Using laser scanning and ray tracing for scaling photosynthesis from leaf to stand level

Martin van Leeuwen[1], Jan van Aardt[1], Nicholas Coops[2], Dave Kelbe[1], Keith Krause[3]

[1] Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, 54 Lomb Memorial drive, Rochester, 14623, NY, USA
[2] Forest Resources Management, University of British Columbia, 2424 Main Mall, V6T 1Z4, BC, Canada
[3] National Ecological Observatory Network (NEON), 1685 38th Street, 80301, Boulder, Colorado, USA

Highlights: We demonstrate ray tracing in virtual coniferous forests and simulate half-hourly time-series of absorbed photosynthetically active radiation (APAR) at the shoot level. We then demonstrate how fine spatio-temporal variation in APAR can be used for scaling leaf-level photosynthesis to the stand and explain 75% variation in eddy-covariance-derived half-hourly GPP.

Key words: *simulation, virtual scene, ray tracing, structure, function, forest*

Introduction

The ability to synoptically describe biophysical characteristics of the Earth's surface across a range of scales is paramount to the application of remote sensing. In forestry, remote sensing has been widely used to capture stand structural characteristics and variables related to the health, vigor, or developmental stage of vegetation. These data typically have been acquired at the stand level and are used by governments and land managers to monitor land-use change and forest growth. Such approaches have served the need to oversee broader landscape management, but a gap remains in the use of remote sensing to explore relationships between fine canopy structure and physiological functions, such as the acclimation of foliage to microclimates, or light competition between individual trees. The application of remote sensing to address research questions at these finer spatial scales is valuable, however, and can be used to calibrate and validate vegetation models that are effective at broader scales.

In this research, we demonstrate techniques for creating virtual stands from combined laser scanning data and tree regeneration models. We simulate light transfer in coniferous canopies, where individual needles and shoots are modeled using a technique known as instantiation. The propagation of light is modeled using stochastic ray tracing in forward mode. Ray tracing provides for radiometric quantities to be estimated with high accuracy and at arbitrary scales or geometric fidelity. Ray tracing has been used in studies to validate canopy-level reflectance and transmission models [1] and to provide antecedent science data for emerging imaging systems [2]. At the finest levels, however, the method becomes computationally intensive, even more so when lighting conditions are dynamic, and this has restricted its use for operational scenarios. Methods have been proposed to derive scattering-related information from ray tracing for use in coarser-level modeling applications [3, 4].

Studies thus far have been restricted to modeling radiometric properties and little effort has been spent on the coupling of ray tracing techniques with plant physiological models, i.e., for the study of structure vs. function relationships. Several precursory studies exist in the literature that have applied ray tracing for these purposes. For example, [5] studied exposure of fruit trees in orchards to hemispherically-downwelling radiation, while [6] investigated light acclimation in peach trees. However, to our knowledge, no attempts in forestry have applied ray tracing for the coupling of photosynthesis-related information at leaf and canopy levels.

Here we present a method to simulate dynamic lighting conditions using forward ray tracing (see Figure 1 below for model detail). The method predicts leaf-level probabilities of light absorption from over a thousand hemispherical directions by individual canopy elements. Once a look-up table of absorption probabilities is computed, dynamic illumination conditions can be simulated in a computationally efficient manner. We subsequently show how fine spatio-temporal variations in photosynthetically active radiation (PAR) can be used for modelling stand-level gross primary productivity (GPP) and for investigating relationships between structure and function.

Methods

A 30 x 30 m plot was selected within a mixed coastal Douglas-fir forest located on Vancouver Island, Canada, near the city of Campbell River. Ground-based laser scans were acquired using the EVI instrument (CSIRO, Australia) and half-hourly GPP along with meteorological records were obtained from an eddy-covariance (EC) tower.

Single EVI scans were used to detect tree stems that were co-registered to a plot-centered coordinate frame. Tree crowns were modelled using tree regeneration software and whorl sizes were manipulated based on a

Voronoi tessellation, using stems as seeds. Foliage was modelled as planar polygons to represent clumping into whorls, and as shoot meshes comprising a woody stem and individual needles. The trees were placed in a scene surrounded by periodic boundaries and absorption probabilities were computed for each canopy element to describe the portion of radiant flux from incident angle Ω absorbed by element *p*. Whorl or shoot level APAR was computed using these probabilities and measured diffuse and direct downwelling radiation.

A leaf-level photosynthesis model was created based on a hyperbolic response curve and down-regulation of photosynthetic capacity and initial quantum yield were modelled as functions of APAR, temperature and humidity. The parameters of this model were optimized as to minimize the difference between EC-derived half-hourly GPP and simulated photosynthetic assimilation integrated over all canopy elements. Finally, the fraction of explained variation in EC-derived GPP was reported for different optimization range restrictions.

