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Directional effects on the spectral response of *Pinus elliottii* stands cultivated in subtropical latitudes

Efeitos direcionais sobre a resposta espectral de plantios de *Pinus elliottii* em latitudes subtropicais

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Abstract

Remote sensing techniques and related products are an efficient and low-cost alternative of great potential for monitoring Pine crops. However, there are no conclusive studies on the magnitude of directional effects caused by variations in the geometry of data acquisition by large field-of-view satellite instruments face to the well-defined canopy architecture of Pine. This paper investigates the viewing geometry influence on the data acquisition of reflectance and vegetation indices used to monitor Pine stands. Two multitemporal series of reflectance measurements of the MOD09GA and MCD43A4 products, without and with the application of nadir normalization, respectively, were acquired and sampled according to the view zenith angle for pairs of consecutive dates with observations made in opposite directions. The influence of directional effects on the response of the Enhanced Vegetation Index, Normalized Difference Vegetation Index, and Wide Dynamic Range Vegetation Index was verified from analysis of variance (ANOVA). The results showed that the reflectance measurements were substantially influenced by the directional effects, showing lower values when calculating from the forward scattering direction, and higher values when obtained from the backscattering direction. From the three studied vegetation indices, the EVI was the most sensitive metric to directional effects. However, when calculating using normalized reflectance measurements to nadir, the directional influence on the EVI was greatly reduced when compared to the other two vegetation indices.
Keywords:
Viewing geometry, MODIS sensor, spectral vegetation indices, forestry.

Resumo

Técnicas e produtos associados de sensoriamento remoto são uma alternativa eficiente e de baixo custo, com grande potencial para o monitoramento de cultivos de Pinus. No entanto, ainda não existem estudos conclusivos sobre a magnitude dos efeitos direcionais causados pela geometria de aquisição de dados por instrumentos orbitais com amplo campo de visada, considerando a arquitetura do dossel de Pinus. Este trabalho investiga a influência da geometria de visada na aquisição de dados de reflectância e índices de vegetação normalmente usados no monitoramento de povoamentos florestais de Pinus. Para a realização do

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trabalho foram adquiridas duas séries multitemporais de medidas de reflectância dos produtos MOD09GA e MCD43A4, sem e com aplicação da normalização ao nadir, respectivamente, sendo essas amostradas de acordo com o ângulo zenital de visada e em pares de datas consecutivas com observações realizadas em direções opostas de imageamento. A influência dos efeitos direcionais na resposta dos índices de vegetação *Enhanced Vegetation Index*, *Normalized Difference Vegetation Index*, e *Wide Dynamic Range Vegetation Index* foi verificada a partir de análise de variância (ANOVA). As medidas de reflectância foram influenciadas pelos efeitos direcionais, apresentando menores valores na direção do espalhamento frontal e maiores valores na direção do retroespalhamento. Dentre os três índices de vegetação estudados, o EVI foi o mais sensível aos efeitos direcionais. Entretanto, quando calculado com reflectância normalizada ao nadir, a influência direcional sobre o EVI foi amplamente reduzida quando comparada com àquela vista sobre os outros dois índices de vegetação.
Palavras-chave:
Geometria de visada, Sensor MODIS, índices espectrais de vegetação, silvicultura.

I. INTRODUCTION

Brazilian forestry has achieved important development in recent decades, becoming the main supplier of raw material for the forest-based industry (IBGE, 2020). In this scenario, the southern region of the country stands out, where large projects are developed to plant species of the *Pinus* genus, especially *Pinus taeda Linnaeus* and *Pinus elliottii Engelm var. elliottii*. The performance of these species mainly results from their adaptive capacity to local edaphoclimatic conditions and from the adoption of efficient management practices. Remote sensing has been used for monitoring the production cycle of *Pinus*. It is an efficient and low-cost alternative for the elaboration of vegetative vigor maps over extensive cultivated areas, using high spatial and temporal resolution data. However, the anisotropic characteristic of forest canopies is challenging for obtaining stable surface radiometric measurements on a multitemporal scale.

Spectral response anisotropy is the intrinsic property of natural surfaces to scattered incident electromagnetic radiation unevenly in all directions (WU et al., 2019). In forest canopies, data acquired by large-of-view or side-looking satellite sensors are affected by the three-dimensional structure of plantations, the optical properties of the leaves, and the effects of the geometry of data acquisition from nadir to large view zenith angles (VZA) and directions (WEN et al., 2018; WU et al., 2019). Thus, the latter factor is a source of uncertainty in remote sensing data analysis (WEYERMANN et al., 2014). In this sense, the understanding of spectral characteristics of the canopies of *Pinus* species forest stands is of fundamental importance for the effective application of remote sensing data in the monitoring of silvicultural projects.

Due to the anisotropy of forest canopies, spectral variations are identified by changes in viewing and illumination geometry, in successive multitemporal observations from large field-of-view satellite sensors such as the

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MODerate-resolution Imaging Spectroradiometer (MODIS) (JUSTICE et al., 1998; BREUNIG et al., 2011; 2015). These sensors produce observations outside the nadir along the orbital plane (or even lateral points), from which different illumination conditions are detected, producing different spectral responses over the same type of canopy (LOBELL et al., 2002). In the backscattering direction, the canopy is observed under a condition of direct incidence of the solar radiant flux, which produces radiometric measurements with greater albedo. In contrast, there is a greater condition of shaded canopy in the forward scattering direction causing a smaller albedo.

Angular effects from variations in viewing-illumination geometry can cause significant changes in reflectance measurements, even over invariant and homogeneous forest stands (GAO et al., 2014). Previous studies have shown that even vegetation indices are highly sensitive to effects caused by viewing-illumination geometries (SIMS et al., 2011). Such effects produce inconsistent results that compromise the estimates of productivity and vegetative vigor (GALVÃO et al., 2016; VAN BEEK et al., 2016).

Although these effects are known and described in the literature, representing a source of radiometric errors that may be associated with remote sensing data in applications focused on vegetation, the angular dependence in canopy observations is still ignored in several studies (LOBELL et al., 2002). On the other hand, most of the studies addressing this topic have been proposed to investigate the directional effects on the spectral response of natural forests (BREUNIG et al., 2015; MOURA et al., 2015) and agricultural crops (BREUNIG et al., 2011; 2012). Meanwhile, investigations on the influence of these effects on silvicultural targets are still scarce.

