

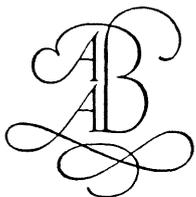
Remote Sensing for Resources Development and Environmental Management

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TURTLE and HARE, two detailed crop reflection models

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ABSTRACT: Yield prediction can be done by means of dynamic simulation, based on crop properties and global environmental conditions. The use of remote-sensing data, interpreted by means of a crop reflection model will improve the quality of the prediction.

Two crop reflection models are presented: both models can be used to predict the reflection of a wide range of crops, even when crop properties vary with crop height. One of them (TURTLE) consumes much computer time and yields a complete flux profile within the canopy, whereas the other one (HARE) is much faster, but produces only the reflection properties of the complete crop.

RESUME: Le rendement des cultures arables peut être prédit par simulation dynamique, basé à les caractéristiques de la culture et les conditions environnementales. L'usage des données obtenues par télédétection et analysées au moyen d'un modèle de réflexion du couvert végétale, peut améliorer la qualité de prédiction.

Deux modèles de ce type sont ici présentés. Tous les deux peut être utilisé pour prédire la réflexion du couvert. L'un deux (TURTLE), exigeant un temps prolongé d'exécution sur ordinateur, produit un profil complet des flux à l'intérieur du couvert végétal, alors que l'autre (HARE) exige un temps d'exécution beaucoup plus court, mais ne produit les caractéristiques de réflexion que pour la culture entière.

1 YIELD PREDICTION BY DYNAMIC SIMULATION

At the Department of Theoretical Production Ecology of the Wageningen University, and in cooperation with the Centre for Agrobiological Research and other institutes, a number of dynamic simulation models for crop growth have been developed during the last decennia (Penning de Vries & van Laar, 1982). Some of these models are especially meant for detailed simulation of the processes in a single plant during one diurnal cycle, whereas other models are used to simulate growth and development of a complete plant stand during a complete growing season.

If the modelled crop grows under well-known circumstances, as in a green house or in a region where weather conditions are fairly stable, then a good correspondence between the real crop and the model results is achieved. When however the knowledge about the actual growing conditions (weather, soil, nutrients) is poor, serious deviations between model results and measured data can occur. This means that the quality of crop yield simulation based on mean environmental conditions hardly exceeds the quality of a prediction that is based on intelligent extrapolation of the yields as obtained in the past under comparable circumstances.

2 GENERAL CROP PRODUCTION THEORY

Light interception is an important factor in biomass production rate, and on the other hand the coverage of a crop is directly related to the intercepted radiation. In the first phase of the growth of a crop, when the crop does not cover the soil totally, interception, and therefore also growth rate, increases with biomass production. This phase is called the phase of exponential growth. During this phase there is a strong positive feedback of biomass on biomass production rate. Therefore relatively small differences between model assumptions and reality will cause serious errors in the simulation.

In the second phase of the growth, when the canopy becomes more and more closed, light interception does

not increase further with biomass production. This phase is called the linear phase, where feedback is less important than in the first phase. But during this phase stress factors like water or nutrient shortage or pests and diseases may play their role in the growth of the crop, so also in this phase the simulation can show serious deviations between the modelled situation at harvest time and the real crop.

3 ENHANCING THE QUALITY OF YIELD PREDICTION

The purpose of this work was to enhance the quality of yield prediction obtained by dynamic simulation by including data gathered during the growing season from the crop itself. Combination of the actual weather data (in stead of mean climatological knowledge) with the deviations between the actual and the predicted state of the crop caused by stress factors will improve yield prediction.

Data collection on the ground can be a problem. A good way to observe the crops themselves seems to be the use of remote sensing techniques and among these, multiband spectral scanning has been proven to be an applicable technique for the detection of crop properties (Bunnik, 1978).

4 DYNAMIC GROWTH MODELS

Before continuing on the topic of the interpretation of reflection data to adjust simulations carried out with dynamic growth models, we will give a brief explanation of the technique of dynamic simulation.

