Accuracy of the DART model to simulate very high spatial resolution satellite images on different genotypes of *Eucalyptus* stands

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Abstract. Fast-growing *Eucalyptus* plantations cover about 5.6 million ha in Brazil, and are among the most productive forest plantations in the world. Various *Eucalyptus* genotypes is cultivated, having distinct biophysical and biochemical characteristics. The use of remote sensing images to estimate *Eucalyptus* stand characteristics is challenging, due to the lack of knowledge on how they influence the reflectance signal. This study uses the DART radiative transfer model to evaluate the effects of forest parameters on their reflectance behavior. The first step was to test the model reliability for the simulation of reflectance images corresponding to *Eucalyptus* forests. We parameterized DART to simulate reflectance images in four bands (blue, green, red and NIR), using extensive measurements from plantations with 54 months old in Itatinga (SP), Brazil. A trial including 16 contrasted genotypes was planted in 10 blocks. Inventories were conducted and leaves, trunk and litter optical properties were measured. Simulations accuracy was evaluated by comparing the mean top of canopy (TOC) reflectance of DART with TOC extracted from a Pleiades satellite image. Results showed a good performance of DART with mean reflectance absolute error lower than 2 % for all bands. The second step consisted in a sensitivity analysis to explore which stand parameters influence more canopy reflectance; LAI, leaf reflectance, trees dimensions and row azimuth were most sensitive parameters. These results open perspectives on the use of DART in inversion mode to extract parameters over spatio-temporal scales.

Keywords: remote sensing, eucalypt, radiative transfer model, 3D modeling, DART, sensoriamento remoto, eucalipto, modelo de transferência de radiação, modelagem 3D, DART.

1. Introduction

Commercial *Eucalyptus* plantations in Brazil cover 5.6 million ha, which accounts for 71.9 % of planted forests in Brazil (IBÁ, 2015). Currently, most areas are planted with several genotypes, mainly on clonal plantations, which have been tested and selected for distinct widespread soils and climatic Brazilian conditions (Gonçalves et al. 2013). These genotypes provide different phenotypes, with distinct canopy structure, leaf morphology and biochemical compounds and biomass production. Due to their high economic importance in Brazil, the understanding of how biophysical parameters of planted forests could explain the spatial-temporal growth dynamics is of paramount importance.

Radiative transfer models (RTM) explicitly take into account stand structural characteristics (tree dimensions and positions, leaf area index, leaf angle distribution, crown cover, etc.) and can simulate the quantitative value of the reflectance spectra of the canopy as observed by satellite. They are based on the knowledge of the physical laws that control the transfer and the interaction of solar radiation in a vegetative canopy (Gastellu-Etchegorry and Bruniquel-Pinel 2001). The DART - Discrete Anisotropic Radiative Transfer - model (Gastellu-Etchegorry et al. 1996; Gastellu-Etchegorry et al., 2015) is a comprehensive three dimensional model that simulates bidirectional reflectance and enables new possibilities of data analysis to evaluate, for example, canopy structure, radiative budget, photosynthesis, LAI, among others.

Despite the successful use of physical approach of DART to retrieve canopies characteristics (e.g., Couturier et al. 2008), few detailed studies have tested in forest canopy ecosystem the efficiency in the model in forward mode (Schneider et al. 2014). This first step is necessary to assess the model reliability, to further estimate biophysical parameters of heterogeneous forest stands. In this study, we parameterized DART model using an extensive in situ measurement dataset. *Eucalyptus* plantations of 16 different genotypes were used to test the accuracy of the simulations generated by DART when compared with experimental images acquired from a very high spatial resolution satellite, Pleiades. In a second step, we performed a simple sensitivity analysis to quantify the effect of the main stand parameters on the canopy reflectance. We finally discussed the use of DART for inversion studies.

