# Construction and validation of a new model for cropland soil moisture index based on MODIS data

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# Construction and Validation of a New Model for Cropland Soil Moisture Index Based on MODIS Data

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## ABSTRACT

Soil Moisture and Vegetation Growth are the most important and direct index in drought monitoring, and the spectrum interpretation of vegetation and soil are serious factors in the judgment of drought degree. To find a more real-time monitoring index of cropland soil moisture by remote sensing, a Cropland Soil Moisture Index (CSMI) was established in this paper based on the effective reflections of Normalized Difference Vegetation Index (NDVI) on deeper soil moisture and well expressions of Surface Water Content Index (SWCI) on surface soil moisture. By validation with different time-series MODIS data, the Cropland Soil Moisture Index (CSMI) not only overcome the limitation of hysteretic nature and saturated quickly of Normalized Difference Vegetation Index (NDVI), but also take the advantage of the Surface Water Content Index (SWCI) which effectively reduce the atmosphere disturbance and retrieval surface soil water content better. The index passed the significant F-tests with $\alpha = 0.01$, and is a true real-time drought monitoring index.

**Key Words:** MODIS data; Cropland Soil Moisture Index (CSMI); Normalized Difference Vegetation Index (NDVI); Surface Water Content Index (SWCI).

## 1. INTRODUCTION

Drought, as a kind of long-term and potential natural disaster, is characterized with long time and abnormal water shortage. Drought will cause severe influence on economies and eco-environments, especially agricultural production. Therefore, it has been the key problem for the scientists and governmental departments concerned to undertake quantitative pre-evaluation on drought.

A lot of research has proved the effectiveness of NDVI in drought monitoring, and it features direct-viewing and easiness for use. Many drought indexes such as AVI, VTCI, EVI, etc. were constructed based on NDVI. Water stress on vegetation is the direct cause of drought. Therefore, effective abstraction of water content information from vegetation is important to drought monitoring. However, NDVI is a conservative index and it has hysteresis relative to drought [1-3], for it may not make timely response itself if there is any change in leaf water content. Besides, there is saturation in the high vegetation coverage area[4-6].

Soil moisture capacity changes vegetation coverage and underlaying surface roughness etc. In this way, it can

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influence energy and water exchange between vegetation, soil and atmosphere. Usually, the more serious the drought is, the lower NDVI is, and reflectivity and temperature at the underlaying surface will be higher. The soil humidity would be decreased even if there is little change in other factors. We can find out characteristic indexes that could show time and space changes in drought by comprehensively considering these factors [7]. A lot of research has proved that there is significant correlation between soil moisture capacity and the ratio of LST/NDVI, and the relationship is quite stable in most atmospheres and at the condition of land coverage[8-9], thus it could be widely applied in monitoring remote sensing of drought.

Short Wave Infrared (SWIR) is sensitive to leaf water content, so it is possible to use short wave Band 6 and Band 7 in MODIS sensor as water sensitive index. As for different vegetation coverage rates, SWIR varies greatly, especially more sensitive to soil moisture capacity changes [10-12]. Considering spectral characteristics of water, Du Xiao et al. took advantage of reflection of vegetation canopy and bare area in the high spectral area and their spectral absorption characteristics, and proposed SWCI model, which could reflect surface water capacity and its changes well, thus it could be fast used in monitoring remote sensing of soil moisture capacity in large scope [13].

With acceleration of growth process, the ratio of root to canopy varies greatly. The less water content in the shallow cropland soil, the deeper the root distribution is, and vice versa. Due to hysteretic nature of NDVI, it is not satisfied in real-time monitoring of soil moisture. Especially in moderate vegetation coverage, most roots are distributed in the depth of 20~50cm and the soil moisture changes greatly influence NDVI spectrum changes, the retrieval of NDVI to soil moisture in the shallow layer are not good. SWCI is better than NDVI in monitoring soil moisture in the shallow layer. With the NDVI spectrum changes to reflect deeper soil moisture and SWCI spectrum changes to reflect soil moisture in the shallow layer then they could be combined to construct a new index, it could improve accuracy in monitoring cropland soil moisture capacity. Therefore, the index of CSMI has been constructed by taking the advantage of NDVI and SWCI which best use of MODIS sensors Channels 1, 2, 6 and 7. It proves effective in real-time monitoring of cropland soil moisture through application and verification.

