Remote Sensing Extraction and Correction of Irrigation Information for Cotton in Early Growth Stage: Post-print

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Abstract

To improve the accuracy of remote sensing monitoring for crop growth during early stages with low coverage, it is essential to eliminate the influence of soil moisture background variations induced by irrigation on the Normalized Difference Vegetation Index (NDVI). To achieve extraction and correction of irrigation information during the early growth stage of cotton and enhance the precision of cotton growth monitoring and yield prediction, this study selected two cotton fields in the San Joaquin Valley, California, USA as the research area, acquired remote sensing imagery during the irrigation process in the early cotton growth stage, developed two irrigation information extraction methods (phased threshold method and irrigation line extraction method), and determined the optimal method for extracting irrigated pixels. Comparative analysis was performed on the relationships between NDVI, Normalized Difference Water Index (NDWI), and Soil-Adjusted Vegetation Index for cotton under irrigated and non-irrigated conditions, pixels containing irrigation information were extracted, and NDVI was corrected to eliminate the influence of irrigation on NDVI. The results demonstrate that: during the early growth stage of cotton, the NDVI change rate between irrigated and non-irrigated pixels reaches 12%, indicating a significant difference; a highly significant linear relationship exists between cotton NDVI and NDWI regardless of irrigation status, with coefficients of determination exceeding 0.80; the irrigation line method achieves higher accuracy in extracting irrigation information compared to the phased threshold method, with accuracy exceeding 88%; the linear regression model after correction achieves an accuracy of 0.95, showing obvious irrigation correction effects, with the NDVI difference between irrigated and non-irrigated pixels reduced to 2%. By correcting the NDVI values of pixels containing irrigation information, this study removes the impact of irrigation on NDVI, reflects true vegetation

information, enables accurate remote sensing monitoring of crop growth during early stages, and facilitates quantitative remote sensing monitoring.

Full Text

Using Remote Sensing to Extract and Correct Irrigation Data During Early Cotton Growth Stage

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Abstract

Vegetation indices are significantly affected by background soil, particularly during early crop growth stages when vegetation cover is low. To improve the precision of remote sensing monitoring of crop growth at the early stage, it is necessary to eliminate the effect of background soil moisture changes caused by irrigation on the Normalized Difference Vegetation Index (NDVI). Agricultural irrigation districts have yet to develop effective methods to eliminate NDVI differences, which has hindered efforts to mitigate irrigation effects on NDVI. This study investigated the impact of soil moisture differences between irrigated and non-irrigated cotton fields on NDVI. Two cotton plots in California' s San Joaquin Valley were selected as the research area. Remote sensing images captured during the irrigation process at the early cotton growth stage were used to construct two irrigation information extraction methods: a staged threshold method and an irrigation line extraction method. The optimal irrigation pixel extraction method was determined, and the relationships among NDVI, Normalized Difference Water Index (NDWI), and soil-adjusted vegetation indices were compared and analyzed under irrigated and non-irrigated conditions. Pixels containing irrigation information were extracted and NDVI was corrected to eliminate irrigation effects.

The results demonstrated that the NDVI change rate between irrigated and non-irrigated pixels reached 12% during the early cotton growth stage, indicating a significant difference. Extremely significant linear relationships existed between NDVI and NDWI for both irrigated and non-irrigated cotton, with coefficients of determination exceeding 0.80. The irrigation line method achieved higher extraction accuracy (greater than 88%) compared to the staged threshold method. After correction, the linear regression model accuracy reached 0.95, demonstrating obvious irrigation correction effects. The NDVI difference between irrigated and non-irrigated pixels decreased from 12% to 2%. This study corrected NDVI values for pixels containing irrigation information, eliminated irrigation effects on NDVI, reduced background soil moisture impacts, and reflected true vegetation information. The approach enables accurate remote sensing monitoring of crop growth during the early stage and provides a convenient method for quantitative remote sensing monitoring.

Keywords: Cotton; Early growth stage; Irrigation information; Vegetation index; Normalized difference vegetation index (NDVI); Normalized difference water index (NDWI)

Introduction

Remote sensing technology has become an emerging tool for crop yield estimation and growth monitoring in recent decades due to its macroscopic, objective, rapid, and low-cost characteristics. Timely and accurate monitoring of vegetation growth during the early crop growth stage enables yield prediction and early assessment. Vegetation indices (VIs) are widely applied in agricultural remote sensing monitoring, with numerous indices used for growth monitoring both domestically and internationally. Among these, the Normalized Difference Vegetation Index (NDVI) is the most extensively utilized. For instance, Pei et al. constructed crop growth monitoring models by developing characteristic parameters from NDVI time series curves using NDVI values from different growth periods within the same season and from the same growth period across different seasons. Huang et al. established a winter wheat area extraction model by determining NDVI thresholds for information extraction using MODIS-NDVI, obtaining growth conditions throughout the 2011 winter wheat growth season.