2. Materials and Methods

2.1 Study site

The study site is located in Itatinga Municipality, in the state of São Paulo, southeastern Brazil, 22°58’04’’S and 48°43’40’’W. A genotype trial experiment of eucalypt was installed in November 2009 with 16 genotypes comprising several genetic origins from different enterprises and regions in Brazil. Fourteen of these 16 genotypes were clones and two had seminal origin. Planting lines were mainly east-west oriented, with plant arrangement of 3.75 m × 1.60 m (1666 trees per hectare). The experiment comprised 10 blocks, each having 16 treatments (genotypes) randomly distributed within a 4 x 4 subplot grid. Each plot within each block comprised 12 lines of 14 trees. Only the trees within the central 10 lines and 10 rows were simulated (100 trees).

2.2 *In-situ* measurements

Complete forest inventories were conducted at 6, 12, 19, 26, 38, 52, 62 and 74 months of tree age. During these inventories, crown circumference (age < 18 months), trunk diameter at breast height (DBH) and tree height were measured. Close to most of these dates, 10-12 trees were cut for each genotype to calibrate allometric relationships. Leaf angle distribution (LAD) was estimated from the leaf angles measured in the field for each genotype with a clinometer. The eucalypt stands were analyzed at the date of May, 2014 (54 months of age), corresponding to the date of satellite image acquisition, using interpolation of the field measurements between inventories at 52 and 62 months. The main characteristics of the genotypes are shown in Table 1.

Table 1. Main characteristics of the 16 genotypes on May, 2014. Average values are presented together with their inter-block standard deviations (in parenthesis). DBH is the diameter at breast height.

Genotype	DBH (cm)	Height (m)	Leaf area (m^2)	Crown height (m)	Crown diameter (m)	Leaf angle (°)	Mortality (%)
1	14.26 (4.09)	21.78 (3.66)	23.33 (17.79)	4.09 (2.15)	3.83 (3.27)	53.8 (15.0)	14.7 (4.6)
2	14.19 (4.07)	21.46 (3.42)	21.09 (16.71)	4.00 (2.14)	3.44 (2.88)	50.9 (17.0)	0.0 (0.0)
3	13.49 (2.54)	20.14 (2.10)	23.12 (11.73)	4.60 (1.24)	3.01 (1.57)	37.6 (13.9)	7.7 (5.0)
4	14.98 (3.28)	22.79 (2.22)	22.41 (14.50)	5.20 (1.56)	2.88 (1.94)	49.3 (15.2)	7.4 (2.8)
5	14.13 (2.25)	22.51 (1.73)	25.12 (10.35)	5.99 (1.27)	2.93 (0.40)	39.9 (16.5)	3.9 (3.5)
6	13.56 (2.91)	20.32 (2.65)	23.27 (13.50)	4.42 (1.57)	3.33 (2.28)	35.2 (14.7)	11.5 (6.9)
7	15.19 (2.42)	22.90 (1.92)	21.18 (8.73)	5.44 (0.71)	3.01 (1.93)	56.5 (12.6)	0.0 (0.0)
8	13.87 (2.10)	22.23 (1.90)	19.72 (7.59)	4.46 (1.01)	2.60 (1.07)	44.6 (14.7)	6.5 (4.3)
9	13.81 (2.53)	20.85 (1.70)	24.06 (11.79)	5.29 (1.13)	3.13 (1.60)	43.1 (15.7)	10.3 (12.4)
10	14.07 (1.93)	22.04 (1.59)	27.58 (10.94)	6.55 (0.79)	3.27 (2.01)	49.1 (16.5)	3.8 (3.5)
11	14.24 (2.01)	21.25 (1.27)	28.48 (12.42)	5.08 (1.32)	3.05 (2.01)	40.2 (18.4)	7.3 (5.8)
12	14.10 (2.93)	22.04 (2.90)	20.31 (10.63)	4.12 (1.42)	2.89 (2.24)	42.3 (17.2)	0.0 (0.0)
13	15.11 (3.27)	21.20 (2.97)	28.01 (17.78)	4.66 (2.11)	3.84 (3.08)	39.7 (16.3)	10.7 (6.1)
14	13.36 (2.75)	21.27 (2.39)	22.28 (12.20)	4.40 (0.86)	2.73 (0.57)	56.0 (14.0)	7.4 (3.6)
15	13.61 (2.07)	20.80 (1.65)	26.05 (9.91)	5.72 (0.62)	3.18 (1.62)	42.5 (14.0)	0.0 (0.00
16	14.78 (2.01)	21.01 (1.55)	17.50 (5.88)	4.54 (0.63)	2.35 (0.84)	64.9 (11.6)	0.0 (0.0)