## 2. THEORIES AND METHODS

### 2.1 Introduction of Normalized Difference Vegetation Index (NDVI)

Green vegetation has strong absorption characteristic in red light area and it mainly lies in the red light section. The denser the vegetation is, the lower its reflectivity is, and the reflectivity in near infrared bands increases. It decreases by 3%-5% in red light area, but the figure could reach 40%-60% in infrared region. The main reason is that vegetation absorption rate in infrared region could be saturated fast, but reflectivity in infrared bands only increases with vegetation density [14]. From red light region to infrared spectrum region, the reflectivity of bare area is quite high but it increases slowly. However, since water has strong capacity of absorbing red light and infrared light, the reflectivity of bare area will decrease dramatically as soil moisture increases, especially significant in infrared bands. Different mathematical methods could be used to make the difference between red light and infrared light significant, which represent such characteristics as vegetation and overlaying drought, and relevant soil information from different pixel materials could be abstracted [15-17].

NDVI is defined as [18] :

$$NDVI = \frac{B_2 - B_1}{B_2 + B_1} \quad : \tag{1}$$

$B_1$ and $B_2$ are reflectivity of MODIS band1 and band2 respectively.

Although NDVI is widely used, it appears saturated as the vegetation in the land becomes denser, and it can not increase with vegetation coverage accordingly; it is limited in dealing with atmosphere interference and atmosphere residual noise seriously influences NDVI; it is susceptible to soil background, especially in moderate vegetation coverage area, for NDVI is likely to increase when the soil background becomes gloomy [19-20].

## 2.2 Introduction of Surface Water Content Index (SWCI)

Soil is the natural complex synthesis of different contents. Soil spectrum is influenced by many complicated factors such as soil parent material, organic material and water content, etc. When other factors such as the soil parent material are stable invariant, soil spectrum is greatly limited by soil moisture. Different soil types vary slightly with water changes, and usually their reflectivity decrease as soil moisture increases, which make it possible to make remote sensing monitoring of soil moisture. Figure 1 is the absorptivity curve. Soil and vegetation have more or less water contain within their body, and water could influence spectrum reflectivity of land materials, but the influence shall be consistent with the spectrum curve. By analyzing water absorption curve, we find that there are two absorption peaks in 1.45μm wave band and 1.9μm wave band respectively, while an absorption valley in 1.9μm wave band. Figure 2 is spectrum reflectivity curve of vegetation, soil and water. There are two reflectivity valleys in 1.45μm and 1.9μm wave bands separately, respectively corresponding to absorption peak of water reflectivity, and it is most obvious for reflectivity changes in 1.9μm wave band; there is a reflectivity peak in 1.65μm wave band, corresponding to absorption valley of water reflectivity. Analysis above shows that soil and vegetation water capacity is an important factor that influences spectrum curve changes [21-22].

Du Xiao [13] et al. established SWCI model on the basis of water absorptivity curve and soil reflectivity curve characteristics：

$$SWCI = \frac{B_6 - B_7}{B_6 + B_7} \tag{2}$$

B6 and B7 are reflectivity of MODIS Band 6 and Band 7 respectively. The model could directly obtain surface water capacity index by research on water absorption's comprehensive influence on vegetation and soil reflection spectrum. The two bands are located in vapor absorption region and they are susceptible to water reflection changes. Comprehensively considering mixed difference of vegetation and soil, the index through combination of MODIS Band 6 and Band 7 can reflect surface water capacity to some extent. Influenced by the water absorption curve, the vegetation or bare area reflection of Band 6 is higher than Band 7, but both of them have similar atmosphere scatter and radiation values. Therefore, B6-B7 can show water capacity in vegetation and soil, and decrease atmosphere influence to the maximum extent [13,18]. Taking B6+B7 as denominator can limit the results to -1~1, and enhanced the comparison between different indexes.