Considering the anisotropic characteristic of forest canopies, marked by a strong directional dependence of the viewing-illumination conditions on their spectral response, this study hypothesizes that the structural and spectral particularities presented by the acicufoliate species, in relation to variable viewing-illumination conditions, may produce significantly different reflectance and vegetation indices (VI) when compared to the nadir observations. Consequently, this study aims to investigate the effects produced on *Pinus* Forest stands by reflectance observations from different geometries of data acquisition used to calculate three VIs: the Enhanced Vegetation Index (EVI), the Normalized Difference Vegetation Index (NDVI), and the Wide Dynamic Range Vegetation Index (WDRVI) in a flat relief area of South of Brazil

II. MATERIALS AND METHODS

Study area

This study was carried out in a forest area composed of *Pinus elliottii Engelm var. elliottii* stands, managed by Florestadora Palmares Ltda. (FLOPAL). The area is located in the municipality of Santa Vitória do Palmar, in the south

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coast of the state of Rio Grande do Sul, Brazil (Figure 1). The forest stands extend over an area of approximately 67 km². It was planted in 1988 with spacing between the cultivars of 2 m x 2 m, presenting a density of 2,500 trees per hectare. From a remote sensing perspective, the canopies are now eminently closed and homogeneous having cultivars at the same stage of development. In the study area, procedures for silvicultural management (e.g., pruning and thinning) have not been applied due to the use of forest stands for resin exudation.

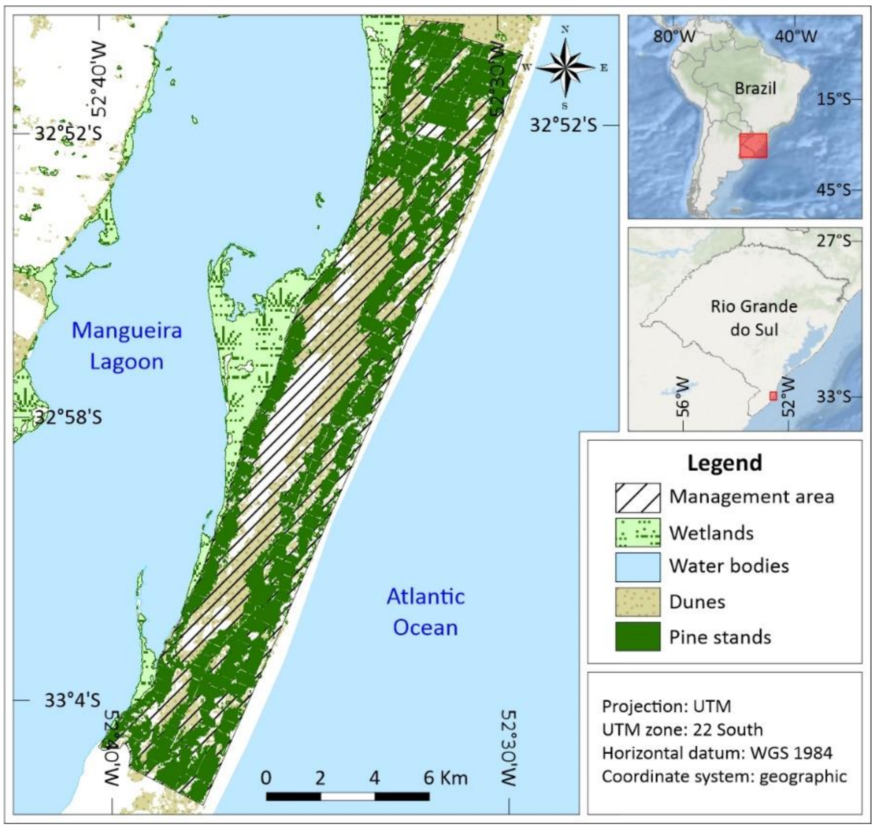

Figure 1 – Location map of the forest management area in southern Brazil.

The forest management area was implemented over the Coastal Plain. It is a region characterized by the occurrence of dune fields along a lagoon-barrier system formed in the Holocene period. The managed forest is located between the Mangueira Lagoon and the Atlantic Ocean (Figure 1). The flat relief of the management area allows remote sensing acquisition of satellite data without the influence of topographic effects (GAIDA et al., 2016). This is important for conducting studies on the geometry of data acquisition.

Acquisition and processing of remote sensing data

The analysis of effects of viewing-illumination geometry on the spectral response of forest stands was carried out using bidirectional surface reflectance measurements from two MODIS products: the MOD09GA.006 MODIS/Earth

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Surface Reflectance Daily L2G Global 1km and 500m product (VERMOTE and WOLFE, 2015), and the MCD43A4.006 MODIS Nadir BRDF-Adjusted Reflectance daily 500m product (SCHAAF and WANG, 2015). The MOD09GA.006 product contains the reflectance measurements of the first seven bands of the MODIS positioned in the visible, near-infrared, and short-wave infrared spectral intervals. This product also includes layers describing the viewing-illumination geometry on a per-pixel basis: the view azimuth angle (VAA), view zenith angle (VZA), solar azimuth angle (SAA), and the solar zenith angle (SZA). On the other hand, the MCD43A4.006 product refers to the acquisition of reflectance measurements adjusted to nadir (NBAR), corrected for the bidirectional effects observed in the previous product.

For both products, we acquired time series of images with daily resolution from January 1 to December 31, 2019. By performing this seasonal analysis, view-illumination effects were analyzed throughout the year over a study area located at subtropical latitude. The acquisition of MODIS products was performed using the Application for Extracting and Exploring Analysis Ready Samples (AppEEARS), available from NASA's Earth Observing Data and Information System (EOSDIS) Land Processes Distributed Active Archive Center (LP DAAC) at the following address: <https://lp daacsvc.cr.usgs.gov/appeears/>. After the acquisition of time series of surface reflectance measurements of the MOD09GA and MCD43A4 products, pixel filtering for retrieving high-quality data was carried out using the quality information from the metadata to eliminate reflectance measurements affected by the presence of clouds or other significant atmospheric effects.

Calculation of spectral vegetation indices

After acquiring the canopy reflectance measurements, the NDVI (Rouse et al., 1973), EVI (HUETE et al., 2002) and WDRVI (GITELSON, 2004) were calculated. The choice of these VIs considered their extensive applications in forestry studies and the performance of WDRVI to estimate biophysical attributes over high biomass conditions.

