SEASONAL BEHAVIOR OF CROP CANOPIES: LINKAGE OF FUNCTIONAL MODELS AND RADIOSITY.

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ABSTRACT

The first objective of a crop production model is the correct simulation of the mechanisms which drive the yield. In order to compute the absorbed photosynthetically active radiation, the LAI time profile is described to characterize the development of the canopy generally considered as a big leaf. The linkage with radiometric measurements in short wavelengths, which allow to monitor crop growth and canopy development during the growing period, is classically realised by the mean of a radiative transfer model. In such models, the canopy is assumed to be a semi-infinite medium with little particules of known optical properties homogeneously distributed. A crop canopy, especially at the beginning of growth, cannot be correctly represented in that way. The AFRCWHEAT model simulates the canopy development with description of the elements at the individual level (population and size of each element). It is then possible to test the radiosity method, in order to compute bidirectional reflectances over the young canopy taking into account the light interception for each element. Results show that the mean features of the visible reflectances are retrieved, with a clear evidence of the hot spot phenomenum.

KEY-WORDS: Functional model, Canopy structure, Reflectances, Radiosity.

1 - INTRODUCTION

Bidirectionnal effects on the surface reflectance are an important limiting factor for the accuracy when using remotely sensed data, mainly for multitemporal studies. Many attempts have been made to modelize these effects, through physical or empirical expressions, in order to take them into account when analyzing the variations of the surface reflectance. If some success have been acquired in this topic, the temporal behavior of the surface due to vegetation activity infers on the variations of the parameters in a way that is hardly known especially when considering heterogeneous structures. This study uses a deterministic description of the surface, based on the radiosity method, with inputs (LAI, geometry, ...) from a crop production model and should be considered as a preliminary step on the path to model confidently a virtual canopy, upon which we would have a total control, well designed for testing existing models and parameter retrieval procedures.

The radiosity method is briefly described in the next section. The simulation of the development of a wheat canopy gives some information about the architecture, which must be completed by empirical estimations of the position and the orientation of the elements. In the third section, the radiosity method will be especially tested at the beginning of growth, over a sparse canopy with low value of LAI.

2 - MATERIALS AND METHODS

2.1. The radiosity method

The radiation transfer regime inside a given kind of canopy has been the main topic of many studies. Still, it appears very complicated to account for all the heterogeneities that occur in natural cover types. Most of the solutions proposed up to now simply assume homogeneity in one or more dimension in order to make possible to solve analytically the radiative transfer equations. An alternative method has been described by Borel *et al.* (1991). The basic principle comes from thermal computations but can be applied to short wavelengths. This method independantly considers all the elements of a canopy, and therefore needs a very accurate description of the architecture of the plants and soils (figure 1). The idea is to compute, for each element, a radiation budget and to solve the obtained set of equations. To achieve this computation, one needs to know three parameters: F the view factor matrix, is the geometric ratio of energy leaving element *i* that can reach the element *j*, E the radiance due to the direct illumination vector which gives the energy directly incident on each element and ρ the individual reflectance vector which gives the reflectance factor for each element, assumed lambertian in this preliminary study. What is unknown in this equation is then the luminance of element *i*, called radiosity B_i. The so called "radiosity equation", which balances incoming and outgoing radiation fluxes on discrete surface elements, can be written as:

$$B_i = E_i + \rho_i \sum_{j=1, j \neq i}^{N} F_{ij} B_i$$

where N is the total number of elements.

B_i: Radiosity on surface element i (total radiation flux density leaving that surface).
E_i: Radiance due to direct illumination (equivalent to "emission" of the element).
$_i$: reflection coefficient.
F_{ij}:"view factor": specifies the fraction of radiant flux leaving another surface j that reaches surface i.

As it can be seen on this equation, an element cannot see itself. This equation leads to a rigorous energy balance: the total radiation flux leaving any surface element i is equal to the sum of its emitted and reflected flux originating from all other surfaces. As said by Gerstl and Borel (1990), the strengh of the radiosity method comes from the fact that leaves are treated as individual surfaces that reflect and transmit radiations. This allows the analysis of radiative effects due to the discrete nature of leaves and stems and their heterogeneous distribution, e.g. mutual shading and clustering of leaves.

