CHAPTER 7

MODELLING THE LIGHT ENVIRONMENT OF VIRTUAL CROP CANOPIES

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Abstract Virtual plants describe functionally and geometrically plants as sets of interconnected organs. As many plant processes are driven by light, virtual plants require the estimation of the light absorbed by each organ. This has motivated the development of dedicated light models taking profit from the 3D geometry provided by virtual-plant models. We first introduce the principles governing the physical interactions between light and a plant canopy. We then review operational models, including fast methods that have been developed for calculating sun and sky light intercepted by plant organs. Such methods may be used for the simulation of processes depending on the UV or PAR radiations. Models taking into account the multiple scattering between plant elements are based either on Monte Carlo ray tracing or on the radiosity method. We present the principle of these approaches and recent developments in their applications to crop modelling.

INTRODUCTION

Scaling up from organ to canopy level

Biological processes occur at the level of plant organ (leaf, bud, internode, fruit). Modelling the crop growth and development requires to scale up the functioning of plant organs to the canopy level. This is performed in usual crop models by using two simplifications: (i) the functioning of a canopy is described by that of one ‘median plant’, whose behaviour is supposed to represent the median behaviour of the plants population; (ii) the structure is described by variables characteristic of the canopy level, e.g., the leaf area index (LAI), which is the quantity of leaf area per unit area of soil. This approach has led to several efficient crop models (see Hanks and Ritchie (1991) for a review), but does not allow considering horizontal heterogeneity and plant-to-plant variability within the population.

An emergent alternative approach consists in modelling the canopy as a population of interacting plants and a plant as a set of interacting organs (Kurth

J. Vos, L.F.M. Marcelis, P.H.B. de Visser, P.C. Struik and J.B. Evers (eds.), Functional-Structural Plant Modelling in Crop Production, 75-89.

1994; Prusinkiewicz 1998; De Reffye et al. 1998; Sievänen et al. 2000). This approach combines a functional description of organ growth with a 3D description of their geometry. Geometry is important because it determines the microclimate sensed by individual organs. This approach is commonly called virtual plant (VP) modelling, architectural modelling, or functional-structural plant modelling (FSPM). Most of these models are based on the L-system theory (Kurth 1994; Prusinkiewicz 1998; De Reffye et al. 1998; Sievänen et al. 2000). Such models require that radiative variables (UV, PAR, blue, red/far-red ratio (R:FR), etc.) may be characterized for each modelled individual organ. This specific light microclimate can be termed the ‘light phylloclimate’ (Chelle 2005).

Light modelling within a canopy

Light models estimate the radiative fluxes received by each organ, by modelling the radiative exchanges between plant organs. They involve the characterization of interactions (reflection, transmission, absorption) between light and organs, and the integration of these local processes over the whole structure. The complexity of this integration depends on the level of approximation in the structural description. We will now discuss the two approaches enabling this integration.

Turbid-medium approach

The turbid-medium (TM) approach is based on radiative transport theory (Chandrasekhar 1950), which considers light propagation in a continuous medium composed of infinitely small scatterers. The spatial variability of the canopy structure is taken into account by dividing the canopy into volume elements and statistically describing the plant organs contained in this volume. A volume element can be a horizontal layer, a tube or a cell. Models based on this approach provide fluxes averaged over volume elements. They are efficient to estimate fluxes at the canopy scale and are intensively used with crop models based on the ‘median plant’ approach. To be used for architectural modelling, their output, which is the field of fluxes averaged by volume element, must be downscaled to the organ level. Thus, the spatial discretization should be fine enough to describe the spatial variations of structure and fluxes, but rough enough such that the transport theory can be applied (Knyazikhin et al. 1998). Early models of this sort were not able to deal with the intra-cell variability of structure and fluxes. Some more recent developments in the TM approach include consideration of the spatial distribution of organs within a volume element (Myneni et al. 1995; Knyazikhin et al. 1998). These formalisms are complex and require parameters that are difficult to estimate. This is the case, for example, for the clumping parameter (Nilson 1971). The intra-cell variability of fluxes may mainly be explained by the finite size of scatterers, which creates spatial discontinuities within the cell. Knyazikhin et al. (1992) proposed a way to introduce finite-dimensional leaves in the TM approach. However, their method took into account these discontinuities only in a statistical sense and then refined only the mean value of fluxes. Anisimov and Fukshansky (1993) considered the statistical moments of the functions describing the structure within a cell. This enables the estimation of the variance associated with the mean fluxes calculated for each cell. This improves the estimation of fluxes compared to classic TM models (Anisimov and Fukshansky 1997). However, the variability of fluxes within a cell is still described at the scale of the cell and not at the scale of an organ.