The calculation of the vegetation indices was performed respectively using Equations 1, 2 and 3 (Table 1) with the B03 (459 – 479 nm), B01 (620 – 670 nm) and B02 (841 – 876 nm) bands of the MODIS instrument. These bands correspond to the wavelength ranges of the blue (ρ_{blue}), red (ρ_{red}), and near-infrared (ρ_{NIR}) regions, respectively. To obtain the WDRVI, it was necessary to calculate the adjustment coefficient for the near-infrared band (α) by using the average reflectance values of the red band ($\bar{X}\rho_{red}$) and the maximum values of the near-infrared band (ρ_{NIRmax}) of the pixels corresponding to each image (Equation 4). Using the MOD09GA and MCD43A4 products, two datasets of VIs were therefore obtained: one with bidirectional effects on the data and another without such effects after data normalization to nadir viewing.

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Table 1 – Vegetation indices calculated from the reflectance measurements of the MODIS sensor system bands.

Vegetation index	Equation		Reference
NDVI	$NDVI = \frac{(\rho_{NIR} - \rho_{red})}{(\rho_{NIR} + \rho_{red})}$	(1)	Rouse *et al*. (1973)
EVI	$EVI = G * \frac{(\rho_{NIR} - \rho_{red})}{(\rho_{NIR} + C_1 * \rho_{red} - C_2 * \rho_{blue} + L)}$	(2)	Huete *et al*. (2002)
WDRVI	$WDRVI = \frac{(\alpha * \rho_{NIR}) - \rho_{red}}{(\alpha * \rho_{NIR}) + \rho_{red}}$	(3)	Gitelson (2004)
	$\alpha = 2 * \left(\frac{\bar{X}\rho_{red}}{\rho_{NIR_{max}}}\right)$	(4)	Henebry *et al*. (2004)

Source: organized by the authors (2021).

Evaluation of the viewing-illumination effects on surface reflectance measurements

The view direction of MODIS data acquisition was determined from the calculation of the relative azimuth angle (RAA), as described by Bourcheidt and Breunig (2017). The RAA presents values between -180° and 180°. RAA values lower than the 90° correspond to MODIS observations in the forward scattering direction, while values greater than 90° indicate acquisitions in the backscattering direction. To calculate the RAA, it was necessary to establish the initial relative azimuth angle (RAAi) for each image, which was determined using Equation 5:

$$RAA_i = VAA - 180 - SAA \quad (5)$$

In cases where the initial relative azimuthal angle values were less than -180° or greater than 180°, the values were adjusted using Equations 6 and 7.

$$RAA_i < -180 \rightarrow RAA_f = RAA_i + 360 \quad (6)$$

$$RAA_i > 180 \rightarrow RAA_f = RAA_i - 360 \quad (7)$$

where RAA_f corresponds to the final relative azimuth angle.

The influence of viewing direction on the canopy reflectance measurements by MODIS was analyzed by organizing a graph using the mean values sampled in the backscattering and forward scattering directions. The sensitivity of spectral reflectance of the MOD09GA product was analyzed by calculating the coefficient of variation (CV) for each band in both view directions.

Subsequently, the set of dates was filtered to define six pairs of MODIS observations in consecutive days. This strategy aimed to obtain the canopy spectral response and VIs in a short period, while reducing the potential influence of other factors in the data analysis (e.g., phenological stages and solar position). The choice

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of the dates considered the variation in local viewing-illumination geometry throughout the year. The dates of the selected pairs of MODIS images are listed in Table 2.

Table 2 – Pairs of MODIS/Terra images obtained in consecutive dates of 2019 with opposite view directions.

Dates	View direction	View zenith angle (degrees)
March 2	Backscattering	-27.7
March 3	Forward scattering	+46.9
June 8	Backscattering	-44.8
June 9	Forward scattering	+30.6
August 2	Backscattering	-37.1
August 3	Forward scattering	+39.5
September 22	Forward scattering	+19.7
September 24	Backscattering	-4.7
October 31	Forward scattering	+30.6
November 1	Backscattering	-56.6
December 23	Forward scattering	+53.3
December 24	Backscattering	-37.1

In order to analyze the effect produced by MODIS angular variations on the canopy spectral response, the MODIS dataset was divided into thirteen classes, considering the VZA (Table 3). These VZA classes were then used for grouping the mean values of bidirectional reflectance over the forest stands for different view angle conditions. For this purpose, the mean value of each class was normalized to the mean value obtained close to the nadir observation (between -5° and 5° of VZA). Plots of the reflectance against the VZA were then obtained.

Table 3 – View zenith angle (VZA) classes defined for the evaluation of MODIS angular effects on reflectance and vegetation indices.

VZA (degrees)		
Backscattering direction	**Nadir**	**Forward scattering direction**
< -55	-5 to 5	5 to 15
-55 to - 45		15 to 25
-45 to -35		25 to 35
-35 to -25		35 to 45
-25 to -15		45 to 55
-15 to -5		> 55

Source: adapted from Bourscheidt and Breunig (2017).

As a function of seasonal variations in SAA and SZA throughout 2019, the evaluation of directional effects considered also clustered reflectance data obtained from the MOD09GA product in the backscattering and forward scattering viewing directions. In this analysis, four classes of SZA were established (< 30°, 30° - 40°, 40° - 50°, and > 50°) and six classes of SAA (< 20°, 20°-30 °, 30°-40°, 40°-50°, 50°-60°, 60°-70°) were considered. From each class and view direction, the average value of the canopy reflectance on each MODIS band was calculated and normalized to class observations having the lowest SZA (< 30°) and to north direction (SAA class < 20°).

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Evaluation of the viewing-illumination geometry on the vegetation indices determination

The influence of the angular effects on response of the NDVI, EVI and WDRVI was first analyzed from the values in the backscattering and forward scattering directions. Using box plots, the differences between the VIs calculated from non-normalized (MOD09GA product) and nadir-normalized data (MCD43A4 product) were evaluated quantitively, both in terms of underestimation and overestimation of values.

The differences between the groups corresponding to the view directions were verified through the analysis of the variance (ANOVA). Because of the size of the groups (n > 1,000 pixels), one-way analysis of variance was used. The occurrence of differences between the viewing directions and VIs with and without correction of directional effects was verified by multiple comparisons between the groups, after applying the Tukey test. All statistical analyses were performed considering a 95% confidence level. Complementary, to highlight the directional effects, graphic and spatial analysis were conducted.

III. Results and discussion

Influence of directional effects on the spectral response of the canopy

From the analysis of canopy spectral response of the *Pinus elliottii* forest stands for different view angles in 2019, the reflectance of the first seven MODIS bands, positioned in the visible, near-infrared and short-wave infrared regions, generally showed a similar behavior. This is characterized by higher reflectance values in the backscattering direction (negative angles in Figure 2), compared to those obtained in the forward scattering direction, where there are greater amounts of shadows viewed by the sensor (positive angles in Figure 2). The reflectance obtained in the backscattering direction (predominance of sunlit canopy components for the sensor) was higher than that found at nadir viewing, even for VZA lower than 10°.