Leaves, trunks and litters optical properties were measured with an ASD FieldSpecPro 4 (Analytical Spectral Devices, Boulder, Colorado, USA) spectrometer in the spectral range from 350 to 2500 nm, 71 months after planting (in October 2015). Three trees per treatment (genotypes) were selected and for each tree, leaves were collected at three crown layers (bottom, middle and top) and two horizontal positions in each layer. Litter and trunk reflectance were collected for each genotype in three different locations in the field in order to generate one composite sample per genotype and measured in the laboratory using a Contact Probe in five different points.

2.3 DART parameterization

DART was used in the so-called "ray tracking and reflectance" mode to simulate top of canopy (TOC) bidirectional reflectance images in four spectral bands corresponding to the blue, green, red and near infrared bands of the Pleiades satellite sensor. The input solar zenith and azimuth angles (respectively, θ_s and φ_s) were computed knowing the exact local latitude, date and hour of satellite overpass. Image acquisition geometry (θ_v, φ_v) was obtained from metadata of Pleiades images. All DART simulated scenes were created using the same landscape extensions (20 x 30 m) relative to the plot extensions and cell size of 0.25 cm. One scene was simulated for each of the 16 genotypes and 10 blocks at 54 months of age. The trees inside each DART scene were computed using their interpolated sizes as described before. Their exact positioning were visually extracted from a panchromatic WorldView-2 image on May, 2010 (0.5 m of spatial resolution), when trees are large enough to be clearly seen, but when their crowns do not overlap yet. For simulating tree crowns, we used the so-called DART composed ellipsoid shape (a crown with two half ellipsoids), which typically fit well with the shape of eucalyptus crown. The ellipsoidal Leaf Angle Distribution (LAD) and leaf area of each tree was computed as described before (Table 1). Leaf optical properties were parameterized based on experimental measurements per genotype and crown layer (lower, middle and upper levels). Litter and trunk reflectance were genotype-specific.

2.4 Pleiades satellite images

Very high spatial resolution multispectral image including four bands (blue: 430-550 nm, green: 490-610 nm, red: 600-720 nm and near infrared: 750-950 nm) from Pleiades satellite were used to validate DART simulations. The image was acquired on May 2014, at 13:36 GMT, with the following geometry of acquisition: φ_v =180.03°, θ_v =76.60°, φ_s =33.43°and

$\theta_s = 44.48°$. Polygons of each plot extension in the field were located in the images and were used as mask to extract the radiance of each band. Atmospheric correction was performed to compute the reflectance of the TOC images using the 6S model (Vermote et al. 1997).

2.5 Comparison between simulated and satellite images

The accuracy of the simulated reflectance TOC images from DART was checked against the TOC reflectance obtained from Pleiades images, for each of the four bands individually and each of the 16 genotypes (average of the 10 blocks). The accuracy level was expressed by the mean absolute error (MAE) (Equation 1) as suggested by Willmott and Matsuura (2005) to assess the average model performance and identify the best and worst simulated band:

$$MAE_\lambda = \frac{1}{n}\sum_1^n |R_{WV2(\lambda)} - R_{DART\,(\lambda)}| \tag{1}$$

where: $R_{WV2(\lambda)}$ is the reflectance measured by Pleiades satellite for spectral band λ, $R_{DART\,(\lambda)}$ is the reflectance simulated by DART for the same spectral band, and n is the number of samples (n=160, product of 10 blocks by 16 clones).The root mean square error (RMSE) was also computed.