However, soil background conditions vary across study areas due to different climatic and hydrological conditions. Vegetation indices are affected by farmland soil background, particularly during early crop growth stages when vegetation cover is low. The impact of soil background on vegetation indices is closely related to crop coverage—leaf area index (LAI)—with greater coverage resulting in weaker soil background effects. Therefore, crop coverage cannot be ignored when studying soil background effects on NDVI. Liu et al. demonstrated a significant correlation between NDVI and LAI through inversion modeling. During early growth stages when crop coverage is low (NDVI < 0.5), soil background effects are pronounced and require elimination.

Rondeaux et al. compared the ability of various vegetation indices, including soil-adjusted vegetation indices, to eliminate soil background effects, noting that different indices perform differently under varying environmental conditions. Although soil-adjusted vegetation indices are widely applied with clear physical meaning, determining soil adjustment parameters presents difficulties, preventing complete elimination of background interference. In irrigated agricultural regions, irrigation throughout the crop growth period creates distinct remote sensing characteristics between irrigated and non-irrigated areas, causing significant NDVI differences. Irrigation leads to uneven soil moisture distribution, and differences in soil moisture cause variations in soil background brightness. For identical canopy structures, NDVI values are higher for dark soil backgrounds than for bright ones. The Normalized Difference Water Index (NDWI) serves as a more direct indicator for moisture remote sensing monitoring, and many scholars have used NDWI to extract water and soil moisture information. Cheng et al. noted that using modified NDWI to monitor crop water content is important for assessing water balance and guiding irrigation management. Lu et al. also extracted NDWI from HJ-1A/B imagery to analyze vegetation water content with high accuracy. However, current research focuses on soil moisture extraction and crop water content monitoring, with few studies proposing effective methods to eliminate NDVI differences in irrigated agricultural regions, thus failing to fundamentally address irrigation impacts on NDVI.

To improve remote sensing monitoring accuracy during early growth stages, this study investigated soil background moisture differences between irrigated and non-irrigated conditions and their effects on NDVI. Using cotton (*Gossypium sp.*) as the research object, the study: (1) analyzed differences in various vegetation indices between irrigated and normal conditions during early cotton growth to eliminate irrigation effects on soil background; (2) obtained time series of NDVI and soil background-reflecting vegetation indices from Landsat 30 m resolution remote sensing imagery for quantitative analysis to identify vegetation indices characterizing post-irrigation soil moisture conditions; and (3) determined irrigation information extraction methods and NDVI correction approaches. The results provide valuable references for NDVI application under low coverage conditions, facilitate accurate early-stage crop growth monitoring, and lay foundations for quantitative remote sensing and precision agriculture development.

1.1 Study Area Description

[Figure 1: see original paper] shows the location and imagery of the study area. The two research plots were both planted with cotton and located on the western side of California's San Joaquin Valley (Fig. 1a), within a river delta region with brown loam soil. The entire farm covered approximately 7,000 hm^2, with each plot measuring about 60 hm^2 (Fig. 1b). The region has a Mediterranean climate with hot, dry summers and cool, wet winters. The rainy season occurs primarily from November to April, but annual precipitation is minimal at approximately 70 mm. The area enjoys abundant light and heat resources, with maximum temperatures exceeding 40°C, high evaporation rates, and diurnal temperature differences around 16°C—conditions favorable for cotton growth that make it a high-yield cotton production region. The study farm implemented irrigation throughout the cotton growth period, using sprinkler irrigation initially followed by furrow irrigation every 2–3 weeks. Figures 1c and 1d show false-color images of Plot A on DOY 174 and DOY 190 in 2002, while Fig. 1e shows Plot B on DOY 174. Figures 1c/e reveal that irrigation proceeded from left to right and top to bottom, with clear differences between irrigated and non-irrigated areas. Figure 1d (DOY 190) shows no obvious irrigation differences, though the same area exhibited clear irrigation boundaries on DOY 174. DOY 190 was selected because irrigation was relatively uniform across the cotton plot at that time, providing contrast to DOY 174. The 16-day difference between DOY 174 and 190 corresponds to the temporal resolution of the Landsat TM/ETM+ imagery used in this study.

1.3 Vegetation Index Selection and Calculation

This study focused on remote sensing imagery during the cotton irrigation period. Based on characteristics of the U.S. cotton growth season, time series Landsat-5 TM and Landsat-7 ETM+ images from 2002 were downloaded for the study area, with a temporal resolution of 16 days and spatial resolution of 30 m. Image data were processed using ENVI 5.1 for radiometric calibration and atmospheric correction, then clipped according to the study area vector boundary.