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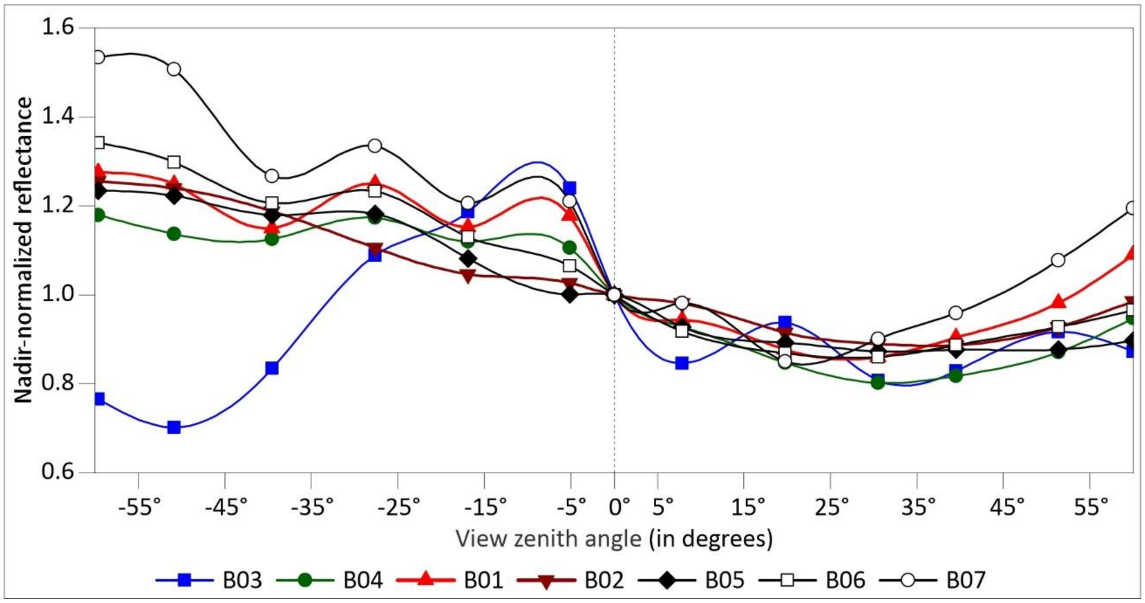

Figure 2 – Behavior of forest canopy reflectance measurements in the backscattering (negative values for VZA) and forward scattering (positive values for VZA) directions. The dashed line indicates the MODIS nadir viewing (0º VZA). The MODIS reflectance values were normalized to nadir observations between -5° and 5°.

Unlike the other bands, the reflectance in the blue presented a different behavior with a comparatively lower spectral response. There was a decreased reflectance in the backscattering direction from -15° to -50º. This behavior may be related to greater availability of radiation to be absorbed by photosynthetic pigments in views close to the hotspot, where the canopy is under direct incidence of solar radiation and the illumination and view directions are collinear. It is also resultant from residual atmospheric effects, which are greater at shorter wavelengths.

Among the bands used in the calculation of the VIs, the red band showed a large variation in their values. It showed a marked increase in values from off-nadir observations in the backscattering direction above -5°. This variation was greater than that found for the near-infrared band. On the other hand, in the forward scattering direction, small variations across directions were recorded between +5° and +35° for all bands.

A similar behavior to that verified in the red band was found for MODIS band B07 (SWIR). Although this band was not used in this study for VI calculation, its measurements in the backscattering direction presented the greatest variation when compared to nadir, especially for VZA values above 5°. In the forward scattering direction, the reflectance showed smaller variations in relation to that found in the backscattering direction between -5° and -30°. In VZA above +30°, as observed before for the red band, there was an increase in the normalized reflectance values.

The measurements of canopy reflectance obtained in the near-infrared wavelengths, although superior to those found in the other bands due to the greater scattering of radiation, presented a low variation of values in relation to the different viewing geometries. In the backscattering direction, the reflectance showed an increase towards the

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boundary of the field of view, although this occurred in a less accentuated way, with the values in the views between 5° and 20° being slightly higher than those verified at nadir. However, from the views obtained above 25°, there was a greater increase in the reflectance values. In the same way as verified in the reflectance measurements of the other analyzed spectral bands, in the forward scattering direction, the smallest values of canopy reflectance were found in the near-infrared wavelengths. Regarding the observations from VZA between 5° and 45°, high amplitudes of variation were not found, with a small decrease in the values towards the larger view angles. On the other hand, unlike the other bands previously analyzed, the values did not show the formation of a sharp peak in the reflectance close to the limit of the field of view, with only a small increase being found in the values obtained in views above 50°.

The analysis of variations caused by directional effects in the spectral response of *Pinus elliottii* forest stands from pairs of consecutive observations showed that the spectral response of *Pinus elliottii* stands are directly influenced by viewing direction. In general, the spectral response of the canopy was higher in the backscattering direction than in the forward scattering direction, where most shading conditions predominated for the sensor (Figure 3). Such a trend was found in other studies on forest targets, such as those conducted by Galvão et al. (2013), Breunig et al., 2015 and Moura et al. (2015).

In this context, the main differences between the spectral responses observed from the backscattering and forward scattering directions were found in the reflectance measurements of the B02, B05 and B06 bands (Figure 3). The spectral response of the canopy in the wavelengths of the B05 band (1,230 – 1,250 nm) was most affected by the viewing effects, presenting differences in the reflectance values that vary between 2.69% and 10.93%. Meanwhile, in the near-infrared band, the influence of directional effects caused differences in the reflectance measurements between 2.44% and 9.69%, verified between the consecutive dates of the analyzed pairs of images. This fact leads to the conclusion that directional effects have different intensities according to the wavelength, as highlighted by GU et al. (2021).

However, the variations observed in the reflectance values, from opposite view directions, do not occur proportionally, which shows that the influence of directional effects is variable, even in the case of highly homogenous canopies. In this sense, from the six pairs of consecutive dates, it was possible to verify that the greatest variations are related to measurements from observations in the forward scattering direction. Considering the pairs of observations in consecutive dates, it was possible to identify the occurrence of certain patterns of difference between the reflectance measurements in each view direction, with a decrease in the amplitude (range of variability) of the reflectance measurements in some cases, both in the visible region, as in the near-infrared one, with the latter being more accentuated.