2.6 Sensitivity analysis for eucalyptus plantations

A simple sensitivity analysis was performed to better understand the effect of different structural, biophysical and biochemical parameters on the simulation output. We selected one of the genotype (G3), grown in one of the block (B2). For each of the parameter listed afterwards, we exchange one by one the G3 value by the value of one other clone. For instance, the LAI of G3B2 was replaced by the one of G1B2, the DART reflectance in the four bands were computed, then a new simulation was done with the LAI of G2B2, etc. At the end, we computed the average, variance and produced a boxplot figure for each reflectance band. We repeated this procedure for LAD, leaf reflectance, trunk reflectance, litter reflectance, trees dimensions, and row azimuth. This procedure allows us to better understand the parameters that driver the reflectance variability among genotypes.

3. Results and Discussion

3.1 Optical properties

Leaves, trunk and litter optical properties are shown in Figure 1. Leaf reflectance in the middle crown layer (expanded mature leaves) for each genotype was similar between genotypes and characterized by high absorption peaks in the blue and red regions due to leaf pigments (Ponzoni and Shimabukuro, 2007). The NIR reflectance was high for all genotypes and relatively constant, with smooth absorption around 980 and 1200 nm caused by water absorption (Sims and Gamon, 2003), and an absorption peak in the water absorption band (1400 nm) in the mid infrared (MID) region. Note that the reflectance ranking between genotypes is conserved in the visible but changes further in the NIR and MID regions. Trunk reflectance showed higher difference between genotypes, as expected from the high differences in trunk color and roughness observed in the field. Interestingly the reflectance was very high in the visible and NIR regions compared to leaf reflectance. Some spectra clearly show an absorption feature in the red region because of the presence of chlorophyll pigments in the bark surface of some genotypes. Litter reflectance showed similar pattern for all genotypes, but with a high inter-genotype variability, with low reflectance in the visible region and an increasing curve along the spectrum and a mild absorption peak in the water absorption band (1400 nm). These differences in litter reflectance are related to the different composition of litter materials (e.g. green or yellowing leaves just fallen, and dead dry leaves, bark and branches).

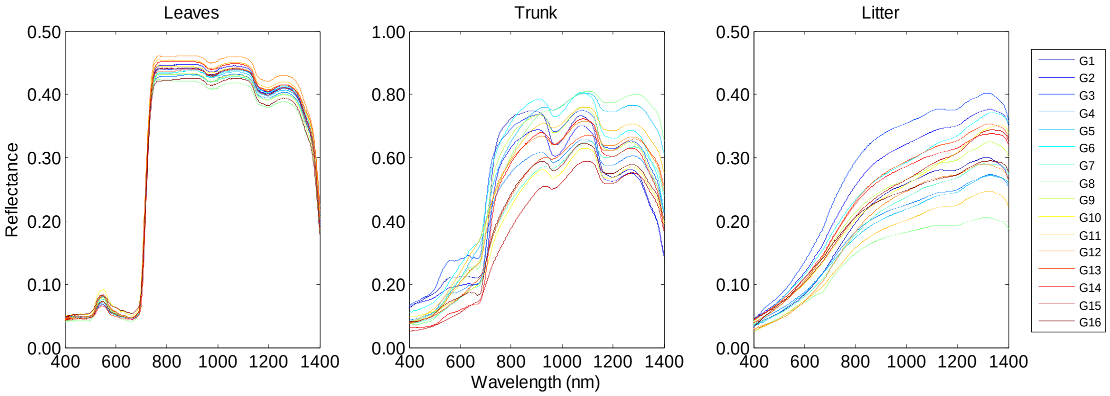

Figure 1.Leaves, trunk and litter optical properties (reflectance) for the 16 genotypes (labeled as G1 to G16) of the study area. The leaves reflectance was from the middle crown layer (expanded mature leaves).

