Canopy Structural Effects on Bidirectional Reflectance Simulated by the LESS model: A Case Study of *Picea Crassifolia* Forests

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ABSTRACT:

Surface albedo is a dominant factor affecting the earth energy balance. Bidirectional reflectance distribution function (BRDF) describes the anisotropic surface reflection of solar radiation. Bidirectional effect is especially noticeable in the forest canopies with three-dimensional canopy structure. Thus, it is challenging to evaluate the canopy structural effects on BRDF using traditional radiative transfer modelling methods, where leaf in canopies is generally assumed to be homogeneous. LESS, a ray-tracing-based three-dimensional (3D) radiative transfer model can effectively simulate bidirectional reflectance factor while fully considering multi-component spectral and structural characteristics of vegetation. In this study, we applied the LESS model to evaluate the impacts of changes in leaf area index (LAI) on canopy reflectance in a *Picea crassifolia* forest. First, canopy structural parameters obtained from forest inventory were used to construct forest scenes and drive the LESS model. Then, we validated the simulation accuracy of the LESS model against BRDF calculated from MODIS BRDF parameter product using kernel-driven Ross-Li bi-directional reflectance function. Finally, we constructed forest scenes with different LAI to investigate the canopy structural effects on BRDF. We found that the BRDF simulated by the LESS model is in good accordance with the MODIS BRDF data in the red (R^2 = 0.97, RMSE = 0.03) and NIR (R^2 = 0.94, RMSE = 0.05) bands. The simulated canopy reflectance in the red band displayed ‘dome’ shape and decreased with increasing LAI. In contrast, canopy reflectance in the NIR band displayed ‘bowl’ shape and increased with increasing LAI. Our study highlighted the sensitivity of canopy BRDF to changes in canopy structure and have implications for retrieving LAI from BRDF data.

1. INTRODUCTION

Albedo is defined as the ratio of the integration of surface energy in hemispheric space to solar radiation, which is an important factor in evaluating the surface energy balance and global climate change (Dickinson, 1983). Vegetation plays an important role in regulating the terrestrial surface albedo. Different wavebands and angles of solar energy are reflected by the vegetation differently. The bidirectional reflectance distribution function (BRDF) is defined as the ratio of outgoing radiance to incident irradiance at a point in the vegetation canopy, which describes the directional reflectance characteristics of the vegetation canopy. BRDF determines the surface albedo (i.e., the ratio of surface reflection to incident radiation) and is closely related to the global energy, carbon, and water cycles (Li et al., 2020), and is an important remote sensing monitoring parameter for Sustainable Development Goals (SDGs). The 3D structure of the forest canopy is complex, and the BRDF effect is significant. Among different vegetation types, forests have attracted the interest of many researchers due to its complex canopy structure. Neglecting the BRDF effect and assuming surface Lambert or replacing albedo with zenith albedo will result in errors of up to 45–60% (Gao et al., 1998).

Leaf area index (LAI) is a key canopy structural and biophysical parameter required in most terrestrial ecosystem models. LAI is defined as the one-sided green leaf area per unit of horizontal ground surface area (Chen and Black, 1992). Thus, LAI is tightly linked to photosynthesis, respiration, transpiration, and canopy light interception and is a key parameter used to simulate the carbon, water, and energy cycles between the terrestrial ecosystem and the atmosphere. Several studies have demonstrated that canopy reflectance is sensitive to changes in LAI (Li et al., 2015; Pu et al., 2020; Sun et al., 2017). The BRDF models follows physical laws and completely considers radiation transfer and interaction within the canopy, providing direct connection between biophysics variables and canopy reflectance. Generally, BRDF models can be classified as three different categories. The first category is the physically based radiative transfer (RT) models. RT models are based on the mechanistic process of light absorption, scattering, and reflection in a homogeneous medium. Thus, RT models are appropriate for simulating canopy reflectance in relative homogeneous vegetation canopies, such as croplands and grasslands. However, between- and within-crown gaps exists in forests. Thus, forest canopies generally deviate from random or uniform distribution and violates with the ‘homogeneous’ hypothesis of 1-D radiative transfer models.

