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Conifer Shoot Bidirectional Scattering: Methodology and Preliminary Results

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Abstract -- Biophysical models describing radiant energy partitioning at the surface are dependent on our knowledge of the distribution of radiation on canopy elements and resulting interactions (i.e., reflectance, transmittance and absorptance) as well as on the existing state of coupled physiological parameters (such as stomatal conductance and photosynthesis). However, research on optical properties of coniferous forest canopy elements, particularly at the conifer shoot level, has been limited. The objective of this paper is to describe the methodology developed in the investigation of scattering from boreal forest conifer shoots and to present preliminary results using the methodology. An automated goniometer system and procedure were developed for characterizing the bidirectional scattering of conifer shoots. The system includes a computer-controlled goniometer, an SE-590 spectroradiometer, projected area device, sample stand, reference panel and artificial light source. Preliminary results of conifer shoot scattering indicate backscattering and forward scattering features specific to illumination-view-shoot geometries. The methodology presented offers an automated and fairly simple means of characterizing the bidirectional scattering from canopy elements where numerous measures are required. Such measurements are important in advancing our understanding regarding the dynamics of shoot-level absorptance of solar energy for physiological processes and interpreting remotely-sensed canopy reflectance in radiative transfer parameterization.

INTRODUCTION

Biophysical models describing radiant energy partitioning at the surface are dependent on our knowledge of the distribution of radiation on canopy elements and resulting interactions as well as on the existing state of coupled physiological parameters. Photosynthetically active radiation (PAR) is the source of energy for the fixation of carbon dioxide via photosynthesis; thus it is essential to understand the absorptance of PAR by canopy elements within a stand to understand canopy fluxes of CO₂ and water vapor. In addition, physiological processes are affected by absorptance of near-infrared (NIR) and longer wavelengths, i.e., the canopy element radiation balance. The heterogeneous structure of coniferous stands contributes to the difficulty in modeling coniferous canopy processes in a realistic yet simple manner [1, 2]. Refinement of existing three-dimensional radiation transfer

models is needed to account for the complex architecture and the interaction of radiation with canopy elements displayed within these vegetation-filled objects, *e.g.*, needle, twig, shoot and branch radiation scattering and absorption. However, research on optical properties of coniferous forest canopy elements, particularly at the conifer shoot level, has been limited (*e.g.*, [3, 4]). This may be due to the difficulties in collecting data, the expense in making measurements within and above forest canopies, and past research emphasis on agricultural crops [3].

Leaves, needles and bark are canopy elements which are important in scattering radiation in boreal forest vegetation [5]. Needle and bark properties can vary considerably depending on age and height in the canopy; elements deep in the canopy may be covered with algae and fungi and shade-induced effects on shoot development may exist [5, 6]. In the NIR portion of the electromagnetic spectrum little radiation is absorbed so that scattering by canopy elements will be significant. In contrast, needles absorb a large portion of PAR [3, 7]. Conifer needles absorb more PAR than deciduous leaves; twigs, especially current year's growth, also absorb PAR [3]. Differences in the magnitude of reflectance between conifer shoots and individual needles, particularly in the NIR and especially in older shoots, have been reported [4]. The difference was attributed to the contribution of the more mature branch bark in the older branches.

Materials presented are only a part of a larger investigation in the Boreal Ecosystem-Atmospheres Study (BOREAS) [8] on the coupling between radiation and gas exchange of canopy elements in a boreal forest; characterization of radiation interaction with conifer shoots through measurement and modelling is required. To achieve this an automated goniometer system was developed for characterizing the bidirectional scattering of conifer shoots. The system includes a computer-controlled goniometer, an SE-590 spectrometer (Spectron Engineering, Denver, CO), sample stand, reference panel, light source and projected area device. The objective of this paper is to describe the methodology developed and to present preliminary results using the methodology.

METHODS

Radiative scattering from conifer shoots was characterized using the bidirectional reflectance factor (BRF). Conifer shoots were oriented in an azimuth relative to the light source azimuth,

designated as ϕ_{shoot} . Illumination, view and shoot orientation are represented as direction $(\theta_i, \phi_i; \theta_r, \phi_r; \phi_{\text{shoot}})$ where θ is the zenith angle, ϕ is the azimuth angle, 'i' indicates illumination direction and 'r' indicates the reflected direction. Thus, the BRF for a particular illumination-view-shoot geometry is defined as:

$$\text{BRF}(\theta_i, \phi_i; \theta_r, \phi_r; \phi_{\text{shoot}}) = \frac{\Phi_r(\theta_i, \phi_i; \theta_r, \phi_r; \phi_{\text{shoot}})}{\Phi_{r,\text{id}}(\theta_i, \phi_i; \theta_r, \phi_r; \phi_{\text{shoot}})} \quad (1)$$