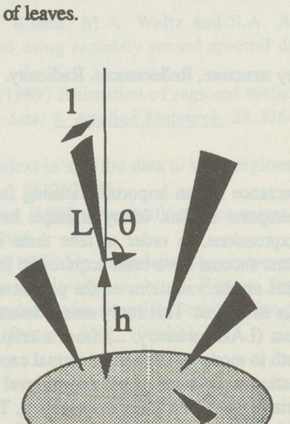


Figure 1: Each element of the canopy is defined by its height h, its length L, its width l, its orientation θ and optical characteristics.

Computing view factor allows to account at once for all possible direct radiative interactions occuring between the different elements. The view factor matrix F is computed according to the fish eye method, also described in Borel *et al.* (1991). The basic principle is to compute, for a given element, a fish eye image of the visible hemisphere from this element, then to compute the relative areas occupied by all the surrounding elements on this image (figure 2).

The direct illumination vector, E is computed by calculating for each element, with a given resolution, what part of its surface is directly lightened by the sun. The individual reflectance vector ρ is given as input, using field measurements. After the radiosity equation is solved through a Gauss-Jordan algorithm, images of the canopy are computed. These images can be generated for any geometric configuration and allow to simulate the bidirectional reflectance of the canopy in all the directions, with any kind of direct illumination.

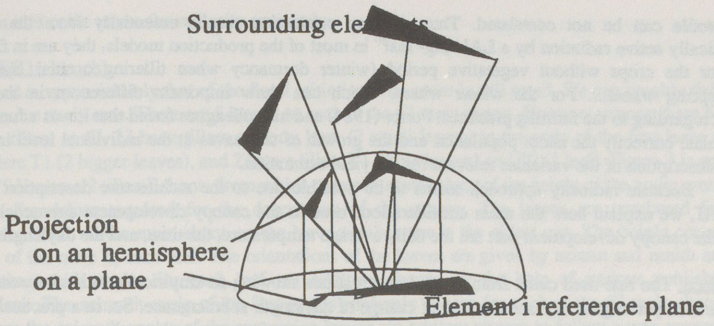


Figure 2: The fisheye method is a double projection that allows to integrate easily the solid angles involved, paying attention to overlaying.

2.2 The crop model AFRCWHEAT2

The original model AFRCWHEAT for winter wheat is described in Weir *et al.* (1984) for the explanation of all the processes related to the phenological development, the light interception, the photosynthesis, the respiration, the dry-matter partitioning, the root growth and the grain growth. This model is distinguishable from other crop production models by a complete and discrete description of the development of the canopy. Very often, the canopy is just represented by a "Big-Leaf", characterized by the value of the LAI, and eventually, the cover fraction. When the photosynthesis is computed at various levels within the canopy, a parameter describing the rate of attenuation of the radiation within the cover is used to allow the computation of the intercepted photosynthetically active radiation at each level. This is the case of the SUCROS crop models (Spitters *et al.*, 1989). Of course, when studying the radiative transfer within the canopy, it appears that this parameter is related to the feature of the distribution of the leaves angles, and more completely, to the architecture and the structure of the canopy. But most of the crop production models can simulate growth and give correct yield estimations without any description of the architecture of the canopy.