Surface-based approach

Different methods have been used to describe 3D canopy structure explicitly as a set of geometric elements (see Chapters 2 and 3 in this book). Progress in computer science has enabled to model radiative transfer within a canopy structure described explicitly (Borel et al. 1991; Dauzat and Hautecoeur 1991; Goel et al. 1991). We will refer to these models as surface-based models. The advantages of this approach are: (i) they provide fluxes distributed on individual geometric elements, and (ii) they take into account the geometry of each foliage element (size, position, orientation). The main disadvantage of the approach is the numerical complexity of the integration when canopy structure is described by a large set of elements.

In this chapter we will consider the estimation of radiative fluxes on individual organs. Thus, we will focus on the surface-based approach for the radiative modelling, including hybrid models that combine the TM and the surface-based approaches. First, the way in which light and organs interact within a canopy will be presented. Second, methods of estimating the amount of light coming directly from sun and sky onto organs will be described. Third, surface-based models enabling the simulation of high levels of multiple scattering will be introduced. Finally, the question of lighting virtual plants will be addressed.

LIGHT PHYLLOCLIMATE

The radiance equation

Disregarding artificial lighting scenarios, we need consider only the sun and the sky as light sources. Solar radiation intercepted by an organ may come directly from the sky hemisphere and indirectly after scattering from other organs. The distribution of primary light within the canopy depends on the structure of the canopy and on the angular distribution of radiance characterizing the sky hemisphere. The light intercepted by an organ is partially absorbed and partially scattered (reflected and transmitted). The proportion of these two phenomena varies significantly with the wavelength and depends on the leaf type, state and age. They have been accurately simulated, e.g., by the PROSPECT model (Jacquemoud and Baret 1990; Bousquet et al. 2005). The angular distributions of the reflected and transmitted light are described by, respectively, the bidirectional reflectance distribution function (BRDF) and the bidirectional transmittance distribution function (BTDF) (Nicodemus et al. 1977).

The quantity of radiation scattered from a surface element S_i and intercepted by another surface element S_j depends on the BRDF or BTDF of S_j as well as on the relative positions and orientations of S_i and S_j. This dependency is quantified by the radiance equation. The radiance equation does not take into account other radiative processes such as fluorescence or polarization because their quantitative contribution to the radiative equilibrium of an organ is weak compared to scattering and absorption for agronomical conditions. This Fredholm equation expresses the radiance scattered by a surface element S_i at a point P in a direction $\vec{\omega}_r$ as a function of the radiance coming in at point P from all the directions $\vec{\omega}$ (Figure 1). The radiance coming in at point P may be decomposed in the contribution of primary light ($L^1(P, \omega_r)$) and the light scattered by soil and other organs toward P ($L^x(P, \vec{\omega}_r)$):

$$L^1(P, \vec{\omega}_r) = \int_{\vec{\omega}_i \cdot \vec{\omega}_r < 0} f_r(\vec{\omega}_i, \vec{\omega}_r) L(P, \vec{\omega}_i) \cos\theta \, d\omega_i + \int_{\vec{\omega}_i \cdot \vec{\omega}_r > 0} f_t(\vec{\omega}_i, \vec{\omega}_r) L(P, \vec{\omega}_i) \cos\theta \, d\omega_i$$

$$L^x(P, \vec{\omega}_r) = \int_{\vec{\omega}_s \cdot \vec{\omega}_r < 0} f_r(\vec{\omega}_s, \vec{\omega}_r) L(P, \vec{\omega}_s) \cos\theta \, d\omega_s + \int_{\vec{\omega}_s \cdot \vec{\omega}_r > 0} f_t(\vec{\omega}_s, \vec{\omega}_r) L(P, \vec{\omega}_s) \cos\theta \, d\omega_s$$

where $\vec{\omega}_i$ belongs to the set of directions in which there is a free path between P and the top of the canopy; $\vec{\omega}_s$ belongs to the set of directions in which there is not a free path; dω is an elementary solid angle around the direction ω; θ is the angle between $\vec{\omega}$ and the normal $\vec{n}$ to S_i at point P; and f_r and f_t are the BRDF and the BTDF, respectively, of S_i at the point P .