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Compared with the nadir-adjusted reflectance measurements obtained from the MCD43A4 product, which were considered as reference measurements in the study, it was possible to verify the occurrence of different behaviors regarding the variation amplitude of the values according to the view direction in which they were obtained. It is noteworthy that the normalized reflectance measurements did not show significant variations in any of the analyzed pairs of dates.

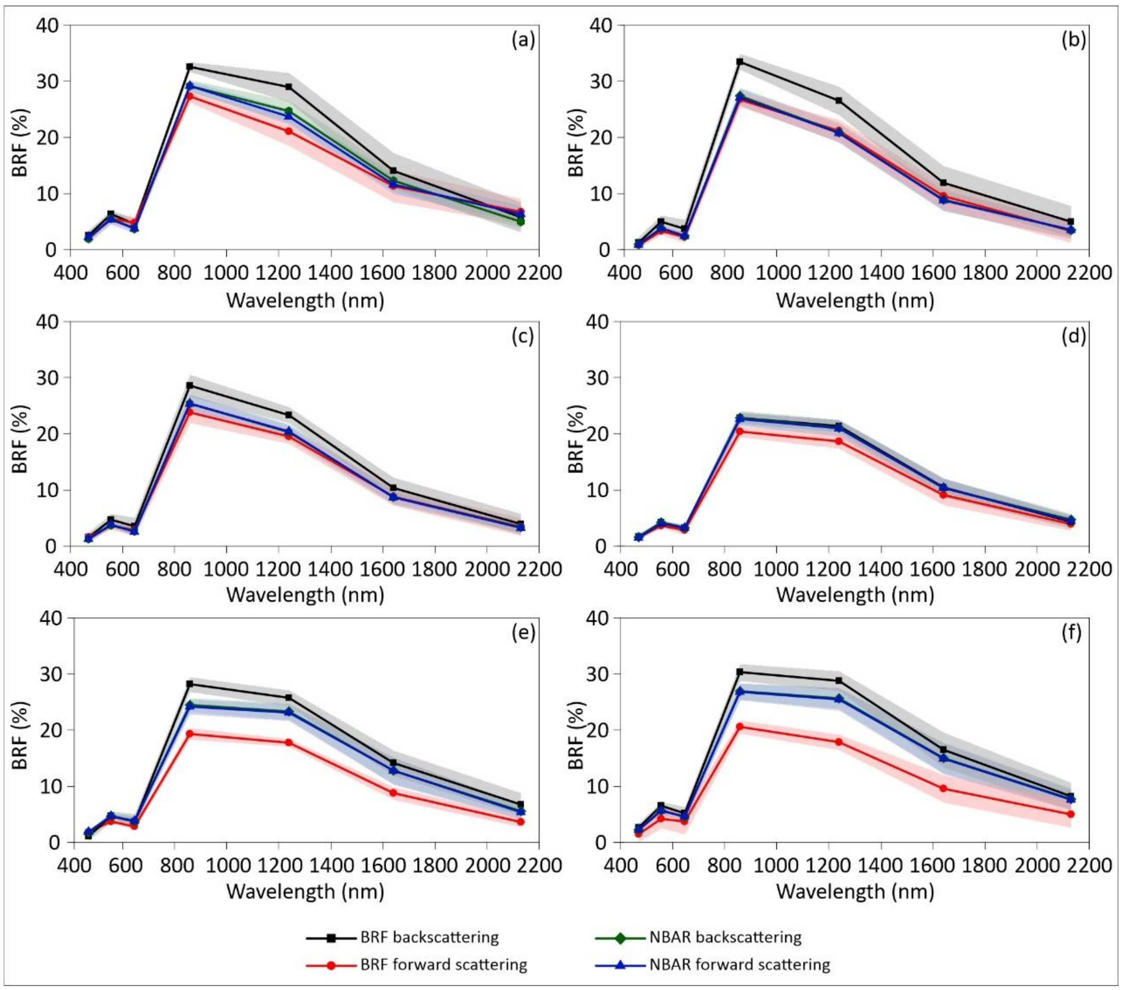

Figure 3 - Spectral response of the forest canopy in the backscattering and forward scattering directions, verified from consecutive dates on (a) March 2nd and 3rd, (b) June 8th and 9th, (c) August 2nd and 3rd, (d) September 22nd and 24th, (e) October 31st and November 1st, and (f) December 23rd and 24th, 2019. Source: prepared with data from the MOD09GA product (VERMOTE; WOLFE, 2015).

Thus, considering that the reflectance measurements obtained in the backscattering direction mainly correspond to the response of the illuminated canopy fraction, in which the canopy is directly exposed to solar irradiation, the bidirectional surface reflectance values should, in theory, be presented close to those found in the reference reflectance measurements. However, this situation was verified in none of the analyzed pairs of images. In most of the data, it was verified that the reflectance measurements obtained in the backscattering

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direction were higher (Figures 3a, 3e and 3f), especially in the wavelengths corresponding to the bands in which the canopy has greater scattering (bands B02, B05 and B06).

On the other hand, in some cases, as verified between the pairs corresponding to the dates of June 8th and 9th, and August 2nd and 3rd (Figures 3b and 3c), the reflectance measurements obtained from the targets in the direction of the forward scattering were closer to the reflectance measurements normalized to the nadir than the measurements from the backscatter direction, which were higher than the others, with the highest values found in bands B01 and B05.

These conditions of reflectance value variation, as a function of the sensor's view geometry, are projected in the temporal aspect, producing oscillations in reflectance measurements that do not exactly characterize the canopy response. In this sense, Figure 4 shows the spatialization of the mean reflectance values obtained in the multitemporal series of the MOD09GA product, separated according to the direction of view in which the canopy was imaged.

Figure 4 – Spatial variation of mean reflectance values from the multitemporal series of canopy observations, obtained from backscattering and forward scattering directions, for the red and near-infrared bands of the MODIS sensor. Source: prepared with data from the MOD09GA product (VERMOTE; WOLFE, 2015).

By the analysis of the spatial distribution of canopy reflectance average values of the multitemporal series, it is possible to verify that the red wavelengths had a lesser influence when observed from different view directions, presenting slight differences in each pixel of the MOD09GA product. In general, the canopy reflectance values in the red wavelengths show a small reduction in the forward scattering direction, although, in some places, values slightly higher than those obtained in the backscattering direction are also found, due to the projected shading to reduce the absorption of incident radiance by foliar pigments in the visible range, as seen in

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Figure 3a. On the other hand, for the reflectance measurements obtained in the near-infrared wavelengths, there is a larger difference, with the values obtained in the backscattering direction presenting, on average, up to 10% higher, in a canopy where there were no changes in its structure during the period of analysis.