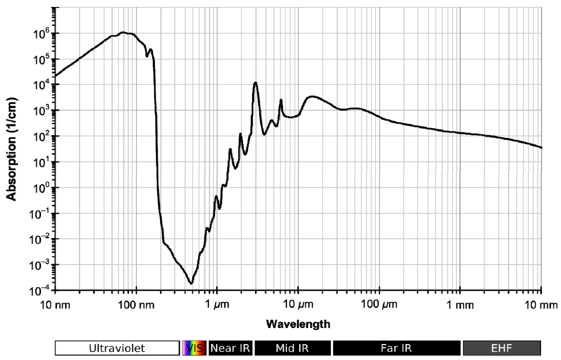


Fig.1 Absorption coefficients for water [23]

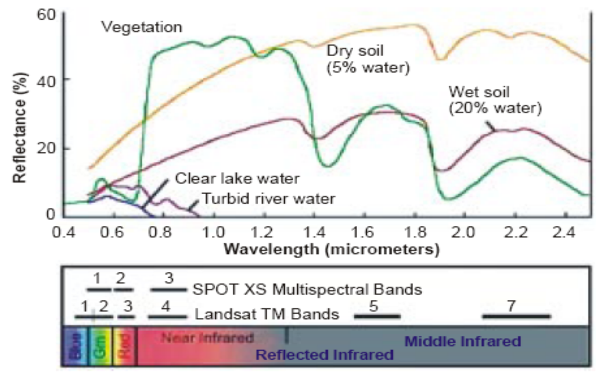


Fig.2 Spectral Reflectivity curves for vegetation, soil and water [23]

### 2.3 Cropland Soil Moisture Index (CSMI)

The root shoot ratio of crops is changing together with its growth. As for most crops, root system mainly lies in 0~20cm layer in the early stage. With acceleration of growth, the root system growth fast. The less the soil moisture is, the deeper of the vertical root distribution is, vise versa. The crop root system is 20-50cm deep in this period, and the soil moisture condition of this layer can be reflected by NDVI [24]. Therefore, the NDVI which calculated from channel 1 and channel 2 of EOS/MODIS is able to show the soil moisture changes in this layer to the maximum extent.

The SWCI model constructed on the basis of water absorptivity curve and soil reflectivity curve fully took advantage of the change of water and soil reflectivity of channel 6 and channel 7, and mainly showed the soil moisture status of the surface [13]. It is more accurate in retrieval soil moisture of shallow layer, but it is not satisfied in retrieval soil moisture of the deep layer.

According to the analysis above, neither NDVI spectrum changes nor SWCI spectrum changes is unable to precisely show the soil moisture changes of cropland in the depth of 0-50cm. In order to realize a better effect, channels 1, 2, 6 and 7 should be combined to construct a new index ----- Cropland Soil Moisture Index (CSMI).

According to the calculation results, it is found that the value of NDVI is always higher than that of SWCI (Table 1).

Table 1 The Comparison between SWCI and NDVI

| Date | Index | Calculation results | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 05/08/2007 | NDVI | 0.5125 | 0.4603 | 0.4452 | …… | 0.6549 | 0.6071 | 0.6237 |
| | SWCI | 0.242 | 0.1439 | 0.1963 | …… | 0.2033 | 0.1823 | 0.210 |
| …… | | | | | | | | |
| 02/10/2009 | NDVI | 0.639 | 0.561 | 0.6027 | …… | 0.5909 | 0.5431 | 0.4906 |
| | SWCI | 0.1687 | 0.1072 | 0.0726 | …… | 0.1369 | 0.0639 | 0.0916 |

For comparison with different drought index, normalized difference methods adopted here to process the two groups data:

$$CSMI = \frac{NDVI - SWCI}{NDVI + SWCI} \tag{3}$$

The formula above can be simplified into the following one by substituting

$NDVI = \dfrac{B_2 - B_1}{B_2 + B_1}$ and $SWCI = \dfrac{B_6 - B_7}{B_6 + B_7}$ :

$$CSMI = \frac{B_2 \cdot B_7 - B_1 \cdot B_6}{B_2 \cdot B_6 - B_1 \cdot B_7} \tag{4}$$

In the formula above, $B_1$, $B_2$, $B_6$ and $B_7$ refer to the reflectivity of channel1, channel2, channel6 and channel7. CSMI not only considers the soil moisture of shallow layer but also takes vegetation index of the soil moisture in deeper layer into account, so that it is able to effectively reduce the unstable effect on the accuracy of soil moisture monitoring caused by the change of vegetation.

