ANALYSIS OF TOPOGRAPHIC EFFECTS ON VEGETATION INDICES

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ABSTRACT

In the field of remote sensing, vegetation indices (VIs) have been wieldy used in vegetation monitoring such as the growth status and fractional vegetation cover. However, topographic influence on VIs is an important and inevitable issue when VIs are applied in the large scale. In this study, theoretical error analysis of topographic effects is applied to various VIs. This error analysis suggests that ratio indices (e.g., NDVI, NDPI, NDWI) are more resistant to the topographic effects than the non-ratio indices (e.g., EVI). Also, single-slope experiments are designed by changing local slope and local incident angle with 3D radiative transfer model to simulate the topographic effects on VIs. Results of simulation experiments can verify the error analysis.

***Index Terms*—** vegetation indices, topographic effects, 3D radiative transfer model

1. INTRODUCTION

As a key indicator, vegetation indices can measure the vegetation biophysical parameters for qualitative and quantitative assessment of vegetation. The Normalized Difference Vegetation Index (NDVI) from remote sensors is the commonly used as an indicator of vegetation growth [1] and is calculated as

$$NDVI = \frac{N-R}{N+R} \quad (1)$$

where *N* and *R* are the reflectance of the near infrared (NIR) and red band, respectively. As one of the most popular vegetation indices, NDVI has been used in many applications [2]. And the Enhanced Vegetation index was proposed based on NDVI to adjust the background and be resistant to atmospheric [3], which can be written as

$$EVI = G\frac{N-R}{N+C_1R-C_2B+L}$$

where *B* represents the reflectance of blue band; *L* is a soil adjustment factor, and C_1 and C_2 are coefficients to correct aerosol scattering. Generally, G =2.5, C_1=6.0, C_2=7.5, and *L*=1.

Due to the saturation of NDVI in high leaf area index (LAI), which might be a limitation in estimating vegetation water content (VWC), the Normalized Difference Water Index (NDWI) includes the shortwave-infrared band sensitive to VWC [4], and is expressed as

$$NDWI = \frac{N-SWIR}{N+SWIR} \quad (3)$$

where *SWIR* is the reflectance of shortwave-infrared band. By combining NDVI and NDWI, [5] proposed the Normalized Difference Phenology Index (NDPI) to contrast vegetation from the background (soil and snow) for monitoring the vegetation spring green-up date, which is written as

$$NDPI = \frac{N-(\alpha R+(1-\alpha)SWIR)}{N+(\alpha R+(1-\alpha)SWIR)} \quad (4)$$

where α is a coefficient, recommended to be set to 0.74.

Although these VIs were designed for specific purpose, they are all affected by topography. [6] showed that non-ratio vegetation indices are more sensitive to topography effects than ratio vegetation. However, there is not a quantitative analysis about topographic effects on VIs which will be helpful for understanding the response of different vegetation indices to topographic changes.

In this study, error analysis is used to prove that band ratio indices, such as NDVI, NDWI and NDPI, can reduce topographic effects to some extent. Furthermore, with 3D radiative transfer model (LESS: LargE-Sclae remote sensing data and image simulation framework) [7], various realistic forest scenes with terrain can be simulated for assessment of topographic effects on different VIs. And the simulated experiments also support the theoretical error analysis.

2. METHOD

The main causes of the topographic effects are as follows: (1) The difference in local incidence angle of the light by the slope, aspect, the solar zenith angle and the solar azimuth angle (Fig. 1(a)): The local incident angle i is an important terrain perturbation, which can be written as

$$cosi = cos\theta_s cos\theta + sin\theta_s sin\theta cos(\varphi_s - A) \quad (5)$$

where θ_s and φ_s are the solar zenith angle and the solar azimuth angle, respectively; θ and A are the slope and aspect of an inclined pixel, respectively. (2) The local geometric relationship between trees and terrain (Fig. 1(b)): The undulations of the terrain and the erect growth of the trees cause changes in the local geometry of the trees and terrain. (3) Shadows caused by mutual occlusion between mountains (Fig. 1(c)): It includes the self-shadow formed by its own steep slope and the projected shadow formed by the adjacent mountain occlusion. (4) The diffuse scattering of the sky is reduced (Fig. 1(d)): Due to the existence of the slope, the ground object receives diffuse scattered light from the sky from the original A+B+C to A. (5) Reflection contribution from surrounding features (Fig. 1(e)): Q point will receive a reflection contribution from the surrounding objects P1 and P2.

