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# Retrieving the Surface Soil Moisture of the Daxing'an Mountains in Inner Mongolia based on High-resolution Remote Sensing Data

Mengzhen Li[1], Ziying Sun[1], Lintao Chen[2], Ruiting Zhao[2], Qiyue Zhang[1], Xiaohan Sun[3]

[1]School of Desert Management, Inner Mongolia Agricultural University, Hohhot 010018, China

[2]China Inner Mongolia Forest Industry Group Co., Ltd., Yakeshi 022150, China

[3]School of Communication Engineering, Hangzhou Dianzi University, Huangzhou 310018, China

## Abstract

**The inversion model has an important influence on the evaluation results of soil moisture. Based on this, this paper takes the scorched area of the Daxinganling fire in Inner Mongolia in 2003 as the study area, takes Landsat8 OLI remote sensing images as the data source, and combines the measured data of surface soil moisture in the study area, respectively. Perpendicular Drought Index (PDI), Modified Perpendicular Drought Index (MPDI) and Vegetation-adjusted Perpendicular Drought Index (VAPDI) were used to construct soil moisture inversion models, and the inversion models were verified and evaluated for accuracy. The final result: the three remote sensing drought indices based on Landsat 8 OLI remote sensing images and the measured data of surface soil moisture in the study area have different degrees of linear negative correlation, and the average R2 is 0.509, 0.5557 and 0.6246, respectively, indicating that the use of high resolution It is feasible to construct a remote sensing inversion model of soil moisture based on the drought index calculated from the reflectance in the red (Red) and near-infrared (NIR) bands of optical remote sensing images. From the quantitative evaluation results of the four model validation accuracy evaluation indicators, the VAPDI inversion model has the highest accuracy. To sum up, PDI is suitable for inversion of soil moisture in burnt areas just after burning; MPDI is suitable for inversion of soil moisture in burned areas where vegetation has partially recovered in the second year after burning; VAPDI is suitable for inversion of most Inversion of soil moisture in revegetated burnt sites. In the soil moisture inversion of the burned area, the VAPDI inversion is the best.**

## Keywords

**Burnt Area; Remote Sensing; Soil Moisture.**

## 1. Introduction

Soil moisture is the limiting factor for vegetation growth. Influenced by various factors such as topography, surface vegetation,soil origin, parent material,etc.,the spatial distribution of soil moisture is complex and shows strong environmental sensitivity[1]. In recent years, studies on the variability of soil characteristics have been a hotspot in ecological research [2], but there are relatively few studies on soil moisture in the forest areas of the Greater Khingan Mountains, Inner Mongolia, especially in the severely burned forest areas.

The Daxing'anling forest area of Inner Mongolia is a typical distribution area of northern China, and has an important ecological status and function. Due to the characteristics of geographical environment and climatic factors, it is also a frequent forest fire area in China. In 2003, a huge forest fire occurred in the Jinhe and Genhe forest areas of Daxinganling, Inner Mongolia, which

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damaged more than 100,000 hectares of forest land, seriously changed the forest ecological environment, and formed a large area of severely burned areas, which greatly affected the local ecosystem [3]. In the process of vegetation restoration, it is of great theoretical value to further reveal the ecological process and mechanism of vegetation restoration, and it is of practical significance to evaluate the effect of vegetation restoration[4].

After years of continuous practice and exploration by scholars at home and abroad, there are many mature models and methods for soil moisture inversion using remote sensing methods [5-6], but for different remote sensing data sources, different research areas and research purposes, the applicability of the inversion method is also different. Based on this, this paper takes the burnt area of the May 5, 2003 fire in the Daxinganling forest area of Inner Mongolia as the research object, and uses the Landsat High-resolution remote sensing data to invert the soil moisture of the burnt area. Reliability and variability of methods in quantifying topsoil moisture in fire-stricken lands. The research results will provide theoretical inspiration and practical reference for further research on the spatiotemporal dynamics of the surface soil moisture in the burnt area.