## 3. ANALYSIS ON THE RESULT OF EFFECTIVENESS VALIDATION

### 3.1 Geography and Drought Characteristics in Henan Province

Henan, located in middle and east part of China and middle-and down-stream of Yellow River, lies in N31°23′～36°22′, E110°21′～116°39′. It covers an area of 167, 000 $Km^2$. Henan is in the eastern monsoon region in China across two natural sections---temperate zone and north semitropics, so it is classic continental monsoon climate with rain and heat in the same season.

The frequency of spring drought and early summer drought is higher than 55% in Henan Province, about a three-year circle [25]. This period is also the prosperous growth times of winter wheat in Henan. As the old saying says "wheat harvest lies in the precipitation of $3^{th}$, $8^{th}$, $10^{th}$ month of the year", March and April are the key period for wheat jointing and tassel. Precipitation in the period will seriously influence later wheat output. Especially as global climate becomes warm, extreme climate incidents frequently occur. There is sharp variability in rainfall distribution in March and April. In most areas, the rainfall tends to decrease, and it could decrease by 3%~20%, so it is very necessary to make research on monitoring drought in the period.

### 3.2 Verification and Analysis of Effectiveness

Drought indexes can provide different monitoring information at different times and ecological systems, while good monitoring information shall contain different underlaying conditions. The satellite remote sensing monitoring materials on $8^{th}$ May 2007, $8^{th}$ Mar. 2008, 9th Mar. 2008, $6^{th}$ Dec. 2008 and $10^{th}$ Feb. 2009 are selected to undertake CSMI analysis, and the 0-50cm soil moisture from the meteorological stations in Henan are adopted to check the analysis. Observed soil moisture in spots are from Henan Meteorological Bureau.

Table2 The regression and effectiveness validation of CSMI, NDVI and SWCI model

| Date | Index | Regression equation | No. of samples | $R^2$ | Related coefficient | F | Prob>F |
|---|---|---|---|---|---|---|---|
| May 8th, 2007 | NDVI | Y = -14.63X+60.20 | 70 | 0.0192 | -0.1386 | 1.33 | 0.25 |
| | SWCI | Y = -109.27X+74.96 | 70 | 0.3902 | -0.6249 | 43.52 | 0.01 |
| | CSMI | Y =87.74X+ 9.95 | 70 | 0.5484 | 0.7414 | 82.59 | 0.01 |
| Mar. 8th, 2008 | NDVI | Y = -7.48X+79.95 | 70 | 0.0009 | -0.0263 | 0.06 | 0.81 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | SWCI | Y = -293.89X+89.4 | 70 | 0.4617 | -0.6778 | 55.75 | 0.01 |
| | CSMI | Y = 72.75X+16.58 | 70 | 0.5869 | 0.7008 | 78.14 | 0.01 |
| Mar. 9th, 2008 | NDVI | Y = -58.44X+94.57 | 70 | 0.0753 | -0.2653 | 3.26 | 0.09 |
| | SWCI | Y = -246.76X+94.94 | 70 | 0.6212 | -0.7866 | 65.60 | 0.01 |
| | CSMI | Y = 90.85X+12.31 | 70 | 0.6185 | 0.7881 | 64.84 | 0.01 |
| Dec. 6th, 2008 | NDVI | Y = -58.90X + 99.55 | 70 | 0.1680 | -0.4109 | 10.97 | 0.01 |
| | SWCI | Y = -128.5X+ 83.85 | 70 | 0.5032 | -0.7012 | 57.24 | 0.01 |
| | CSMI | Y = 66.15X + 24.16 | 70 | 0.5130 | 0.7168 | 70.69 | 0.01 |
| Feb. 10th, 2009 | NDVI | Y = -42.30X+95.13 | 70 | 0.0356 | -0.1874 | 2.29 | 0.13 |
| | SWCI | Y = -2.55X+ 0.94 | 70 | 0.9400 | -0.7014 | 971.33 | 0.01 |
| | CSMI | Y = 75.18X+ 19.78 | 70 | 0.5135 | 0.7146 | 65.45 | 0.01 |

