Ecological Modelling 368 (2018) 233–245

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

A reverse ray-tracing method for modelling the net radiative flux in leaf-resolving plant canopy simulations

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ARTICLE INFO

Article history:
Received 24 July 2017
Received in revised form
26 November 2017
Accepted 27 November 2017
Available online 12 December 2017

Keywords:
Functional-structural plant model
Graphics processing units
Radiation model
Ray-tracing

ABSTRACT

Radiation is a direct or indirect driver of essentially all biophysical processes in plant systems, and is commonly described through the use of models because of its complex distributions in time and space. Detailed radiation transfer models that represent plant-scale heterogeneity have high computational resource requirements, thus severely limiting the size of problems that can be feasibly considered, while simplified models that can represent entire canopies usually neglect heterogeneity across a wide range of scales. This work develops new methods for computing radiation absorption, transmission, scattering, and emission using ray-tracing approaches that can explicitly represent scales ranging from leaves to canopies. This work focuses on developing a new "reverse" ray-tracing method for describing radiation emission and scattering that ensures all geometric elements (e.g., leaves, branches) are adequately sampled, which guarantees that modelled radiative fluxes are bounded within a reasonable range of values regardless of the number of rays used. This is a critical property when complex model geometries are used, which can be subject to severe sampling errors even when very large ray counts are used. The presented model uses graphics processing units (GPUs) along with highly optimized software to efficiently perform ray-object intersection tests in parallel. This allowed for the simulation of >500 fully resolved trees on a desktop computer in under five minutes.

1. Introduction

A fundamental challenge in studying plant systems is understanding how processes of interest translate across the wide range of relevant scales (Ehleringer and Field, 1993). Plant biophysical processes are often studied locally at the organ level, which are coupled with other plants by environmental processes that traverse the range of scales from leaf to canopy or beyond. Directly measuring physical processes across this wide range of scales is typically not feasible, and generally requires the use of a model at some level. However, representing this range of scales in models is also a considerable challenge, and requires significant simplifications in order to make problems tractable. This means that models usually seek to represent average or representative behaviour and cannot directly resolve plant-scale heterogeneity (e.g., Sinclair et al., 1976; Harley and Baldocchi, 1995; DePury and Farquhar, 1997).

Functional-structural plant models (FSPMs) are a relatively new tool in modelling biophysical processes in plant systems, and seek to describe the three-dimensional development of plant structure over time as influenced by their local environment and physiological function (Vos et al., 2010). These models consist of a coupled set of sub-models that describe various processes involved in plant development such as photosynthesis, nutrient/water transport, carbon allocation, and plant architecture.

FSPM development has progressed rapidly, and holds great potential to aid in our understanding of complex plant system topologies across scales otherwise inaccessible through traditional experimentation. However, despite the continued increase in computing power, FSPMs are often limited in terms of the range of scales they can feasibly represent. Most FSPMs represent the plant at the leaf- and branch-scales, but are typically only able to represent one to a few plants (depending on plant size and model complexity) before computational cost becomes prohibitively expensive (e.g., Allen et al., 2005; Pearcy et al., 2005; Ma et al., 2008; Vos et al., 2010; Sarlikioti et al., 2011). In many cases, this can limit their application in studying plant-to-plant interactions and competition at the field or ecosystem level.

A bottleneck in FSPM computations is the calculation of radiation fluxes absorbed by plant tissues, which directly or indirectly drives nearly all sub-models of physiological processes. Faithfully modelling the transport of radiative energy is complex, particularly when accounting for scattering by millions of elements (e.g., leaves,

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https://doi.org/10.1016/j.ecolmodel.2017.11.022
0304-3800/

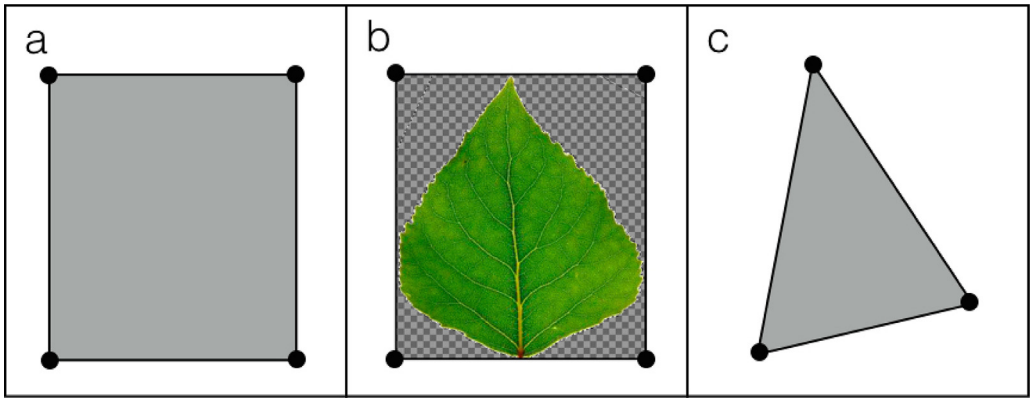

Fig. 1. Geometric element types: (a) patch, (b) alpha mask, and (c) triangle. In (b), the checkered area denotes the portion of the element where material is removed based on the alpha (transparency) channel value.