Influence of illumination geometry

Due to the location of the study area in subtropical latitude (33°S), seasonal variations in SZA throughout the year make the forest canopy of the analyzed management area be observed under different illumination conditions. The analysis of illumination geometries, in which observations were carried out at the time of passage of the *Terra* satellite, showed that there was a variation of 50.49° in SZA and of 60.38° in the SAA along the multitemporal series, which causes the illumination conditions to oscillate from north to east between January and July, and from east to north between August and December.

Considering the reflectance as a function of the illumination geometry, decreasing reflectance values were associated with the lowest SZA in the backscatter direction, from which the directly illuminated fraction of the canopy was observed. This was verified in all studied bands, with exception of B02 band. The B03 (459 – 479 nm) and B07 (2,105 – 2,155 nm) bands presented the greatest sensitivity to illumination conditions (Figure 5a).

Unlike the other bands, the measurements of canopy reflectance obtained in the near-infrared (B02) wavelengths showed higher values in the observations carried out under illumination conditions characterized by high SZA, with less direct incidence of solar radiation on the canopy and increased internal and projected shading. The increase in reflectance values was proportional to the increase in SZA, with the highest values found in observations carried out with a SZA higher than 50°.

In the forward scattering direction, the measurements of canopy reflectance obtained in the green band (B04) of the MODIS sensor presented a different behavior from that found in the other bands of the visible region. A peak of normalized reflectance was observed at medium SZA (SZA between 40° and 50°). However, in the observations under high SZA conditions (SZA > 50°), a marked reduction behavior in the reflectance values was identified, which may be related to observations of the shaded fraction of the canopy, in which the incident illumination results from the diffuse scattering of solar radiation.

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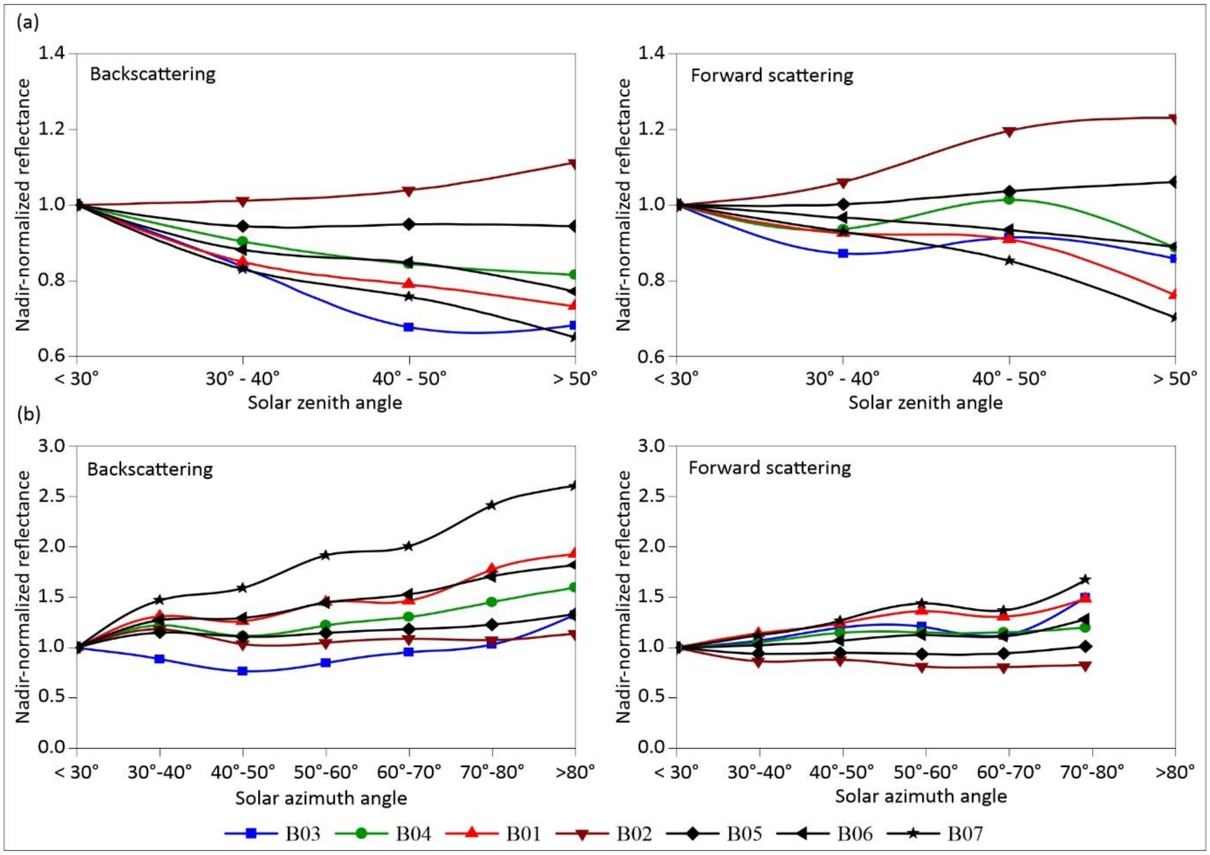

Figure 5 – Influence of illumination geometry on the spectral response of *Pinus elliottii* forest stands, considering the seasonal variations of the solar (a) zenith and (b) azimuth angles, during the time series of data acquisitions. Source: prepared by the author (2021) with data from the MOD09GA product (VERMOTE; WOLFE, 2015).

The measurements of canopy reflectance in the near-infrared and short-wave wavelengths of the B02 and B05 bands, respectively, presented a behavior characterized by the increase of the values in the observations carried out with the occurrence of high SZA (SZA > 30°), with higher values regarding those observed near the zenith. On the other hand, the reflectance measurements obtained by B01, B06 and B07 bands, corresponding to the red and short-wave infrared wavelengths, presented a different behavior from the other bands, characterized by the reduction of values according to the increase in solar zenith angle. In these bands, the highest reflectance values were identified in observations with lowest SZA (SZA < 30°), with a marked decrease in the values of B01 and B07 bands from observations carried out with views above 50° (Figure 5).

