Adapting an instantaneous canopy photosynthesis model to simulate potato net primary productivity using remotely sensed data

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Abstract

Thornley's model uses a three-parameter non-rectangular hyperbola to describe the exponential light decay down the canopy for simulating the contribution of sun and shade leaves to the instantaneous photosynthesis of the plant. This paper summarizes a series of experiments to develop a bottom up modeling approach to convert this instantaneous plant canopy photosynthesis model into a crop model, using the potato as a prototype. Several steps were required for transforming this instantaneous model into a dynamic procedure capable of integrating the amount of carbon fixed by the plant from emergency through harvest. Model parameters were estimated using remotely sensed data, thus generating a model that could be parameterized with non-destructive and non-invasive methods. Those parameters included the light extinction coefficient, the proportion of light transmitted by the leaf, the fraction of incident diffuse photosynthetically active radiation (PAR), and the leaf area index. A spectroradiometer, a chlorophyll meter and a multispectral camera were used to derive the required parameters both within controlled and field conditions. The estimation of parameters with remotely sensed data presented R^2 ranging from 0.89 to 0.99. These parameters were integrated into a MATLAB net primary productivity model and tested with growth chamber and field data using commercial potato varieties as well as new clones. Simulated results explained above 85% of the variation in the actual yield data.

Keywords: PAR, NDVI, chlorophyll determination, autotrophic respiration.

Introduction

Remote sensing is generally defined as a group of techniques that permit the collection of data without a physical contact with the object or area under study. In our case, that object is the plant or crop canopy and the required data is the incident and reflected radiation. For agronomic applications, the region of the solar radiation spectrum that is of interests, is the range from the ultraviolet (UV) to the near infrared (NIR) and in particular the bands corresponding to the PAR, from 400 up to 700 nm.

The net primary productivity simulation model presented in this paper is based on the instantaneous canopy photosynthesis concept developed by Thornley (2002), which describes mathematically the assimilation of atmospheric carbon dioxide into plant dry matter as driven by photon flow. Thornley's model is based on four important assumptions: 1) the canopy is horizontally uniform; 2) light decays exponentially from the top to the lower strata of the foliage, with the same decay extinction coefficient regardless of the radiation source; 3) the leaf photosynthetic response can be described by a non-rectangular hyperbola model (NRH); and 4) the light dependency of an individual leaf is summarized in a single parameter of the NRH model that describes the light saturated photosynthetic rate (P_{max}), which is assumed to be proportional to the average irradiance received by the leaves.

In our adapted model, the accumulation of photosynthates per leaf area unit was calculated using a numerical integration with hourly steps. Parameters such as the leaf area index (LAI), the extinction coefficient (k), the percentage of PAR transmittance through the leaf (m) and the diffuse component of incident PAR -considered as constants in Thornley's model- were replaced with dynamic parameters that account for the temporal and spatial variability of the photosynthesis process. These parameters were approximated through remotely sensed data. Canopy photosynthesis estimates constitute the first step for the calculation of the net primary productivity, since the photosynthesis is the principal process by which plants increase their dry matter, notwithstanding part of this chemical energy is used by the plants for processes of maintenance and growth as the autotrophic respiration that decreases the daily photosynthate accumulation.

Methodology

Thornley's model was adapted by converting it from an instantaneous canopy photosynthesis calculator into a dynamic one. The modified model calculates the gross canopy primary productivity (P_{canopy}) by way of integrating CO_2 fixed from plant emergence to harvest.