branches). Most physiological processes have a strong temperature dependence (Johnson and Thornley, 1984). Thus, if temperature is to be included in the model, radiative emission typically must be considered, which adds considerable complexity as each individual element in the domain of interest interacts directly through emission rather than indirectly through scattering. Because of these challenges, models must make compromises in terms of complexity and scale of representation: the more complex the radiation model, the smaller the problem size can be considered.

A very wide range of three-dimensional methods are available to model the transport of sunlight in plant systems (e.g., Ross, 1981; Myneni, 1991; Chelle and Andrieu, 1998; Widlowski et al., 2013), but relatively few are able to model emission of terrestrial radiation. The radiosity method is the standard approach for modelling radiative emission between surfaces or "elements", and solves a coupled set of equations that represents radiation exchange due to emission and reflection by every element in the domain of interest (Goel et al., 1991; Modest, 2003). Although the radiosity approach is robust, it can quickly become prohibitively expensive as the problem size is increased. This is due to the fact that the radiosity approach involves solving an $N \times N$ system of equations (N being the total number of elements in the domain), which has computational expense that scales as N^3 (cf. Press et al., 2007). Other radiosity-based methods have been developed to improve this scaling by using a multi-scale approach, such as the "nested radiosity" approach of Chelle and Andrieu (1998), which simplifies the contributions due to distant sources of radiation.

When small elements are present in ray-tracing simulations, so-called "reverse" ray-tracing can be used in which radiation is traced backwards by launching rays from elements toward sources, which is common in both computer graphics applications (e.g., Shirley and Morley, 2003) and canopy modelling applications (e.g., Lewis and Muller, 1992; North, 1996; Lewis, 1999; Cieslak et al., 2008). This method has the advantage that every element is guaranteed to be sampled, and thus are more robust when computational cost limits the number of rays that can be afforded. The disadvantage of reverse methods is typically most apparent when scattering of radiation is considered. When a reflection or transmission event occurs along a ray path, the ray traversal becomes irreversible, meaning that tracing of the ray in forward or backward directions is no longer equivalent. This means that more complicated methods must be devised to deal with scattering when the reverse approach is used, which typically leads to increased requirements for memory and run-time.

Currently, methods are not available to effectively model emission of terrestrial radiation using a reverse ray-tracing approach. Using forward methods to model emission in the case of small geometric elements presents similar problems when modelling shortwave radiation, although they may be more severe in the case of emission. Bailey et al. (2016) noted that using a forward tracing method with very small elements resulted in significant sampling errors unless a very large number of rays were used, which could result in substantial errors in the modelled net radiative flux. When coupled with the energy balance equation, it was also noted that very large errors in temperature could result, which led to problematic violations of the second law of thermodynamics.

This paper presents a consistent approach for computing radiative emission in fully-resolved plants using what can be considered a reverse ray-tracing approach adapted to emission. It was hypothesized that using a reverse ray-tracing approach for emission would reduce errors in the modeled net longwave radiation flux. The method is generalized to devise a means for modelling radiation scattering, which is used to produce a complete reverse ray-tracing model of radiation transport due to collimated, point, or terrestrial sources of radiation. The ultimate goal was to develop a model for computing the three-dimensional net radiative flux distribution in fully-resolved canopies that is efficient enough to simulate canopy-scale problems over seasonal time scales in a feasible amount of time.

2. Model description

2.1. Element geometry

It is assumed that the environment of interest is populated by a large number of discrete planar objects, which are termed 'elements'. In this work, three possible element types will be considered (Fig. 1), which can be combined to form any arbitrary geometry:

- *Patch:* A patch is a planar rectangle defined by four vertices. The patch normal vector $\vec{n}_e$ is defined using a right-hand rule, i.e., following vertices in an anti-clockwise pattern yields an upward pointing normal.
- *Alpha Mask:* An alpha mask (also known as a 'transparency mask') is the same as a patch, except that a portion of the patch is removed by specifying a two-dimensional grid of pixels that determines whether or not material is present. The pixel grid is specified using the alpha or transparency channel of a PNG image file.
- *Triangle:* A polygon defined by three arbitrary vertices. The triangle normal vector $\vec{n}_e$ is also defined using a right-hand rule.