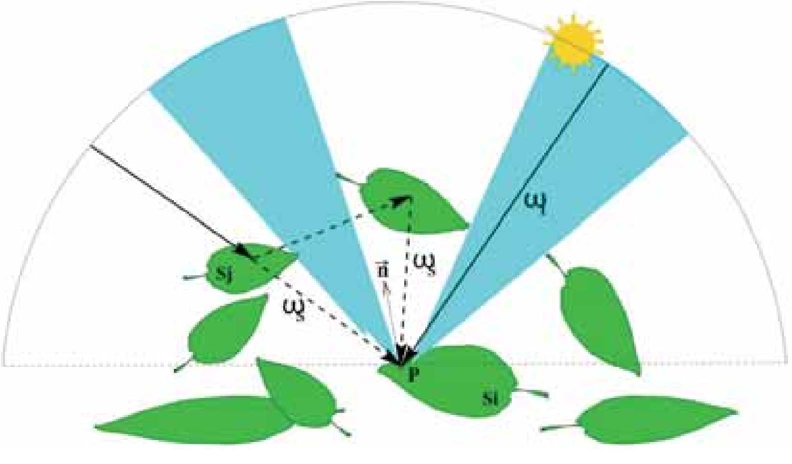

Figure 1. *Radiative budget of a plant organ at point P (shaded circle sectors correspond to the solid angle through which P is directly lit by the sky)*

The solution of the radiance equation is the field of radiance $L(P, \vec{\omega}_r)$ over the set of surfaces describing the canopy, at a time t and for the wavelength λ. Absorbed energy or irradiance is directly calculated from this field of radiance. The radiance equation is numerically solved by integrating it over space, direction, time and wavelength. Integration steps for these variables must be carefully chosen because light may vary spatially and temporally with a high frequency due to the movements of plants and those of sun and clouds (see sun flecks studies such as Norman et al. 1971; Pearcy et al. 1990) and because the organ responses to light may be strongly non linear (see Chelle 2005 for details).

Simplifications of the radiance equation

A surface-based model adapted to architectural modelling can be used to solve the radiance equation for several intervals of space, time and wavelength, but due to the complexity of this equation, simplifications must generally be applied to generate efficient but restricted models.

The number of organs for which radiative variables have to be estimated depends on the biological model. For example, photosynthesis includes all green leaves, whereas some photomorphogenetic models may focus on light phylloclimate of apices or internodes. This has led to two main schemes of radiative modelling: the source-based and recipient-based approaches. In the source-based approach, the radiative variables are estimated for all organs. In the recipient-based approach, the radiative variables are estimated for a restricted number of organs, which reduces the number of calculations.

The complexity of the radiance equation comes mainly from the calculation of multiple scattering. The weight of multiple scattering in the incoming light on organs varies spectrally. For practical applications, two spectral domains may be defined: (i) the UV and PAR, where multiple scattering is low for a green canopy, and (ii) the infrared, where it is high. Estimating fluxes in the UV and PAR domains can be highly simplified if multiple scattering is neglected. For the near-infrared domain, the radiance equation has to be solved, which necessitates complex numerical methods. We will now describe how primary light and multiple scattering are calculated using the surface-based approach.

PRIMARY LIGHT

Principle

Calculating the primary lighting of a set of surfaces requires directional sampling of the sky hemisphere and spatial sampling of the plant surfaces and to determine (P, $\vec{\omega}_r$) for each element within the sample, if there is a direct path from the point P to the top of canopy in the direction ω. In the source-based approach, this sampling is done by following the propagation of light from sampled directions over the sky hemisphere and determining the surface element hit by each light ray. For the recipient-based approach, the sampling is performed by following the inverse sense of light propagation, from the surface elements of interest to the sky hemisphere.