Figure 2 shows the leaves reflectance in the green, red and near infrared bands for each crown level and genotypes. There was no significant difference between the crowns layers (ANOVA analysis under Matlab 2014b) and higher range of values in the near infrared. There were some significant differences between genotypes for each band and the highest differences were found for clones 10, 12 and 16 in the green and red bands and clones 10 and 12 in the NIR band. These statistics show that the use of different spectra for upper, middle and lower part of the canopy could be unnecessary. However, since some genotypes showed different spectra for upper layer, which is important for TOC simulation, we preferred to keep this detailed description in the simulations.

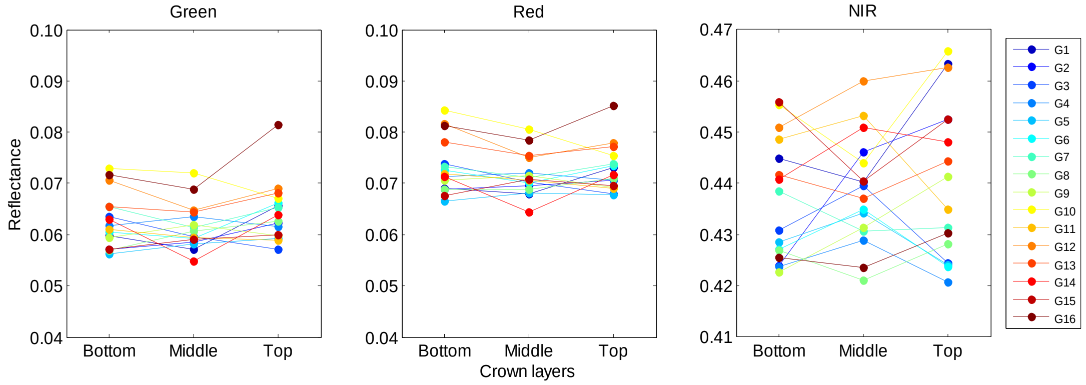

Figure 2. Leaves reflectance in the green, red and near infrared regions at bottom, middle and top crown layer for the 16 genotypes (labeled as G1 to G16).

3.2 Analysis of DART simulated images

The TOC reflectance simulated by DART and acquired by the Pleiades at the four multispectral bands for each genotype is shown in Figure 3, averaged by genotype. In general, the mean TOC reflectance from DART simulations showed a good agreement with the mean TOC reflectance of the Pleiades images for all four bands and genotypes. Discrepancies were found mainly for the blue band (430-550 nm) for all genotypes, and some discrepancies appeared in the near infrared band (750-950 nm) for some genotypes (e.g., genotypes 7, 8 and 14). A numerical comparison between the reflectance simulated by DART and acquired by Pleiades images was performed using the MAE and RMSE for all blocks and genotypes. The MAE values were 0.0179, 0.0062, 0.0167 and 0.0183 and the RMSE were 0.00179, 0.00305, 0.00209, 0.0321, respectively, for the bands blue, green, red and near infrared. MAE and RMSE values were very low, which corroborate the results of Figure 3. The lowest values were found for the bands in the visible and higher for the near infrared. It could be explained by the fact that the differences between genotypes were very large for trunk and litter optical properties than leaves, and the bands in the near infrared are more subject to computation of scattering and, therefore, more sensitive to LAI. Besides, the reflectance in these bands has different deviances absolute values, smaller for the visible than NIR bands.

In terms of bi-directional TOC reflectance, the comparison between simulated and real satellite images from forest stands is a difficult task, since the average signal of the image is dominated by the macroscopic properties of the illuminated and shadowed crowns as well as ground surface (Couturier et al., 2008). Considering this aspect, the pixel size and model ability to assess the elements of forest heterogeneity of the crown and the understory spectral signature are important factors. In this study, the pixel size of 0.25 m and the massive input information of trees were as much as possible representative of the reality of stands, which gave good agreement between simulated reflectance at TOC level and TOC reflectance from Pleiades.