i.e., the ratio of the reflected (scattered) flux $[\Phi_r(\theta_i, \phi_i; \theta_r, \phi_r; \phi_{\text{shoot}})]$ from the shoot to the reflected flux from an ideal Lambertian surface $[\Phi_{r,\text{id}}(\theta_i, \phi_i; \theta_r, \phi_r; \phi_{\text{shoot}})]$ [9]. Output from the SE-590 is proportional to the scattered radiant flux. The scattered flux from an ideal Lambertian surface $[\Phi_{r,\text{id}}(\theta_i, 0; \theta_r, \phi_r; \phi_{\text{shoot}})]$ was estimated from a nadir-viewed calibrated Spectralon reference panel (Labsphere, Inc., North Sutton, NH) illuminated under the same conditions as the sample $[\Phi_{r,\text{ref}}(\theta_i, 0; 0, \phi_r; \phi_{\text{shoot}})]$. Nadir-viewed fluxes from the reference panel were corrected for the horizontal projected area of the sample [i.e., projected area in the direction of the light source ($A_{\theta_i, \phi_{\text{shoot}}}$) divided by $\cos\theta_i$] and for view angle ($\cos\theta_r$) to represent the reflected flux from an ideal Lambertian surface:

$$\Phi_{r,\text{id}}(\theta_i, 0; \theta_r, \phi_r; \phi_{\text{shoot}}) = \frac{A_{\theta_i, \phi_{\text{shoot}}}}{A_{\text{ref}} \cdot \cos\theta_i} \cdot \Phi_{r,\text{ref}}(\theta_i, 0; 0, \phi_r; \phi_{\text{shoot}}) \cdot \cos\theta_r \cdot \text{CF}(\theta_i). \quad (2)$$

A_{ref} is the area of the spot size as "seen" from the SE590 in the nadir position, $\cos\theta_r$ corrects the flux for that in the scattered direction, and $\text{CF}(\theta_i)$ is the calibration factor for the reference panel. The target was illuminated by a light source with an output within the 400 - 900 nm range from a quartzline projection lamp characterized with a 2° divergent beam and irradiance variation of 5% along the minor axis and 12% along the major axis of the illuminated spot.

The projected area of the sample was estimated using an imaging camera with the shoot sample suspended by nylon monofilament line within a sample ring positioned over a light table. The sample ring was rotated and tilted so that the sample was projected in the same direction toward the imaging camera as it was toward the light source for scattered flux measurements (yielding projected area, $A_{\theta_i, \phi_{\text{shoot}}}$). Once the projected area for each illumination and shoot orientation condition was measured for a particular shoot, the sample ring was removed from the imaging system with the shoot sample still in place and then mounted under the goniometer for scattered flux measurements. The cut end of the sample was kept in a water-filled vial at all times to reduce moisture loss from the sample.

Bidirectional scattering of shoots was measured using an SE-590 spectrometer with a 6° field of view mounted on the automated goniometer yielding a 3.75cm diameter target spot. A constant distance of 36.5cm was maintained between the sample and sensor at all view angles. Shoot segment length was limited to 2.5cm to maintain the shoot sample within the SE-590 spot size at all view angles and to maximize the sample area within the spot size. Samples were mounted horizontally in a sample ring at various azimuthal orientations (ϕ_{shoot}) relative to the illumination azimuth so as to capture variations due to sample-light geometry. Scattered radiant flux from the shoot was measured at selected view zenith and azimuth angles and illumination angles.

RESULTS

Scattering from conifer shoots can be complex as indicated from bidirectional reflectance factors from jack pine (*Pinus banksiana*) shoots. Preliminary results indicate view direction had a much greater effect on scattering than did illumination angle (Fig. 1). Shoot orientation relative to the light source altered the sunlit and shaded portions of conifer shoot in the direction of the sensor so that ϕ_{shoot} had a similar effect on scattering from conifer shoots as did view angle (Fig. 2). Backscattering and forward scattering features varied for particular shoot-view geometries (data not shown).

Fig. 1. Spectral bidirectional reflectance factors for a jack pine (*Pinus banksiana*) shoot oriented with the shoot tip directed away from the illumination azimuth ($\phi_{\text{shoot}} = 0^\circ$) and illuminated at zenith angles (θ_i) of 45° and 60° viewed at azimuth angles (ϕ_r) of 20°.

Fig. 2. Spectral bidirectional reflectance factors for a jack pine (*Pinus banksiana*) shoot illuminated at zenith angle (θ_i) of 60° and oriented with the shoot tip directed away from the illumination azimuth ($\phi_{\text{shoot}} = 0^\circ$) and oriented with the shoot axis perpendicular to the illumination azimuth ($\phi_{\text{shoot}} = 90^\circ$). Shoot was viewed at an azimuth (ϕ_v) of 20° .

DISCUSSION

The methodology presented offers an automated and fairly simple means of characterizing the bidirectional scattering from canopy elements where numerous measures are required. Such measurements are important in advancing our understanding regarding the dynamics of shoot-level absorptance of solar energy for physiological processes and interpreting remotely-sensed canopy reflectance in radiative transfer parameterization. Our overall goal is to analyze and synthesize field data through the use of mathematical models of conifer shoot radiative properties and gas exchange. The measurements of shoot scattering will enable us to test models of shoot radiative scattering and absorption in a step toward accomplishing our overall goal.

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