## 2. Study Area and Data

### 2.1. Overview of the Study Area

The study area is located in the forest area of the Daxing'anling Mountains, Inner Mongolia (Fig.1), where the "Jinhe Yihe" forest fire burned in 2003. It is located in the northeastern part of China, in the northern section of the Daxing'anling Mountains. The geographical coordinates are 120°12′E~122°55′E and 50°20'N~52°30'N The altitude is 737~1388m. The average temperature is -5.3°C, the extreme minimum temperature is -58°C, and the freezing period is more than 210 days. The annual precipitation is 450-500 mm, the annual rainy season is mainly concentrated in July-August, the snowfall period is from late September to early May of the following year, and the snowfall thickness is 20-40 cm. The terrain is high in the northeast and low in the southwest. With forest resources as the main source and abundant forest resources, it is the main timber producing area in China. The forest coverage rate of the entire Genhe City is 91.7%, and the forest area is 174.5×106hm2, The main tree species are Xing'an larch, Pinus sylvestris, birch, aspen and so on[7].

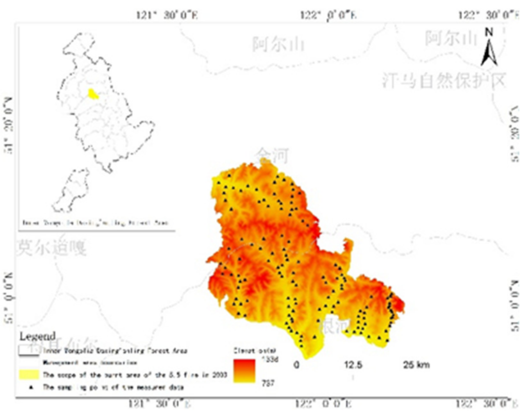


**Fig 1.** Overview map of the study area

### 2.2. Data Sources

In order to facilitate the subsequent study of the spatiotemporal dynamics of soil moisture on the surface of the burned surface, the multi-spectral satellite data that is publicly available and has strong continuous observation capability, namely the Landsat series of NASA satellites, was selected for this study. For: http://glovis.usgs.gov, the acquired images are free of cloud cover

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and are Level 1T products, which have been geometrically corrected. After inspection, the geographic location of the images is superimposed accurately, so no geometric correction is required, but the data needs to be adjusted. After further preprocessing, the preprocessed remote sensing data are obtained after radiometric calibration, atmospheric correction and fusion cropping (Fig.2).

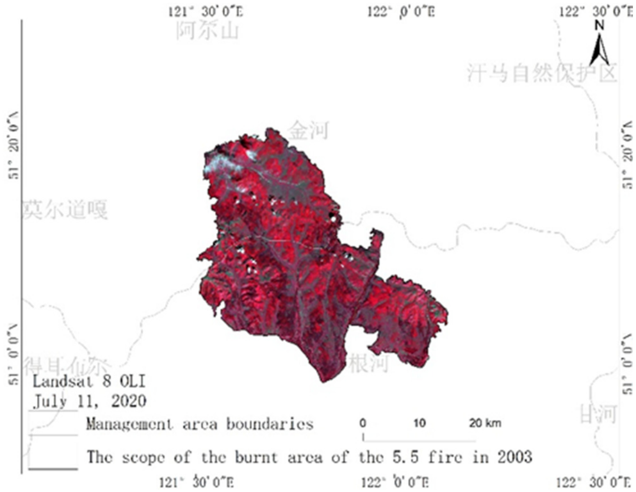


**Fig 2.** Preprocessed false-color remote sensing images of vertebrae

From July 8 to July 15, 2020 (sunny weather, similar to the L8 transit conditions in the same period), the soil moisture meter TDR300 was used to measure the surface (0~10cm) of 135 sample points (Fig.1) soil moisture measurement, and the range normalization of the measured data of surface soil moisture of 135 sampling points, after removing 6 abnormal points, the final remaining 129 sampling point values, as the verification to compare the accuracy of each inversion model data.

## 3. Research Method

Perpendicular Drought Index (PDI) and its extended Modified Perpendicular Drought Index (MPDI) and Vegetation Adjusted Perpendicular Drought Index (VAPDI) can be applied to areas with different degrees of vegetation coverage. The near-infrared band reflectance information is used to calculate the drought index values respectively, and the soil moisture inversion model can be established by combining with the field measured soil moisture data. The parameters used are few, the calculation is simple, and it is easy to implement, and it can take advantage of the characteristics of High-resolution remote sensing images.Therefore, this paper decided to select three remote sensing drought indices (PDI, MPDI, VAPDI) for comparison and research on soil moisture in the burned area.