The second category is the geometric optical (GO) models. GO models are based on the light and shadow surfaces produced by direct sunlight-exposed vegetation and assume that the radiant brightness values recorded by the sensor are composed of four components, which are sunlit background, shaded background, sunlit canopy, and shaded canopy (Li and Strahler, 1986). GO models are primarily developed for forests and assume that a forest canopy is composed of trees with a simple geometry with known geometry (e.g., cylinder, ellipsoid, cone, and sphere) and optical properties. In GO models, the geometric projection features of the vegetation canopy may be employed to estimate

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the BRDF characteristics. GO models considers between- and within-crown gaps and could be applied to simulate the bi-directional canopy reflectance of dense and open forests. However, GO models still assume that trees are distributed randomly, which cannot accurately consider the detailed structure and distribution characteristics of the canopy, which is also inapplicable to dense vegetation canopy with overlap. With the rapid advancement of remote sensing technology, collecting high-resolution multi/hyper-spectral and multi-angle images has grown simpler, so the GO model can no longer match the requirement for high-precision signal processing.

The third category is the 3-D radiative transfer (3-D RT) models based on ray-tracing technology. The 3-D RT models are characterized by simulating the entire vegetation geometry and optical properties, depicts the effect of various morphological and growth structure characteristics of vegetation on light action and may consider the reflection, transmission, and multiple scattering processes of lighting interaction with canopy components in great detail. However, it is constrained by the processing power and complexity of the situation. Thus, there are substantial uncertainties in studying the relationships between changes in canopy structure and canopy reflectance. LESS (LargE-Scale remote sensing data and image Simulation framework) is a newly developed 3-D RT model (Qi et al., 2019), that can accurately and efficiently simulate multispectral and multiangle images and radiation properties of complex realistic landscapes. The accuracy of LESS is evaluated with other models as well as field measurements in terms of directional BRFs and pixel-wise simulated image comparisons, which show very excellent agreement. The primary inputs of the LESS model are the 3-D structure (e.g., tree height), component spectrum (e.g., leaf reflectance), sun-sensor geometry, and illumination parameters (e.g., skylight proportion) of the scene. LESS can simulate the transmission process (absorption, reflection, and transmission) of incident light in a scene based on a ray-tracing strategy and output the corresponding simulated variables (such as directional reflectance, albedo, LAI, and so on) (Yan et al., 2022). Due to the high computation efficiency, solid theoretical foundation, and well-assessed accuracy, the output of the LESS model can be used as a benchmark for various applications in remote sensing (Chen et al., 2019; Jiao et al., 2019; Yan et al., 2020). As a result, the development of the LESS model provides a new chance to investigate the BRDF characteristics of the forest canopy.

Based the on above analysis, this study used the canopy structure information of *Picea crassifolia* measured by the Watershed Allied Telemetry Experimental Research (WATER) as an example and applied the LESS model to design 3D scenes of forest canopy with consideration of canopy structure, tree distribution, and component optical properties. In this study, we mainly address the following two questions. First, how accurate can LESS simulate canopy BRDF in compare with satellite observations. Second, how do canopy BRDF change with LAI in two typical optical bands, i.e., the NIR and Red bands. By answering these questions, our study would help us better understand the accuracy of the LESS model and influence of LAI on canopy reflectance.

2. MATERIALS AND DATA

2.1 Field Data

The study site is Dayekou Guantan forest station (100°15’E, 38°32’N, 2835m), which was located in Heihe river basin in Zhangye, Gansu, China (Li et al., 2013). All the site-level input data for the LESS model were obtained from the Watershed Airborne Telemetry Experimental Research (i.e., WATER) during June 2 and June 10, 2008. The true LAI and clumping index (Ω) (Chen, 1996) of the study site were measured by the Tracing Radiation and Architecture of Canopies optical instrument (TRAC, Natural Resources Canada, Canada Centre for Remote Sensing, Saint-Hubert, QC, Canada) (Chen and Cihlar, 1995). In addition to LAI, four additional canopy structural parameters were also measured for single trees at the study site, including crown diameter, tree height, trunk height, and diameter at breast height (DBH). A laser altimeter (TruPulse 200, Laser Technology Inc. (LTI), Norristown, PA, USA) was used to measure the height of trees in the forest station. Single tree forest inventory data were used to provide a priori knowledge of canopy structure parameters to parameterize the LESS model.

