Modeling light phylloclimate within growth chambers.

Michaël Chelle[1], Christophe Renaud[2], Samuel Delepoulle[2], Didier Combes[3]

[1] INRA, UMR1091 Environnement et Grandes cultures, F-78850 Thiverval-Grignon , France
[2] Laboratoire d'Informatique du Littoral (LIL), BP 719, F-62228 Calais, France
[3] INRA, UR4 Écophysiologie des Plantes Fourragères, BP6, F-86600 Lusignan, France
chelle@grignon.inra.fr

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Introduction

Functional-structural plant modeling (FSPM) requires accurate data on plant growth. These data are often obtained by experiments in growth chambers. Most genomic studies also use plants grown in controlled conditions. For such studies, a well-controlled and spatially homogeneous climate is necessary to be able to strictly compare results from different treatments or genotypes (and not phenotypes).

A large variety of growth chambers with differing geometry, materials, lighting and control system exist. Each growth chamber should be considered as a unique radiative system, characterized by a specific spatial light distribution. Moreover, although it has been designed to minimize the spatial heterogeneity of climate, measurements have shown that plants may experience different microclimate conditions depending on their location within the same chamber (Measures et al., 1973; Boonen et al., 2002a ; Chelle et al., 2004). The effect of the light variability on the plant population heterogeneity would be higher for small plants (small specie (*Arabidopsis thaliana*); seedling) than for tall plants. However, for tall plants, the light variability would perturb studies at organ scale (Fig. 1). By-passing the "growth chamber" effect for light in ecophysiology could be done by estimating the light phylloclimate (Chelle, 2005).

Measurement of light phylloclimate could not automatically be done during growth chamber experiments, because the required number of sensors would perturb the plant growth (Chelle, 2005). Cavazonni et al. (2002) and Boonen et al. (2002b) independently proposed a light model dedicated to growth chamber. However, their model relies on the turbid medium approximation, which does not enable the estimation of the irradiance of individual plants or organs. Modeling light phylloclimate implies that the 3D structure of individual plants and the directionality of radiation are taken into account. Chenu et al. (2005) proposed a two-step method consisting on the measurement of above-plant radiances using a 6-face turtle PAR sensor (Den Dulk, 1989) and the "projection" of this incident radiance distribution on a 3D plant using the Archimed model (Dauzat & Elroy, 1997). The method was used to estimate the PAR irradiance of *Arabidopsis thaliana* plants. However, the extension to other spectral band and to the case of tall plants (Fig. 1) has to be assessed. In this paper, we propose a full-modeling approach based on a 3D description of the growth chamber, its lighting system, and plants, as proposed by Chelle et al. (2004).

SEC2, a photon tracing dedicated to growth chamber

In a previous study (Chelle et al., 2004), measurements and Radiance simulations (Ward, 1994) in an empty growth chamber were analyzed, mainly regarding the relative contribution of first, second and higher order of scattering. A deeper analysis of these results led us to propose general specifications for light models dedicated to growth chamber phylloclimate:

- Taking into account the 3D geometry of the growth chamber, its lighting system, and plants;
- Taking into account multiple light sources, which may be punctual or surfacic and have anistropic emission;
- Taking into account diffuse, specular, and translucent materials;
- Estimating the irradiance of several plant organs and of virtual light sensors;
- Easy implementation, maintenance, and use;

- Reasonable simulation time.

From these specifications, we developed a lighting simulator (SEC2) dedicated to growth chambers. It is based on models and algorithms currently in use in Computer Graphics (CG) research area. Indeed, CG researchers have developed efficient methods for computing global illumination in any environment with arbitrary materials and light sources. These methods provide both photorealistic images and physically accurate results (Sillion et al., 1994; Shirley et al., 1996).