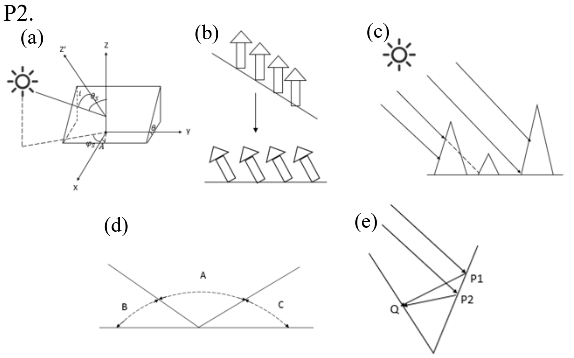

Fig. 1 Main causes of the topographic effects

Among the main causes for the five topographic effects, the first two belong to the single slope model, which is the focus of this paper. The remaining three belong to the multi-slope model, which is not considered in this paper.

The topographic effects on vegetation index (NDVI) can be converted into the various bands that make up NDVI, which can be expressed as

$$NDVI_T = \frac{N+\Delta N-R-\Delta R}{N+\Delta N+R+\Delta R} \quad (6)$$

where $NDVI_T$ is NDVI affected by topography; ΔN and ΔR are the increments of N and R in the terrain compared to the plane, respectively. Based on first-order Taylor expansion, the expression (6) can be written as

$$NDVI_T = NDVI_P + \frac{2R\Delta N-2N\Delta R}{(N+R)^2} \quad (7)$$

where $NDVI_P$ is NDVI without topography. So the topographic effects on NDVI can be written as

$$\Delta NDVI = \frac{2R\Delta N-2N\Delta R}{(N+R)^2} \quad (8)$$

Also, topographic effects on other VIs can be written as

$$\Delta NDWI = \frac{2R\Delta S-2S\Delta R}{(S+R)^2} + \frac{-2R\Delta S^2+2S\Delta R^2+2(S-R)\Delta S\Delta R}{(S+R)^3} \quad (9)$$

$$\Delta NDPI = \frac{2(\alpha R+(1-\alpha)S)\Delta N-2\alpha N\Delta R-2(1-\alpha)N\Delta S}{(N+\alpha R+(1-\alpha)S)^2} \quad (10)$$

$$\Delta EVI = G\frac{((C_1+1)R-C_2B+L)\Delta N-((1+C_1)N+C_2B-L)\Delta R+C_2\Delta B}{(N+C_1R-C_2B+L)^2} \quad (11)$$

From equation (8-11), the topographic effects on different vegetation indices can be derived. Generally, the topographic effects on VIs depend on reflectance value and its increment affected by topography in each band. Moreover, due to their design, the topographic effects on non-ratio VIs may be also depending on some constants.

For further analysis, Lambertian hypothesis is introduced and the radiance from an inclined surface (L_T) can be written as [8]

$$L_T = \beta L_P \quad (12)$$

where L_P is the radiance from a plane; β is the coefficient which is independent of wavelength and only depends on $cosi$. And the increments of any wavelength reflectance will be equal to each other under the same topography, which is expressed as

$$\Delta B = (1-\beta)B \quad (13)$$

$$\Delta R = (1-\beta)R \quad (14)$$

$$\Delta N = (1-\beta)N \quad (15)$$

$$\Delta S = (1-\beta)S \quad (16)$$

Therefore, the topographic effects on ratio indices (NDVI, NDWI, NDPI) can be derived as

$$\Delta NDVI = \Delta NDWI = \Delta NDPI = 0 \quad (17)$$

And the topographic effects on non-ratio index (EVI) can be derived as

$$\Delta EVI = G(1-\beta)\frac{(L-C_2B)(N+R)+C_2B}{(N+C_1R-C_2B+L)^2} \neq 0 \quad (18)$$

Obviously, topographic effects on ratio indices can be reduced well. In contrast, non-ratio indices, such as EVI, will be affected by topography.

3. SIMULATION EXPERIMENTS

To support the theoretical analysis, simulation experiments with 30 m × 30 m scenes are constructed by LESS. The sensor type is set to the orthographic. View zenith and view Azimuth are set to 0° and 180°, respectively. In this study, these settings of sensor are fixed for simplicity. Four bands (blue, green, red and NIR) are simulated for calculating different vegetation indices. What needs to be mentioned is that the atmosphere is not considered in this study. In each experiment, same spectrum (leaf, trunk and soil) for the object are used, which is showed in Fig. 2.

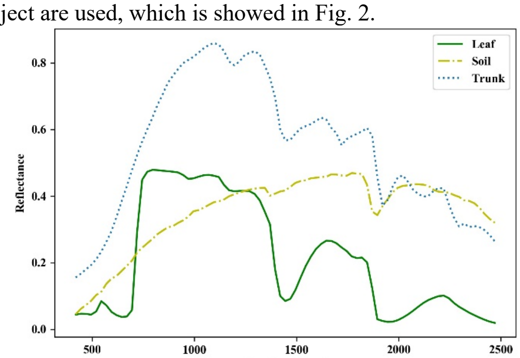

Fig. 2 Spectrum in simulation

The 3D trees in the simulation can be constructed by importing 3D objects (branches and leaves). For simplicity, the trees are the same size in the scenes and the soil is set to Lambert. And the example of 3D scenes with trees in the plane are showed in Fig. 3.