2.2 MODIS MCD43A1 Product

The Moderate Resolution Imaging Spectroradiometer (MODIS) MCD43A1 Version 6 Bidirectional Reflectance Distribution Function and Albedo (BRDF/Albedo) model parameters dataset is produced at daily temporal scale and 500-m spatial resolution (https://appeears.earthdatacloud.nasa.gov/). In this study, long time series MODIS data covering the study area was selected for model validation. More specifically, MCD43A1 data with good quality between January 2000 and December 2020 were downloaded for model validation purposes. The red band and the near-infrared (NIR) band are two typical spectral bands, which are most commonly used for studying vegetation optical characteristics. Thus, we selected the red and the NIR bands to study the relationship between canopy BRDF and LAI. The canopy BRDF at the NIR and the red band were calculated from MCD43A1 data in band 1 (red, 620-670 nm) and band 2 (NIR, 841-876 nm) using the RossThick-LiSparse-Reciprocal (RTLSR) semi-empirical kernel-driven BRDF model (Schaaf et al., 2010, 2002).

2.3 RossThick-LiSparse kernel-driven BRDF model

The MODIS BRDF model parameters product (MCD43A1) includes the results of fitting 16-day pixel-wise reflectance observations to the RTLSR model (Schaaf et al., 2010, 2002). using three parameters (i.e., f_{iso} , f_{vol} , and f_{geo}), each one characterizing a different surface scattering process (Lucht et al., 2000). The first parameter, the isotropic parameter f_{iso}, describes Lambertian reflectance. The RTLSR model suggests a constant diffuse reflection, which is an intrinsic property of the surface independent of the sun and observation geometry. The second parameter, the volumetric parameter f_{vol}, describes intra-crown volume scattering by leaves in the canopy. The value of f_{vol} is sensitive to the optical properties and volume density of leaves in canopies. The third parameter, the geometric parameter f_{geo}, describes the mutual shadowing effects of canopy gaps or protrusions. The geometric and volumetric terms are functions of the sun and viewing geometry, while the isotropic term Is independent of either.

The MCD43A1 product provides weight parameters for seven bands associated with the RTLSR model, which describes surface reflectance anisotropy. For a given red and NIR band in the MCD43A1, the corrected reflectance can be computed using such three parameters (i.e., f_{iso}, f_{vol}, and f_{geo}), the solar zenith angle (i.e., θ_s), the view zenith angle (i.e., θ_v), and the relative azimuth angle (i.e., ϕ). We modelled canopy reflectance at nadir-view (i.e., θ_v=0, ϕ =0). The RTLSR model uses the following equation to calculate canopy BRDF (Roujean et al., 1992):

$$BRDF(\theta_s,\theta_v,\phi,\lambda) = f_{iso}(\lambda) + f_{vol}(\lambda)\,K_{vol}(\theta_s,\theta_v,\phi,\lambda) + f_{geo}(\lambda)K_{geo}(\theta_s,\theta_v,\phi,\lambda) \quad (1)$$

where $BRDF(\theta_s,\theta_v,\phi,\lambda)$ is the directional reflectance at band λ; K_{vol} and K_{geo} are the volumetric scattering kernel (RossThick kernel) and geometric optical kernel (LiSparse Reciprocal kernel), respectively. K_{vol} and K_{geo} are functions of solar zenith angle (θ_s), view zenith angle (θ_v), and relative azimuth angle (ϕ); $f_{iso}(\lambda)$, $f_{vol}(\lambda)$, and $f_{geo}(\lambda)$ are the weights for the isotropic, volumetric, and geometric kernels at band λ, respectively. The Ross-Li model can simulate directional reflectance at any specified illumination and view angle. Parameters for the RTLSR model were listed in Table 1.

*SZA, VZA, RAA are solar zenith angle θ_s, view zenith angle θ_v, and relative azimuth angle ϕ.

*Red and NIR bands are band λ.