### 3.1. Perpendicular Drought Index (PDI)

Due to the strong absorption characteristics of water in the red band (Red) and the near-infrared band (NIR), the reflectivity of the soil in these two bands is affected by soil moisture. The lower the reflectivity in the infrared band, and vice versa, while the vegetation leaves have strong reflectivity in the near-infrared band, and the higher the vegetation coverage, the higher the near-infrared reflectivity. Therefore, in the two-dimensional spectral feature space composed of the remote sensing image NIR-Red, the reflectance scatter of each remote sensing pixel has a typical triangular distribution, and each reflectance value in the soil red band has a minimum reflection in the near-infrared band. Corresponding to the rate, this set of characteristic data forms an approximate straight line, namely the soil line (BC), On this basis, the construction theory and calculation method of the perpendicular dryness index are proposed.

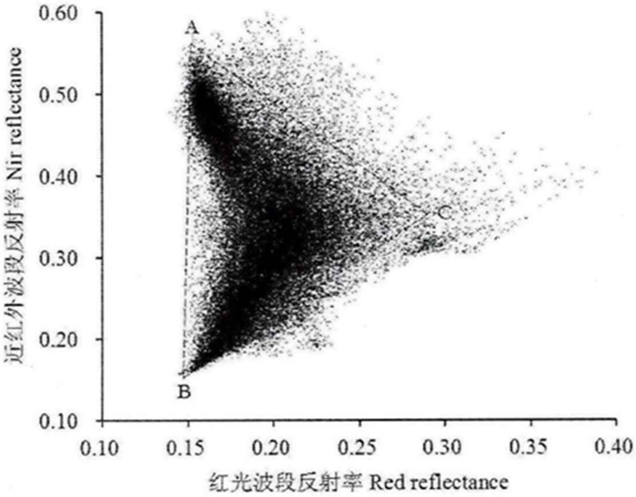


**Fig 3.** Spatial distribution map of Nir-red spectral features of remote sensing images

A is the surface covered by complete vegetation, B is the bare soil with high soil moisture, C is the dry bare soil surface, and BC is the soil line (Fig.3).The expression is:

$$R_{nir,s} = MR_{red,s} + I \tag{1}$$

In the formula, M is the slope of the soil line, I is the intercept of the soil line on the ordinate, Rnir,s and Rred,s are the near-infrared and red light band reflections of the bare soil pixels in the remote sensing image after atmospheric correction, respectively. The soil line expression can be calculated by fitting the scatter plot of the pixels in the Nir-Red spectral feature space by ENVI 5.1 [9].

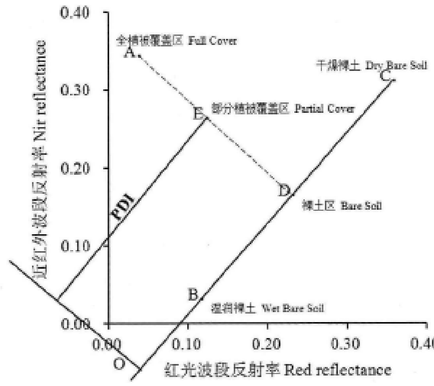


**Fig 4.** Schematic diagram of perpendicular drought index (PDI) construction

The normal line O is perpendicular to the soil line BC through the origin of the Nir-Red spectral feature space coordinate. The distance from any point E to O in the NIR-Red spectral feature space can describe the soil moisture status at that point, that is, the perpendicular drought index. PDI, the larger the PDI value, the farther the pixel point is from O, indicating that the surface is drier, and vice versa (Fig.4). The formula for calculating PDI is:

$$PDI = \frac{R_{red}+R_{nir}}{\sqrt{M^2+1}} \tag{2}$$

## 3.2. Modified Perpendicular Drought Index (MPDI)

The perpendicular drought index does not take into account the strong scattering effect of surface vegetation cover on the red and near-infrared bands, so it is mainly suitable for remote sensing inversion of soil moisture in low vegetation coverage or bare land areas. The performance accuracy is not ideal [10-11]. In view of this limitation, in order to improve the application range of the model, Abduwasit introduced the Forest Vegetation Coverage (FVC) to decompose the mixed pixels of the medium and remote sensing images in the two-dimensional spectral feature space, to overcome the scattering of vegetation to the red and near-infrared bands. To obtain the pure soil pixel reflectance related to soil moisture, the improved perpendicular drought index MPDI was obtained [12].

