Article

TOPOGRAPHIC EFFECT ON SPECTRAL VEGETATION INDICES FROM LANDSAT TM DATA: IS TOPOGRAPHIC CORRECTION NECESSARY?

Efeito topográfico sobre índices de vegetação obtidos com dados Landsat TM: é necessário correção topográfica?

Eder Paulo Moreira*

Márcio de Morisson Valeriano

Ieda Del Arco Sanches

Antonio Roberto Formaggio

Instituto Nacional de Pesquisas Espaciais – INPE, Av. dos Astronautas, 1758, Jardim da Granja, CEP 12227-010, São José dos Campos – SP, Brasil. E-mails: eder@dsr.inpe.br;valerian@dsr.inpe.br;ieda@dsr.inpe.br;formag@dsr.inpe.br

*Corresponding Author: Eder Paulo Moreira; Cell Phone: (12) 982425118.

Abstract:

The full potentiality of spectral vegetation indices (VIs) can only be evaluated after removing topographic, atmospheric and soil background effects from radiometric data. Concerning the former effect, the topographic effect was barely investigated in the context of VIs, despite the current availability correction methods and Digital elevation Model (DEM). In this study, we performed topographic correction on Landsat 5 TM spectral bands and evaluated the topographic effect on four VIs: NDVI, RVI, EVI and SAVI. The evaluation was based on analyses of mean and standard deviation of VIs and TM band 4 (near-infrared), and on linear regression analyses between these variables and the cosine of the solar incidence angle on terrain surface (*cos i*). The results indicated that VIs are less sensitive to topographic effect than the uncorrected spectral band. Among VIs, NDVI and RVI were less sensitive to topographic effect than EVI and SAVI. All VIs showed to be fully independent of topographic effect only after correction. It can be concluded that the topographic correction is required for a consistent reduction of the topographic effect on the VIs from rugged terrain.

Keywords: radiometric effect; land cover; Digital Elevation Model; NDVI; SRTM.

Resumo:

Os índices de vegetação (IVs) possuem limitações tais como a influência da atmosfera, do solo subjacente e do relevo (efeito topográfico). Em relação ao efeito topográfico, sua correção foi pouco investigada no contexto dos IVs, apesar da atual disponibilidade de técnicas e de Modelos Digitais de Elevação (MDE) para sua correção. Neste estudo, foi realizada a correção topográfica de bandas espectrais do Landsat 5 TM utilizando dados MDE-SRTM e avaliada a influência do efeito topográfico em quatro IVs: NDVI, RVI, EVI e SAVI. A avaliação foi baseada nos valores de média e desvio padrão dos IVs e da banda 4 (infra-vermelho próximo), e com a análise de regressão linear entre estas variáveis e o cosseno do ângulo de incidência solar na superfície. Os resultados indicam que o efeito topográfico é menor nos IVs, em comparação com a banda 4. O NDVI e o RVI foram menos sensíveis ao efeito topográfico que o EVI e o SAVI. Porém, somente após a correção topográfica é que todos IVs mostraram-se independentes do efeito topográfico. Conclui-se que é necessária a correção topográfica para uma consistente redução do efeito topográfico nos IVs de áreas com topografia irregular.

Keywords**:** dados radiométricos; cobertura da terra; Modelo Digital de Elevação; NDVI; SRTM.

1. Introduction

Remote sensing data have become an important source of information for studying vegetation on regional, continental and global scale. Vegetation indices (VIs) calculated from remote sensing data are widely used to either estimate biophysical attributes such as biomass, leaf area index (LAI) and the photosynthetic activity (Lehmann et al., 2012; Dube and Mutanga, 2015) or for monitoring and mapping land cover and land cover change (Kolios and Stylios, 2013; Sexton et al., 2013). Most VIs are based on the red and near infrared spectral information, since green vegetation usually decreases the spectral response in the red due to chlorophyll absorption and increases the spectral response in the near infrared.

However, in rugged mountainous areas the use of remote sensing data can be limited by the topographic effect (Horn, 1981). The topographic (or illumination) effect consists in variations of radiance levels of spectral data caused by differences in surface slope angle and aspect of the terrain, in combination with solar zenith and azimuth angles (Holben and Justice, 1980). Consequently, a certain land cover/use type may not have the same spectral response at different topographic positions (Figure 1). The topographic effect is responsible for a large part of the spectral variation of the land cover in rugged terrain (Civco, 1989; Hantson and Chuvieco, 2011).

It is assumed that topographic effect is considerably reduced in band ratio compared to single spectral bands (Holben and Justice, 1981). Based on this rationale, most studies consider that band ratio VIs (for example, the Normalized Difference Vegetation Index - NDVI) can overcome topographic effects on radiometric levels (Lee and Kaufman, 1986; Ekstrand, 1996; Huete at al., 1999). However, some studies showed that topography significantly affects VIs in rugged mountainous area (Verbyla et al., 2008; Veraverbeke et al., 2010; Wang et al., 2012). For example, Deng et al. (2007) observed that the NDVI and the Normalized Difference Infrared Index (NDII) showed a significant correlation (r^2) ($p = 0.001$) with topography variables such as slope and the cosine of the aspect.

In order to correct topographic effect, a range of methods have been developed (Smith et al., 1980; Teillet et al., 1982; Shepherd and Dymond, 2003; Kobayashi and Sanga-Ngoie, 2009). The methods are based on the cosine of the solar incidence angle on the surface (*cos i*) (Sellers, 1965). The *cos i* is a factor related the the solar illumination at each pixel of the scene. Low values of *cos i* indicate pixels under low illumination and high *cos i* are well-illuminated pixels (Dubayah and Rich, 1995).