Observation Time	Model	Bands	Fitting Parameters		
			f_{iso}	f_{vol}	f_{geo}
SZA=40° VZA=40° RAA=0°	RTLSR	Red	0.1141	0.0621	0.0289
		NIR	0.2333	0.1324	0.0573

Table 1. Kernel parameters (f_{iso}, f_{vol}, f_{geo}) retrieved by RTLSR model using the MODIS MCD43A1.

2.4 LESS Model

The single tree is the basic unit of the forest. Although single trees differ, single trees of the same species have structural similarities. To represent single trees with similar structures in various simulation scenarios, we employed a standard single tree model (Figure 1). Comparable trees have similar branching and leaf dispersion features in general. Based on the WATER ground-measured data, this study obtained the single tree structural parameters inputted in the LESS model to determine the structural parameters and limit the number of control structural parameter variables during the construction of the single tree model: crown shape, crown height, crown diameter, trunk height, diameter at breast height (DBH), single leaf area, leaf number, and leaf angle distribution (LAD) (Table 2).

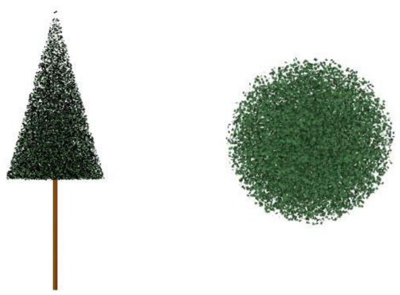

Figure 1. The single tree model is constructed by LESS, with the front view on the left and the top view on the right.

Parameter	Unit	Value
Crown Shape	–	Cone
Crown Height	m	5.58
Crown Diameter	m	3.24
Trunk Height	m	3.68
DBH	m	0.14
Single Leaf Area	m^2	0.0025
Leaf Numbers	–	25000
LAD	–	Spherical

Table 2. Single tree structure parameters.

2.5 Canopy Reflectance Simulation

In this study, the structural and optical characteristics of the *Picea crassifolia* forests at the WATER station were collected as the research purposes. We generated the canopy 3D scene and calculated the canopy BRDF using the LESS model. The accuracy of the LESS model in simulating canopy reflectance is validated against that calculated from MODIS MOD43A1 data.

We also compared canopy reflectance simulated under different LAI conditions using the LESS model (Figure 2). LAI typically ranges from 2 to 6 m^2/m^2 for forests, which could represent the major forest conditions throughout the world (Hu, 2019). Thus, we simulated the canopy BRDF at the red and NIR bands by changing LAI to 2.0 m^2/m^2, 4.0 m^2/m^2, and 6.0 m^2/m^2, with all other parameters maintained constant (Table 3). All canopy reflectance simulations were performed along the solar principal plane as shown in Figure 2.

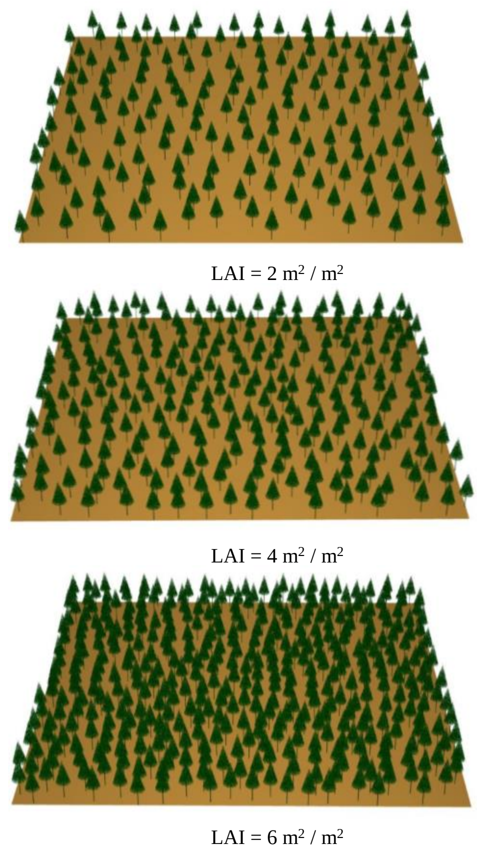

Figure 2. LAI scenarios based on LESS model simulation.