The core of SEC2 is based on the photon tracing approach (Arvo, 1986; Jensen 2001), which consists in tracing photons from their emission point on light sources to their absorption location after several bounces onto the 3D models surfaces. Contrary to CG where measurements are mainly performed through each pixel of the computed image, SEC2 requires making measurements at specific locations in the chamber. Thus, SEC2 enables the inclusion of different kinds of sensors into the scene, these sensors being either virtual (recording irradiances without affecting the light propagation) or real (in the same way as light sensors are used in an actual growth chamber). Moreover, SEC2 enables the estimation of the irradiance and the light absorption of plant organs. Optionally, SEC2 is able to provide views of the simulated environment using different CG rendering methods (Fig. 2b).
SEC2 was developed in C++ following an Object Oriented approach, which provides both efficiency and easy software maintenance capabilities.

First results

A virtual growth chamber was built from the measurement of a Strader growth chamber (Angers, France), whose features are a complex lighting system (1) (2 rows of discharge lamps surrounded by three glossy reflectors), a white working table (2), 4 vertical grey walls (3), and two specular panels (4) to mimic canopy boundary conditions (Fig. 2a).

The ability to reproduce a virtual growth chamber as well as the correctness of SEC2 were assessed by comparing measured and simulated transversal profiles of PAR irradiance at two elevations in an empty room (Fig .3). The angular and spatial distribution of radiance appeared satisfyingly simulated; the pseudo-homogeneity at 1.0m height as well as the pattern due to the anisotropy of light sources observed at 1.8m height. Figure 4 shows how highly variable was the simulated PAR irradiance of horizontal sensors within the virtual Strader chamber. This result confirmed the interest in a full-modeling approach to estimate light phylloclimate, as conceptually established in Figure 1.
Moreover, the SEC2 model enables the simulation of the light distribution within the growth chamber, that is table and walls, with plants included, that is of primary interest for the FSPM community. Figure 2b presents such a simulation in the case of a heterogeneous canopy containing three various types of virtual plants (2 young maize (Drouet, 2003); 16 young and 4 adults and true myrtle (Beaujard et al., 2001); 40 *Arabidopsis thaliana* (Chenu et al., 2005)).

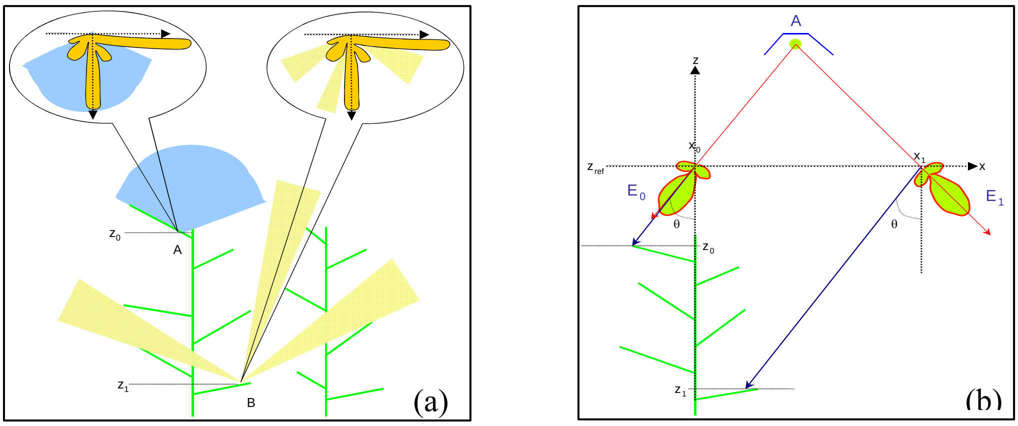

Figure 1: Scheme illustrating the difference in the directional sampling (a) and in the angular distribution (b) of the incident light field between leaves located in the top (A) and the bottom (B) of a canopy.