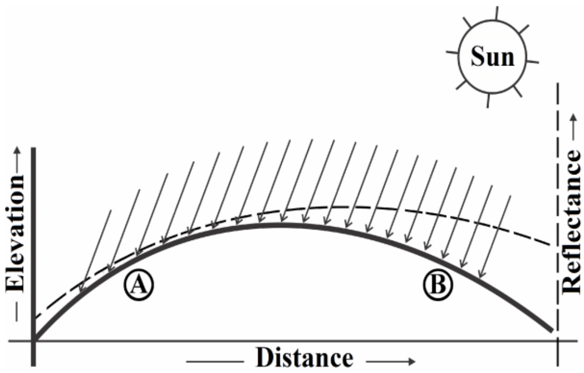

Figure 1: A schematic diagram illustrating the variation of reflectance on Landsat spectral data as function of topography and illumination effects. A: Slope facing away from the sun (weakly illuminated area); B: Slope facing to the sun (well-illuminated area). Source: Modified from Moreira (2014).

The influence of topographic effect on VIs and the correction performance varies according to the applied vegetation index, spectral and topographic data, study area, methodology of correction, among other factors (Teillet et al., 1997; Vanonckelen et al., 2013). Despite the broad availability of Digital Elevation Models (DEM) data and the development of correction methods, there are still few studies about topographic effects on VIs addressing topographic correction (Matsushita et al., 2007). Thus, the objective of this study was to assess the topographic effect on four widely used VIs, through the examination of uncorrected and topography-corrected Landsat 5 TM data: the NDVI (Rouse et al., 1974), the Ratio Vegetation Index (RVI) (Pearson and Miller, 1972), the Enhanced Vegetation Index (EVI) (Liu and Huete, 1995) and the Soil Adjusted Vegetation Index (SAVI) (Huete, 1988).

2. MATERIAL AND METHODS

2.1 Study area and processing resources

The study site is an agricultural region of Brazil in the south of Minas Gerais State, with undulating relief type, with varied conditions of illumination and land cover types (Figure 2). It is an area of 11,5 per 11,5 km located in the municipalities of Alfenas and Machado and it is covered predominantly by agriculture, and sparse patches of forest fragments from the Atlantic Forest biome. The main crops in the region are coffee, corn and beans (IBGE, 2013).

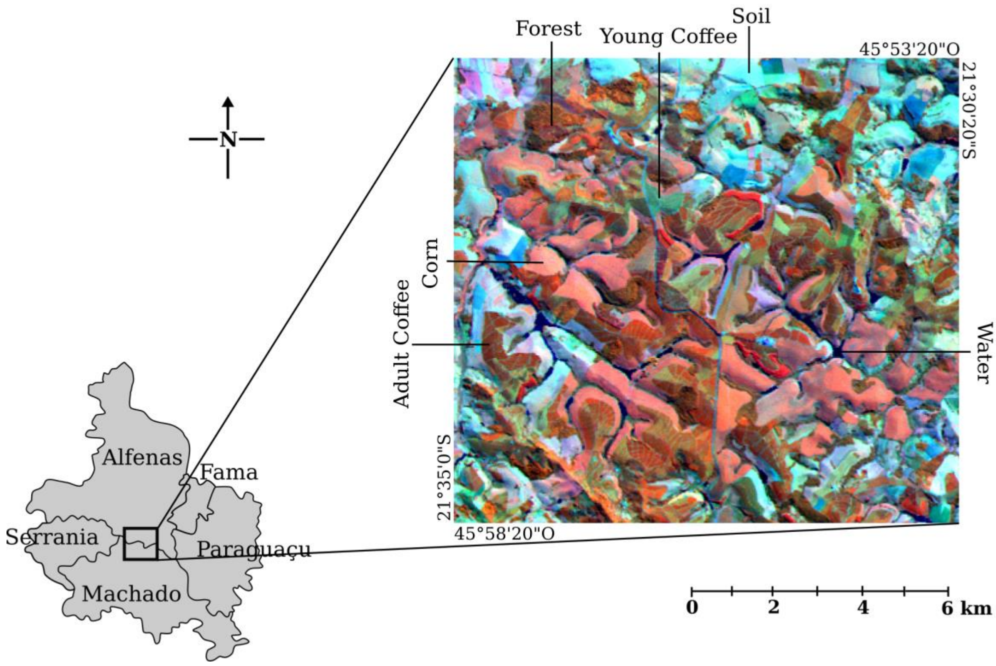

Figure 2: Location of the test site in south of Minas Gerais State, Brazil. Landsat 5 TM 453 (RGB) composition with the identification of the land cover types.

According to the used topographic data, the slope average is 7.5° with a maximum of 35° and altitude ranges from 765 to 1030 meters. Figure 3 presents the momentary variation among pixel values of *cos i* at the time of the optical image acquisition and the occurring values of slope and aspect within the test site. These plots show a continuous and relatively homogeneous distribution of the variables, without significant gaps that could disturb result analysis due to poly-modal effects. Slope values were concentrated below 15°, in an indication of a relatively gentle terrain (Figure 3-b). Indeed, there was no negative value of *cos i* in the area, what would indicate pixels with no direct solar illumination due to extreme shadowing (Figure 3-c).