A dynamic crop simulation model can be considered as a set of simultaneous ordinary or partial differential equations, in which each equation represents the in- or decrease in one quantity of interest, like leaf weight or dry matter stored in the kernels. The state of the system at the start of the simulation (for instance the beginning of the growing season) defines the initial values, whereas the environmental conditions such as rainfall, radiation and temperature are the boundary conditions

of the system. In vector notation: at each moment t the rate vector $R(t)$ is described as a function of the state of the system $S(t)$ and the environmental conditions $E(t)$ at the same time:

$$R(t) = f(S(t), E(t)) \quad (1)$$

The state of the system $S(t)$ is calculated by integration of $R(t)$, starting with $S(0)$, the initial situation:

$$S(T) = \int_0^T R(t) \cdot dt + S(0) \quad (2)$$

The environmental conditions are not affected by the changes in the system itself, so they can be written as a function of time only:

$$E(t) = g(t) \quad (3)$$

The influence of the states S on the rates R , as expressed in a general way by equation 1, will cause feedback so that the rates R are not a function of time only. The most common feedback loop is the one [biomass \rightarrow leaf area index (LAI) \rightarrow growth \rightarrow biomass]. In figure 1, this loop is drawn by arrows. These arrows represent flows of information (dashed in the figure). The last one is a flow of material, closing the loop by an integration (solid arrow). Figure 1 serves only as an example, it is obvious that the dynamic models that can be applied for yield prediction are much more complicated than this one.

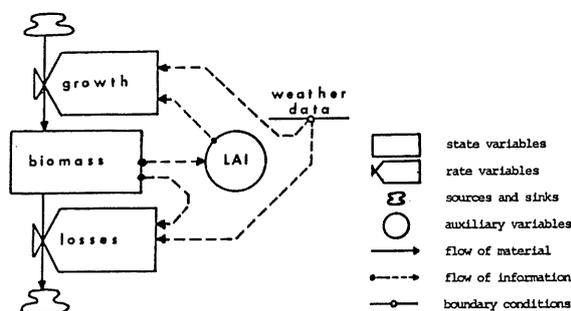


Figure 1. Some relations in a dynamic simulation model for crop growth (simplified).

An important decision is to be made on the boundaries of the system: they depend on the total simulation time and on the desired level of detail. For instance, soil water content is fairly constant over one day, so in a simulation that only concerns one diurnal cycle it may be considered to be constant. When the soil water content in a porous sandy soil is mainly a function of human interventions in the level in surrounding ditches, it is a function of time and at last, when the water uptake by the plants plays an important role in the soil water content, soil water must probably be taken in the state vector S of the model and the changes in it in the rate vector R .

All relations in the models are defined as mathematical expressions, as tabular functions or as combinations of both. The complexity of the relations between S , E and R prohibits generally the application of an analytical solution of integral S , so only a numerical solution can be applied. Because of the discontinuities in E , Euler's integration method is generally used to solve expression (2). This means that this expression is rewritten to:

$$S(T+\Delta T) = S(T) + \Delta T * R(T) \quad (4)$$

where ΔT is the integration time step. For simulations that concern one diurnal cycle, ΔT is set

to five minutes or less, for a complete growing season of 100 - 150 days, generally one day is a good choice for ΔT . Phenomena that show a large amplitude during one timestep (for instance incoming radiation during one day) must be averaged or totalised over each step.

5 COUPLING REMOTE SENSING DATA AND GROWTH MODELS

A problem in the incorporation of remote sensing data in simulation models is the difference between the type of information that is used in the models like biomass or LAI and the type of data as collected with remote sensing techniques. It is obvious that a coupling mechanism must be applied. Roughly spoken three types of coupling mechanisms are possible:

1. Statistics: from a wide range of crops growing under different circumstances and in different stages of development, the reflective behaviour must be available. The measured reflection is compared to the data set of known reflections. This can probably give the information which we are interested in, but it requires a tremendous data collection in advance.

2. Direct calculation of the crop state from the measured reflection. This means that it must be possible to invert the set of functions that describes the relation between crop properties and reflection.

There exists no unique relation between reflection and crop status. Therefore both the first and the second method will give ambiguous results.

3. Starting with the simulated crop, the reflection of this crop is estimated and compared with the measured data. When differences are detected between these two, the most likely parameters in the growth simulation are changed and a new simulation run is made. This process is repeated until a good correspondence between measured and estimated reflection is achieved.

In this work, the choice is made for the third method, because it takes into account additional knowledge from ground truth and about relations between parameters concerning crop and soil. Therefore a model is needed to calculate the reflection of a crop from its optical properties and leaf density distribution. A model that can serve for this purpose must fulfil two conflicting requirements:

1. The model must be complicated in view of generality, because it must be possible to calculate the reflection of a crop in any arbitrary direction as a function of crop properties, soil reflection and the spatial distribution of the incoming radiation. Too many limitations of the model cause the computation results to be a function of the model restrictions rather than a function of the crop properties.