The sampling of the sky hemisphere usually relies on a discretization in solid angle elements $\Delta\omega$, so that the radiance within $\Delta\omega$ may be assumed constant. This amounts to approximating the continuous sky hemisphere as a finite set of punctual collimated light sources. Because the dimensions of a crop canopy are small compared to the distance to the light sources, any extended light source can be approximated as a set of punctual light sources, so that the approach is very general. Standard CIE sky radiance distributions may be used for clear skies or overcast skies (SOC or UOC (CIE 1994)). However, these distributions are coarse. More sophisticated sky models have been developed (Perez et al. 1993), but their usability as well as the improvement on irradiance estimation within a canopy has to be assessed.

As the irradiance of a surface is the sum of the contribution for each individual source, we will now focus on the calculation of primary light from a single source. The irradiance of a surface S_i due to the light coming from a single direction is proportional to the apparent surface S_i^*, which is the surface that would be seen by an observer looking at the canopy from the position of the light source. The apparent surface depends on the orientation of S_i relative to ω and on the possible shading due to other surfaces. It can be estimated by ray casting or by projection.

Ray casting

In the source-based approach, this method consists of casting several rays from the light source to the canopy. Rays are cast from points stochastically sampled on a plane above the canopy. The propagation of a ray stops when it intersects an element (Figure 2, left). S_i^* is proportional to the number of rays caught by S_i. The drawback of this method is the large number of rays required to reach a satisfying accuracy.

For the recipient-based approach, rays are cast from points randomly sampled on the surfaces of the organs of interest in the direction $-\omega$. S_i^* is then proportional to the number of rays starting from S_i and reaching the sky hemisphere (Figure 3, left).

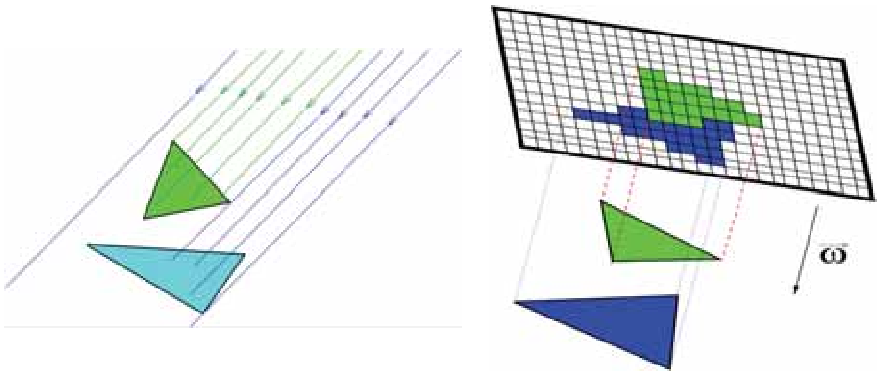

***Figure 2**. Interception of the light coming from a collimated light source by two surfaces calculated using the source-based approach by ray casting (left) and by parallel projection (right)*

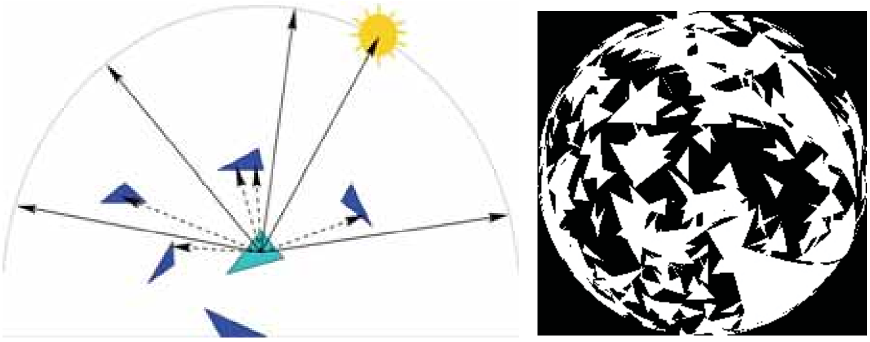

Figure 3. Interception of the light coming from a collimated light source by a surface calculated following the recipient-based approach by ray casting (left) and by hemispherical projection (right)