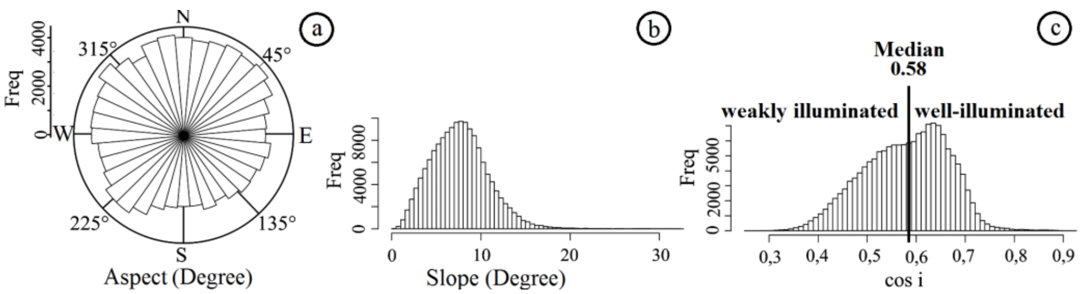

Figure 3: Aspect (a), slope (b) and *cos i* (c) distributions for the test site. The *cos i* was calculated considering parameters of the solar geometry at the local and time of the Landsat image acquisition: solar zenith angle equal to 54.32°; and solar azimuth angle equal to 37.01°(NE).

The spectral bands 1 (450-520 nm), 3 (630-690 nm) e 4 (760-900 nm) of Landsat 5 TM, scene 219/75 (path/row), obtained from INPE's image catalog (http://www.dgi.inpe.br/CDSR) were used in this study. The date of the Landsat image was June 8, 2011, acquired with solar zenith angle of 54.32° and solar azimuth angle of 37.01° (NE). Aspect and slope layers (Figure 3 a and b) corresponding to study site were downloaded from Topodata Project, available on the website www.dsr.inpe.br/topodata (Valeriano and Rossetti, 2012). High-resolution image from Google Earth, acquired in 2011, were consulted for verification of land cover in the control sample positions. All processing steps were performed using the R programming language, version 3.0 (R, 2013).

2.2 Methodology

Figure 4 shows the data flow and the processes of this research. As an initial phase of processing, we performed the registration and preparation of the data in the geographic coordinate system (non-projected), with WGS 1984 as geodetic datum. The original data were already georeferenced and, to maximize co-registration, a simple displacement of the spectral data based on distinctive corner points with sharp contrast to their surroundings observed on all datasets was necessary to match spectral and topographic data. The notable features in both sources were drainage junctions, which were promptly contrasting in optical images. For topographic data, the sharp positioning of the drainage features required the use of second-derivative thalweg delineation (based on plan curvature), also available among Topodata products (Valeriano et al., 2006). In order to align pixels between data, the pixel positions were structured with the nearest neighbour resampling method.

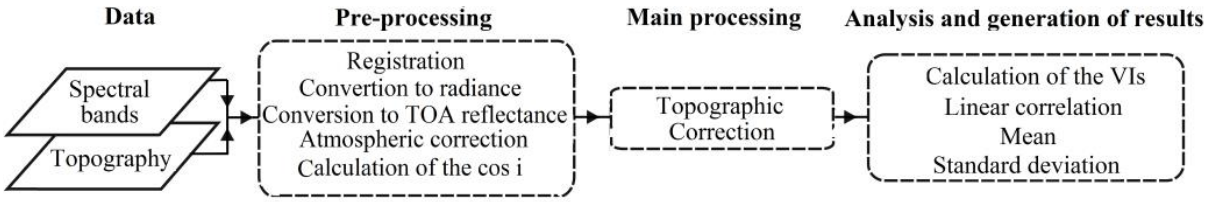

Figure 4: Data flow and processes performed in this research.

According to the methodology described by Chander et al. (2009) the digital numbers of the image were converted to radiance and then to top of atmosphere (TOA) reflectance. Atmospheric correction was performed using the DOS (Dark Object Subtraction) technique proposed by Chavez (1988) based on the analysis of histogram frequency of the spectral bands. Subsequently, we calculated the cosine of the solar incidence angle on surface (cos i), which was used for the correction of topographic effect.
Based on a previous study (Moreira and Valeriano, 2014) the c-correction method proposed by Teillet et al. (1982) was chosen to be applied in this study:

$$\rho_{c\lambda ij} = \rho_{\lambda ij}\left(\frac{\cos\theta_s + c_\lambda}{\cos i + c_\lambda}\right) \quad (1)$$

$$c_\lambda = \frac{b_\lambda}{m_\lambda} \quad (2)$$

Where, $\rho_{c\lambda ij}$ is the corrected reflectance of band λ and pixel ij, $\rho_{\lambda ij}$ is the uncorrected reflectance, b_λ and m_λ are parameters from the linear regression represented by the equation:

$$\rho_{\lambda ij} = b_\lambda + m_\lambda \cos i \quad (3)$$

The estimation of c_λ parameter was based on samples and calculated for each land cover class. The classes used in this study were the predominant in the study area, which were coffee, corn, forest and soil. Figure 5 shows the distribution of slope values, aspect and *cos i* for the samples. Land cover samples were distributed in a wide range of slope, aspect and *cos i*, what is important for the estimation of c_λ parameter (Reese and Olsson, 2011) and for the correction evaluation.
Samples of land cover were classified by illumination (cos i) classes, where *cos i* higher than 0.58 (median of *cos i*) are well-illuminated samples and *cos i* equal or lower than 0.58 are weakly illuminated. The criterion to define weakly or well-illuminated pixels is illustrated in Figure 3 (c). This classification was carried out only to evaluate the differences in the VIs between these two illumination classes.