On the opposite, in AFRCWHEAT, the stems and leaves are countable. Simulation of emergence, growth and senescence is done for individual leaves, in a quantitative way: lentgh and width are computed, and the maximum dimension of each kind of leaf is known. The model explains the production of the tillers, followed by their death or their survival. Details of the simulation of tiller and leaf growth are given in Porter (1984). The first version of the model was usable for a crop without water or nutrients limitations, which is generally the case for most of the winter wheat fields in the temperate regions, at least in Europe. However, the new version AFRCWHEAT2 (Porter, 1993) now incorporates responses to water and nitrogen, taking into account the soil characteristics. An important improvment in the AFRCWHEAT2 version is the stronger linking than before between the canopy development and the photosynthesis assimilates sent to leaves. The canopy development submodel computes the potential daily increase in the leaf area resulting from the growth of the active leaves. The photosynthesis and partitionning submodels compute the assimilated dry matter potentially sent to the leaves. Interaction is done in order to reduce the increase in the LAI if the dry matter sent to the leaves is limited. The daily meteorological records required to run the model are solar radiation, minimum and maximum temperature, dry bulb and wet bulb temperature at 09:00 GMT, precipitation and wind.

Apart from the satisfaction to be able to reproduce the architecture of the canopy, the interest to use such a rather complex description in a crop model for which the main objective is to estimate correctly the yield, and not the number and the area of the leaves, is real and must be detailed a little bit. The crop production is linked to the grain weights and to the number of grains per square meter. The number of grains per square meter is related to the number of shoots able to carry ears: main shoots, plus the surviving tillers. To reproduce the population behavior, three initial parameters due to the farming practices are very important: the day of sowing, the sowing density, and the chosen variety. The variety is essentially characterized by its sensitivity to the photoperiod. The well managed fields reach generally a number of shoots at anthesis which could be guessed at the first order more simply. However, depending on the values of the three parameters discussed above, the behavior of the canopy development in the first phenological stages, in terms of shoot population time profile and

LAI time profile can be not correlated. Thus, if crop production results essentially from the absorbed photosynthetically active radiation by a LAI "big- leaf" in most of the production models, they are in fact, more successful for the crops without vegetative period (winter dormancy when tillering occurs) like: maize, sugarbeets, spring wheat.... For the winter wheat, which can show important differences in the canopy development regarding to the farming practices, Porter (1984) and his colleagues found that it was a fundamental point to simulate correctly the shoot population and the growth of the leaves at the individual level in order to have a good description of the variables relevant for the yield estimation.

Because radiosity approach seems to be possible due to the architecture description made by AFRCWHEAT, we explain here the main considerations used in the canopy development submodel. Driving variables of the canopy development part are the daily average temperature, the time, and the daylength.

Leaf appearance: The rule used came from ground observations showing an empirical relation between the rate of leaf appearance per degree day and the rate of change of daylength at emergence. So, in a practical way, the phyllochron interval (thermal time required between the appearance of successive leaves), computed at the day of emergence, is bigger for early sowing fields than for late sowed fields, because emergence day is closer to the equinoxe date in the first case than in the second case. A mean value of the phyllochron interval is 100 - 110 degres.days.

Tiller production and survival: When the stage "4 leaves on the main shoot" is reached, tillers are produced until the double-ridge stage. A time step of 7 days is used for the simulation: the number of tillers initiated in a week depends on the temperature of the previous week, and on a shoot production rate. Tiller production stops at double ridge stage. The survival of each tiller group is calculated from the accumulated thermal time since double ridge, taking into account the existing shoot density at the birth of each tiller group. Higher is this density, more reduced is the proportion of surviving tillers. In a practical way, it means that the first born tillers have a chance to survive of about 0.9 or 0.95, when the tillers born near the double ridge stage generally do not survive. At anthesis stage, tiller death stops, and all live shoots are assumed to carry ears.

Leaf growth and senescence: The maximum dimensions of the leaves are defined and depends on the position of the leaves on the stem. Each leaf reaches its final size in 1.8 phyllochrons. The model simulates the leaf growth by describing the daily length and width growth of both laminae and sheaths. Because various observations during the main period of vegetative growth showed that there are generally between 3 and 4 active green leaves on a shoot, the thermal time required from the attainment of maximum size to zero active area is estimated to be 3.5 time the phyllochron interval for most of the leaves. Each leaf remains totally active before the beginning of the senescence during approximately the 2 thirds of that time.