Regarding the influence of seasonal variations in the incidence angle of solar radiation on the directional effects, an increase in reflectance values was identified in relation to the displacement of the solar azimuth towards the East. The highest values of canopy reflectance were found in the observations carried out with the highest solar azimuth angle, as shown in Figure 5b. Among the analyzed bands, measurements of canopy reflectance obtained in the B07 band were the most influenced by seasonal oscillations of the solar azimuth angle, with an increase almost

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three times higher than the values obtained from observations with solar azimuth angle less than 30° (north direction), whereas the measurements of canopy reflectance from the near-infrared band presented the smallest values variations regarding changes in the direction of solar incidence.

Such increase in the reflectance measurements was identified in the observations carried out in both view directions. However, the mean variation amplitude of the reflectance measurements observed in the forward scattering direction were lower than those corresponding to the backscattering direction, which is directly related to the observation of the shaded fraction of the canopy. On the other hand, the reflectance measurements obtained in the near-infrared band presented a decreasing behavior in their values, being more accentuated in observations carried out with solar azimuth direction above 50°.

The increasing behavior in canopy reflectance values regarding the increase in the solar azimuth angle may result from the influence caused by seasonal variations in the SZA, since the study area does not present altimetric variations to produce topographical effects for the sensor. In addition to the canopy homogeneity, it reduces the influence of the planting lines direction in relation to the influence of projected shading conditions, which would justify the influence of the change in direction on the solar flux. In this context, the analysis of the influence of seasonal variations in the local illumination geometry showed that the SZA oscillations cause different responses of the canopy reflectance measurements according to the view direction, unlike solar azimuth variations, which produced a similar effect on the spectral response in both view directions.

Sensitivity of vegetation indices to the effects of variation in view geometry

The analysis of the influence of directional effects on the VI response showed that they are less sensitive to these effects than canopy reflectance measurements, although variations in the amplitude according to directions are identified (BREUNIG et al., 2011; GALVÃO et al., 2011). NDVI measurements obtained for the canopy of *Pinus elliottii* forest stands presented the smallest oscillation in their values in relation to the different view directions of observation of the canopy (Figure 6). NDVI values obtained in the forward scattering direction presented a greater amplitude of variation compared to the observations acquired in the backscattering direction, as shown in Figure 6 (BREUNIG et al., 2011).

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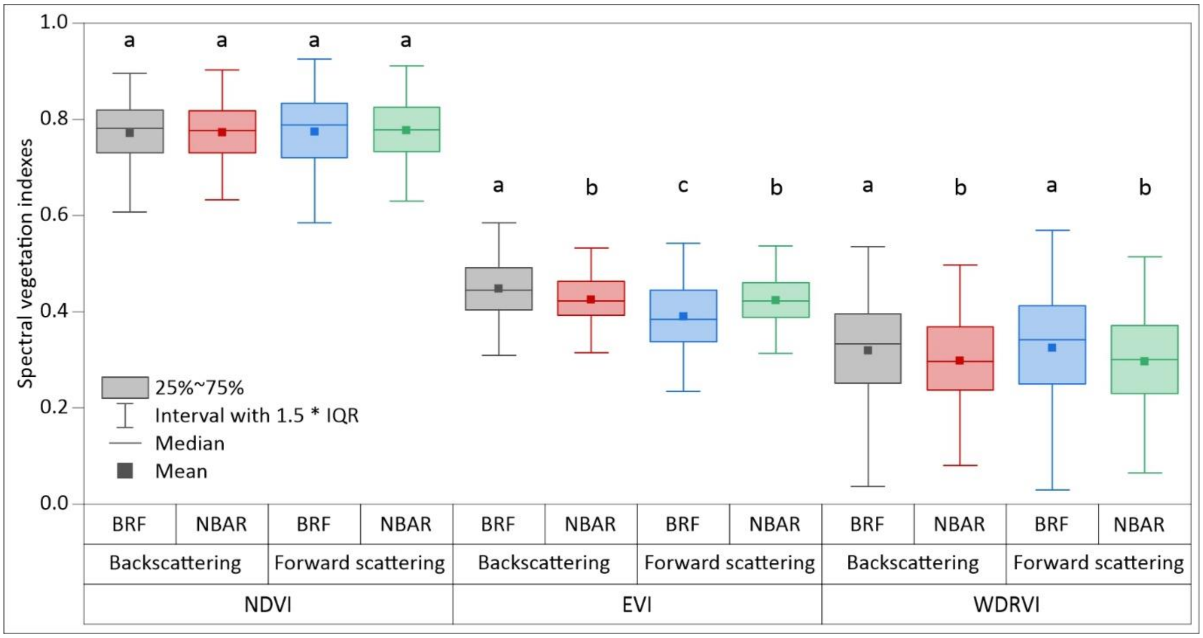

Figure 6 – Variations in NDVI, WDRVI and EVI for observations retrieved from the backscattering and forward scattering directions, and from corrected (NBAR) and non-corrected (BRF) data for bidirectional effects.

The ANOVA applied to the NDVI measurements showed that this index did not present statistically significant differences (p-value < 0.05) in its values obtained from different view directions for the aforementioned application on the canopy of *Pinus elliottii* forest stands (Table 4). No disparities were verified regarding the values from reflectance measurements with and without application of normalization processing to the nadir.

Table 4 – Results of the ANOVA for differences between mean values of vegetation indices, grouped according to the view directions and level of correction for directional effects at a significance level of 95%.

		Degrees of freedom	**Sum of squares**	**Mean square**	***F*-value**	***P*-value**
NDVI	Groups	3	0.0194	0.0065	1.5635	0.1961
	Residue	5404	22.4066	0.0041		
	Total	5407	22.4260			
EVI	Groups	3	2.2806	0.7602	246.8504	0.0000
	Residue	5512	16.9748	0.0031		
	Total	5515	19.2554			
WDRVI	Groups	3	0.6322	0.2107	22.9733	0.0000
	Residue	5215	47.8334	0.0092		
	Total	5218	48.4655			

This result is similar to that found by Sims et al. (2011), when analyzing the influence of directional effects on the NDVI measurements of closed canopy forests. The authors verified the absence of statistically significant differences between the measurements obtained between the forward and backscattering directions. In contrast, some studies (e.g., Los et al. (2005), Verrelst et al. (2008), and León-Tavares et al. (2021)) point out a small sensitivity of this index to the directional effect, which has been related to the influence of the projected shading due to the

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lower density of the analyzed canopies. On the other hand, the EVI measurements of the forest canopy presented a behavior similar to that observed in the analysis of bidirectional reflectance measurements in the near-infrared band, with the highest values found in the observations carried out in the backscattering direction, compared to those obtained in the forward scattering direction, in which the greatest amplitude of variation in the measurements was verified (Figure 5). Moreover, values from the reflectance measurements normalized to nadir had identical behavior in both view directions.