Projection

The second method for the source-based approach consists of projecting the element on a discretized screen located above the canopy and normal to the direction of light (Figure 2, right). Shaded elements are determined by applying the Z-buffer algorithm (Foley et al. 1990), which consists of updating a pixel of the discretized screen with the identifier of the closest element to the screen. Thus, S_i* is proportional to the number of pixels covered by the projection of S_i. This method is very efficient in terms of speed and accuracy, but of course may suffer from inaccuracies when the resolution of the digitized screen is coarse regarding the projection of S_i , e.g., for small elements.

In the recipient-based approach, the irradiance due to the whole sky hemisphere is generally calculated successively for each S_i. A hemispherical projection centred on a point P of S_i provides an image where each pixel corresponds to a solid angle (Figure 3, right). An empty pixel corresponds to a direction in which the sky light reaches point P directly. The irradiance at point P is calculated by summing the irradiances due to the sky radiances associated to each empty pixel. To get the irradiance of S_i, the method is applied for several points P over S_i.

MODELLING MULTIPLE SCATTERING OF LIGHT

Estimating multiple scattering requires solving the radiance equation. As this equation is set at one point, integration over all surfaces is required. Two approaches enable this integration: the Monte Carlo method and a deterministic method derived from the finite elements: the radiosity method.

Monte Carlo ray tracing

Stochastic ray tracing relies on the Monte Carlo method (Kalos and Whitlock 1986) to solve the required multi-dimensional integrals. It consists of successively calculating the path and interactions with surfaces of a large sample number of photons, until they exit the canopy or they are absorbed by surfaces. Source-based and recipient-based approaches have been developed (see Disney et al. (2000) for a review): rays are traced, respectively, from the light sources to the canopy or from the organs of interest to the light sources. The Monte Carlo approach is very general and requires few assumptions. Thus, Monte Carlo models enable simulations for nearly any type of light source, canopy structure and optical properties of organs. They enable the simulation of a large set of variables, such as fluxes over individual organs, canopy BRDF, and the radiance distribution at different levels within the canopy. Moreover, they enable the separation of the contribution of the different orders of scattering to the radiative variables.

Results from Monte Carlo ray tracing are statistical estimates of mean values. The numerical variance associated with an estimated variable depends on the number of photons that contribute to this result. This number may be low for very small or weakly illuminated surfaces. In these cases, getting low variances for such surfaces requires either to privilege these surfaces by using the recipient-based approach or to trace a large number of rays in the case of the source-based approach. The variance on each result can be estimated at the end of a simulation (Chelle et al. 1997). To reach an expected accuracy, the simulation can be performed by iterations, variances being estimated at the end of each step. Satisfying irradiance estimation for a large number of organs requires tracing a large number of rays, which implies very large simulation times on usual computers.

The Monte Carlo approach enables one in principle to deal with any kind of BRDF/BTDF at the organ level. However, taking into account anisotropic BRDF often requires using time-consuming procedures to sample the direction of scattering. Moreover, it requires accurately describing the 3D shape of leaves to avoid numerical artefacts. Thus, due to computational complexity, the case of anisotropic BRDF has seldom been addressed in radiative simulations on plant canopies, and leaves are generally considered bi-Lambertian (stems and other organs Lambertian) (see Chelle (2006) for details).

Owing to these features, the Monte Carlo method is generally used as a tool to investigate the radiative behaviour of a canopy or as a reference to evaluate simpler models. However, the use of the quasi-Monte Carlo methods has speeded up the convergence of ray tracing (Keller 1996; Csébfalvi 1997), making ray tracing efficient to estimate leaf irradiances within a canopy (Allen et al. 2005).