$$MPDI = \frac{R_{red}+M \cdot R_{nir}-FVC(R_{red}+M \cdot R_{nir},v)}{1-FVC\sqrt{M^2+1}} \quad (3)$$

Rred,v, Rnir,v are the reflectivity of vegetation in the red and near-infrared bands, M is the slope of the soil line; the vegetation coverage FVC can be calculated using the pixel binary model method [13]:

$$FVC = (\frac{NDVI-NDVI_S}{NDVI_V-NDVI_S})^2 \quad (4)$$

NDVIV and NDVIS represent the normalized vegetation indices of vegetation and bare soil in the study area, respectively. In the Nir-Red two-dimensional spectral feature space (Fig.3), the direction perpendicular to the soil line represents the change of vegetation coverage with MPDI, and the direction parallel to the soil line represents the change of soil moisture with MPDI, soil moisture and vegetation cover Decreasing the degree will increase the value of MPDI, and vice versa [14].

## 3.3. Vegetation Adjusted Perpendicular Drought Index (VAPDI)

In order to further analyze the influence of mixed pixels in the Nir-Red spectral feature space on soil moisture spectral information and improve the inversion accuracy of soil moisture in the vegetation coverage area, Wu Chunlei et al. introduced the perpendicular vegetation index after analyzing the error distribution law of the PDI model. (PVI) represents the vegetation coverage information of different pixels, adjusts the PDI model in the PVI-PDI two-dimensional space, and proposes a vegetation-adjusted perpendicular drought index (VAPDI) suitable for soil moisture remote sensing inversion in high vegetation coverage areas [9].

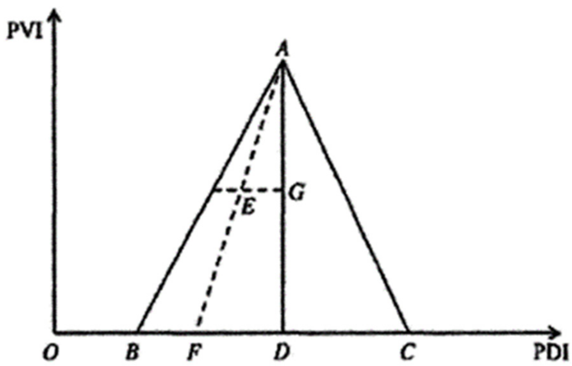


**Fig 5.** Schematic diagram of spatial pixel scatter distribution of PVI-PDI spectral features

As shown in the figure(Fig.5), the contour lines formed by all the soil moisture in the triangle ABC are approximately straight lines, and each contour line intersects at point A. In the bare soil area with PVI=0, it is more accurate to use PDI to estimate soil moisture, so ABC The PDI at any point E can be replaced by the PDI at the intersection F of the soil moisture contour AE and the abscissa axis, where the length of OF can be used as the corrected PDI at point E. According to the triangle similarity principle, the VAPDI calculation formula of any X point can be obtained [9]:

$$VAPDI(X) = PDI(A) - \frac{|PDI(A) - PDI(X)| \cdot PVI(A)}{PVI(A) - PVI(X)} \tag{5}$$

The formula for calculating the perpendicular vegetation index PVI is as follows:

$$PVI = \frac{|R_{nir} - M \cdot R_{red} - 1|}{\sqrt{M^2 + 1}} \tag{6}$$

Theoretically speaking, for the bare soil area, that is, when PVI tends to 0, VAPDI is equal to PDI.