The comparative analysis between the defined groups based on the view directions and processing of the reflectance measures used for their calculation (presented in Table 4) showed the occurrence of statistically significant differences (p-value < 0.05) between EVI measurements from view directions outside the nadir. Among the vegetation indices analyzed, this VI was the most affected by the differences in canopy illumination observed in the different acquisition geometries of spectral measurements, even in the case of a closed canopy, with less influence of projected shading.

Table 5 - Results obtained by applying the Tukey Test to identify differences between measurements of the EVI and WDRVI indices, calculated from the bidirectional reflectance fraction (BRF) and bidirectional reflectance adjusted to the nadir (NBAR), obtained in the view directions from backscattering and forward scattering.

	Groups*	Center	Inferior limit	Superior limit	*p*-value
EVI	2 – 1	-0.0227	-0.0278	-0.0176	0.0000
	3 – 1	-0.0579	-0.0634	-0.0524	0.0000
	4 – 2	-0.0010	-0.0065	0.0045	0.9692
	4 – 3	0.0342	0.0284	0.0400	0.0000
WDRVI	2 – 1	-0.0180	-0.0268	-0.0092	0.0000
	3 – 1	0.0076	-0.0019	0.0172	0.1682
	4 – 2	-0.0005	-0.0107	0.0097	0.9992
	4 – 3	-0.0262	-0.0370	-0.0153	0.0000

*1 – FRB backscattering, 2 – NBAR backscattering, 3 – BRDF forward scattering, 4 – NBAR forward scattering.
Source: prepared by the author (2021).

The greater sensitivity of the EVI to directional effects is directly associated with its high dependence on the response of the near-infrared band, as discussed by Galvão et al. (2011), which makes it sensitive to the influence of radiometric effects arising from changes in the canopy response as a function of the incident radiation distribution. Its spectral dependence is the response of the canopy in the near-infrared wavelengths up to five times higher in relation to the NDVI in some cases, as shown by Samanta et al. (2012). In this context, the results from the analysis of the EVI values regarding the view directions and variations in the canopy illumination geometry are similar to those found in studies carried out by Galvão et al. (2011), Moura et al. (2012) and Breunig et al. (2015), in which the authors found that the EVI is more sensitive to variations in the target geometry than the indices from normalized difference, such as the NDVI. Sims et al. (2011) highlight the need to adopt procedures to correct directional effects in multitemporal applications using EVI.

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However, when calculated from normalized reflectance measurements at nadir, the EVI showed the best performance among the analyzed vegetation indices. No differences were found in the behavior of their response that are directly associated with the influence of directional effects.

The analysis of the WDRVI measurements, obtained from the different view directions, showed that it presents a behavior very close to that of the NDVI, with the highest values found in the observations made from the forward scattering direction. In this view direction, the greatest amplitude of variation in its values was also found.

Although the WDRVI measurements presented small variations regarding the view directions, the variance analysis showed the absence of statistically significant differences between their values. However, the results from the multiple comparisons test (Table 4) indicated differences between the data in relation to the processing level of the reflectance measurements, with a smaller oscillation of values found in the WDRVI measurements from normalized data at nadir, as well as smaller ones in relation to the values from the MOD09GA product. On the other hand, the test also points out the absence of differences between the values of this index, calculated from the product MCD43A4 in relation to those aimed outside the nadir of the MODIS sensor system.

Although the sensitivity to directional effects in the WDRVI response is still little explored in the literature, the results obtained allow us to conclude that its calculation results in a greater range of data when the influence of directional effects is ignored. There were no significant differences found between the observations carried out outside the nadir, but the effect of the view geometry causes an increase in this index measurements in both directions. The use of the adjustment coefficient for the near-infrared response is a factor that may be related to greater sensitivity to variations in observed illumination conditions, making the index more sensitive to the dependence of variations caused in the measurements of the near-infrared band.

The low variation found between the backscattering and forward scattering view directions may be related to factors such as the characteristic of the vegetation indices in highlighting the high vegetative vigor found in the analyzed forest stands, as well as the spectral characteristics of the canopy associated with the conditions of illumination and the aspect on the indices capacity to detect high biomass concentrations.

The low variations found between the measurements of the NDVI and WDRVI indices between the views obtained in opposite directions may be associated with the probability of photon recollision in the internal structure of the canopy during the radiative transfer process, which is a specific spectral characteristic of the acicufoliate species, as verified by Stenberg et al. (2016) and Rautiainen et al. (2018). This feature makes a photon reflected or transmitted from a needle interact with the canopy again. Although spectrally invariable, it is more pronounced in the band corresponding to the near-infrared wavelengths due to the greater spectral

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response found in these (SMOLANDER and STENBERG, 2005; SIMS et al., 2011). This effect is higher according to the increase in the canopy leaf area index (LAI), as pointed out by Stenberg et al. (2016).

On the other hand, the factor related to the saturation effect of the NDVI and EVI indices in applications on canopies with high biomass may also influence the attenuation of directional effects. In this sense, Käfer et al. (2018), when analyzing the saturation time of vegetation indices throughout the productive cycle in the same management area, concluded that the NDVI presented saturation over the canopy at the age of 18 years, while the EVI saturated its response after the plantations completed 14 years. Thus, considering the age of the cultivars in 2019, around 30 years, they are above the response saturation limit of these indices.

From the results obtained, it was possible to note that even observations outside the nadir with small variations in the VZA (less than 10°) are substantially influenced by the view angle effect, which allows us to conclude that even sensor systems with medium field of view such as Operational Land Imaging (OLI) and MultiSpectral Instrument (MSI) may be subjected to the influence of the directional effect, mainly in the backscattering direction.

IV. CONCLUSIONS

The analysis of the VI performance, in relation to sensitivity to directional effects, showed that the way they were formulated can influence the level of sensitivity to these effects. Among the analyzed VIs, although the EVI initially presents greater sensitivity to directional effects, when calculated using reflectance measurements normalized to the nadir, it has lesser influence to viewing-illumination geometry than the already corrected NDVI and WDRVI. This emphasizes the need to adopt procedures to mitigate these effects for monitoring the vegetative vigor of forest stands.

The present work also highlighted the need for studies on the spectral behavior of forest stands of species of the *Pinus* genus, as a way to broaden the understanding of the factors responsible for controlling the response of this target due to variations in illumination conditions. Almost all the studies involving acicufoliate species are limited to natural coniferous forests.

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