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*Abbreviations include leaf area index (LAI), bidirectional reflectance distribution function (BRDF), view zenith angle (VZA), view azimuth angle (VAA), solar zenith angle (SZA), and solar azimuth angle (SAA).
*VZA step of 10° from -60° to 60°, negative and positive VZAs represent the backward and forward observation directions, respectively.
*The optical properties of the leaves and soil were set as the default configuration of the optical database in the LESS.

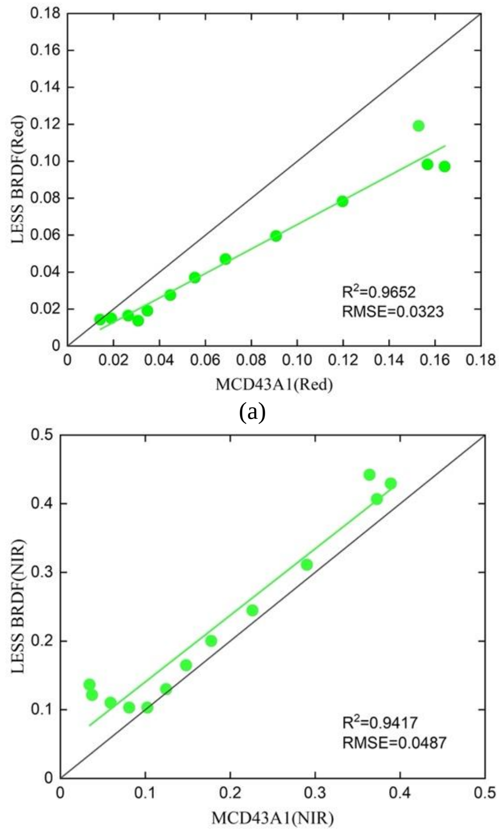
Scene	Unit	1	2	3
LAI	m^2 / m^2	2	4	6
BRDF Type	_	Lambertian	Lambertian	Lambertian
Terrain	m × m	100×100	100×100	100×100
Pixels	m × m	500×500	500×500	500×500
Bands	_	Red / NIR	Red / NIR	Red / NIR
VZA	°	-60, 60; 10	60, 60; 10	60, 60; 10
VAA	°	90	90	90
SZA	°	45	45	45
SAA	°	90	90	90
Branch Reflectance	_	0.11 , 0.48	0.11 , 0.48	0.11 , 0.48
Soil Reflectance	_	0.19 , 0.35	0.19 , 0.35	0.19 , 0.35
Leaf Reflectance	_	0.06 , 0.48	0.06 , 0.48	0.06 , 0.48
Leaf Transmittance	_	0.06 , 0.49	0.06 , 0.49	0.06 , 0.49

Table 3. Simulation parameter design.

3. RESULTS

3.1 Evaluation of LESS Model Performance

The canopy BRDF simulated by the LESS model was validated against the MCD43A1 BRDF at 500 m resolution in this research. Figure 3 (a) shows the results of the comparison of the simulated BRDF and MCD43A1 BRDF at the red band with an RMSE of 0.03 and an R^2 of 0.97. Figure 3 (b) shows the results of the comparison of the simulated BRDF and MCD43A1 BRDF at the NIR band with an RMSE of 0.05 and an R^2 of 0.94. The validation results indicated that the LESS model could simulate the canopy reflectance accurately and in consistency with satellite observations.



(b)

Figure 3. Comparison of the simulated BRDF by the LESS model and MCD43A1 BRDF in the (a) red band and (b) NIR band.

Figures 4 illustrated the BRDF in red and NIR bands simulated by the LESS model and that calculate from MCD43A1 data using the RTLSR model. The BRDF simulated by LESS and the MCD43A1 BRDF is asymmetric in the red and NIR bands along the principal plane. Canopy reflectance in the backward direction (with VZA < 0°) is lower than that in the forward direction (with VZA > 0°). It is worth mentioning that both model simulations and satellite observations indicate strong hot-spot effect and bowl-edge effect. The hot-spot effect means that canopy reflectance reaches the maximum value when viewing from the sun direction (i.e., VZA = SZA = 45°). The canopy reflectance simulated by LESS and the MCD43A1 canopy reflectance first increase with VZA from -60° to 45°, and then the BRDF simulated by the LESS model decreases next and increases with VZA from 45° to 60°. However, the BRDF of MCD43A1 is increasing with VZA from 45° to 60°. The bowl-edge effect means that canopy reflectance would reach relative high values when VZA is large (e.g., -60° and 60°). In addition, the BRDF simulated by LESS is lower in the red band than MCD43A1, but higher in the NIR band. For example, the hot-spot canopy reflectance at red band and NIR band simulated by the LESS model is 0.12 and 0.44, respectively. The hot-spot canopy reflectance at red band and NIR band based on MCD43A1 data is 0.15 and 0.36, respectively.