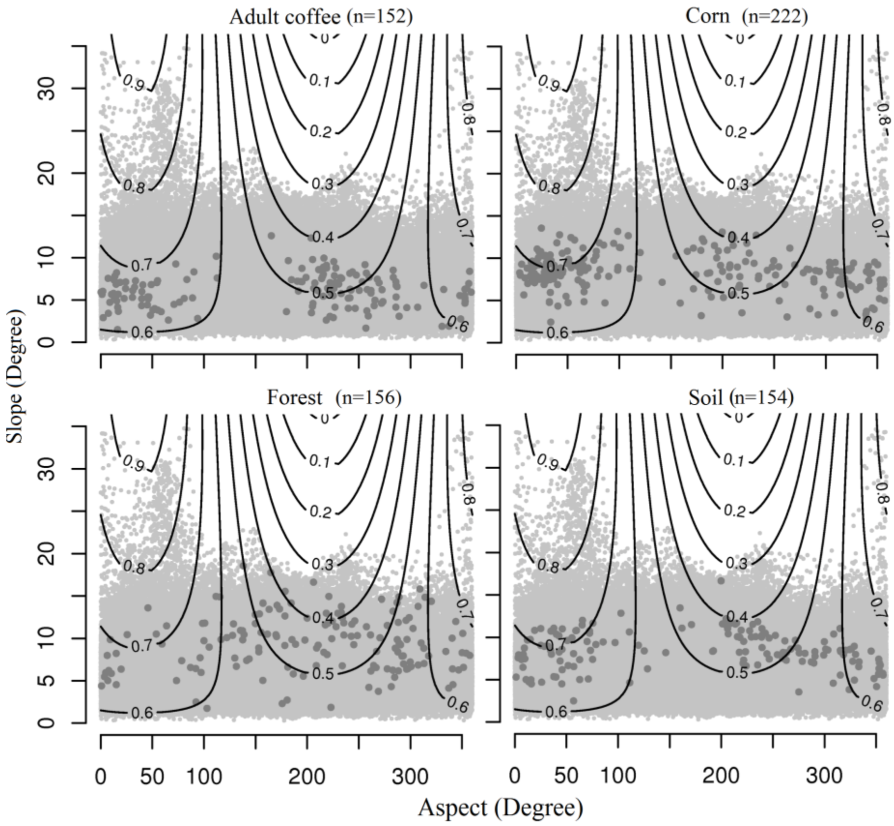

Figure 5: Sample distribution (dark grey points) of the land cover types in relation to slope, aspect and *cos i* (isoline). The points in light grey represent values of the whole test site.

The four different VI formulations tested in this study were chosen regarding mostly the wideness of their use in different applications, but simple ratio was included because of the fundamental simplicity, which would theoretically result in variations free from *cos i* effects. The VIs were calculated according to the equations shown in Table 1. To determine the influence of topography on the VIs, some statistics were computed. Firstly, the coefficient of determination (r^2) of the linear regression between VIs and *cos i* was calculated and evaluated. The radiometric levels of the spectral bands tend to vary together with the incident flux density, resulting in a correlation with *cos i*, which is the fundamental mechanism of topographic effect. Topographic correction techniques are developed to remove this effect, thus topography-corrected VIs should have lower correlation (r^2) to *cos i* than uncorrected VIs (Meyer et al., 1993; Mcdonald et al., 2000).

Standard deviation (SD) was also used in this study to evaluate the topographic effect on VIs, before and after correction. SD of radiometric levels theoretically decreases after correction, since the topographic effect, which increases radiometric variations, is removed or minimized (Hantson and Chuvieco, 2011). Finally, the means of VIs of pixels located in weakly illuminated areas and well-illuminated areas were compared. These means are expected to exhibit a statistical difference when calculated from original images, which should be significantly reduced or removed after topographic correction. The t-test was performed to verify whether the two means (from weakly illuminated versus well-illuminated pixels) are statistically different.
All evaluations were performed for each vegetation index calculated for each land cover classes. In order to compare single band reflectance with VIs, band 4 also was included in all analyses. It is expected that VIs levels are less sensitive to topographic effect than single band reflectance.

Table 1: Vegetation index analyzed in this study

Vegetation index	Reference
$\mathrm{RVI} = \frac{\mathrm{NIR}}{\mathrm{Red}}$	Pearson and Miller (1972)
$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}}$	Rouse et al. (1974)
$\mathrm{SAVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red} + \mathrm{L}}\,(1 + L)$	Huete (1988)
$\mathrm{EVI} = \mathrm{G}\frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{L_2} + \mathrm{NIR} + \mathrm{c_1.RED} - \mathrm{c_2.Blue}}$	Liu and Huete (1995)

Where, NIR, Red and Blue are near-infrared, red and blue reflectance, respectively; $L = 0,5$; $L_2 = 1$; $G = 2,5$; $c_1 = 6$; and $c_2 = 7,5$. In this study, NIR, Red and Blue spectral regions correspond to band 4 (760-900 nm), band 3 (630-690 nm) and band 1 (450-520 nm) reflectance from Landsat 5 TM, respectively.

3. RESULTS AND DISCUSSION

For the topography-uncorrected data, band 4 reflectance showed the highest correlation with *cos i* (Figure 6), wherein 58%, 54%, 45% and 35% of the band variations are expressed by the topographic effect (*cos i*) for the land cover classes corn, coffee, forest and soil, respectively. These correlations for Landsat TM band 4 are larger than those obtained by Veraverbeke et al. (2010), which were 2 and 14% for burned areas of two dates, but comparable to the 41% in forested area observed by Meyer et al. (1993). The comparison of r^2 coefficients between VIs and band 4 indicates that VIs is less sensitive to topographic effect than band 4. SAVI and EVI showed larger r^2 than NDVI and RVI for the studied land covers. Considering the forest cover, r^2 between *cos i* and band 4, RVI, NDVI, SAVI and EVI were 45, 22, 22, 41 and 40%, respectively. In this case, SAVI and EVI respond to topographic effect similarly to band 4, what was not very different from other vegetation classes. A noticeable contrast occurred in results from soil areas, where the topographic effect was not apparent in VIs (Figure 6).