## 3.4. Estimation Accuracy Evaluation

The constructed PDI, MPDI and VAPDI soil moisture inversion models were validated using the 44soil moisture measured data in the validation samples, and The Coefficient of Determination (R2), Mean Relative Error (MRE), Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) four model accuracy evaluation indicators are used to quantitatively evaluate the accuracy of each inversion model. The connotation and calculation methods of the four model accuracy evaluation indicators are as follows:

(1) Coefficient of Determination ($R^2$): Indicates the degree of linear fit between the soil moisture inversion value ($x_i$) based on remote sensing images and the measured soil moisture value ($y_i$), also known as the coefficient of determination or goodness of fit, $R^2$ The larger the value, the better the stability of the model. The calculation formula is as follows:

$$R^2 = \frac{\left[\sum_i^n (x_i - \bar{x})(y_i - \bar{y})\right]^2}{\sum_i^n (x_i - \bar{x})^2 (y_i - \bar{y})^2} \tag{7}$$

(2) Mean absolute error (MAE): The absolute error is the difference between the inversion value of soil moisture ($x_i$) and the measured value of soil moisture ($y_i$). When the inversion result is greater than the measured value, the error is positive, otherwise it is negative; The error represents the average value of the absolute error between the inversion value of soil moisture and the measured value of soil moisture. This index can better reflect the degree of deviation between the inversion value of soil moisture and the measured value of soil moisture. The calculation formula is as follows:

$$MAE = \frac{1}{n} \sum_{i=1}^n |x_i - y_i| \tag{8}$$

(3) Average relative error (MRE): The relative error is the ratio of the absolute error to the measured value, and the average relative error represents the average value of the relative error between the soil moisture inversion value ($x_i$) and the measured value of soil moisture ($y_i$). Compared with the mean absolute error, it can better reflect the credibility of the soil moisture inversion value. The calculation formula is as follows:

$$MRE = \frac{1}{n}\sum_{i=1}^{n}\frac{|x_i - y_i|}{x_i} \tag{9}$$

(4) Root Mean Square Error (RMSE): Indicates the square root of the square root of the deviation of the soil moisture inversion value ($x_i$) and the soil moisture measured value ($y_i$), and the ratio of the total number of verification samples n, which can accurately reflect the soil moisture inversion. The degree of dispersion of the difference between the value ($x_i$) and the measured value of soil moisture ($y_i$). The smaller the RMSE, the closer the inversion value of soil moisture is to the measured value of soil moisture, indicating that the prediction ability of the model is better. The calculation formula is as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \tag{10}$$

References are cited in the text just by square brackets [1]. (If square brackets are not available, slashes may be used instead, e.g. /2/.) Two or more references at a time may be put in one set of brackets [3, 4]. The references are to be numbered in the order in which they are cited in the text and are to be listed at the end of the contribution under a heading References, see Table 1.

**Table 1.** Three Scheme comparing

| Numble | Scheme 1 | Scheme 2 | Scheme 3 |
|---|---|---|---|
| 1 | 456 | 456 | 123 |
| 2 | 789 | 213 | 644 |
| 3 | 213 | 654 | 649 |

# 4. Results and Analysis

## 4.1. Remote Sensing Parameter Calculation

The figure below is a scatter plot of the spatial characteristics of the redlight band and the near-infrared band after the bare soil pixels are extracted from the Landsat8 remote sensing image with envi5.3. The linear straight line in the figure is the soil line, and the soil line extraction result can be used to obtain the soil line in the study area. The slope M is 1.2867 and the intercept I of the soil on the ordinate is 0.0449 (Fig.6).

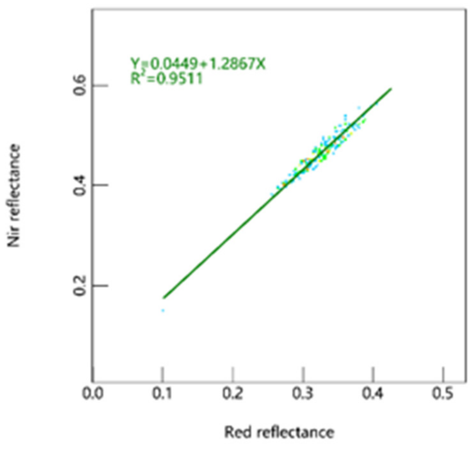


**Fig 6.** Soil line

The following figures are Normalized Difference Vegetation Index (NDVI), the Forest Vegetation Coverage (FVC), and Perpendicular Vegetation Index (PVI) remote sensing images obtained by envi5.3 after calculating the preprocessed remote sensing data in the study area (Fig.7,8,9).