The light extinction coefficient (k) characterizes the light absorption by the canopy, and depends on the type of light, the position and the characteristics of the leaves; it varies during the day according to the solar zenithal angle. Assuming a spherical angular distribution, with leaves distributed at random within the canopy volume, the coefficient of extinction is defined as (Goudriaan, 1977, 1982):

$$K = \frac{1}{2\sin(\theta)} \qquad (1)$$

The transmittance coefficient (m) is calculated by integrating the PAR energy transmitted through the leaf mesophyll. The light transmittance characterizes the physiological state of the leaf and is an indicator of its pigment concentration. The transmittance usually represents 10% of the incident energy, and it is sensitive to the chlorophyll A concentration in the leaves. The model estimates m as:

$$m = \frac{CL\_A_{max}}{CL\_A} * 0.1 \qquad (2)$$

Where:

Cl_A: Relative Chlorophyll A concentration
Cl_A_{max}: Maximum relative chlorophyll A concentration

Chlorophyll A determination

It is widely known that alterations of the PAR reflectance, in particular the corresponding to the NIR (690 - 740 nm) range, result from the sensitivity of chlorophyll A in the leaves (Knipling, 1970). In this study, the reflectance spectra were obtained using an integrating sphere - active remote sensing accessory of the spectroradiometer LI 1800- whose design presents a highly reflecting chamber in the visible and NIR regions of the spectrum and uses as source a tungsten lamp that simulates the incident solar spectrum.

The validation was conducted against chlorophyll estimates obtained from a calibrated Minolta SPAD 502 meter. This active remote sensing equipment estimates the relative chlorophyll concentration per unit of leaf area by calculating the transmittance of the leaf to specific wavelengths generated by illuminating leds.

Once the reflectance data was obtained, it was processed to calculate its first derivative w.r.t. the wavelength (DR_λ) and correlated with the relative concentrations of chlorophyll provided by the Minolta SPAD 502. The derivatives were calculated as:

$$DR_{\lambda} = \frac{R_{\lambda+1} - R_{\lambda-1}}{2} \tag{3}$$

Where:

$R_{\lambda+1}$ y $R_{\lambda-1}$: Reflectance in the wavelength $\lambda+1 \; y \; \lambda-1$

LAI- NDVI relationship

The LAI - ratio of total upper *leaf* surface of *vegetation* divided by the land *surface area*- is the most influential parameter in terms of the capacity for growth of a crop and its variation in time is an indicator of the growth stage (Maas, 1998a; 1998b; Guissard et al., 2005). LAI is also an indicator of the photosynthetic capacity of the crop and it is closely related to the final production. The LAI can be estimated from the Normalized Difference Vegetation Index (NDVI), which is the most used index to detect live green plant canopies in multispectral remote sensing data. The NDVI, which reflects the seasonal changes related to the vegetation instead of the quantity of vegetation, is a nonlinear transformation of the visible (red) and NIR bands of incident radiation (Rouse et al., 1974). The NDVI is calculated as follows:

$$NDVI = \left(NIR - R / NIR + R\right) \tag{4}$$

In our work the NDVI was estimated using the Dycam agricultural camera and regressed against LAI obtained from periodic destructive methods; this procedure allowed us to obtain a LAI-estimating function based on NDVI.

Diffuse PAR component

Photosynthesis simulation models commonly assume constants or consider alternating conditions of clear and overcast sky during the day, to address the difference between direct and diffuse irradiance. This approach usually generates over- or under-estimation of the diffuse component of incident radiation. Since the upper layer of the plant canopy interacts with the total PAR (direct plus indirect components) whereas the lower layers of the foliage only interact with the diffuse component of the incident PAR, it is important to calculate the diffuse component.

Following the equations of a black body defined by Planck, it has been demonstrated that the extraterrestrial PAR irradiance is a function of the temperature (equation 5).

$$I_{PAR-EXTRA}\left(Wm^{-2}\right) = \left(F\left(x_{700}\right) - F\left(x_{400}\right)\right)\sigma T^{4} \tag{5}$$

With:

$$F(x) = \frac{15}{\pi^4} \sum_{n=1}^{\infty} \frac{\exp(-nx)}{n} \left(x^3 + \frac{3x^2}{n} + \frac{6x}{n^2} + \frac{6}{n^3} \right)$$

$$x_{700} = \frac{hc}{(700)kT} \quad \wedge \quad x_{400} = \frac{hc}{(400)kT}$$

Where:

$\sigma = 5.67 * 10^{-8}$ Wm^{-2} K^{-4}. Stefan-Boltzmann's constant

$k = 1.38 * 10^{-23}$ J / K^{o}, Boltzmann's constant

$h = 6.62 * 10^{-34}$ J / s , Planck's constant

c = 3 * 10 8 m / s, Light speed in the vacuum

Spitters *et al.* (1986), calculated the quantity of global diffuse irradiance based on the incident total irradiation and the extraterrestrial global irradiation. Based on the fact that the total irradiance and the PAR at the top of the atmosphere are functions of temperature and that PAR radiation constitutes 50% of incident global radiation, (Tiba and Leal, 2004; Grossi Gallegos, 2003), Spitters' model can be modified to estimate the diffuse component of the PAR irradiance.

The results of the modified Spitters' model were validated with field measurements taken with an ASD FieldSpec VNIR (350-1075 nm) spectroradiometer and a band of black polyethylene coated with a soot sheet of 5 cm width. Measurements were taken in conditions of cleared, overcast and partially cloudy skies with the spectroradiometer shaded by the coated polyethylene throughout the data collection.

Respiration

Around 20 to 30 % of produced photosynthates are lost due to respiration (McCree, 1970). The autothrophic respiration or the respiration of photosynthetic organisms is directly proportional to the dry matter (DM) accumulation by different plant organs. Therefore, this component is determined empirically by destructive sampling throughout the growth period. The autotrophic respiration (R_a) is in turn divided into maintenance respiration (R_m) and growth respiration (R_g) (Running and Coughlan, 1988; Ryan, 1990, 1991):

$$R_a = R_m + R_g = \sum_i \left(R_{m,i} + R_{g,i} \right) \qquad (6)$$

Where i denote the plant organ (leaf, stem, root, and tuber)

Finally, the net primary productivity (NPP) is calculated as the difference between the gross primary productivity (P_{Canopy}) and the autotrophic respiration (R_a):

$$NPP = P_{Canopy} - R_a \qquad (7)$$

Results and discussions

Chlorophyll A determination

A high correspondence between the amplitude of the first derivative of the reflectance spectra in the region from 718 up to 726 nm and the concentrations of chlorophyll A per unit of area in three potato varieties was found (Table 1). Chlorophyll A can be adequately estimated with this remotely sensed data to parameterize the model.

Table 1. Wavelength presenting the highest determination coefficient with the chlorophyll A concentration per unit of area, for each of the three potato varieties

Variety	Wave length (nm)	Determination coefficient (R^2)
INC.-2563	725.5	99,40%
Pumamaqui	722.5	91,93%
Purranca	717.5	90,91%

LAI- NDVI relationship

The following exponential growth equation was the best predictor of LAI as a function of NDVI (R^2=0.9). This result shows the feasibility of using a multispectral camera to calibrate the LAI parameter in the model.

$$LAI = 0.2067 * \exp(2.963 * NDVI) \qquad (8)$$

Diffuse PAR component

Table 2 summarizes the relationships among simulated and gauged diffuse PAR. The slopes seem to be homogeneous while the intercepts are different and estimated with greater error. Simulated data explained at least 68 % of the gauged variance. The relationships tended to be parallel but the scaling factor (Y intercept) varied with the degree of cloudiness. Although the model used is an empirical one, the results are quite good with the advantage that accessible minimum input data is required.

Table 2. Regression equations among simulated and gauged diffuse PAR radiation for clear, overcast, and cloudy skies

	Clear Sky	Overcast Sky	Cloudy Sky
Slope	0.6376 ± 0.1437	0.7507 ± 0.1405	0.5016 ± 0.1411
Intercept in Y	2.04 ± 19.21	12.71 ± 17.44	44.29 ± 15.07
Intercept in X	-3,199	-16.93	-88.30
R^2	0.7665	0.8263	0.6779
P value	<0.05	<0.05	<0.05

Net primary productivity (NPP) Simulation.