Results and Discussion

The use of whorl and shoot level absorption probabilities proved successful in deriving APAR at the respective canopy element level and guaranteed that energy was conserved. The method provides for the simulation of half-hourly APAR at the canopy element level for over 2,000 observations in time, covering the growing season from May 1 to September 17, 2009. Limitations of the method were observed, mostly among the lower canopy strata, and relate to the low sampling density of photons in the Monte Carlo ray tracing simulations, and indicate a need for additional acceleration techniques to improve the proposed method. EC-derived GPP was explained with R^2 varying from 0.66 for a case without down-regulation of photosynthesis, to $R^2 = 0.75$ for a case with modifier functions based on relative humidity, temperature and APAR. Considerable variation in GPP remained and can be attributed, for example, to EC-related errors, inaccuracies in the virtual scene representation and irradiation maps, as well as negligence of the broader set of photosynthetic drivers including soil moisture and nutrient conditions. Estimates of quantum yield and photosynthetic capacity were within previously reported ranges, demonstrating the ability of the proposed method to converge towards realistic optima. Biases in GPP estimates remain, notably around Noon, and this is consistent with earlier findings and may relate to extreme stomatal closure as well as underestimation of daytime soil respiration [7].

Despite the high level of complexity of the presented approach, a number of limitations remain, including the fidelity and realism of the three-dimensional forest scene, and variations in relative humidity and temperature within the canopy space. For example, shading within shoots establishes significant effects on quantum yield and photosynthetic capacity [7] and these effects are neglected when APAR estimates are averaged at the shoot or whorl level. Moreover, artificial canopies were constructed using tree regeneration software, however, higher resolution point clouds essentially provide for a more faithful representation of actual canopy structure. Along with ground-based plant physiological instrumentation, simulations of this nature allow for a tighter coupling of structural and functional aspects in primary productivity models and could provide novel analytic insight derived from first principles.

Conclusion

In this study, a method was presented that provides for rapid updates of the canopy radiation regime, after an initial, computationally intense model initialisation phase. The model relies on the population of a look-up table that stores probabilities of absorbing PAR by individual scene elements and handles the dynamic changes in the canopy PAR that result from solar tracking and changes in atmospheric conditions. Improvements to the model representation, canopy structure, and the inclusion of the transfer of longwave radiation, sensible and latent heat, and *in situ* sensor network data bear great potential to refine model estimates and may lead to a tighter coupling between eddy-covariance stand-level estimates of gross primary productivity and leaf-level observations of photosynthesis.

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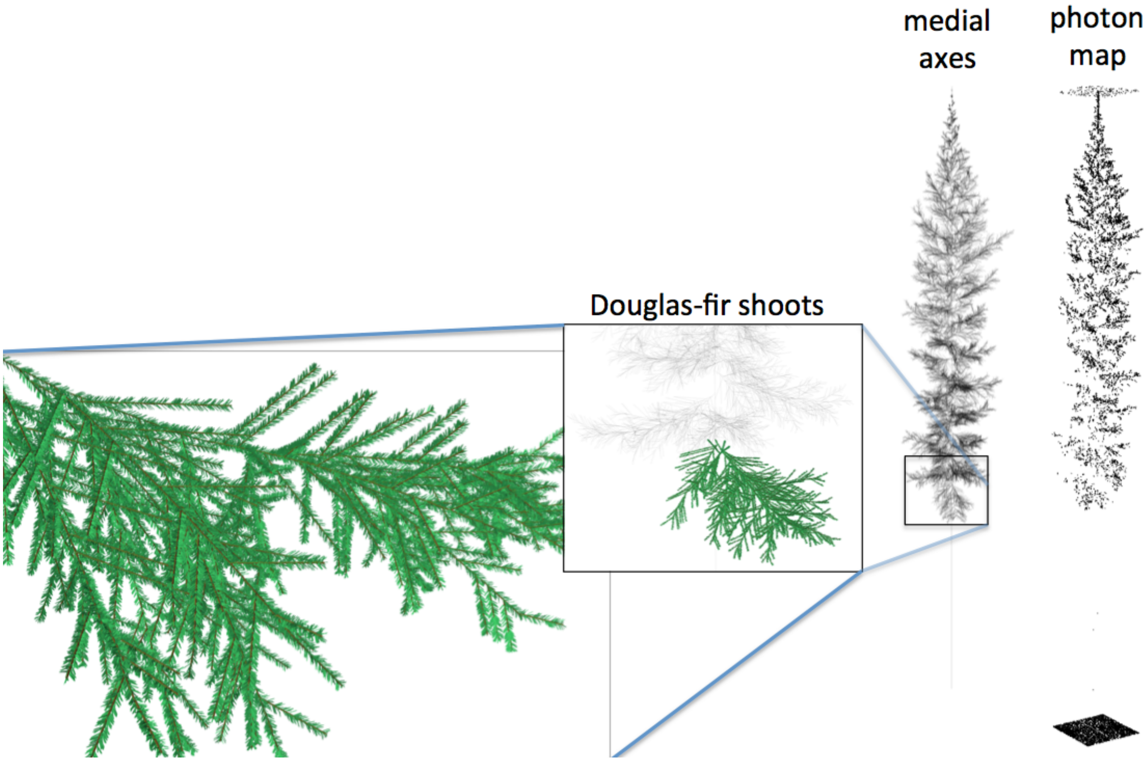

Figure 1. Instantiated conifer shoots and partial results from the ray tracing solution that computes absorption probabilities from directional incident radiation.