2. The model must be simple in view of its frequent iterative application, so one run with the program may not exceed an acceptable level of use of computer resources.

6 SOME EXISTING MODELS

Several models published before are investigated on these needs. All are rejected on their limitations.

The Suits-model (Suits, 1972) is based on a very simplified crop geometry. Especially for off-nadir observations or in the situation where the sun's direction deviates from the zenith, the model results show only a qualitative relation with experimental data.

A second model that is considered is the model published by de Wit (1965), which is enhanced later by Goudriaan (1977). These models are developed to estimate the absorption of incoming radiation. Therefore, these models are based on a simplified leaf reflection submodel and on aggregating functions for reflection by crop layers. Although the overall

crop reflection is computed fairly accurate with these models, the directional distribution of the reflected radiation is oversimplified. However, remote sensing is based on measuring the radiation in one single direction, so for the use in an remote sensing environment this distribution must be modelled more carefully than in these models.

The third model that is studied is the model of Chen (1984). This model is based on the adaptation of the Kuebelka-Munk equations (Kuebelka & Munk, 1931) to matrix-vector algebra. In this models fluxes are presented as vectors and reflection and transmission properties of a crop layer as matrices. Chen distinguishes 324 different directions (36 azimuthal, 9 inclination classes), so vectors have 324 and matrices 104976 (= 324^2) elements. The evaluation of the double inversion of the matrices involved in the calculations is so laborious even for a large main-frame computer that for practical reasons this model can only be used when a very simple crop geometry is assumed.

7 DEMANDS FOR A CROP REFLECTION MODEL

Before we present our own models, we will recapitulate the demands of a model that fulfil the stated requirements. These demands are:

1. The model must be applicable for layered crops (crops with a vertical component in the description of the crop properties), for instance to model flowering;
2. The model must not limit leaf density and leaf distribution functions;
3. It must be possible to handle different types of leaf surface reflection properties;
4. The spatial distribution of the incoming radiation, the direction of the sun and the ratio between diffuse and direct incoming radiation may not be limited by the model;
5. Computations with the model must yield the radiation intensity in any direction, at least within a cone around the zenith with a half top angle of 45 degrees;
6. At last, computations with the model must be practically carried out on a normal computer, so neither program seize, nor computing time may exceed reasonable limits.

8 BASE OF OUR MODELS TURTLE AND HARE

On the principles as described in the former section, two discrete models for crop reflection are developed: TURTLE (The Universal Reflection and Transmission model for Layered crop Experiments) and HARE (Handy and Accurate Reflection model for crop Experiments). The base of these models is:

1. Because of the transparency of the air inside the crop, the radiation regime in the crop is only affected by the leaves. Therefore the vertical axis is expressed in LAI in stead of meters.
2. A crop is separated in thin layers. Each layer is assumed to be so sparse that mutual shading and other in-layer interactions may be neglected: the intercepted and remitted fraction of a ray of light will not be intercepted again in the same layer. Practically an LAI of 0.1 or less suits for this purpose.
3. Each model layer may have different properties for reflection and transmission of the leaves and for the leaf density function. If desired, calculations may be repeated for each wave length band, using the same geometrical definition of the crop.
4. A set of 46 direction vectors is defined, each vector representing a pentagonal or hexagonal cone around it. All cones cover an equal solid angle of 0.137 sr., so together they cover a hemisphere. All angles between adjacent directions are 0.40 ± 0.02 rad, so a fairly regular pattern of reference directions is created (figure 2). These directions are used for

two purposes:

- as reference directions for rays;
- as normal-vectors on leaf planes.

The equality of all represented solid angles prevents the use of many weight factors in the calculations.

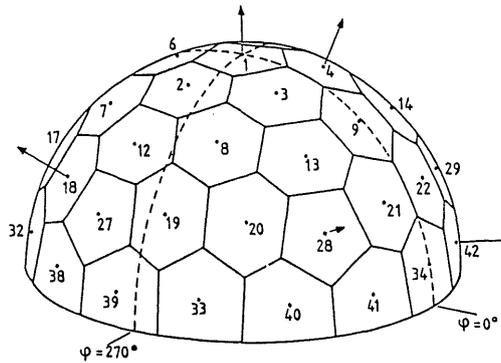


Figure 2. Distribution of polygons over a hemisphere as used in our models. For some directions the reference directions are also drawn as arrows, originating in the centre of the sphere.