An example of the simulation results is given in Figure 1. The model explained 99 % of the variance in the measured data, and the residuals were randomly distributed around zero. In order to obtain this level of accuracy, experimental data on maximum light-saturated photosynthesis (P_{max0}) and photosynthetic efficiency (α) is needed. When the required lab equipment to produce the data is not available, reference literature values can be verified through iterations with the model, testing them against experimental calibration data under the environmental conditions to be modeled. The example presented was conducted using the following initial values: $P_{max0} = 0.2.10^{-6}$ $kgCO_2m^{-2}s^{-1}$ and $\alpha = 10^{-8}$ $kgCO_2$ $(JPAR)^{-1}$

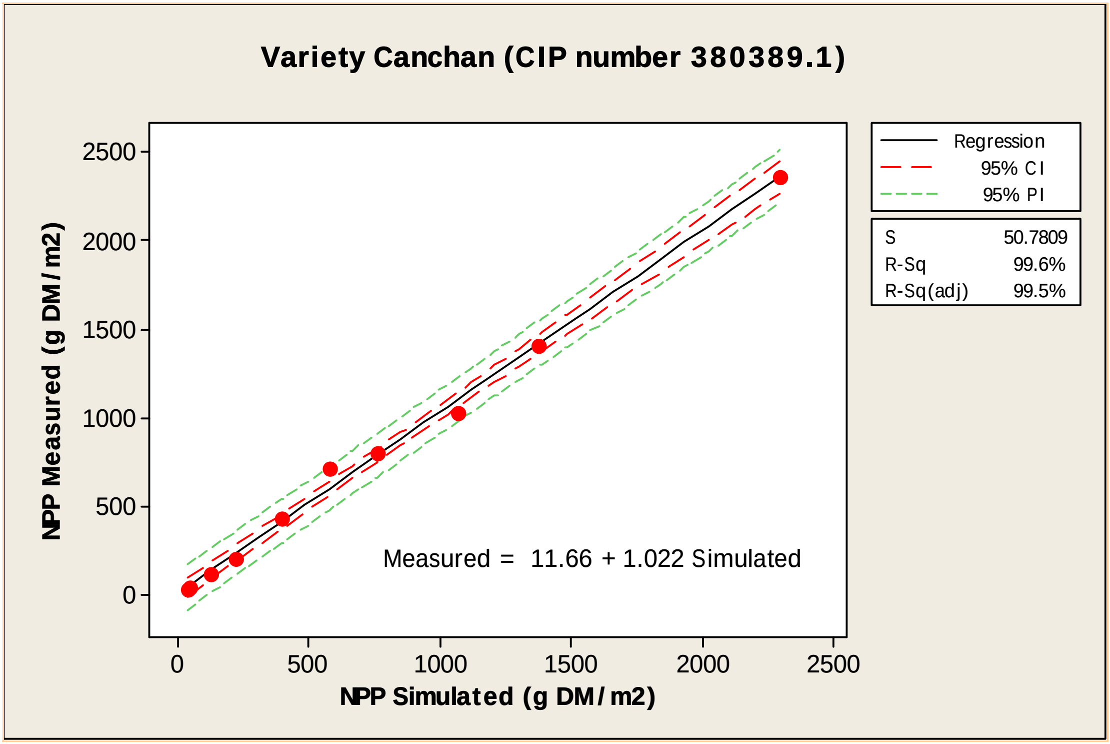

Figure 1. Net primary productivity simulation (grams of dry matter /m^2), for potato plants, variety Canchan.

Running an hourly periodicity of assimilation of photosynthates allows for a more realistic simulation of the photosynthetic process. It accounts for the nonlinear changes in solar radiation throughout the day, which are better mimicked, and events such as the stomatal closure when radiation is above the saturation threshold thus providing more accurate DM accumulation estimates. Models with daily steps, using average light conditions or pool energy levels, tend to overestimate DM production.

There are other sources of errors in this model, which are embedded in Thornley's assumptions. Assuming a horizontal uniform canopy tends to simplify the different levels of illumination received by leaves. This simplification overestimates the light interception, since leaves located in different positions in the canopy volume can have different levels of illumination. Moreover, assuming an exponential decay of the light within the canopy can underestimate the amount of light actually intercepted by the leaves located within it.