Radiosity-based methods

The radiosity method (Sparrow 1963; Goral et al. 1984) is based on the assumptions that surfaces are (bi-)Lambertian and that radiative fluxes over an element are constant. This enables the radiance equation to be approximated as a system of linear equations. The radiosity equation expresses the radiant exitance or radiosity B_i over a surface S_i as a function of the reflection and the transmission of the incoming light. This incoming light is expressed as a linear combination of the radiosities B_j of the other surfaces. The coefficients of this linear combination are called form factors and represent the proportion of energy scattered by a surface S_j that reaches a surface S_i. A form factor (or view factor) between S_j and S_i is calculated by integration over the two surfaces. If there are no surfaces between them, a standard numerical integration can be performed. Moreover, if S_i and S_j are polygons, an analytical formulation of the form factor has been established (Schröder and Sweldens 1995). When there are occlusions, the contributions from free paths between S_i and S_j need to be determined and calculations are more complex. These calculations are usually simplified by calculating the form factor between S_i and an elementary surface located at the centre of S_j. This method is called the method of point-surface form factor. This approximation is incorrect for some geometrical configurations (Baum et al. 1989), mainly when the two surfaces are very close.

No recipient-based approach has been developed for radiosity: models use a global scheme. Early radiosity models consisted of computing the form factors between each pair of surfaces (S_i, S_j) and solving the resulting system. The requirement in memory storage and in simulation time was proportional to N^2, where N is the number of elements describing the 3D structure. This limited the use of these models to simple structures. Various works in computer graphics have improved the ability of this method to deal with large sets of elements (see Cohen and Wallace 1993; Sillion and Puech 1994; Mastal et al. 1999 for reviews). These optimizations were developed for scenes within buildings. It is difficult to apply these methods to plant canopies, whose optical and geometrical characteristics differ from that of building scenes because: (i) the spatial distribution of surfaces is typically broader in a vegetation canopy than in a room; and (ii) the contribution of high order of scattering is important in the near-infrared for vegetation canopies, which makes the iterative schemes that were developed for building scenes inefficient. Other researches in computer graphics have extended the radiosity method to non-Lambertian surfaces (Baum et al. 1989; Schröder and Sweldens 1995; Christensen et al. 1994). However, these methods seem to be too complex to be applied to vegetation at this time. Moreover, the leaf irradiance calculation within a dense canopy has been shown to be sufficient under the assumption of bi-Lambertian leaves (Chelle 2006).

Considering that the radiosity method is well-adapted to compute the distribution of light over a small set of surfaces and that TM models satisfactorily estimate the spatial distribution of mean fluxes, we have developed a nested-radiosity approach (Chelle and Andrieu 1998) for the calculation of light in crop cultures. The irradiance of a surface S_i due to multiple scattering is calculated in two parts. First, the energy coming from all the organs far from S_i is estimated statistically from the field of mean fluxes provided by the SAIL multilayer TM model (Verhoef 1985). Second, the contribution of close organs is calculated by the classic radiosity method. The partition between close and far surfaces from S_i is realized by a sphere centred on S_i. The sphere diameter is chosen by the user. Sillion (1995) has developed a similar approach for large scenes in computer graphics. The principle of their method is an extension of the hierarchical radiosity approach (Baum et al. 1989), which gathers close surfaces into volumetric objects (clusters) which are treated as a turbid medium. Designed for building scenes where clusters are obvious to define, the application of this method to a crop canopy composed of entwined plants is less obvious, although this has been achieved by Soler et al. (2003).

LIGHTING VIRTUAL PLANTS

The radiative models described above have been used in two main types of application: (i) studying how a given canopy intercepts light; and (ii) providing organ irradiances to virtual plant models to simulate the plant–light interactions dynamically. There are significantly more references on the former than on the latter type of application, although this is slowly changing (see other chapters in this book). For both types, research has tended to focus on PAR or UV light, which enables efficient (simple) light models such as those based on projection.

For example, Dauzat (1993) used projections of canopy elements to simulate fish-eye views of a forest and the light pattern at the ground level beneath an oil palm stand. Several studies have followed this studying how canopy features such as phyllotaxis, plant density, as well as leaf size and orientation are influenced by the light regime (Valladares and Pearcy 2000; Maddonni et al. 2001; Pommel et al. 2001; Takenaka et al. 2001; Falster and Westoby 2003; Valladares and Brites 2004; Pearcy et al. 2005; Sinoquet et al. 2005). These studies have focused mainly on photosynthesis. Several other processes have also been studied, such as the nitrogen distribution within a plant (Drouet 2004), plant transpiration (Dauzat et al. 2001) and the survival of bioinsecticides to UV (Smits and Sinoquet 2004). To facilitate such studies, computer tools have been developed, such as Yplant (Pearcy and Yang 1996) and Vegestar (Adam et al. 2004).

