MODIFIED TRIANGLE METHOD TO ESTIMATE SOIL MOISTURE STATUS WITH MODERATE RESOLUTION IMAGING SPECTRORADIOMETER (MODIS) PRODUCTS

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ABSTRACT:

Soil moisture condition is one of the key parameters in environmental and agricultural modeling. In this paper, a modified triangle method (Ts/VI space) is suggested. Both NDVI and EVI are used in constructing the space. Based on this method we calculated the Temperature-Vegetation Dryness Index (TVDI) using 20 MODIS images (Land surface temperature and vegetation index products) to estimate the soil moisture condition in Northern China Plain. *In situ* moisture data from 133 agricultural stations are used to validate the TVDI. Finally, the relationship between TVDI and rainfall is examined. We found that the triangle method can be a fast and simple method to estimate regional soil moisture conditions.

1. INTRODUCTION

Remote sensing of soil moisture can be tracked back to the 1970s (Watson, 1971). Recently, many new methods have emerged and one of them is the triangle method which uses a land surface temperature/vegetation index space to estimate regional soil moisture status (Carlson et al., 1994). The space is a scatter plot of remotely sensed surface temperature and vegetation index which often results in a triangular shape (Price, 1985). The basic idea of the triangle method is that land surface temperature is sensitively associated with the soil moisture content and the vegetation cover. Vegetation index is not so sensitive to the soil moisture change because when the water stress begins, the leaves are still green. Land surface temperature is quite sensitive to the soil moisture conditions. However, it should be used with the presence of fraction of vegetation cover (Sandholt et al., 2002).

In order to derive the soil moisture content with the triangle method, someone combined the ground measured soil moisture data with triangle method, and then derived the relationship between soil moisture and triangle method using second order polynomial function (Wang et al., 2007). Another method is to combine the triangle method with the Soil-Vegetation-Atmosphere Transfer (SVAT) model to derive soil moisture status (Carlson, 2007). Those methods are based on the derivation of both "wet edge" and "dry edge". Many methods are proposed to calculate the "wet edge" and "dry edge" (Gillies et al., 1995; Wan, et al. 2004). In those researches, only "dry edge" is calculated by linear regression while "wet edge" is constant. The selection of vegetation index may affect the shape of the triangle. NDVI would be saturated in densely vegetated areas, while the Enhanced Vegetation Index (EVI) takes into account of soil background and may perform better than NDVI (Huete et al., 2002).

In this paper, we proposed a modified triangle method to extract the two edges and calculate an index (Temperature-Vegetation Dryness Index, TVDI) to infer the soil moisture condition in the study area. Both NDVI and EVI are used in constructing the temperature-vegetation feature space. The soil moisture data from agricultural station are used to validate the effects of TVDI. Finally, the temporal variations of TVDI are analyzed on the station scale.

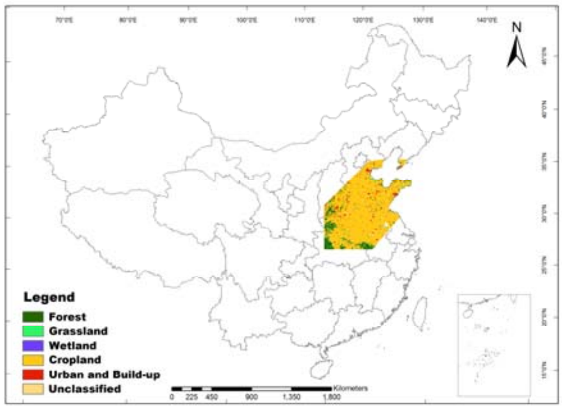

Figure 1 Study area and its land use

2. STUDY AREA AND DATA SOURCE

The study area (Figure 1) is in northern China (110°~123° E; 33°~40°N) which is generally plain with very modest relief. Under the control of Asia monsoon, the average annual precipitation in this area is about 500~600mm yet not stable.