NDVI is the most widely used vegetation index for growth monitoring. The Soil Adjusted Vegetation Index (SAVI) improves upon NDVI by reducing background soil information and enhancing vegetation signals. The Modified Soil Adjusted Vegetation Index (MSAVI) is the simplest among soil-adjusted vegetation indices, avoiding the need to obtain soil lines and soil adjustment parameters. NDWI utilizes near-infrared and shortwave infrared bands to study vegetation water content, and this study selected NDWI for irrigation information research. The vegetation index calculation formulas are as follows:

SAVI = NIR RED NIR RED NIR RED NIR RED 2NIR 1 (2NIR +1) 8(NIR RED) MSAVI = 时, 推荐 L 值为 0.25.

In the formulas, RED, NIR, and SWIR represent reflectance in the red, near-infrared, and shortwave infrared bands, respectively. L is the soil adjustment parameter describing soil reflection characteristics. When vegetation coverage is low, an L value of 1.0 is recommended; for medium coverage, 0.5; and for high coverage, 0.25.

1.4 Timing Selection for Cotton Irrigation Information Study

Canopy spectral reflectance and the degree of soil background influence are related to crop coverage (LAI), with greater coverage resulting in weaker soil background effects. This study focused on irrigation imagery during the crop growth period. Time series curve characteristic parameters (Fig. 2a [Figure 2: see original paper]) revealed that cotton NDVI increase rates accelerated from DOY 174, with NDVI values below 0.5. Based on the correlation between NDVI and LAI, DOY 174 was selected as the critical period for irrigation information study (June 23, 2002), as vegetation coverage was not yet high and soil background effects on NDVI remained pronounced.

1.5.1 Standard Deviation Method

Standard deviation reflects the dispersion degree of a dataset. The standard deviation under non-irrigated conditions reflects the normal dispersion of crop NDWI. This study used the standard deviation of NDWI for non-irrigated pixels (STDEVNDWI) as a staged threshold for irrigation information extraction. According to the formula STDEV, irrigation information was extracted based on NDWI+NDWI gradient NDVI, abbreviated as the STDWI method.

1.5.2 Irrigation Line Method

The irrigation line method, abbreviated as IR_L, was used for irrigation pixel extraction. Scatter plots between NDVI and NDWI (Fig. 3 [Figure 3: see original paper]) revealed clear boundaries between irrigated and non-irrigated pixels, defined as the irrigation line. As coverage increases (i.e., NDVI increases), the distance between trend lines for irrigated and non-irrigated pixels gradually decreases. The irrigation line equation slope uses the average of irrigation and non-irrigation trend line slopes, while the intercept uses the average of both line intercepts, thereby reducing the impact of weakened soil background information under high vegetation coverage.

NDWI +

In the formula, Kir and Knir represent the slopes of linear models between NDVI and NDWI under irrigated and non-irrigated conditions, respectively, while bir and bnir are the intercepts of scatter plots for irrigated and non-irrigated pixels.

1.5.3 Irrigation Correction Method

This study aimed to eliminate irrigation effects on NDVI by adjusting irrigated pixel NDVI values to non-irrigated status, making pre- and post-irrigation vegetation indices comparable. Based on this principle, a correction method was proposed using the slopes and intercepts of trend lines for irrigated and non-irrigated pixels as parameters, abbreviated as the IR_L method.

NDVI + (

In the formula: NDVIIR_L represents the adjusted non-irrigated cotton NDVI, NDVIIR is the NDVI after irrigation, Kir and Knir are the slopes of linear models between NDVI and NDWI under irrigated and non-irrigated conditions, respectively, and bir and bnir are the intercepts of the linear models for irrigated and non-irrigated pixels.

1.5.4 Accuracy Validation

Irrigation pixel extraction accuracy (α) was calculated using the following formula:) 100%

In the formula, Nt represents the number of actual irrigated pixels, and Nc represents the number of misclassified pixels incorrectly assigned to the non-irrigated class during extraction.

For NDVI correction accuracy validation, the principle of using Plot A for experimentation and Plot B for validation was adopted. Correction accuracy α was determined, and the dispersion degree of scatter plots after NDVI correction was compared.

Results

2.1 Comparative Analysis of Differences Between Irrigated and Non-Irrigated Pixels During Bare Soil and Growth Periods

Figures 4a and 4b show differences in band reflectance between irrigated and non-irrigated cotton pixels during the bare soil period (May 30, 2002) and the growth period with medium growth vigor, respectively. Figure 4c illustrates differences in four vegetation indices between irrigated and non-irrigated pixels (June 23, 2002). During the bare soil period, significant differences in band reflectance indicate that irrigation causes substantial soil background changes. During the growth period, band reflectance differences between irrigated and non-irrigated pixels remain significant, demonstrating that irrigation still affects canopy reflectance on DOY 174, causing obvious variations across bands. Among the four vegetation indices (Fig. 4c), all irrigated pixel values exceed non-irrigated values. NDWI shows minimal change, while NDVI changes by approximately 12%. The other three soil-adjusted vegetation indices exhibit even greater changes than NDVI, failing to fundamentally eliminate soil background effects and thus cannot reflect true vegetation growth conditions.

