0.31	0.20	0.13	0.38	0.37	0.38	0.29	0.29	0.08	0.02	0.33	0.21	0.27	0.20
Averages																
Average (homogeneous sites)			0.61	0.62	0.66	0.58	0.58	0.63	0.61	0.67	0.67	0.66	0.65	0.64	0.63	0.65
Average (heterogeneous sites)			0.41	0.44	0.28	0.35	0.44	0.31	0.37	0.43	0.44	0.21	0.36	0.41	0.25	0.35
Average (silt loam soil)			0.60	0.64	0.64	0.59	0.63	0.61	0.62	0.66	0.68	0.66	0.67	0.69	0.65	0.67
Average (loam soil)			0.34	0.44	0.33	0.22	0.28	0.23	0.31	0.38	0.38	0.23	0.23	0.20	0.16	0.26
Average (all sites)			0.54	0.56	0.53	0.50	0.53	0.51	0.53	0.58	0.59	0.50	0.55	0.56	0.50	0.55

[a]The sites with time lags are in italics.

synchronous with the smoothed MODIS NDVI and NDWI time series. Five years of seasonal NDVI, NDWI, and FWI time-series plots were subsequently analyzed and compared using correlation coefficient (r) analysis between NDVI/NDWI and FWI.

4. Results and Discussions

4.1. Correlation Between NDVI/NDWI and FWI During the Summer

[10] Table 1 presents the correlations (r values) between the FWI and both the NDVI and NDWI during a 4-month summer period for the 17 Oklahoma Mesonet sites. The temporal relationship between the indices was examined over two windows: 1) "equivalent periods, "where the FWI, NDVI, and NDWI values were analyzed for the same period and 2) "1 period" (8-day) time lag, where the FWI was compared to NDVI and NDWI values for the following period to analyze any inherent time delay between soil moisture and plant response.

[11] The average r values between the NDVI and FWI for the "equivalent periods" across all sites were ~0.54 for the 5-cm and 60-cm layers, and 0.56 for the 25-cm layers. The average r between NDWI and FWI were ~0.50 for the 5-cm and 60-cm layers, and ~0.53 for the 25-cm layer. All these correlations between FWI and NDVI/NDWI are statistically significant at the 0.01 level of significance [sample size N ~70]. The results indicate that both NDVI and NDWI had slightly higher statistically significant correlations with the 25-cm layer soil moisture, which indicates both indices have slightly stronger responses to the soil moisture variation at this intermediate depth. The weaker correlation at the 5-cm layer may be partially due to the higher variability that existed in the 5-cm FWI data. Some vegetation does not tap into the shallow soil moisture as their rooting depths are deeper than 5 cm and would be a reason for the weaker correlation at the shallow layer. The weaker correlation at the 60-cm layer may be related to the process by which a longer time is required for near-surface soil water (e.g., rainfall) to infiltrate to the deeper soil depths, which leads to a weaker correlation between FWI and NDVI/NDWI at the deep soil layer. It might also be explained by some vegetation with shallow roots that are not able to tap into the deeper soil

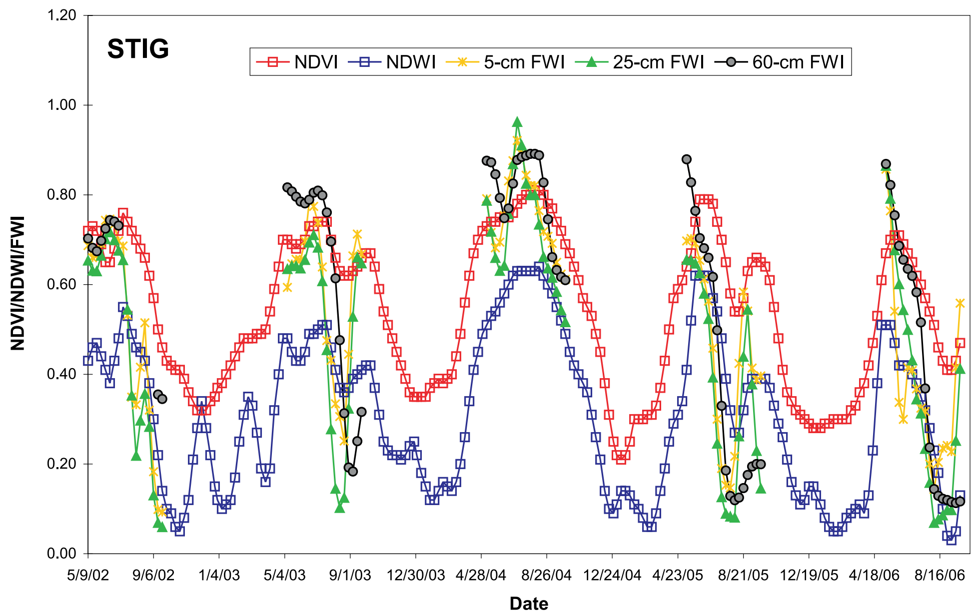

Figure 2. Time series plots of NDVI, NDWI, and FWI (5-cm, 25-cm, and 60-cm layers, May to September) for Stigler (STIG) site in Oklahoma.

moisture reserves, resulting in a weaker correlation at the deep soil layer.