5. The models permit that leaves show specular reflection, diffuse reflection and diffuse transmission. Both types of reflection may depend on the angle of incidence.
6. Reflection and transmission coefficients of leaves and soil may be chosen freely.
7. Any arbitrary leaf angle distribution can be modelled by assigning weight factors to all 46 leaf plane directions.
8. Two options for the soil reflection pattern are built in: the first is a flat surface with Lambertian reflection properties, the second is a rugged surface.

9 CALCULATION STEPS

After the desired crop and soil properties are chosen, the calculations are carried out according to the following steps:

1. For all different crop layers four different matrices are computed, two for layer reflection (upperside and lower side) and two for layer transmission (downward and upward). Each element (j,i) of each matrix represents the fraction of the flux coming from direction i that is remitted to direction j. The elements (i,i) of the transmission matrices include also the transmission in direction i through the interleaf-spaces. As the assumption is that no double interactions occur within one layer, each element can be computed as the sum of the contribution of all leaves, counted over 46 leaf directions.

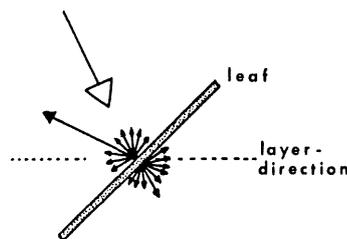


Figure 3. Interaction of a leaf with the intercepted radiation. Notice that leaf reflection sometimes yields layer transmission (and vice-versa).

2. A similar reflection matrix for the soil is derived from the soil reflection type and reflection coefficient.

3a. In the TURTLE-model, the reflection of the crop is computed with the adding algorithm (Van der Hulst, 1980), starting with the soil matrix and the matrices of the lowest layer. In succeeding steps the influence of one layer is added at a time until the top of the canopy is reached. In a second series of calculations, all relation matrices between incoming flux and the fluxes between all model layers are computed, starting with the top layer.

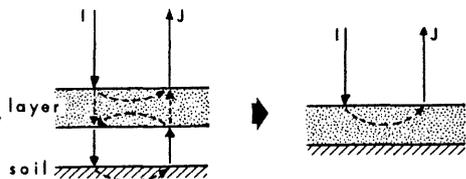


Figure 4. One step of the adding algorithm as used in the TURTLE-model.

3b. In the HARE-model, a little extension of the adding algorithm is used to combine eight matrices of two layers to four matrices of the combined layer. This extension consists of the calculation of the combined transmission matrix. This process is repeated until all crop layers are incorporated. As long as identical crop layers are involved, the algorithm is used to double layers in stead of adding layers one by one. At last, the standard adding algorithm is used to add the soil to the crop.

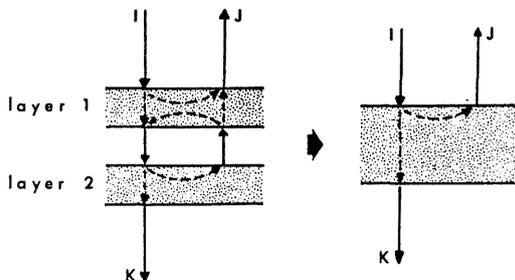


Figure 5. One step of the adding algorithm as used in the HARE-model.

4. A vector for the incoming radiation is computed, based on the sky irradiation pattern (including the sun). This vector is premultiplied with the matrices as derived in calculation steps 3a or 3b. To calculate the reflection of the same crop under different sky conditions, only this last step has to be repeated. The matrix (HARE) or matrices (TURTLE) that represent the crop behaviour are defined separately from the actual incoming radiation.

As can be seen, with the TURTLE-model the total flux profile within a canopy can be computed. It is obvious that this result is obtained only after an enormous number of calculations. Because in a remote sensing environment generally only the reflection of a complete crop is of interest, the HARE-model, which consumes only about 10-20 % of the computer resources of the TURTLE model, will be sufficient.

10 CALCULATION RESULTS

The models as described in the former sections are used for calculations of crop reflection in different wavebands and their combinations such as vegetation index as affected by:

1. leaf angle distributions, including azimuthal preference;
2. soil reflection coefficient;
3. optical properties of the leaves;
4. reflection and transmission coefficients of the leaves;
5. sun direction and sky irradiance;
6. observation direction.