Dynamic lighting of virtual plants has mainly been achieved for photosynthesis estimation (PAR region only) using projection (Fournier and Andrieu 1999), quasi-Monte Carlo (Allen et al. 2005; Cici et al. 2005) or radiosity (Soler et al. 2003) methods. Some works have focused on photomorphogenesis using Monte Carlo ray tracing (Gautier et al. 2000) or nested radiosity (Evers et al. 2005).

Dynamic lighting of virtual plants is likely to be further developed in the near future, mainly due to the recent availability of suitable modelling tools, e.g., open L-system modeller (Měch and Prusinkiewicz 1996; Fournier and Andrieu 1999) and platforms such as the SOLEIL project (Soler et al. 2003), the NEXUS platform (Anzola Jürgenson 2002) and the ALEA project (Pradal et al. 2004).

CONCLUSION AND FUTURE DIRECTIONS

The development of 3D architectural models of plants by providing an explicit description of the canopy geometry and by requiring the distribution of light energy on each plant organ has motivated the development of a surface-based model for light.

To study biological processes sensitive to PAR and UV radiation, multiple scattering may be neglected allowing fast calculations even on large 3D structures. The simulation of processes depending on infrared radiation or located in shaded zones has to take into account the multiple scattering of light between organs. Radiosity-based methods appear convenient, especially because of the dissociation of geometric and radiative calculations. However, the point-surface method is not appropriate for the calculation of form factors when surfaces are very close. This makes it difficult to estimate light conditions in some specific plant parts, such as the whorl of gramineous plants.

A remaining question in phylloclimate modelling is how to describe the 3D plant structure in the most efficient way, knowing that the more accurate this description is, the more accurate the calculation will be, but also the more intensive the associated computation task. This question has no direct answer, because it depends on the process being studied. However, a way to determine the sufficient precision for the 3D description is to perform a sensitivity analysis of the light model, as pioneered by (España et al. 1999) studying the importance of the undulations of maize leaves.

It should be noted that using a detailed 3D description would be a limitation to modelling phylloclimate in the case of larger, taller and more complex canopies such as ecosystem or forest, because the simulation time is a function of the number of geometric elements that describe the canopy structure. Research should then focus on multi-scale description and modelling, as it has been initiated for example by Chelle and Andrieu (1998), Chen and Leblanc (1997) or Soler et al. (2003).

Finally, regarding 3D plant description, another potential stumbling block is the effect of plant movements. It is obvious that these movements affect the light penetration (Roden and Pearcy 1993a; 1993b; Baldocchi et al. 1980), but several questions remain open regarding its importance, which should be evaluated for each process, condition and canopy type. Sensitivity analyses, as for geometrical details, have to be performed to evaluate this importance before starting research in this direction.

Plant growth and development are of course also studied using growth chambers and greenhouses. Modelling light within these environments differs from the case of the canopy in a field in several aspects: (i) there are radiative interactions between walls (large surfaces) and plants (set of small surfaces); (ii) the number of plants involved tends to be small; and (iii) there is a high spatial heterogeneity of plants and light sources. Owing to these features, the TM approach does not seem to be appropriate for this environment. The complementarity between computer graphics models adapted to building scenes and canopy models seems to be an interesting starting point to develop a model for indoor canopies (Chelle et al. 2004).

Finally, a surface-based model taking into account the exact geometry of the canopy has also been used for remote-sensing studies (Ross and Marshak 1988; Borel et al. 1991; Govaerts and Verstaete 1994; España et al. 1999; Disney et al. 2000). These models could improve the knowledge of the link between radiative and structural properties of a canopy and signals acquired by satellites. That would enable a more efficient assimilation of spatial data in crop models.

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