Corn

	cos i	B4	C4	RVI	NDVI	SAVI	EVI	RVIc	NDVIc	SAVIc
B4	0.58									
C4	0	0.43								
RVI	0.14	0.51	0.45							
NDVI	0.14	0.52	0.45	0.99						
SAVI	0.48	0.94	0.49	0.73	0.74					
EVI	0.36	0.83	0.50	0.81	0.81	0.94				
RVIc	0	0.23	0.51	0.87	0.86	0.43	0.54			
NDVIc	0	0.22	0.51	0.86	0.86	0.42	0.54	0.99		
SAVIc	0	0.39	0.91	0.70	0.70	0.54	0.60	0.80	0.80	
EVIc	0	0.34	0.77	0.73	0.72	0.49	0.65	0.83	0.83	0.92

Soil

	cos i	B4	C4	RVI	NDVI	SAVI	EVI	RVIc	NDVIc	SAVIc
B4	0.35									
C4	0	0.64								
RVI	0.01	0.14	0.31							
NDVI	0	0.16	0.31	0.98						
SAVI	0.04	0.47	0.52	0.85	0.88					
EVI	0.02	0.37	0.46	0.91	0.92	0.98				
RVIc	0	0.18	0.31	0.99	0.98	0.88	0.93			
NDVIc	0	0.19	0.32	0.97	1	0.90	0.94	0.98		
SAVIc	0	0.34	0.55	0.92	0.94	0.96	0.96	0.93	0.94	
EVIc	0	0.28	0.48	0.95	0.95	0.94	0.98	0.95	0.96	0.98

Adult Coffee

	cos i	B4	C4	RVI	NDVI	SAVI	EVI	RVIc	NDVIc	SAVIc
B4	0.54									
C4	0	0.46								
RVI	0.16	0.44	0.30							
NDVI	0.15	0.42	0.29	0.98						
SAVI	0.44	0.90	0.46	0.74	0.73					
EVI	0.37	0.78	0.41	0.78	0.77	0.93				
RVIc	0	0.17	0.35	0.85	0.84	0.43	0.50			
NDVIc	0	0.15	0.34	0.82	0.84	0.41	0.48	0.99		
SAVIc	0	0.38	0.83	0.63	0.63	0.55	0.55	0.75	0.74	
EVIc	0	0.30	0.65	0.65	0.65	0.49	0.63	0.78	0.77	0.89

Forest

	cos i	B4	C4	RVI	NDVI	SAVI	EVI	RVIc	NDVIc	SAVIc
B4	0.45									
C4	0	0.54								
RVI	0.22	0.65	0.45							
NDVI	0.22	0.62	0.42	0.97						
SAVI	0.41	0.95	0.55	0.82	0.81					
EVI	0.40	0.89	0.50	0.84	0.82	0.96				
RVIc	0	0.29	0.57	0.76	0.75	0.46	0.48			
NDVIc	0	0.30	0.55	0.77	0.77	0.47	0.49	0.98		
SAVIc	0	0.50	0.93	0.62	0.61	0.59	0.56	0.80	0.79	
EVIc	0	0.44	0.82	0.64	0.62	0.54	0.60	0.82	0.81	0.93

Figure 6: Coefficient of determination (r^2) of the linear regression between the studied variables for each land cover class. Where, *cos i* is the cosine of solar incident angle, B4 is the uncorrected band 4, c (subscript) indicates that data has topographic correction.

The NDVI is highly correlated with the RVI (high r2) and moderately correlated to band 4, thus we assume that NDVI behave as band ratios, which would be the less sensitive formulation to topographic effect (Holben and Justice, 1981). As opposed, SAVI and EVI are moderately correlated to RVI and highly correlated to band 4, that is more sensitivity to topographic effect. According to Matsushita et al. (2007) EVI does not behave like the RVI because of soil adjustment factor "L". The authors concluded that it is the soil adjustment factor in the EVI that makes it much more sensitive to the topographic effect than NDVI.

After applying the topographic correction on the spectral data, the band 4 and all the VIs showed no topographic effect, according to the values of r^2 between corrected data and *cos i*, which is zero for all land cover classes (Figure 6). A comparison of the standard deviation of band 4 and VIs between the results of data analyzed before and after the topographic correction (Figure 7) leads to similar conclusions of those obtained from the r^2 evaluation. In general, the standard deviation decreased after correction. Minor differences between the standard deviation before and after topographic correction were observed for the NDVI and RVI, what was expected due to their lower sensitivity to the topographic effect, as previously discussed. The average levels of band 4 and VIs were similar when comparing values before and after correction (Figure 7). This was already expected because the VI values from well-illuminated areas (high *cos i*) decrease

after correction as those of weakly illuminated areas increase. Therefore, the overall mean of the samples should maintain similar after correction. However, this may not happen for a single land cover class which is predominantly located in one illumination condition (for example, weakly illuminated areas). This can explain the greater mean of forest samples after correction, which is the less extent class and predominantly distributed on weakly illuminated areas (Figure 5).
The results of r^2 and standard deviation for the uncorrected band 4 indicate that data of “corn” and of “soil” classes showed the largest and the smallest presence of topographic effect in the studied area, respectively. This can be explained by the spectral variability of both classes. In the study area, corn is a quite homogeneous class, with little phenological variation and little appearance of self-shadowing, which would increase the spectral variability in and between patches in addition to the topographic effect, as observed on other cover types, like forest and coffee. In the other hand, soil class presents quite a spectral variation among its patches, due to the variety of conditions comprised in this class, including plowed soil, soil with crop residues and degraded pasture, each of these varying in relation to other factors, such as moisture and roughness (Moreira, 2014). Because of this greater spectral variability, the topographic effect is less apparent in the soil class.