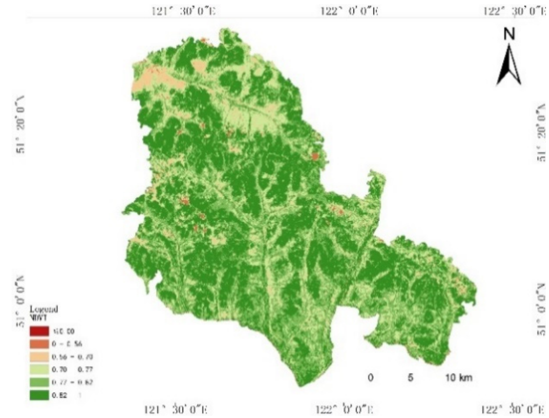


**Fig 7.** NDVI

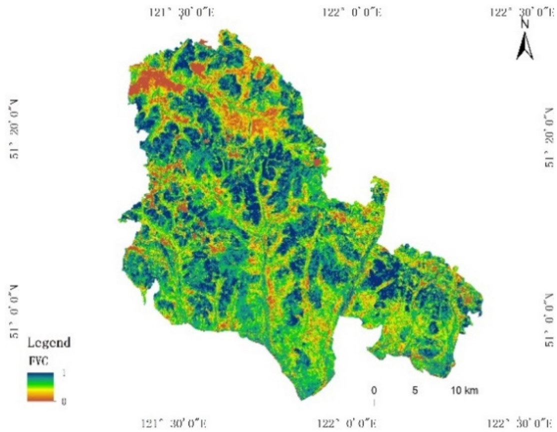


**Fig 8.** FVC

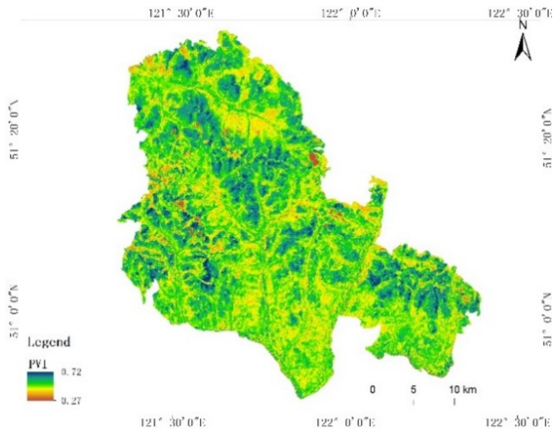


**Fig 9.** PVI

The picture below shows the remote sensing images of the Perpendicular Drought Index PDI, the improved perpendicular drought index MPDI, and the vegetation-adjusted perpendicular drought index VAPDI, which are further calculated by the envi5.3 software with the parameters mentioned above. (Fig.10,11,12)