[12] Correlations at the 5-cm and the 25-cm layers increased at 11 sites when an 8-day time lag between the FWI satellite-based vegetation indices was analyzed (italic fonts in Table 1), suggesting that satellite indices were more responsive to soil moisture changes with an 8-day delay for most of the sites. For the other six sites, the r values were similar or slightly less when the time lag was considered. No improvement of correlation with time lags was found at the 60-cm depth for 13 sites. Because different cover types or spatial heterogeneity (e.g., grass, row crops, and small grains) in a 500-m pixel can result in the NDVI and NDWI signals having a very weak relationship with FWI over time, only homogeneous sites surrounded by grassland cover types (i.e., graminoid, pasture/hay) were plotted for the time series analysis in this study. Figure 2 is an example of the time-series NDVI, NDWI, and FWI (5-cm, 25-cm, and 60-cm layers) plots for a homogeneous site (STIG) with grass cover type. Both NDVI and NDWI had similar but delayed responses to the FWI variations over the 5-year study period, shown in Figure 2. More pronounced 1- to 2-week (or even longer) time lags existed at the two shallow depths (5 cm and 25 cm) are also illustrated in Figure 2.

4.2. Influence of the Land Cover and Soil Types on the Correlation Between the Satellite-Based Indices and FWI

[13] Results from this study showed that the correlations between the MODIS 500-m satellite indices and the soil moisture index are highly dependent on both the level of land cover heterogeneity and soil type. Sites with homogeneous vegetation cover types and silt loam soils (ELRE, MIAM, STIG, WIST, and VINI in Table 1) had the highest correlation between satellite-based indices and FWI, with an average r of 0.73 between NDVI/NDWI and FWI (statistically significant relationship at the 0.01 level of significance) across all layers (for 8-day period time lag). In contrast, sites with heterogeneous vegetation cover types on loam soils (STIL and PERK in Table 1) had the lowest average correlation ($r \sim 0.22$) between NDVI/NDWI and FWI across the three depths. Sites with heterogeneous land cover types (e.g., crops, graminoid, and small grains) usually have a composited spectral signal at the 500-m resolution from the various cover types, which often have different phenological behaviors, that confound (reduce) NDVI/NDVI-FWI relationships. To demonstrate these lower correlations, the average r values for both homogeneous and heterogeneous sites were calculated at the three different soil layer depths (Table 1). Results showed that the homogeneous sites consistently yielded statistically significant higher NDVI/NWDI-FWI correlations (~0.65 on average) at all soil depths than the heterogeneous sites (~0.35 on average).

[14] Average r values for all sites that had the same soil type at the three different soil layer depths were also calculated, and average r values for sites that had loam soil versus sites with silt loam soils are listed in Table 1. Results showed that loam soil sites had much lower NDVI/NWDI-FWI correlations (~0.26 on average, no statistically significant relationship at the 0.10 level of significance) at all the soil depths than the silt loam sites (~0.67 on average, statistically significant relationship at the 0.01 level of significance). Lower correlation between NDVI/NDWI-FWI on loam soils may be explained by the different characteristics of the soil types. The loam soil has a lower available water capacity because of a higher sand content than the silt loam soil (http://soils.usda.gov/sqi/publications/files/avwater.pdf; http://www.noble.org/Ag/Soils/SoilWaterRelationships/Index.htm), which means the loam will not exhibit soil moisture variations when it reaches saturation. This would lead to a low correlation between satellite indices and FWI across the entire soil layers for loam soil types. Heat dissipation sensors do not perform well in highly sandy soil (e.g., loam), leading to another possible cause for low correlations in such conditions.

4.3. NDVI and NDWI: Which Index is More Sensitive to Soil Moisture Fluctuations?

[15] Results showed that the FWI had a slightly higher correlation with NDVI than NDWI in all layers and the correlation between $r_{\text{FWI-NDVI}}$ and $r_{\text{FWI-NDWI}}$ for all layers is statistically significant at the 0.10 level of significance. Considering the existence of high-frequency noise in the FWI time series and other uncertainties such as spatial scale differences between the measurements (e.g., soil properties vary widely over short distances, the satellite indices were calculated from 500m x 500m pixel while the FWI was measured at a single point; therefore the FWI value at a certain point may not be representative of a 500-m pixel) and biases in observation due to the vagaries of the orbit of the MODIS sensor (the MODIS sensor records data from a slightly different patch of ground on each pass), these slight differences were negligible. Therefore, the NDVI and NDWI were found to have comparable sensitivities to soil moisture fluctuations expressed in the FWI and both are suitable for vegetation drought monitoring. The NDVI is the more commonly used index and no additional benefit was gained by the NDWI.

5. Conclusions and Future Work

[16] Results from this study indicate that the relationship between satellite-derived vegetation indices and soil moisture is highly dependent on the land cover heterogeneity and soil type. Homogeneous vegetation cover on silt loam soils had the highest correlation between FWI and both vegetation-related indices ($r \sim 0.73$), while heterogeneous vegetation cover on loam soils had the lowest correlation ($r \sim 0.22$). The FWI had a slightly stronger statistically significant correlation with NDVI and NDWI at the 25-cm layer than at the 5-cm and 60-cm layers, suggesting that both satellite-derived indices were most responsive to soil moisture change at intermediate soil depths. From the time-series plots of the 10 homogeneous grassland sites, 1- to 2-week time lags for the satellite indices' response to the soil moisture variation at the 5-cm and 25-cm layers were found in seven sites. Over homogeneous vegetation cover, both NDVI and NDWI were sensitive to changes in soil moisture which are strongly related to vegetation drought conditions. NDVI and NDWI both exhibited similar relationships with FWI variations, suggesting that both indices are appropriate for monitoring drought stress on vegetation.

[17] These results improved our understanding of how satellite-based vegetation indices responded to soil moisture fluctuations and suggested that, under homogeneous vegetation covers and soil types, satellite-derived indices could provide proxy soil moisture information for those places that do not have any soil moisture measuring capability. We recommend continued evaluation and validation of the NDVI and NDWI as vegetation drought monitoring tools for different geographic regions and multiple spatial scales (e.g., Landsat 30-m and MODIS 250-m) to better establish their utility beyond the initial findings of this study.

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