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Satellite data is downloaded from NASA EOS Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/), which includes MOD09 reflectance and MOD11 land surface temperature products (Granule no.: h27v05). Meteorological and agricultural data are acquired from China Meteorological Data Sharing Service System (CMDSSS). The total numbers of meteorological station (MS) and agricultural station (AS) in the study area are 133 and 71, respectively. Soil moisture data acquired from every AS are volumetric water content (%). Those stations are almost evenly distributed. Both the satellite and meteorological data are from April 1st, 2002 to October 31st, 2002 (14 days' MODIS data are missing from the data centre).

3. METHODS

3.1 Data Preprocessing

Vegetation index are calculated from MOD09 reflectance products. NDVI is the normalized ratio of the NIR and the red bands, while Enhanced Vegetation Index (EVI) is optimized to enhance the vegetation signal and reduce the soil background influences. Those two index are calculated in this form (Huete et al., 2002):

$$NDVI = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \quad (1)$$

$$EVI = G\frac{\rho_2 - \rho_1}{\rho_2 + C_1 \times \rho_1 - C_2 \times \rho_3 + L} \quad (2)$$

where ρ_1, ρ_2, ρ_3 = MODIS band 1 (620nm~670nm), band 2 (841~876 nm), band 3 (459~479 nm)
G (gain factor) = 2.5
C_1 = 6
C_2 = 7.5
L = 1

Vegetation index data are aggregated from 500m to 1km. Land pixels are selected according to the QC flag. In the same way, those pixels which are contaminated by cloud are excluded using the QC flag.

3.2 Triangle method

Theoretically, the scatter plot formed by vegetation index and land surface temperature should be like a triangle (Figure 2). The upper edge of the triangle is defined as dry edge while the lower one is wet edge. Pixels close to the dry edge are comparatively drier while those close to the wet edge are wetter. The position of the pixel in the scatter plot defines its moisture condition.

Thus the core issue of triangle method is to calculate the ideal dry edge and wet edge. In previous researches, people only calculate the dry edge while consider the wet edge as a horizontal line, but in real situations the wet edge may not be horizontal but a little oblique. In this paper, a linear function is applied to both the upper and lower envelop of the triangle to calculate the dry edge and cold edge, respectively.

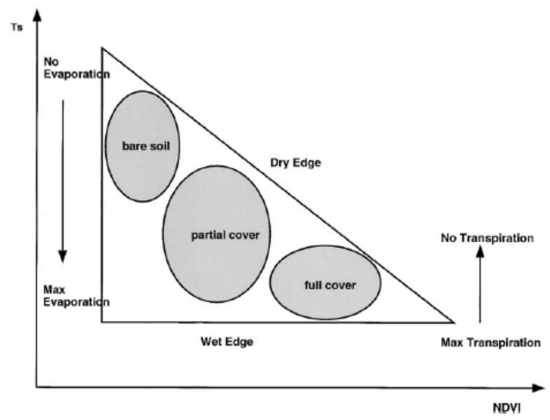

Figure 3. Simplified NDVI/Ts Space (after Lambin & Ehrlich, 1996, and Sandholt et al., 2002)

3.3 Temperature-Vegetation Dryness Index (TVDI)

Once the edges are defined, the Temperature-Vegetation Dryness Index (TVDI) can be calculated as:

$$TVDI = \frac{T_s - f(VI)_{\min}}{f(VI)_{\max} - f(VI)_{\min}} \quad (3)$$

where T_s = land surface temperature of a pixel
VI = vegetation index of a pixel
Both $f(VI)_{\max}$ and $f(VI)_{\min}$ are the linear function of vegetation index

$$f(VI)_{\max} = a_{\max} + b_{\max} \times VI$$
$$f(VI)_{\min} = a_{\min} + b_{\min} \times VI \quad (4)$$

where a_{max}, b_{max} = linear regression parameters for dry edge
a_{min}, b_{min} = linear regression parameters for wet edge