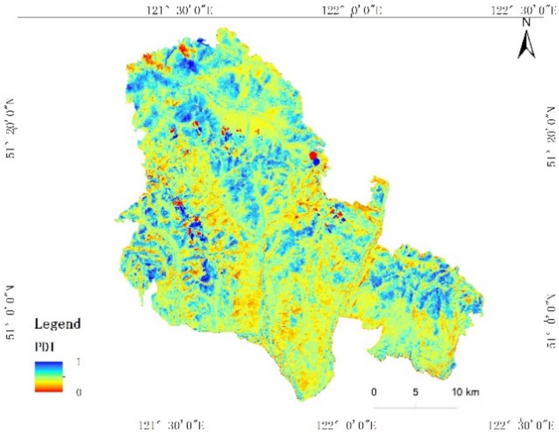


**Fig 10.** PDI

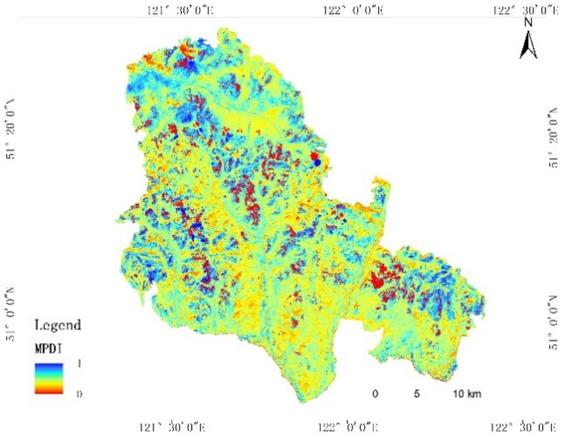


**Fig 11.** MPDI

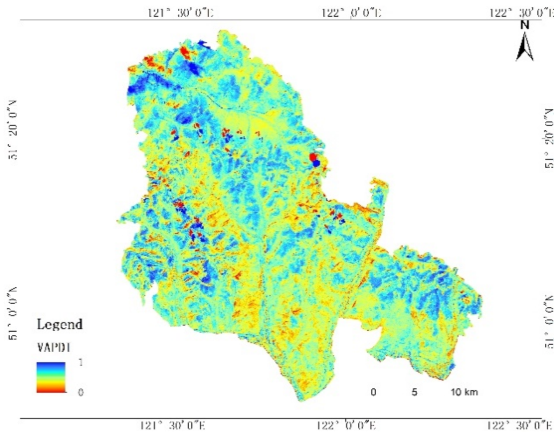


**Fig 12.** VAPDI

## 4.2. Inversion Model Construction

In order to meet the accuracy verification requirements of the subsequent inversion model, before constructing the soil moisture inversion model based on PDI, MPDI and VAPDI, 85 sampling points were selected from the 129 sampling points in the study area as the modeling sample set, and the remaining 44 sampling points were used as the modeling sample set. As a validation sample set for verification and evaluation of the accuracy of the inversion model. At the same time, in the process of selecting the modeling sample set and the verification sample set, ensure that the sampling points in each sample set are in different land cover types, vegetation coverage, terrain and slope.

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The PDI, MPDI and VAPDI calculated based on the Landsat8 OLI remote sensing image and the soil moisture measured data of the modeled sample points in the study area were linearly fitted in SPSS software, and the inversion model of the Landsat8 OLI remote sensing image PDI, MPDI and VAPDI soil moisture was obtained. (Fig.13,14,15).

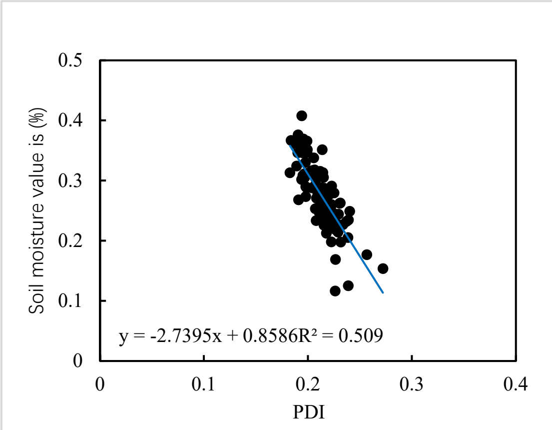


**Fig 13.** PDI related analysis

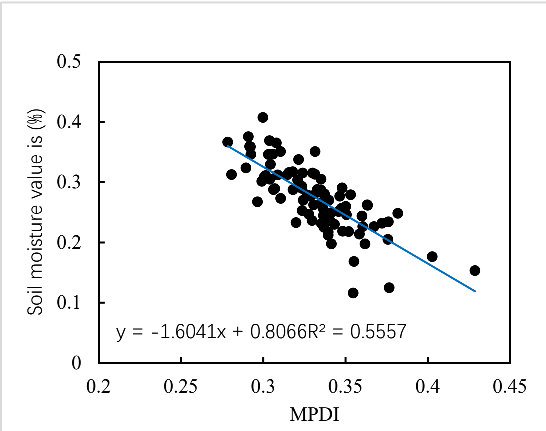


**Fig 14.** MPDI related analysis

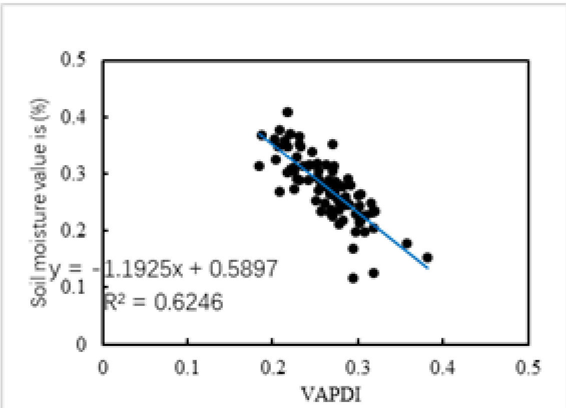


**Fig 15.** VAPDI related analysis

After summarizing the regression models established by remote sensing images PDI, MPDI, VAPDI and soil moisture measured data, see Table 2.

