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LEAF AGING AFFECTS THE VARIABILITY OF CANOPY REFLECTANCE WITH STAND DEVELOPMENT IN EVERGREEN CHINESE FIR PLANTATION

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ABSTRACT

Despite the long-term records of satellite observations, factors controlling the seasonal and interannual variations in canopy reflectance remain poorly understood. Leaf optical properties (LOP, including leaf reflectance and transmittance) changes as leaves age, and thus impact the seasonal pattern of canopy reflectance, i.e., the “leaf age effect”. Here, we combined the Geometric Optical Radiative Transfer (GORT) model with continuous field measurements of leaf- to stand-scale characteristics to simulate canopy reflectance in a Chinese fir plantation with stand development (1-33 yr).

We found that canopy structure controls the variations in canopy reflectance during young stages (<10 yr) and that leaf age controls the variations in canopy reflectance after canopy closure. Moreover, we found that the “leaf age effect” get enhanced with stand development, with R^2 increased from about 0.1 to 0.56, 0.67, 0.92, and 0.82 for young, half-mature, near-mature, and mature stages, respectively. This study reveals the stand age dependence of leaf age effect on canopy reflectance which improves our interpretation and understanding of satellite observations to study the ecosystem function of forests.

Index Terms: leaf age, leaf optical properties (LOP), stand age, canopy structure, canopy reflectance

1. INTRODUCTION

Evergreen forests make up a large portion of forest ecosystem in the world, and play a vital role in ecosystem goods and services that are essential for human well-being. Remote sensing (RS) is the only viable approach to monitor the spatiotemporal dynamics of forests over large areas [1, 2]. Due to its unique feature of perpetual greenness, understanding the factors that contributes to the seasonal and interannual variation of evergreen forests canopy dynamics to remote sensing signals are critical to infer their ecosystem functions.

Leaf optical properties (including leaf reflectance and transmittance) displayed strong age-dependence due to development in leaf intercellular structure, decrease in water content with leaf aging process, and increasing pigments with new leaf maturation process [3]. Such age dependence of LOP widely exists across different biomes and growing environment [3-7]. The “leaf age effect”, refers to the change in canopy reflectance due to changes in leaf optical properties (LOP, including leaf reflectance and transmittance) caused by the flushing of new leaves and aging of mature leaves. However, the importance of the “leaf age effect” at canopy scale are rarely explored with only a few exceptions [7, 8].

Earlier studies found dependence of canopy spectral signals on stand ages [9]. However, how canopy structure and leaf age jointly affect the inter- and intra-annual dynamics in canopy reflectance with forest successional stages remains poorly understood. Our limited knowledge in how leaf age-dependent LOP affect canopy spectral reflectance at different stand stages calls for more robust biophysical interpretation of long-term RS signals in evergreen forests.

2. STUDY AREA AND DATA

2.1. Permanent Chinese fir plots with annual forest inventory data

Our study is conducted in pure Chinese fir forests located in southern China (26° 40′ N, 109° 26′ E). Four permanent plots (i.e., ZH1, FZ1, WS2, and WS3), planted in 1983, 1983, 1996, and 1988, respectively, were selected for research purposes. ZH1 is selected as the main plot to estimate canopy reflectance dynamics. FZ1, WS2, and WS3 are auxiliary plots which provide supplement long-term forest inventory data (diameter at breast height (DBH), tree height (H), and leaf area index (LAI)) and canopy satellite observations for validation.

Trees in our study sites grows naturally except for a few management measures. Chinese fir stands can be classified into the following five growing stages: young (1-10 yr), half-mature (11-20 yr), near-mature (21-25 yr), and mature (>25 yr) forests. Chinese fir needles at four ages (0 a, 1 a, 2 a, and 3 a) co-exist in canopies. In the following text, we designate unit “a” for leaf age and “yr” for stand age.