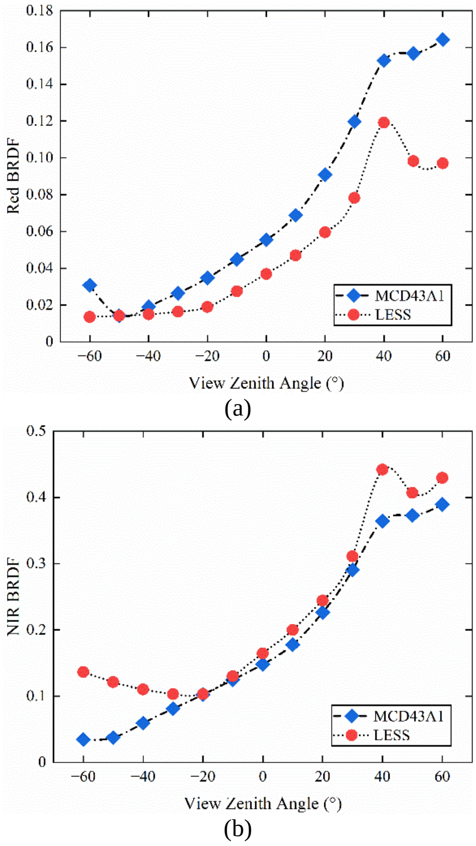


Figure 4. Comparison of the simulated BRDF by the LESS model and MCD43A1 BRDF along with the VZA in the (a) red band and (b) NIR band.

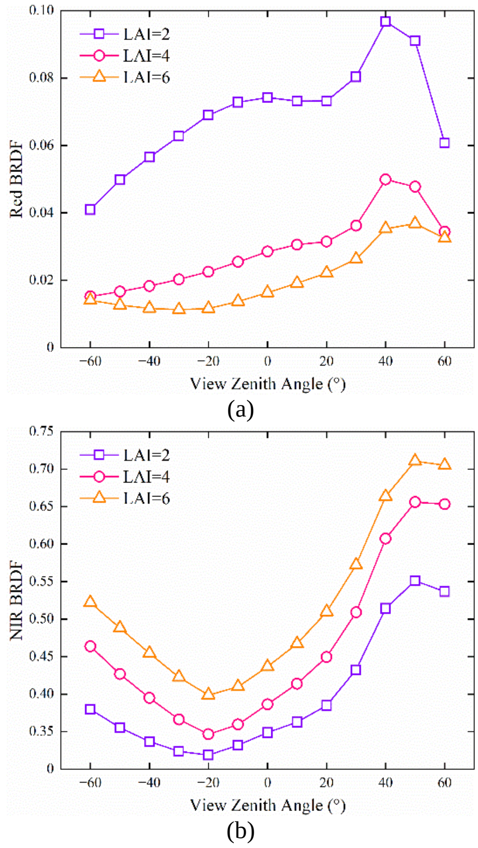


Figure 5. BRDF simulated the LESS model along with the increased LAI against the VZA in the (a) red band and (b) NIR band. LAI was gradually increased from 2 m^2/m^2 to 6 m^2/m^2 with a data change interval of 2 m^2/m^2.

3.2 LAI Effect on Canopy BRDF

We then applied the LESS model to simulate the canopy reflectance with varying LAI in the principal plane of the red and NIR bands. According to LESS simulations, canopy BRDF in the red band looks like a dome shape, while canopy BRDF in the NIR band looks like a bowl shape. The model simulated BRDF displayed strong hot-spot effect in both the red and NIR bands.