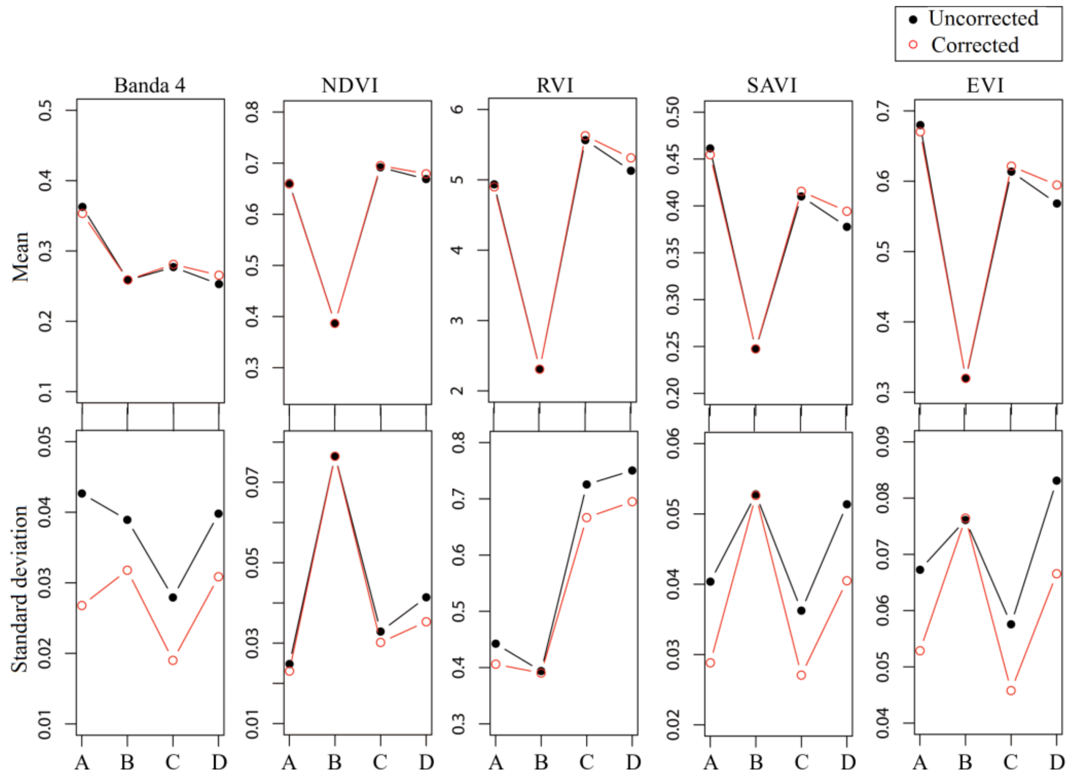

Figure 7: Mean and standard deviation of the corrected and uncorrected band 4 (B4) and vegetation index. Land cover: A - Corn; B - Soil; C – Coffee; e D – Forest.

Comparing well-illuminated pixels with pixels under weak illumination, the averages of band 4 and VIs showed to be statistically different (significance level of 0.01) (Table 2). After correction of the topographic effect, band 4 and also the VIs were statistically equal in the two illumination classes. This indicates that the illumination, or the topographic effect, has relevant influence on the band 4 reflectance and on the values of VIs. The topographic correction contributed significantly to reduce this influence (Table 2).

Table 2: Mean values of band 4 and of vegetation index (NDVI, RVI, SAVI, EVI) of the corn land cover class in well-illuminated pixels (***cos i*** > 0,58 – class I) and weakly illumination pixels (***cos i*** ≤ 0,58 – class II), before and after applying topographic correction

Data	Solar illumination	Uncorrected*	Corrected*
Band 4	I	0.31 [a]	0.35 [a]
	II	0.38 [b]	0.35 [a]
NDVI	I	0.64 [a]	0.65 [a]
	II	0.66 [b]	0.65 [a]
RVI	I	4.72 [a]	4.89 [a]
	II	5.03 [b]	4.90 [a]
SAVI	I	0.42 [a]	0.45 [a]
	II	0.47 [b]	0.45 [a]
EVI	I	0.62 [a]	0.66 [a]
	II	0.70 [b]	0.67 [a]

*Mean values followed by distinct letter are statistically different (t test, *p-value* < 0.01).

In summary, topography can affect the approached vegetation indices. In addition, it was shown that the applied correction method could fully remove their statistics characteristics related to topographic effect. It is expect that topographic effect reduce the ability of vegetation indices to estimate biophysical parameters of the vegetation or to be used in automatic process of land cover classification, as supported by other studies (Verbyla et al., 2008; Cuo et al., 2010; Vanonckelen et al., 2013; Moreira and Valeriano, 2014). We suggest for further studies that authors address different types of relief, latitude, date of image acquisition and sensors. In addition, it is recommended to evaluate other topographic correction methods, including non-empirical based methods (Shepherd and Dymond, 2003; Zhang and Gao, 2011).