4. RESULTS AND DISCUSSION

4.1 Ts/VI plot

The plot of land surface temperature/NDVI (Figure 3) and land surface temperature/EVI (Figure 4) are both shown in below. From April to October, we select the 8th, 18th and 28th day of every month to draw the feature space. Those days correspond to the time every agricultural station to measure the soil moisture condition. From those plots we found that pixels in most of the scatter plots can form a triangle, indicating a very wide soil moisture condition range. Comparing with the plots formed by NDVI/LST and EVI/LST, we found that the triangles of EVI/LST are much smaller than those of NDVI/LST, mainly because EVI would not increase so fast in dense vegetated areas as NDVI.

The parameters (amin, bmin is for wet edge and amax, bmax is for the dry edge, R is the regression coefficient.) of the dry and wet edges are listed below (Table 1, Table 2). Most of the regression coefficient (R) is around 0.9, indicating a good linear fitting. We examined the temporal evolution of the slope of dry and wet edges. The temporal evolution of both dry and wet edge slope is irregular. However, the change trends of the two edges embrace some characteristics: when the slope of dry edge declines, the slope of wet edge also declines (away from 0). Those trends can be both found in Figure 5 and Figure 6. This indicates that the shape of the scatter plot is always like a triangle, which is a result of wide soil moisture condition variation.

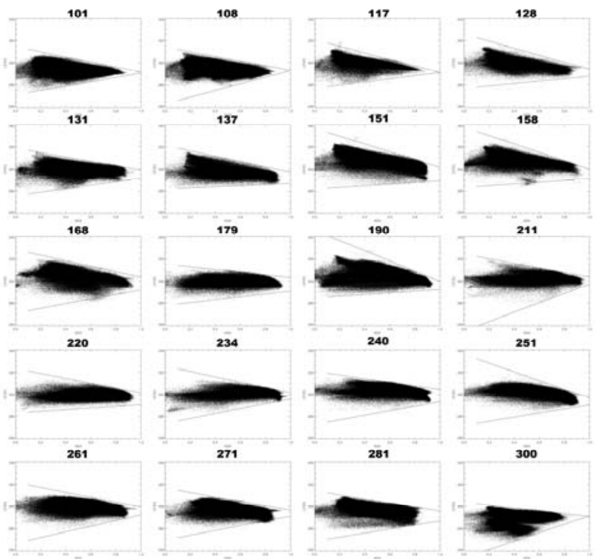

Figure 4. T_s/NDVI Space. The numbers are DOY (Day of Year).

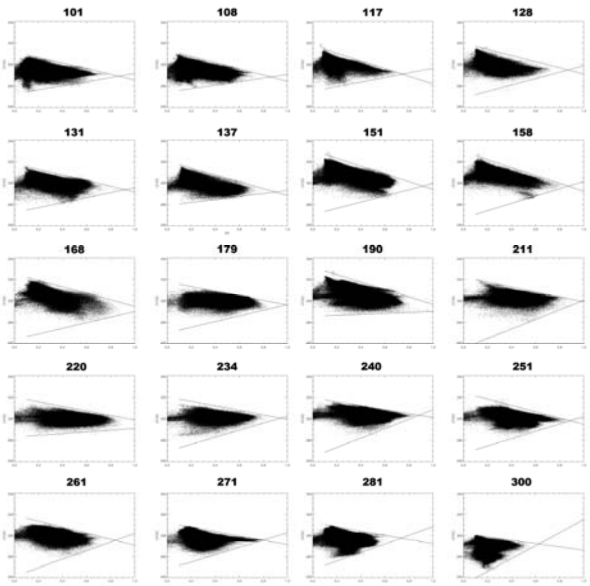

Figure 5. T_s/EVI Space. The numbers are DOY (Day of Year).