Our results confirm the ability of DART to simulate remote sensing data under several eucalypt forest conditions. Therefore, it may be possible to take advantage of this ability to analyze the effect of biophysical parameters, such as LAI, photosynthetically absorbed radiation and leaf angle, over real and hypothetical spatio-temporal field situations and trees structures.

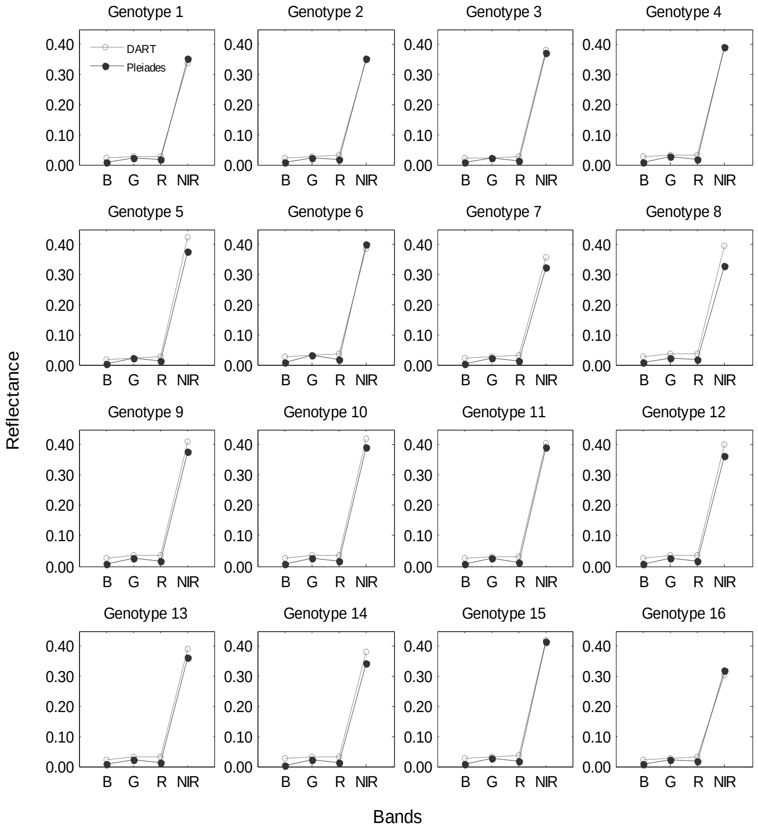

Figure 3. DART (light gray) and Pleiades (dark gray) mean top of canopy (TOC) reflectance of four bands (B=blue, G=green, R=red, NIR=near infrared) for each genotype

3.3 Sensitivity analysis for eucalyptus plantations

The results of the sensitivity analysis of the simulated reflectance for the blue, green, red and NIR bands according to stand parameters (LAI, LAD, leaf reflectance, trunk reflectance, litter reflectance, trees dimensions and row azimuth) are presented in Figure 4. Genotype 3 in the block 2 was used as reference, since it is the most planted clone in the area. LAI, leaf reflectance, trees dimensions and row azimuth had the highest sensitivity and explain most of the difference between genotypes in the visible bands. Trunk and litter reflectance and LAD showed the weakest sensitivity in these bands. NIR band showed the most similar reflectance results among the replacing tests, and showed the highest inter-genotype standard deviations compared to the others bands. The higher influence of the LAD, trunk and litter reflectance parameters in the NIR band can be explained by the higher canopy penetration capabilities in this region (Houborg et al. 2007).

Numerous studies have proved that vegetation reflectance is strongly affected by LAI (Shi et al 2016; Xiao et al. 2014). The leaf reflectance, which represents the different leaves pigments contents, is another important factor that drives the canopy reflectance, mainly in the visible region. These results are in agreement with Xiao et al. (2014), which performed a sensitivity analysis of vegetation reflectance and found more influence of leaves pigments content in the visible and LAI in the NIR regions at canopy scale. They also showed a weak effect of leaf angle in this scale.