4. CONCLUSIONS

In this study, we evaluated the topographic effect on four vegetation indices from uncorrected and topography-corrected Landsat 5 TM data. The studied vegetation indices partially contributed to reduce the topographic effect on the spectral data. NDVI and RVI were less sensitive to the topographic effect than EVI and SAVI. Band 4 reflectance and the four vegetation indices proved to be fully independent of the topographic effect only after topographic correction, evidencing the conceptual fragility of the use of vegetation indices to overcome topographic effects in satellite images, in contrast to techniques specifically developed for topographic correction. This study reinforces that prior to vegetation indices estimation, proper pre-processing steps of satellite imageries need to be conducted. The topographic correction is important for data from rugged terrain. The prospects supported by this research indicate the importance of similar studies to be conducted under different relief, latitude and acquisition situations, as well as tests with other methods of topographic correction. On the other hand, given the availability of DEM used in this work, the gains from the topographic correction are potentially available to all those who deal with radiometric variables obtained by satellite sensors of medium spatial resolution, like Landsat 5 TM.

ACKNOWLEDGEMENTS

The authors are scholarship holders of CNPq, the Brazilian Council for Science and Technology, and of CAPES, Coordination for the Improvement of Higher Education Personnel, at National Institute for Space Research (INPE). The authors thank the anonymous referees for all comments and suggestions, which led to improvements of this paper.

REFERENCES

Chander, G.; Markham, B. L.; Helder, D. L. Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. *Remote Sensing of Environment*, v. 113, n. 5, p. 893–903, 2009. doi: 10.1016/j.rse.2009.01.007

Civco, D. Topographic Normalization of Landsat Thematic Mapper Imagery. *Photogrammetic Engineering & Remote Sensing*, v. 55, n. 9, p. 1303-1309, 1989.

Chavez, P. S. An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data. *Remote Sensing of Environment*, v. 24, p. 459–479, 1988.

Cuo, L.; Vogler, J. B.; Fox, J. M. Topographic normalization for improving vegetation classification in a mountainous watershed in Northern Thailand. *International Journal of Remote Sensing*, v. 31, p. 3037–3050, 2010.

Deng, Y.; Chen, X.; Chuvieco, E.; Warner, T.; Wilson, J. P. Multi-scale linkages between topographic attributes and vegetation indices in a mountainous landscape. *Remote Sensing of Environment*, v. 111, p. 122–134, 2007.

Dubayah, R.; Rich, P. M. Topographic solar radiation models for GIS. *International Journal of Geographical Information Systems*, v. 9, n. 4, p. 405–419, 1995.

Dube, T.; Mutanga, O. Evaluating the utility of the medium-spatial resolution Landsat 8 multispectral sensor in quantifying aboveground biomass in uMgeni catchment, South Africa. *ISPRS Journal of Photogrammetry and Remote Sensing*, v. 101, p. 36–46, 2015. doi: 10.1016/j.isprsjprs.2014.11.001

Ekstrand, S. Landsat TM-Based Forest Damage Assessment: Correction for Topographic Effects. *Photogrammetric Engineering & Remote Sensing*, v. 62, n. 2, p. 151–161, 1996.

Hantson, S.; Chuvieco, E. Evaluation of different topographic correction methods for Landsat imagery. *International Journal of Applied Earth Observation and Geoinformation*, v. 13, n. 5, p. 691–700, 2011. doi: 10.1016/j.jag.2011.05.001

Holben, B.; Justice, C. The topographic effect on spectral response from nadir-pointing. *Photogrammetic Engineering and Remote Sensing*, v. 46, n. 9, p. 1191–1200, 1980.

Holben, B.; Justice, C. An examination of spectral band ratioing to reduce the topographic effect on remotely sensed data. *International Journal of Remote Sensing*, v. 2, n. 2, p. 115–133, 1981. doi: 10.1080/01431168108948349

Horn, B. K. P. Hill Shading and the Reflectance Map. *Proceedings of the IEEE*, v. 69, p. 14–47, 1981.

Huete, A. R. A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment*, v. 25, p. 295–309, 1988.

Huete, A. R.; Justice, C.; Leeuwen, W. V. *Modis Vegetation Index Algorithm Theoretical Basis*. Report, 120p., 1999.

IBGE. Produção agrícola municipal, Tabela 1612 – *Área plantada, área colhida, quantidade produzida e valor da produção da lavoura temporária*. 2013.

Kobayashi, S.; Sanga-Ngoie, K. A comparative study of radiometric correction methods for optical remote sensing imagery: the IRC vs. other image-based C-correction methods. *International Journal of Remote Sensing*, v. 30, p. 285–314, 2009.

Kolios, S.; Stylios, C. D. Identification of land cover/land use changes in the greater area of the Preveza peninsula in Greece using Landsat satellite data. *Applied Geography*, v. 40, p. 150–160, 2013. doi:10.1016/j.apgeog.2013.02.005

Lee, T. Y. L. T. Y.; Kaufman, Y. J. Non-Lambertian Effects on Remote Sensing of Surface Reflectance and Vegetation Index. *IEEE Transactions on Geoscience and Remote Sensing*, v. 24, n. 5, p. 699–708, 1986.

Lehmann, E. A.; Wallace, J. F.; Caccetta, P. A.; Furby, S. L.; Zdunic, K. Forest cover trends from time series Landsat data for the Australian continent. *International Journal of Applied Earth Observation and Geoinformation*, v. 21, p. 453–462, 2012. doi: 10.1016/j.jag.2012.06.005

Liu, H. Q.; Huete, A. R. A feedback based modification of the NDV I to minimize canopy background and atmospheric noise. *IEEE Transactions on Geoscience and Remote Sensing*, v. 33, p. 457-465, 1995.

Matsushita, B.; Yang, W.; Chen, J.; Onda, Y.; Qiu, G. Sensitivity of the Enhanced Vegetation Index (EVI) and Normalized Difference Vegetation Index (NDVI) to Topographic Effects: A Case Study in High-density Cypress Forest. *Sensors*, v. 7, p. 2636–2651, 2007.