2.2. Leaf spectral measurements

Green Chinese fir shoots at four age classes (0 a, 1 a, 2 a, and 3 a) were collected every month during the 2017 growing season. Leaf reflectance and transmittance spectra from 350 nm to 2500 nm were measured using a field portable spectroradiometer (HR-1024, Spectra Vista Corporation, New York, USA). A total of n groups of 0 a (n = 22, 15, 26, 30, 37, and 35) and 1-3 a (n = 20, 4, 31, 22, 32, and 45) needle samples were measured on 4th May, 24th June, 28th July, 18th September, 13th October, and 15th December, respectively. Each bundle sample includes 7 to 10 needles. We primarily focused on the visible (400-700 nm) and NIR (700-900 nm) spectra throughout the study. According to difference significance test (Paired Sample t-Test) for the average leaf spectra for needles from 0 a to 3 a (Figure 1). We simplified the leaf age into two age groups, i.e., new (0 a) and mature (1-3 a) leaves. The average LOP were estimated from measured LOP by interpolating leaf area proportions for new and mature leaves with phenology.

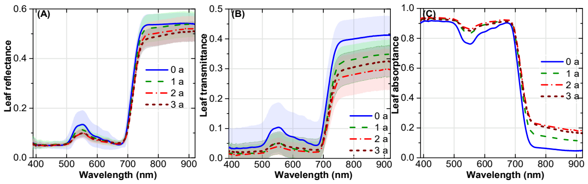

Figure 1. Leaf reflectance, transmittance, and absorptance spectra for 0-3 a leaves

3. METHODOLOGY

The GORT model simulates forest canopy reflectance based on canopy structure and spectral signatures of four scene components (sunlit background and canopy and shaded background and canopy) [10, 11]. We can simulate the impact of age dependence of LOP and canopy structure on canopy directional reflectance under given sun-sensor geometry. The canopy structural parameters needed as inputs to GORT were listed in Table 1.

Table 1. Canopy structure parameters needed for the GORT model to simulate canopy reflectance

Symbols	Parameters	Source	Frequency
	Canopy Structure Parameters		
h1	lower boundary of canopy center height (m)	FI[1]	Y[4]
h2	upper boundary of canopy center height (m)	FI	Y
R	horizonal mean crown radius (m)	FI	Y
b/R	crown spheroid ellipticity	1.17 (O[2])	-
λ	tree stem density (trees/m^2)	FI	Y
FAVD	foliage area volume density (m^2/m^3)	3-PG[3]+ FI	M[5]
k	extinction coefficient	Campbell [12]	-
	Component Spectral Parameters		
r_L	leaf reflectance	O	M
t_L	leaf transmittance	O	M
r_b	soil/background reflectance	O	M

[1] FI stands for data derived from forest inventory data.[2] O stands for field observations.[3] FAVD is calculated from LAI estimated by a forest growth model (3-PG) [13] and crown volume estimated from forest inventory data; [4] Y and [5] M stands for data collected at yearly and monthly time frequency, respectively.

3. RESULTS AND DISCUSSION

During the new leaf expansion period, leaf water content and leaf internal anatomy changed rapidly with leaf maturation, which results in slight increase in leaf reflectance (from 0.5 to 0.56) and seasonality in leaf transmittance in the NIR spectrum (from 0.37 in May to 0.43 in July to 0.38 in December). Meanwhile, leaf water content decreased with mature leaf aging process, which results in large increase in leaf NIR transmittance (from 0.26 in April to 0.35 in December). As a result, the mean up-scaled leaf reflectance (red line) shows small seasonality (Figure 2 (A)) while leaf transmittance shows larger seasonality (Figure 2 (B)) in the NIR spectrum during the growing season.