Figures 5 showed that when the LAI increases, the BRDF in the red band decreases, while the BRDF in the NIR band increases. Changes in BRDF at canopy-scale matches with the typical leaf optical properties for healthy green canopies in different spectral bands. In the NIR band, leaf reflectance is high, thus, canopy BRDF increases with increasing LAI due to strong scattering effect. In contrast, leaf strongly absorbs most of the solar radiation in the visible spectrum (such as the red band). Thus, canopy BRDF decreases with increasing LAI in the red band. These findings demonstrated that the LESS model can be used to study the relationship between canopy reflectance and LAI. LAI and other canopy structure parameters are not independent in the model, thus, these results only indicated that the LESS model had the same characteristics in the valid range of the input parameters.

4. DISCUSSION AND FUTURE WORK

The results indicated that the BRDF simulated by the LESS model matched well with the MODIS BRDF data (Figures 3). The R^2 and RMSE were 0.97 and 0.03 in the red band, and 0.94 and 0.05 in the NIR band, respectively. The relatively high R^2 and low RMSE indicated that the LESS model could accurately simulate canopy BRDF. However, there still existed some inconsistency between the MODIS BRDF data and the BRDF simulated by the LESS model (Figures 4). This was partly due to the scale effect. For example, the simulated BRDF was directly related to the field-measured data, which only represented a 100 m×100 m scene. However, the spatial resolution of the MCD43A1 BRDF products is only 500-m, and such mismatched pixel sizes might cause some uncertainties. In addition, model simulations were only an approximation of the real world, and the LESS model adopted several assumptions and simplifications. For example, the reflectance simulation was assumed to be a Lambertian reflection, but in fact, most are non-Lambertian reflections. Wind and clouds were also atmospheric variables that might be neglected. Even so, the LESS model clearly illustrated the hot-spot effect of the multi-angle canopy reflectance, including the dome effect in the red band and the bowl-edge effect in the NIR band.

The LESS model enabled the estimation of LAI for different scenes directly and rapidly, which supported the analysis of the LAI effect on canopy reflectance. The LAI is one of the most significant canopy structure parameters, influencing the vegetation canopy reflection characteristics. The LESS model was used in this study to simulate canopy reflectance under varying LAI. However, we assumed that there was no shielding and that the tree crowns were distributed uniformly. We also did not consider changes in leaf angle distribution (LAD) (Xie et al., 2017). This study also did not focus on studying how the underlying surface reflectivity impact canopy reflectance (Li et al., 2021), which pointed to the direction where further improvements could be considered. The comprehensive impact of LAD, clumping index and LAI on canopy reflectance will be considered and analysed in the future.

5. CONCLUSIONS

In this study, a ray-tracing based 3D radiative transfer model LESS was applied to create a single tree model to simulate canopy reflectance based on the canopy structural features of *Picea crassifolia* forests collected in field. The simulated directional canopy reflectance in the red and NIR bands in the principal plane was validated against satellite observations. LAI is one of the most essential factors influencing vegetation canopy reflectance characteristics; thus, this research further utilized the LESS model to analyse leaf quantity change effect on canopy reflectance under varying LAI scenarios in the principal plane.

The results showed that the LESS model is highly consistent with MODIS MCD43A1 in capturing the BRDF effect of forest canopies, indicating that LESS is feasible for simulating canopy reflectance and studying how changes in LAI impact on canopy BRDF. In the red and NIR bands, canopy BRDF simulated by the LESS model at hot-spot first decreased and then increased with strong bowl-edge effect at large view zenith angles. As the LAI increases, the canopy BRDF decreased in the red band but increased in the NIR band. The BRDF of forest canopies showed strong hot-spot effect in the red and NIR bands. However, the red BRDF presents a dome shape while the NIR BRDF exhibits an evident bowl shape. Although the LESS model can efficiently simulate canopy BRDF, however, due to the simplification and abstraction of a portion of the scene structure when using the single tree model to construct forest scenes for reflectance simulation, the simulation results still have some differences from the satellite observations. This study suggests that the LESS model generally well captured canopy BRDF and can be used to further study the impacts of additional elements, such as terrain, tree type, and light conditions, that affect canopy reflectance in the future.

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