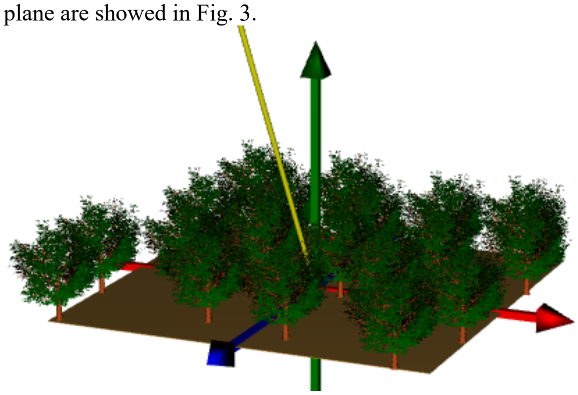

Fig. 3 The 3D scenes with trees in the plane simulated by LESS: The yellow line is the sun ray; The colorful arrows are the axes.

In order to exploring different cause of topographic effects, various scenes with random distribution of trees (LAI of whole scene is set to 3.199) in the terrain. First, an ideal condition that is not affected by topography need to be the reference. Then incident angle of sun ray is controlled by changing the solar zenith angle and solar azimuth angle for simulating different incident angle. At last, slope of terrain is changed for simulating different local geometric.

The single-slope model design of simulated experiments and the corresponding parameters are showed in Fig. 4 and Table 1, respectively.

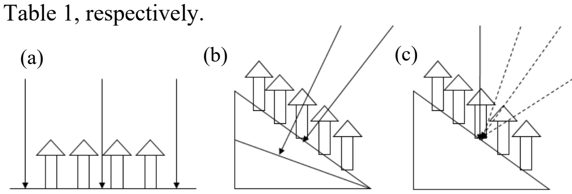

Fig. 4 Design of simulated experiments. (a) Ideal condition: no topographic effects. (b) Incident angle: change the solar zenith. (c) Local geometric: change the slope of terrain.

Table 1. Parameters in simulated experiments

Parameter	Incident angle	Local geometric
Solar zenith angle(°)	Vertical to slope	[0,50], step=5
Solar azimuth angle(°)	Vertical to slope	-90,0,90
Slope of terrain(°)	[5,40], step=5	20

For comparing with the ideal condition which is not affected by the topography, the evaluation of topographic effects on VIs (Modified standard deviation: MSTD) is expressed as

$$MSTD = \sqrt{\frac{\sum_{i=1}^{n}(v_i - v_p)^2}{n-1}} \quad (19)$$

where v_i is the value of VIs in incident angle experiment (Fig. 4(b)) or local geometric experiments (Fig. 4(c)). v_p is the value of VIs in ideal condition (Fig. 4(a)). Fig. 5 shows the results of simulated experiments.

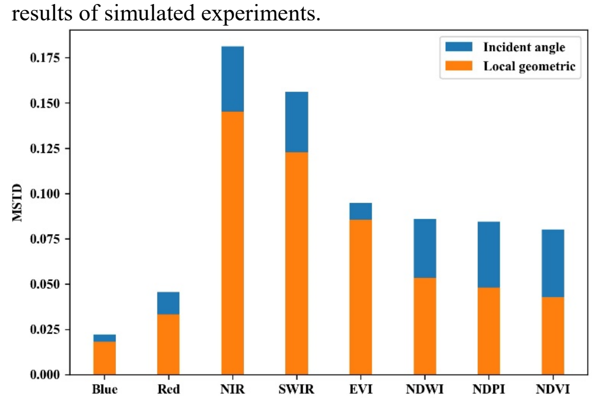

Fig. 5 The results of simulated experiments.

From the results above, NIR band and SWIR band are more sensitive to topography than blue band and red band. And the ratio indices can reduce topographic effects in the local geometric experiments better than in the incident angle experiments. Moreover, NDWI is more sensitive to topography than NDVI, because of introducing the SWIR band. And the sensitivity of topography for NDPI is between the NDVI and NDWI, owing to its design. The non-ratio index, EVI, is affected by topography obviously in two experiments, which support the theoretical analysis.

4. DISCUSSION AND CONCLUSION

This paper provides the theoretical analysis about the topographic effects on various VIs under the assumption that the surface is Lambertian, and simulated experiments by 3D radiative transfer model also verify that the ratio indices (NDVI, NDWI, NDPI) can reduce topographic effects to some extent. EVI was designed to adjust background and correct aerosol scattering, but it lost ratio form to reduce topographic effects.

In the future work, we need to abandon the Lambertian assumption, because it's not appropriate in many cases for high spatial resolution remote sensing data. The analysis based on the non-Lambertian surface will be more quantitative for the evaluation of topographic effects on VIs. And it's necessary to simulate scenes in the large scale with LESS for the analysis of topographic effects by multi-slope. Moreover, the satellite data will be used to support the study in the future.

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