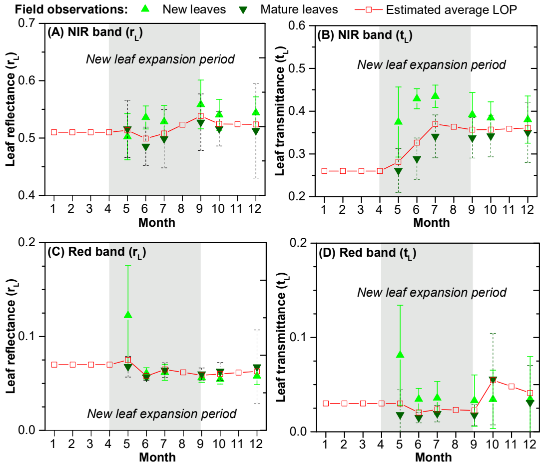

Figure 2. Seasonal variations in leaf reflectance and transmittance in the NIR and red bands

Considering the sparse Landsat observations in a given year, the simulated results were grouped into four successional stages to validate the seasonal pattern of canopy NIR reflectance (Figure 3 (B), (D)). In the red band, the GORT-simulated canopy reflectance showed little correlation with Landsat-observations due to low leaf albedo and strong atmospheric contamination in the visible region [8].

In the NIR band, when LOP was allowed to track the seasonal pattern of field measurements, the simulated-canopy NIR reflectance follows that measured by Landsat fairly well- (R^2=0.56-0.92). In addition, the periodic error of model estimation diminished after including the leaf age effect (Figure 3 (D)). Using the early season LOP for mature leaves over the entire season substantially underestimates the canopy reflectance during the growing season. However, this approach is often implicitly used when tissue optics measured at some time were extrapolate to other periods [14]. Moreover, we also found that the "leaf age effect" was enhanced with stand development. The R^2 values for young to mature stages increased from 0.1, 0.1, 0.24, and 0.11 to 0.56, 0.67, 0.92, and 0.82, explaining 45%, 57%, 68%, and 71% more variability in canopy reflectance at the NIR band, respectively after considering age-dependent LOP.

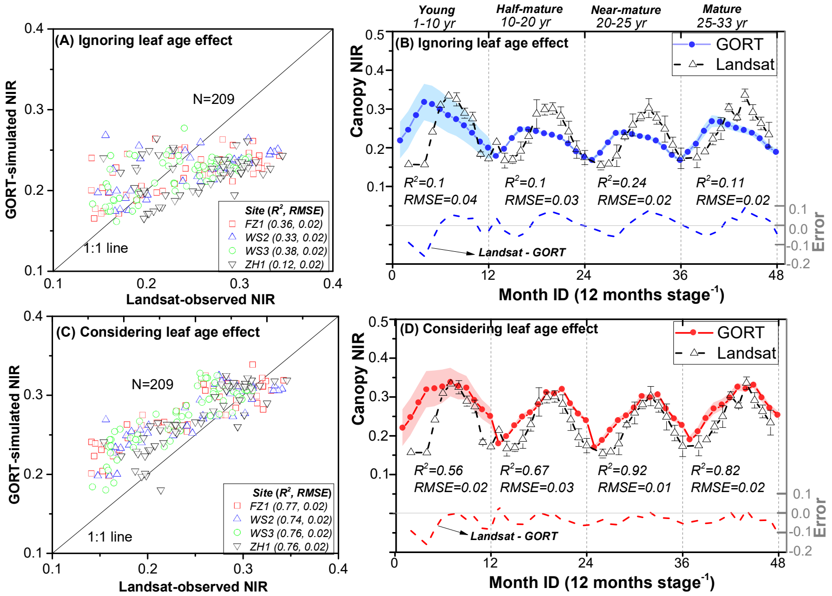

Figure 3. Validation of GORT-simulated canopy reflectance before and after considering the "leaf age effect"

5. CONCLUSION

Quantification of the leaf and structural attribute affecting canopy reflectance provides an avenue to improve our understanding of biological and non-biological factors controlling the seasonal and interannual variations in canopy reflectance. Forest growth is easy to be detected by satellite data before canopy closure; while changes in leaf optics due to leaf aging largely influenced canopy NIR reflectance after canopy closure. This study lays the foundation for the use of RS time-series data to monitor canopy phenology, estimate biological parameters (for example, leaf albedo, leaf age, and stand age) and thus study forest responses to climate changes and environmental stress with possible impacts on leaf vitality.

6. ACKNOWLEDGMENTS

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