DOY	a_{min}	b_{min}	R	a_{max}	b_{max}	R
101	314.721	-23.1441	-0.976449	271.101	19.6170	0.949475
108	314.437	-21.2325	-0.975909	262.971	30.0107	0.894233
117	320.926	-29.7138	-0.969518	277.078	14.1889	0.818144
128	325.827	-31.5291	-0.988479	276.924	10.9057	0.532975
131	318.819	-19.4143	-0.958593	275.817	15.9004	0.866930
137	321.289	-23.8511	-0.966802	281.939	5.11206	0.708337
151	336.418	-34.4940	-0.941371	282.033	7.26085	0.611929
158	337.496	-37.2456	-0.986199	283.353	8.08872	0.387127
168	328.046	-24.2238	-0.975774	271.131	21.0328	0.715373
179	315.588	-12.1671	-0.878281	277.727	13.3368	0.836308
190	345.237	-45.1938	-0.981133	284.993	7.46402	0.915454
211	324.119	-20.1313	-0.971374	255.163	42.2380	0.968150
220	323.389	-21.7685	-0.930893	283.107	7.79206	0.731804
234	325.518	-23.7681	-0.965581	273.643	22.5269	0.952402
240	320.935	-16.2536	-0.940525	272.745	20.8665	0.785959
251	335.830	-38.7587	-0.984974	271.981	18.6234	0.853532
261	321.899	-22.3796	-0.925162	266.980	25.3204	0.854462
271	316.939	-20.4169	-0.962735	269.832	21.3538	0.820349
281	314.348	-18.5229	-0.946032	268.841	18.0822	0.802562
300	303.765	-12.9132	-0.947409	253.756	37.7256	0.964508

Table 1. Parameters for dry and wet edge of T_s/NDVI space

DOY	a_{min}	b_{min}	R	a_{max}	b_{max}	R
101	311.704	-26.0654	-0.990079	272.609	19.0194	0.891260
108	313.289	-28.9491	-0.989522	274.133	16.5670	0.881120
117	317.632	-35.8060	-0.987684	275.043	21.4372	0.975047
128	319.639	-28.5096	-0.947538	269.026	29.7290	0.808206
131	318.090	-26.5133	-0.984368	272.503	23.0659	0.897399
137	320.416	-32.3094	-0.987155	279.035	13.9104	0.887121
151	330.486	-36.6509	-0.970569	270.716	28.7204	0.659027
158	329.322	-37.1605	-0.992082	267.556	33.7670	0.920576
168	324.962	-30.1085	-0.962467	264.074	26.0440	0.915844
179	317.424	-21.3164	-0.933979	270.214	26.3797	0.923737
190	331.302	-34.5921	-0.936629	285.566	4.63390	0.670620
211	322.160	-23.2297	-0.988252	256.174	44.3377	0.982187
220	319.877	-21.1085	-0.964813	282.843	8.10663	0.762502
234	320.306	-21.0127	-0.951356	269.682	32.8684	0.957477
240	319.299	-18.1964	-0.993919	264.557	43.7195	0.972944
251	323.997	-29.1957	-0.942736	267.863	34.0918	0.959154
261	319.061	-28.0642	-0.983375	261.281	40.9454	0.898918
271	311.848	-20.2481	-0.986752	267.930	34.9030	0.980894
281	311.928	-19.4576	-0.975437	267.683	40.7038	0.920343
300	302.064	-15.7723	-0.988085	253.869	61.0685	0.961940