2.3 Radiosity experiment.

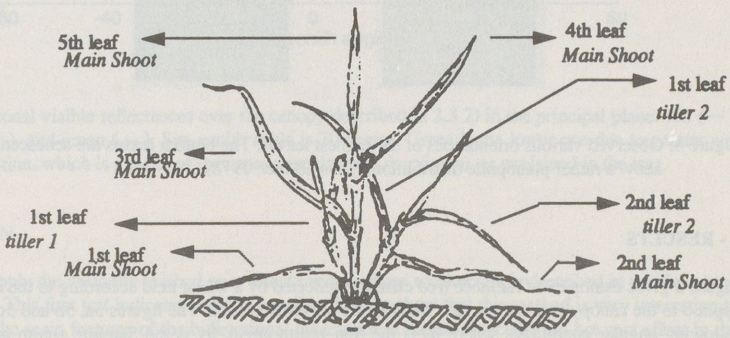
We want to examine the results of a radiosity computation at early stage of the growing season of the winter wheat. The program of the functional runs with a daily time step. When the day processed is a day chosen for the computation of the radiosity, all the variables related to the description of the structure are written in an output file. It means: a) per square meter: main shoot population, population of the first category of tillers (on the first leave of the main shoot), of the second category, etc.... , b) dimension of all the existing leaves: width and length of lamina and sheat areas, c) percent of senescent area on the various leaves.

To keep computation time (which is very high with the radiosity technique) within reasonable limits, we restrict our study area to a quater of square meter. Then, with an original sowing density of 250 shoots/ square meter, we worked with 63 main shoots on our study area, which allows an easy representation in 7 rows of 9 shoots. The space between the rows is approximately 7 cm, and the space between 2 shoots in the same row is between 5 and 6 cm. The x y positions of the main shoots are then defined. The x y position of any tiller is the x y position the main shoot where this tiller appeared, plus a deviation of 1 or 2 cm following an azimuth direction which is randomly chosen.

Some other information, which are not simulated by the model are needed to use the radiosity techniques: the height and the orientation of each element. Many graphic representations or pictures of a wheat shoot at various phenological stages have been consulted in general agronomic literature (e.g. Soltner, 1978), as well as some reported values of height or leaf inclination which were found in published studies. The values used in that work are arbitrary, even if they are carefully chosen. In a future study, the use of empirical relation should be used to add to the canopy development submodel, the simulation of the position (especially the height) and the orientation of the leaves. For some particular days, we present now the structure of the canopy and our way to represent it in order to use the radiosity approach:

1) Day 70 (11 March)

The period is approximately that of the floral initiation. The cover is still small. We can roughly define 4 kinds of shoots on our study area. There are 5 leaves on each of the 63 main shoots. However, among these 63 shoots, 5 do not have tillers at all, 23 have tillers recently born (2 small leaves) at the node of the first leave (T1), 12 have older tillers T1 (2 bigger leaves), and 23 have tillers T1 (2 big leaves) and T2 (1 leaf). Figure 3 is an example of a typical "5 leaves + 2 tillers" shoot, from which representative values of the height of the nodes were taken. Table 1 shows the values required for the description of the canopy. The leaves are numbered following their appearance order on the main shoot, so the leave number one is the oldest one. The height corresponds to the position of the node of each leaf. The orientations of the leaves are given by azimut and zenith angles. As said before, the zenith angles for each leaf are arbitrary chosen by the help of various published images or descriptions. The azimuth angle of the first leaf is randomly chosen for each of the 63 main shoot of our study area. Then the azimuth angles of the successive leaves are arbitary chosen to follow a rule assuming that a leaf approximately appears in the opposite direction than the previous leaf on the same shoot. The azimuth directions of the first, second and more leaves define the direction of the deviation of the x y coordinates of the tillers born on the nodes of the first, second and more leaves. The widths and lengths of the various leaves, as well as their population, are the outputs of the canopy development part of AFRCWHEAT2. The heights, the deviations of the x y position for some elements, and the orientation angles are empirically chosen.