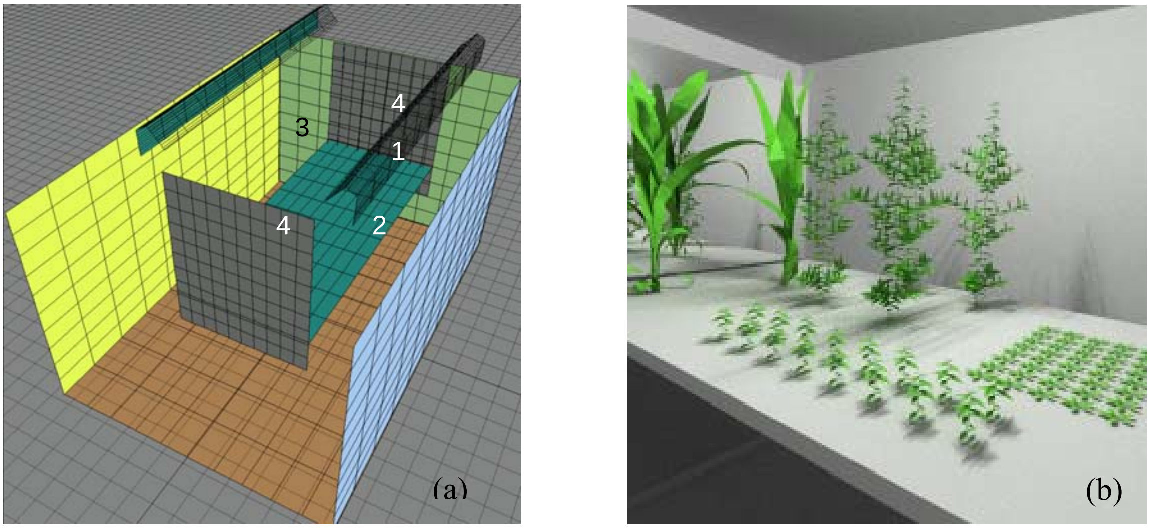

Figure 2 The virtual Strader growth chamber (a) and its simulated light distribution when filled by a heterogeneous canopy (maize, true myrtle, arabidopsis) (b).

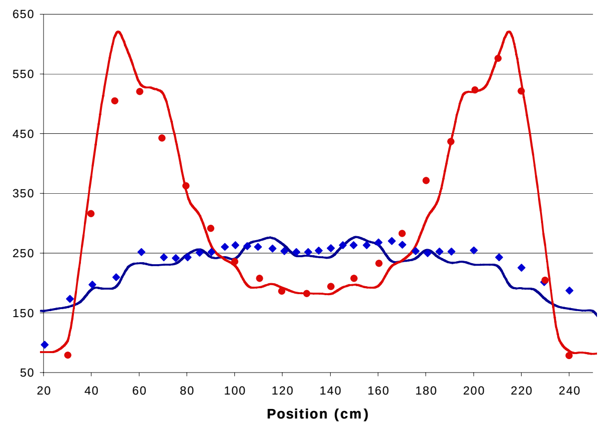

Figure 3 Measured (symbols) and simulated (solid lines) transversal profile of PAR irradiance within the empty Strader growth chamber at two elevations (1m (blue), 1.8m (red) height).

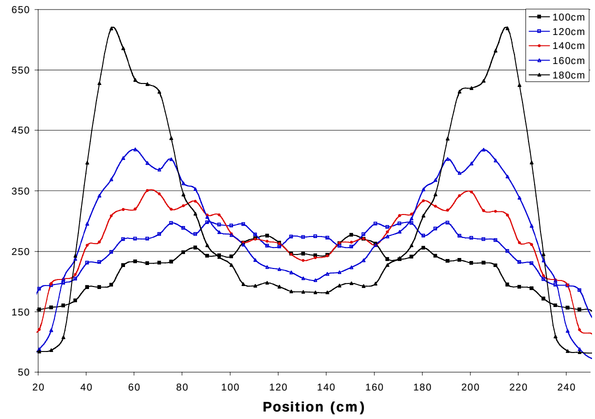

Figure 4 Simulated transversal profiles of PAR irradiance within the Strader growth chamber at 5 elevations (1, 1.2, 1.4, 1.6, 1.8 m height).

In conclusion, SEC2 would be an useful tool to estimate the light phylloclimate of plants grown in controlled conditions, which is required to by-passed the intra- and inter-growth chamber light variability. Next simulation steps will focus on the inter-plant and intra-plant variability of light and be discussed regarding ecophysiological processes. Finally, it could be used to design new types of growth chamber providing a low heterogeneity of light phylloclimate.

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