Table 2. Parameters for dry and wet edge of T_s/EVI space

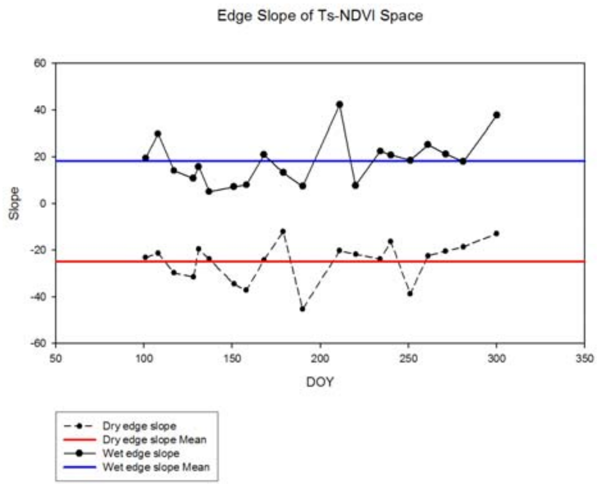

Figure 6. Edge slopes of Ts/NDVI Space

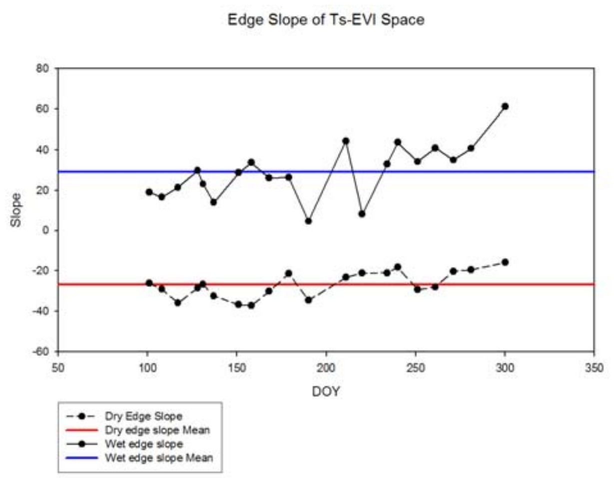

Figure 7. Edge slopes of Ts/EVI Space

4.2 Validation with *in situ* soil moisture data

There are 133 agricultural stations in the study area, which measures soil moisture condition in the 8th, 18th and 28th day of every month. They measure soil moisture in five different soil depths: 10cm, 20cm, 50cm, 70cm, and 100cm. Considering that we are using visible and near-infrared bands, we only selected the soil moisture at 10cm and 20cm to validate TVDI (Table 3.). For the reasons like cloud covering or no measurement conducted in that day, the number of agricultural stations with valid data may varies from day to day, as listed in the table.

	108	117	137	151	158	190
VS	33	18	16	42	25	36
N:SM10	-0.493**	-0.265	-0.377	-0.253	-0.102	-0.182
N:SM20	-0.535**	-0.252	-0.246	-0.203	-0.064	-0.200
E:SM10	-0.521**	-0.293	-0.456	-0.398**	-0.205	-0.322
E:SM20	-0.502**	-0.253	-0.493	-0.333**	-0.219	-0.351*
	211	220	234	240	251	261
VS	17	25	13	33	87	97
N:SM10	0.025	-0.358	-0.330	-0.386*	-0.261*	-0.221*
N:SM20	0.080	-0.335	-0.217	-0.250	0.114	-0.229*
E:SM10	-0.413	-0.377	-0.477	-0.418*	-0.299**	-0.264**
E:SM20	-0.415	-0.377	-0.355	-0.279	-0.199	-0.254*

**p<0.01
*p<0.05

Table 3. Correlation coefficients between TVDI and soil moisture. VS stands for the number of valid station without cloud contamination, N stands for the NDVI-calculated TVDI, E stands for the EVI-calculated TVDI, SM10 and SM20 stands for soil moisture at 10cm and 20cm depth.

Theoretically, TVDI should be between 0 and 1. The larger the TVDI, the drier the pixel is. Thus, TVDI should be negatively correlated with soil moisture. From the table we found that in most of the time (except DOY 211) TVDI is negatively correlated with 10cm and 20cm soil moisture. NDVI-calculated TVDI is more sensitive to the SM20 comparing with SM10, while EVI-calculated TVDI is more sensitive to SM10. EVI-calculated TVDI is better than NDVI-calculated TVDI in most cases.