Models based on photon conversion into photosynthates do not take into account the stomatal saturation or closing by effects of temperature or other abiotic agents, thus overestimating the results. Biochemical models based on the kinetics of the enzyme Rubisco, such as the model described by Farquhar *et al.* (1980), explain with greater precision the photosynthesis process. Nonetheless, this type of models requires more input parameters and specialized equipments to estimate them, which makes them less accessible for most plant researchers. Therefore, dynamic models such as the one presented in this paper, based on light absorption, constitute a good alternative for predicting net primary productivity of C_3 plants.

Conclusions

The dynamic model presented here provides an efficient method for calculating the potential NPP of C_3 plants such as the potato. The model includes analytical solutions to substitute for initial parameters difficult to estimate without specialized equipments thus this model provides a practical analytical tool that does not demand large computational resources. Moreover, the possibility of estimating some of the key biophysical parameters e.g. the concentrations of chlorophyll A, the LAI and the diffuse component of PAR by means of non-destructive remotely sensed data, makes this model a good and reliable alternative to conventional techniques.

References

Farquhar, G.D.; Caemmerer, S.; Berry, J.A. 1980. A biochemical model of photosynthetic CO2 assimilation in leaves of C3 species. Planta 149(1), 78-90.

Goudriaan, J. 1977. Crop micrometeorology: A simulation study. PhD Dissertation. Wageningen University, p. 249.

Goudriaan, J. 1982. Some techniques in dynamic simulation. In: Penning de Vries, F.W.T.; van Laar, H.H. (eds.). Simulation of plant growth and crop production. Simulation Monographs. Pudoc, Wageningen, pp. 66-84.

Grossi Gallegos, H. 2003. Estimación de la distribución espacial en Argentina de la Radiación Fotosintéticamente Activa (PAR). En Anais do XIII Congresso Brasileiro de Agrometeorologia, Santa María, RS, Brasil, Vol.1, pp. 543-544.

Guissard, V.; Lucau-Danila, C.; Defourny, P. 2005. Crop specific LAI retrieval using optical and radar satellite data for regional crop growth monitoring and modelling. In: Owe, M.; D'Urso, G. (eds.), Remote Sensing for Agriculture, Ecosystems, and Hydrology VII, Proceedings, Bruges, Belgium, Vol. 5976, 1-12.

Maas, S.J. 1988a. Using satellite data to improve model estimates of crop yield. Agronomy Journal 80(4), 655-662.

Maas, S.J. 1988b. Use of remotely-sensed information in agricultural crop growth models. Ecological modelling 41(3-4), 247-268.

McCree, K.J. 1970. An equation for the rate of respiration of white clover plants grown under controlled conditions In: Setlick, I. (ed), Prediction and measurement of Photosynthetic productivity; proceedings IBP/PP technical meeting, Trebon. Centre for Agricultural Publishing and Documentation, PUDOC, Wageningen, The Netherlands, pp. 221-229.

Rouse, J.W.; Haas, R.H.; Schell, J.A.; Deering, D.W.; Harlan, J.C. 1974. Monitoring the vernal advancement of retrogradation of natural vegetation. Final Report, Type III, NASA/GSFC, Greenbelt, MD, 371 pp.

Spitters, C.J.T.; Toussaint, H.A.J.M.; Goudriaan, J. 1986. Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis. Part 1. Components of incoming radiation. Agricultural and Forest Meteorology 38(1-3), 217-229.

Thornley, J.H.M. 2002. Instantaneous canopy photosynthesis: Analytical expressions for sun and shade leaves based on exponential light decay down the canopy and an acclimated non-rectangular hyperbola for leaf photosynthesis. Annals of botany 89(4), 451-458.

Tiba, C.; Leal, S. 2004. Medidas e modelagem da radiação PAR para o Nordeste do Brasil. Anais do AGRENER 2004 - V Encontro de Energias no Meio Rural, Campinas, San Pablo, Brasil