By abstracting CSMI, NDVI and SWCI index from 5 time series remote sensing images and the observed soil moisture (Table 2) to make analysis, the related coefficient of soil moisture and CSMI of the 0~50cm layer is as high as over 0.7 and qualified in the F significance test with $\alpha$=0.01. Meantime, in the early vegetative period (in small vegetation coverage), the effectiveness of SWCI retrieval soil moisture is very close to CSMI. Therefore, it can be concluded that in moderate vegetation coverage, CSMI method is better in monitoring soil moisture in 0~50cm soil layer. In the area with sparse vegetation coverage (early vegetative period), SWCI can be directly used for soil moisture retrieval of cropland.

Through abstracting the remote sensing data and observed soil moisture on 8th May 2007, then adopting ENVI and ArcGIS to make distribution map according to the latitude and longitude, it is demonstrated that in the areas of most western and part of middle in Henan province suffered from serious drought with the relative soil moisture ≤40%, which is shown as the area with CSMI≤0.40; the soil moisture in northern and southeastern area of Henan is better, and CSMI distribution is almost the same as what the RSM map shows.

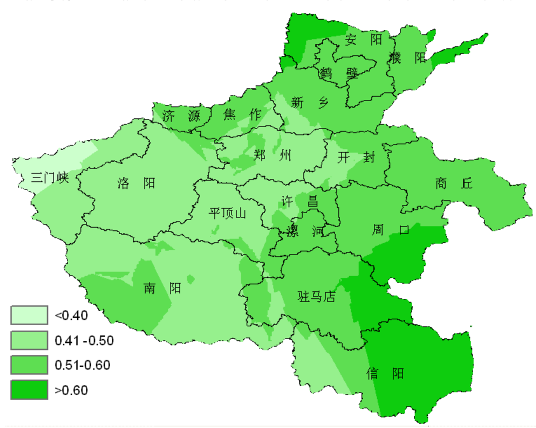


Fig.3 The sketch map of CSMI on May, 8th, 2007

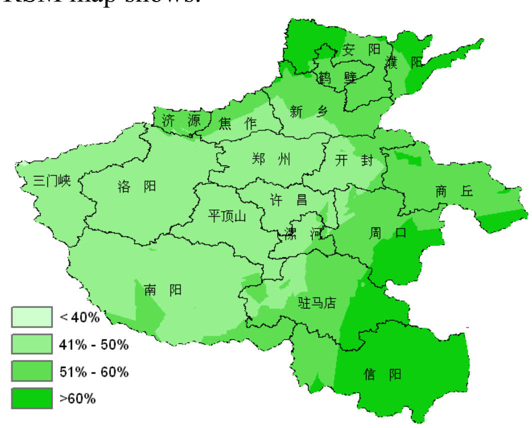


Fig.4 The sketch map of RSM in spots on May, 8th, 2007

## 4. CONCLUSION AND DISCUSSION

(1) CSMI gets the information directly by reflecting the spectrum change of the soil moisture of deeper layer

through vegetation indexes and analyzing the comprehensive effect of vegetation indexes on the spectrums of reflectivity and vegetation. Band 6 and Band 7 adopted are able to effectively reduce the disturbance of atmosphere and get the surface water capacity. The combination of the 4 bands well reflects the CSMI changes, so it is especially suitable for soil moisture monitoring for the farmland with moderate vegetation coverage.

(2) Viewing from application effects at several time series, SWCI retrieval effect of soil moisture is very close to CSMI in sparse vegetation coverage, so SWCI can be directly adopted to carry out cropland soil moisture retrieval in early stage, while CSMI can be used to make cropland soil moisture retrieval in moderate vegetation coverage.

(3) In order to verify real-time applicability of CSMI, we select MODIS data at five different time series to check CSMI application effect in monitoring remote sensing monitoring of soil moisture at different vegetation coverage, and it is quite satisfied in results. At the same time, we notice that it is not perfect as a new monitoring index. Its application effect needs further real-time verification and consummation, and modified indexes may be proposed according to different underlaying surfaces.

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