4.3 Temporal analysis

The relationship between rainfall and TVDI is analyzed on a station basis. We selected those stations without the disturbance of clouds in the 8th, 18th and 28th day of each month. In this way we can calculate the TVDI value to represent the soil moisture condition of the 10-day period. From the figure (Figure 7) below we can see that after every rainfall event, TVDI would go down; while in the dry days, TVDI would go up. This is mainly because rainfall would increase the relative soil moisture content, which means TVDI would be close to the wet edge and become smaller. And after a long time of dry days the soil moisture content would decrease, which in turn would result in the increment of TVDI.

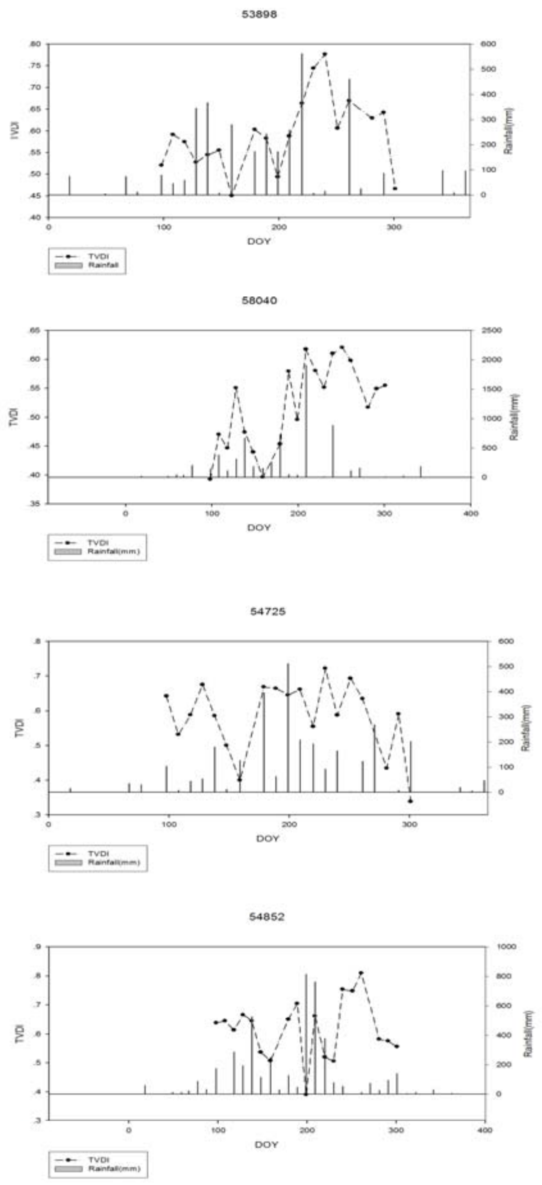

Figure 8. Temporal evolution of TVDI and its relationship with rainfall in four stations (The title is the code of the station). The Y axis is TVDI (left) and Rainfall (right, unit: mm). The X axis is day of year (DOY).

5. CONCLUSION

In this paper, we modified the triangle method and used it in soil moisture monitoring. Both NDVI and EVI are used in the construction of Ts/VI space. And their efficiencies in estimating soil moisture condition are evaluated. Finally, we studied the temporal trend of TVDI in conjunction with rainfall data. We found that:

(1) The modified triangle method can clearly define the shape of Ts/VI space in most of the cases.
(2) NDVI-calculated TVDI is much sensitive to the soil moisture in 20cm, while EVI-calculated TVDI is much sensitive to the soil moisture in 10cm.
(3) Comparing with NDVI-calculated TVDI, EVI-calculated TVDI is much better in estimating soil moisture condition in most cases.
(4) There is a good relationship between TVDI and rainfall. Rainfall would increase the soil moisture condition, which in turn would result in a low TVDI.

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