**Table 2.** Summary of Regression Models

| Model | Formula | Coefficient of determination | Standard deviation |
|---|---|---|---|
| PDI | y =-2.7395x+0.8586 | 0.509** | 0.04 |
| MPDI | y =-1.6041x+0.8066 | 0.5557** | 0.109732 |
| VAPDI | y =-1.1925x+0.5897 | 0.6246** | 0.109732 |

According to the linear fitting results between the remote sensing images PDI, MPDI, VAPDI and the measured soil moisture data in the above figure and the regression model summary in the above table, it can be seen that the burnt area is in the three soil moisture regression models. There was little difference in the correlation between moisture. Overall, the correlation coefficient of the soil moisture regression model constructed based on VAPDI remote sensing images was the highest, and the correlation coefficient of the soil moisture regression model constructed based on MPDI remote sensing images was the lowest.

## 4.3. Comparative Analysis of Inversion Model Validation and Accuracy Evaluation

In the verification process of the inversion model, the PDI, MPDI and VAPDI of the 44 verification sample points were firstly calculated from the Landsat8 OLI remote sensing image, and then the three remote sensing drought index values were respectively brought into the corresponding inversion model to obtain each verification sample. Finally, the inversion value is correlated with the measured soil moisture value, and the summary results of R2, MAE, MRE and RMSE of each inversion model, see Table 3.

**Table 3.** Model Accuracy Verification Metrics Comparison

| Model | R2 | MAE | MRE | RMSE |
|---|---|---|---|---|
| 1 | 0.5962 | 0.041836 | 0.074513 | 0.045903 |
| MPDI | 0.6716 | 0.03424 | 0.55480 | 0.36691 |
| VAPDI | 0.7475 | 0.021104 | 0.040118 | 0.025405 |

The comparison and analysis of the accuracy verification indicators of the three soil moisture inversion models in the above table shows that the VAPDI soil moisture inversion model R2, MAE, MRE, and RMSE based on Landsat8 OLI remote sensing images are significantly better than PDI and MPDI. Among the four verification accuracy indicators, the PDI index has the lowest inversion accuracy. This is mainly because the inversion model based on the PDI index does not consider the scattering effect of the surface vegetation cover on the red light and near-infrared bands, resulting in the PDI index on the vegetation cover. The regional soil moisture retrieval accuracy is low, so the soil moisture retrieval model based on the PDI remote sensing drought index is more suitable for areas with low vegetation coverage or bare areas. MPDI and VAPDI respectively introduce vegetation coverage FVC and perpendicular vegetation index PVI to correct the vegetation spectral reflectance information in remote sensing images, so the inversion accuracy of soil moisture is higher than that of PDI; however, MPDI has different effects on different vegetation coverage. Therefore, MPDI is more suitable for soil moisture inversion with large differences in vegetation coverage; VAPDI is constructed based on adjusting the two-dimensional spectral information of PDI by introducing the perpendicular vegetation index PVI, which is more suitable for high vegetation. The remote sensing index of the covered area shows that the burnt area has been restored for more than ten years since the fire broke out. Although most of the restored vegetation is shrubs, the vegetation coverage has recovered to more than 95%.

## 5. Conclusion

The three remote sensing drought indices based on Landsat 8 OLI remote sensing images all have different degrees of negative linear correlation with the measured data of surface soil moisture in the study area. The average R2 is 0.509, 0.5557 and 0.6246, respectively. It is feasible to construct a remote sensing inversion model of soil moisture based on the drought index calculated from the reflectance in the light band (Red) and near-infrared band (NIR). From the quantitative evaluation results of the model validation accuracy evaluation indicators, the VAPDI inversion model has the highest accuracy. To sum up, PDI is suitable for inversion of soil moisture in burnt areas just after burning; MPDI is suitable for inversion of soil moisture in burned areas where vegetation has partially recovered in the second year after burning; VAPDI is suitable for inversion of most Inversion of soil moisture in revegetated burnt sites. In the soil moisture inversion of the burned area, the VAPDI inversion is the best.

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