The geometric parameters of the trees - mainly crown dimensions that is correlated with LAI - also strongly influences the canopy reflectance of forest stands (Rautiainen et al 2004). This influence is mainly observed in the NIR domain (Figure 4). Furthermore, the presence of empty spaces (dead trees) in some of the plots increased canopy heterogeneity, which also increased the contribution of this parameter to the variability of reflectance. The gaps created by these dead trees, in association of the high variability of the blocks orientation (with different rows and inter-rows spatial distribution of the plots), contributed for a higher shaded/illuminated effect between the trees and, consequently, lead to a higher sensitivity of the row azimuth.

These results confirm the relevance of using 3D models such as DART, as they are particularly suitable to explicit the influence of tree shape, leaf pigments and plot heterogeneity on the canopy reflectance. It corroborates the necessity of using this type of modeling to provide relations between biophysical variables and reflectance of forest stands.

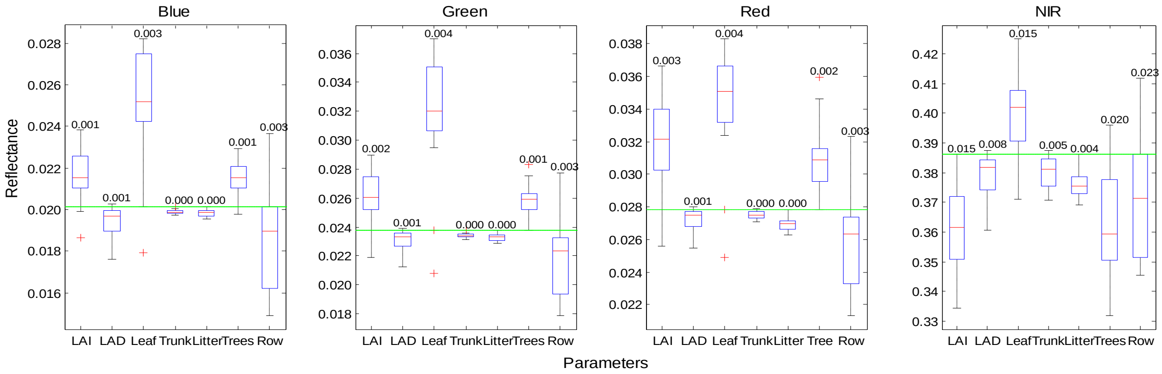

Figure 4. Sensitivity analysis of the reflectance in blue, green, red and near infrared bands relative to stand parameters (respectively, LAI, LAD, leaf reflectance, trunk reflectance, litter reflectance, trees dimensions and row azimuth). Dashed green line represents the reflectance of the genotype 3 (reference). Numbers above each boxplot are the standard deviation.

Further step will be to simulate a comprehensive database along forest growth stages, and use this database to estimate some variables such as the LAI through inversion procedures.

4. Conclusion

In this study we developed a validation approach of DART model potential for simulating reliable reflectance spectra of several *Eucalyptus* genotypes. The mean top of canopy (TOC) reflectance from DART simulations showed a good agreement with the mean TOC reflectance of the Pleiades images for all four bands and genotypes (low MAE, <2%). The use of a large structural and spectral database to parameterize the model has shown to be efficient for simulating the reflectance. Some of the parameters tested here showed moderate sensitivity on simulated reflectance, which is the case for trunk and litter reflectance. Therefore, average values could have been chosen for these parameters. In contrast, canopy reflectance showed high sensitivity to LAI, leaf reflectance, trees dimensions and row azimuth. Our results suggest that DART is suitable for realistic simulation of the reflectance based on forest biophysical parameters over real dataset. Since DART is a physically based model, its ability to simulate reflectance on other eucalyptus ages or stands is comforted. It allows better understanding of the link between ecosystem characteristics and the reflectance behavior, and opens perspectives for the development of methods for the estimation of vegetation properties e.g. eucalyptus LAI based on simulated reflectance.

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