Tillering at floral initiation stage

Figure 3: Example of representation used in order to define node height and leaves orientation. *(Soltner, 1978).*

Leaf	height	dist.	directi	length	width	φ	θ
MS 1	1.25	1.0	0.0	77.89	5.84	0.0	100.0
MS 2	2.5	2.0	170.0	79.67	5.98	170.0	90.0
MS 3	3.5	0.0	0.0	78.62	5.90	340.0	45.0
MS 4	5.5	0.0	0.0	48.06	3.60	150.0	45.0
MS 5	5.5	0.0	0.0	16.84	1.26	0.0	0.0
T1 1	2.5	2.0	170.0	37.30	2.80	20.0	40.0
T1 2	4.0	3.5	170.0	22.52	1.69	230.0	90.0
T2 1	3.0	2.0	0.0	16.84	1.26	100.0	10.0

Table 1: Characteristic of the structure of a wheat shoot at floral initiation stage with 2 tillers. MS: Main Shoot, T1: tiller 1, T2: tiller 2. Height and distance to MS in cm. Length and width in mm. Zenith angles θ and azimuth angle φ in degrees.

2) Day 157 (June 6th): Phenological stage is "Begin ear growth", or "Heading". The AFRCWHEAT2 simulation gives 787 shoots/square meter: 250 Main Shoots with 11 leaves, 219 Tillers 1 with 8 leaves, 77 Tillers 2 with 8 leaves, 108 Tillers 2 with 7 leaves and 133 Tillers 3 with 6 leaves. Various sizes of leaves are obtained for Tillers on same category depending on age. From leaf 6 on Main Shoot, leaf 5 on Tiller 1, and so on, the complete leaf is described by a sheat area and a lamina area. The model gives information on the senescent parts, which consequently have different optical properties. To avoid very expensive computational time, the area tested for the radiosity computation is limited to a 25 x 25 cm square. This leads to 417 leaves, but 679 leaf elements because sheats and laminas have different dimensions and orientations, and some leaves are turned down, as it can be seen on figure 4. Due to the high density, the x-y positions are randomly chosen.

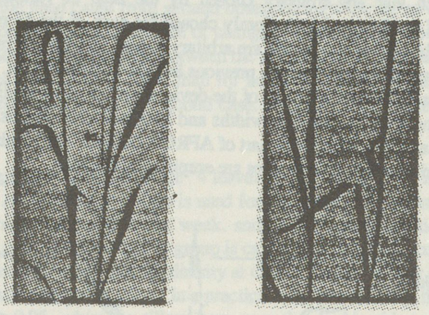


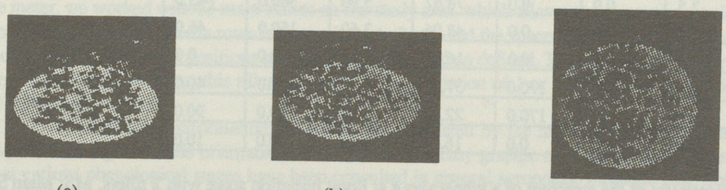
Figure 4: Observed various orientations of the highest leaves. The bottom leaves are senescent at this period and show a rather planophile distribution. *(from Soltner, 1978).*

3 - RESULTS

Figure 5 gives examples of radiance (red channel) reflected by a wheat field according to the radiosity equations applied to the canopy architecture described in the previous section. The figures 5a, 5b and 5c correspond to the following angular conditions, where θs is the Sun zenith angle, θv is the Satellite zenith angle, and ψ is the relative azimutal angle:

a) θs:0 degre, θv: 60 degres, ψ : 0 degre.
b) θs: 30 degres, θv: 30 degres, ψ : 135 degres.
c) θs: 30 degres, θv: 60 degres, ψ : 135 degres.

We must point out that soil is clearly visible. In fact, it obviously has too much importance, regarding the chosen period, and this is due to the difficulty to correctly represent the architecture of leaves when they are numerous, long and with various curves. Our too simple description leads to elements which are crossing each others, which is completely irrealistic. However, the hot spot effect is perfectly retrieved as it can be observed on figure 6, where reflectances in the principal plane are plotted for several view angles.