The calculations show that all crop properties in the list above influence the reflection properties of a crop, and that the interpretation of reflection data may lead to errors in the estimation of the cover percentage up to 15 %. When the nadir-reflection in one wavelength band is used, crop geometry, soil reflection level and optical behaviour of the leaves are the main sources of these errors. When the vegetation index is used in stead of the reflection in one single band, the importance of the crop geometry decreases, but the influence of the soil brightness and the optical behaviour of the leaves remains an important source of possible mis-interpretation.

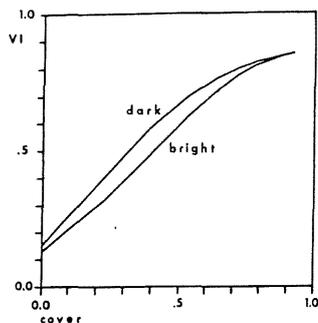


Figure 6. Vegetation index VI as function of cover percentage for two soils, which differ in brightness. Sun's inclination is 60 deg., the leaf angle distribution of the crop is spherical, the observation direction is nadir.

In addition to the uncertainties caused by crop and soil properties, the observation direction introduces important deviations in the radiance. When an aircraft is used as the observation platform, the viewing direction may deviate as much as 45 degrees

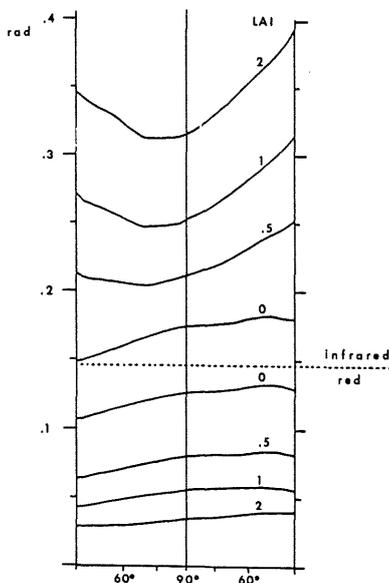


Figure 7. Influence of the observation direction on the uncorrected reflection in the red and infrared spectral band for different values of the LAI.

from the nadir-direction. The effect of this can be an increase up to 25% in the measured radiation in the infrared band, where the measured radiation in the visible part of the spectrum is influenced hardly under most circumstances. It is obvious that this effect may not be neglected.

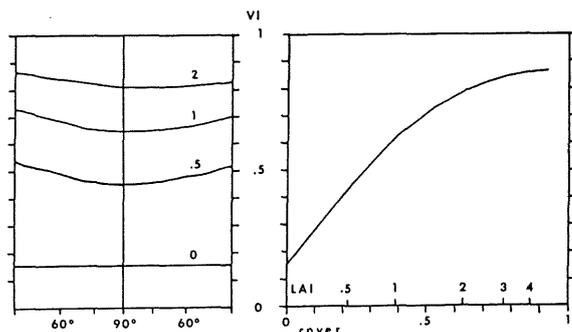


Figure 8. Vegetation index VI derived from the data in figure 7 and the relation between VI and coverage as computed for the nadir direction.

To cope with this problem, usually the pixel-values are corrected by means of a quadratic equation. When crops with different properties show a uniformly distribution pattern over the observed area, this correction is shown to work quite well, but when gradients occur in the observed area, the correction primarily corrects for the gradient itself rather than for the differences in radiation caused by the observation geometry.

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Much has changed in the field of image interpretation in the last decade. Non-photographic remote sensing has evolved, opening hitherto unused parts of the electromagnetic spectrum for recording. The satellite imagery that is now available has revolutionized small-scale mapping procedures, giving new impetus to monitoring of the environment and resulting in the introduction of image interpretation in fields such as meteorology and oceanography. Digital methods of data recording and image enhancement have become common practice. The French SPOT satellite, launched earlier this year, marks the advent of the second generation of satellites with higher spatial resolution and better general performance. Detailed surveys can be made using the stereoscopic capacity of the imagery. Photogrammetric and cartographic circles are very interested in the wealth of information that is now being produced continuously. There are new developments in data handling and compressing techniques, and increasing emphasis is given to geo-information systems. Technological progress on all fronts resulted in a wide range of papers. These proceedings indicate new approaches and form a state-of-the-art.

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