Crop growth monitoring primarily provides timely and accurate crop growth information for field management and early yield estimation. Remote sensing monitoring fully demonstrates the comprehensive, timely, and economical characteristics of remote sensing technology. In recent decades, many studies have used high spatiotemporal resolution remote sensing data to rapidly obtain large-scale crop growth information. However, in reality, sensors receive only partial signals from targets due to atmospheric and soil background influences, along with some noise, which consequently affects NDVI. Lower coverage results in greater soil background impact on NDVI. This study selected DOY 174, when NDVI values were below 0.5 and crops remained in the early growth stage. Based on the correlation between NDVI and LAI, soil background significantly affects NDVI under low coverage conditions. Therefore, this study analyzed soil background effects caused by irrigation during early crop growth and performed remote sensing extraction and correction of NDVI, which holds significance for crop growth monitoring and facilitates precision irrigation implementation.

2.2 Linear Regression Relationships Between NDWI and VIs for Irrigated and Non-Irrigated Cotton

Scatter plots of four VIs for irrigated and non-irrigated pixels (Fig. 4c [Figure 4: see original paper]) revealed minimal NDWI variation, indicating limited irrigation impact. Therefore, NDWI was used as the independent variable to analyze quantitative relationships with three VIs (Fig. 5 [Figure 5: see original paper]). Figures 5a and 5b show that NDVI and MSAVI values differ between irrigated and non-irrigated conditions, with irrigated cotton pixel values significantly higher (by over 10%). All three VIs exhibited extremely significant linear relationships with NDWI for both irrigated and non-irrigated cotton plots. Linear regression models are presented in Table 1 . For both Plots A and B, the three VIs showed extremely significant correlations with NDWI, with Plot A achieving higher determination coefficients (above 0.93) and Plot B reaching 0.90. These results demonstrate that irrigation causes substantial vegetation index changes, with maximum differences reaching 12.26%. Therefore, ensuring NDVI accuracy is crucial for precision crop growth monitoring.

2.3 Irrigation Pixel Extraction and Accuracy Assessment Based on STDWI and IR_L Methods

Irrigation pixel extraction was performed on Plot A using both IR_L (irrigation line) and STDWI (standard deviation) methods, with extraction accuracies shown in Table 2 . The IR_L method achieved 94.72% accuracy, proving more suitable for irrigation information extraction than the STDWI method. Plot A was used for experimentation and Plot B for validation. Applying the IR_L method to Plot B confirmed its applicability, with accuracy reaching 88.41%.

2.4 Remote Sensing Correction of Cotton Irrigation Information During Early Growth Stage

Figure 6 [Figure 6: see original paper] shows the scatter plot of NDWI versus corrected NDVI for Plot A. Compared with the uncorrected NDWI-NDVI scatter plot (Fig. 5a), the corrected NDVI shows significantly reduced differences. Post-correction NDVI differences decreased from 12% to 2%, with scatter plot trends becoming consistent across the entire plot.

Discussion

This study analyzed differences in vegetation indices and band reflectance between irrigated and non-irrigated cotton pixels during early growth stages in California. Using the extremely significant linear relationship between NDVI and NDWI for irrigated and non-irrigated pixels, two irrigation extraction methods were constructed, enabling rapid and accurate extraction of irrigated cotton pixels during early growth stages with accuracy exceeding 88%. The irrigation line model effectively corrected NDVI values for irrigated pixels, successfully removing soil moisture effects on NDVI.

The results address the problem of irrigation-induced NDVI overestimation, reflecting true vegetation information and enabling accurate remote sensing monitoring of early-stage crop growth. The findings provide valuable references for NDVI application under low coverage conditions and promote quantitative remote sensing monitoring and precision agriculture development. By comparing NDVI, NDWI, SAVI, and MSAVI differences before and after irrigation, this study demonstrated that NDWI shows minimal variation while soil-adjusted vegetation indices cannot completely eliminate soil background effects. Most soil-adjusted vegetation indices are linear models based on soil line calculations, yet soil lines are difficult to obtain in practice. This study used the linear relationship between minimally varying NDWI and NDVI to correct post-irrigation NDVI, partially eliminating soil background effects under low coverage and reducing irrigation-induced soil moisture impacts. This facilitates quantitative remote sensing monitoring, enables more accurate crop growth prediction, promotes precision irrigation, conserves water resources, and supports sustainable agriculture.

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Note: Figure translations are in progress. See original paper for figures.