(a) (b) (c)

Figure 5: Rendering of wheat field canopy with the radiosity method, in visible wavelength (red). Illuminations and viewing conditions are explained in the text.

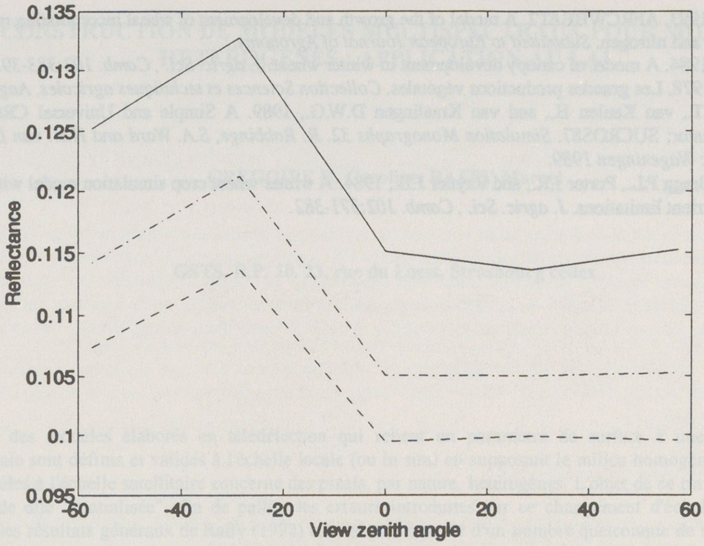


Figure 6: Bidirectional visible reflectances over the canopy described in 2.3 2) in the principal plane: red (—), blue (- ·), and green (--). Sun zenith angle is 30 degres. Green is the lower one due to greater soil contribution, which is a result of the canopy architecture description, as explained in the text.

4 - CONCLUSION

We have tried to apply the radiodity method on a wheat canopy whose architecture is described in part by a crop production model. This first test indicates that it is possible. Results show that this method is very interesting to correctly retrieve the main features of the bidirectional reflectance, it means especially the hot spot effect in the principal plane. However, the complete and correct description of the structure of such a canopy has not been yet correctly achieved in this study. Clearly, the first objective of the canopy development submodel in AFRCWHEAT2 is to simulate useful information for the yield estimation, and we must take into account specific works regarding the temporal changes in the structure of a canopy to improve the description which we need in order to be more confident in our computation of the view factors. Following improvements would be to consider that the individual elements are not Lambertian, and the association of elements to define objects would allow to work with a more important number of leaves.

ACKNOWLEDGEMENTS

The authors thank J.Porter for providing the original AFRCWHEAT2 code.

REFERENCES

Borel C.C., Gersl S.A.W., and Powers B.J., 1991. The Radiosity Method in Optical Remote Sensing of Structured 3-D Surfaces. *Remote Sens. Environ. 36:13-44.*

Gerstl S.A.W. and Borel C.C., 1990. Principles of the radiosity method for canopy reflectance modeling. *Proc. IGARSS'90 Vol.3, pp 1735-1737.*

Porter J.R., 1993. AFRCWHEAT2. A model of the growth and development of wheat incorporating responses to water and nitrogen. *Submitted to European Journal of Agronomy.*
Porter J.R., 1984. A model of canopy development in winter wheat. *J. agric. Sci. , Camb. 102:383-392.*
Soltner D., 1978. Les grandes productions végétales. *Collection Sciences et techniques agricoles, Angers.*
Spitters C.J.T., van Keulen H., and van Kraalingen D.W.G., 1989. A Simple and Universal CROp growth Simulator: SUCROS87. *Simulation Monographs 32. R. Rabbinge, S.A. Ward and H.H. van Laar (Eds). Pudoc Wageningen 1989.*
Weir A.H., Bragg P.L., Porter J.R., and Rayner J.H., 1984. A winter wheat crop simulation model without water or nutrient limitations. *J. agric. Sci. , Camb. 102:371-382.*