Mcdonald, E. R.; Wu, X.; Caccetta, P.; Campbell, N. Illumination correction of Landsat TM data in South East NSW. *Proceedings of the 10th Australasian Remote Sensing Conference*, 2000, p. 1–13.

Meyer, P.; Itten, K. I.; Kellenberger, T.; Sandmeier, S.; Sandmeier, R. Radiometric corrections of topographically induced effects on Landsat TM data in an alpine environment. *ISPRS Journal of Photogrammetry and Remote Sensing*, v. 48, n. 4, p. 17–28, 1993.

Moreira, E. P. *Correção radiométrica do efeito de iluminação solar induzido pela topografia*, 2014. Dissertação de mestrado em Sensoriamento Remoto, Instituto Nacional de Pesquisas Espaciais - INPE. Accessed 30/10/2014. <http://urlib.net/8JMKD3MGP7W/3FHCR62>

Moreira, E. P.; Valeriano, M. M. Application and evaluation of topographic correction methods to improve land cover mapping using object-based classification. *International Journal of Applied Earth Observation and Geoinformation*, v. 32, p. 208–217, 2014. doi: 10.1016/j.jag.2014.04.006

Pearson, R. L.; Miller, L. D. Remote mapping of standing crop biomass for estimation of the productivity of shortgrass prairie, Pawnee National Grasslands, Colorado. *Proceedings of the 8th International Symposium on Remote Sensing of the Environment*. Anais... . 1972. Ann Arbor, MI. p.1355–1379.

R: *A language and environment for statistical computing*. , 2013. Viena, Austria: R Foundation for Statistical Computing. Accessed 10/05/2014. <www.r-project.org>.

Reese, H.; Olsson, H. C-correction of optical satellite data over alpine vegetation areas: a comparison of sampling strategies for determining the empirical c-parameter. *Remote Sens. Environ.* 115, 1400–1987, 2001. doi: 10.1016/j.rse.2011.01.019.

Rouse, J. W.; Haas, R. H.; Schell, J. A.; Deering, D. W. Monitoring vegetation system in the great plains with ERTS. Proceedings of the Third Earth Resources Technology Satellite-1 Symposium. *Anais*... . 1974. Greenbelt, USA: NASA SP-351. p. 3010–3017

Sellers, W. D. Physical climatology. Chicago: University of Chicago Press, 272p. 1965.

Sexton, J. O.; Urban, D. L.; Donohue, M. J.; Song, C. Long-term land cover dynamics by multi-temporal classification across the Landsat-5 record. *Remote Sensing of Environment*, v. 128, p. 246–258, 2013. doi: 10.1016/j.rse.2012.10.010.

Shepherd, J. D.; Dymond, J. R. Correcting satellite imagery for the variance of reflectance and illumination with topography. *International Journal of Remote Sensing*, v. 24, p. 3503–3514, 2003.

Smith, J. A.; Lin, T. L.; Ranson, K. L. The Lambertian assumption and Landsat data. *ISPRS Journal of Photogrammetry and Remote Sensing*, v. 46, n. 9, p. 1980, 1980.

Teillet, P. M.; Guindon, B.; Goodenough, D. G. On the slope-aspect correction of multispectral scanner data. *Canadian Journal of Remote Sensing*, v. 8, p. 84–106, 1982.

Teillet, P. M.; Staenz, K.; William, D. J. Effects of spectral, spatial, and radiometric characteristics on remote sensing vegetation indices of forested regions. *Remote Sensing of Environment*, v. 61, p. 139–149, 1997.

Valeriano, M. M.; Kuplich, T. M.; Storino, M.; Amaral, B. D.; Mendes, J. N.; Lima, D. J. Modeling small watersheds in Brazilian Amazonia with shuttle radar topographic mission-90 m data. *Computers and Geosciences*, v. 32, p. 1169–1181, 2006.

Valeriano, M. M.; Rossetti, D. F. Topodata: Brazilian full coverage refinement of SRTM data. *Applied Geography*, v. 32, n. 2, p. 300–309, 2012. doi: 10.1016/j.apgeog.2011.05.004

Vanonckelen, S.; Lhermitte, S.; Rompaey, A. Van. The effect of atmospheric and topographic correction methods on land cover classification accuracy. *International Journal of Applied Earth Observation and Geoinformation*, v. 24, p. 9–21, 2013. doi: 10.1016/j.jag.2013.02.003

Veraverbeke, S.; Verstraeten, W. W.; Lhermitte, S.; Goossens, R. Illumination effects on the differenced Normalized Burn Ratio's optimality for assessing fire severity. *International Journal of Applied Earth Observation and Geoinformation*, v. 12, p. 60–70, 2010.

Verbyla, D. L.; Kasischke, E. S.; Hoy, E. E. Seasonal and topographic effects on estimating fire severity from Landsat TM/ETM+ data. *International Journal of Wildland Fire*, v. 17, n. 2006, p. 527–534, 2008.

Wang, Y.; Hou, X.; Wang, M.; Wang, M.; Wu, L.; Ying, L.; Feng, Y. Topographic controls on vegetation index in a hilly landscape: a case study in the Jiaodong Peninsula, eastern China. *Environmental Earth Sciences*, v. 70, p. 625–634, 2012. doi: 10.1007/s12665-012-2146-5

Zhang, W.; Gao, Y. Topographic correction algorithm for remotely sensed data accounting for indirect irradiance. *International Journal of Remote Sensing*, v. 32, p. 1807–1824, 2011.

Recebido em abril de 2015.
Aceito em agosto de 2015.