



Modeling Light-Interception for a Cotton Population Model

E. Jallas^{1,2}, R.A. Sequeira³, S. Thanisawanyangkura^{4,5}, H. Sinoquet⁵, S. Turner¹ and M. Cretenet²

¹USDA-ARS-CSRU, P.O. Box 5367, Mississippi State, MS 39762, USA.

²Programme Coton, CIRAD-CA, BP 5035, 34032 Montpellier Cedex 1, France.

³USDA-APHIS-CPHST, 1509 Varsity Drive, Raleigh, NC 27606, U.S.A.

⁴Dept. of Botany, Faculty of Sci., Kasetsart Uni., 10900 Bangkok, Thailand.

⁵INRA Bioclimat. -PIAF, Dom. de Crouelle, 63039 Clermont-Ferrand Cedex 02, France.

ABSTRACT

Light-interception by crops has been intensively studied since the early 1960s. Simple models of light interception for single plant, crop-rows, and for continuous canopy have been developed. More complex models, using crop geometry, have also been investigated and some of the studies tried to model plant competition. However, the majority of these light models have not been integrated with models of photosynthesis and plant growth. Since the beginning of the 1970s up to fifteen different models of cotton development have been proposed and published. Some of them have been proposed for management but none of these models integrate a light interception sub-model able to simulate light interception for competing plants. In this study we developed a new light model based on some of the main crop architectural and agronomic characteristics. This new model was integrated with the GOSSYM-COMAX decision support system, and it gives the same results for the conditions where the original model was valid. It is also able to simulate the effects of plant competition for light. The new model provides the foundation for a plant population model as an alternative to currently used average plant models.

Introduction

Even though cotton simulation models such as GOSSYM-COMAX have been used to manage large areas, its use has been restricted mostly to traditional USA management practices (i.e., conventional row-spacing, near-optimal water and nitrogen availability) and for soil conditions assumed to be near uniform (hydrologically and texturally). These “common” management practices correspond to those used to develop GOSSYM: a row-spacing of about 1 m, a plant spacing within the row between 5 to 10 cm and a plant population ranging from 80,000 to 100,000 plants per hectare. Recent studies on “narrow row” cotton (i.e., cotton sown in rows less than 1 m) show its profitability to farmers (Heitholt, 1994) and reports indicate increasing use of narrow row cotton. However, GOSSYM does not correctly simulate the effects of plant population density (Jallas, 1991) and is not sensitive to row-spacing variations. Light interception in GOSSYM is a function of plant height and plant spacing. Paradoxically, despite its mechanistic detail, GOSSYM does not integrate Beer’s law (or other more mechanistic light attenuation models) as do other crop models, which are overall simpler in their approach to the integration of key physiological responses. The objective of this study was to replace the GOSSYM light interception sub-model by one able to correctly reproduce plant density effects and plant light competition.

The GOSSYM Model

The GOSSYM system is based on the “mechanistic process” paradigm, which tries to maximize the number of causal relations present in the model and to minimize empiricism at a given level of observation. GOSSYM describes the development and growth of cotton plants on a daily basis. Baker *et al.* (1983), Jallas (1991) and Sequeira and Jallas (1995) have published the description of the theoretical background and most mathematical functions.

GOSSYM Light Interception and Photosynthesis Sub-models. In GOSSYM, net photosynthesis is calculated as the gross photosynthesis minus respiration (maintenance respiration, light respiration and growth respiration). The gross photosynthesis is expressed as a product of the potential of gross photosynthesis of a canopy multiplied by the percent of light interception, multiplied by ground area per plant, multiplied by a water stress reduction factor and multiplied by a CO₂ correction factor. The equation is:

$$Pg = pstand \times int_ \times popfac \times ptsred \times pnetcor \times 0,001 \quad (1)$$

where *pstand* is the potential gross photosynthesis per unit area of canopy intercepting light, *int_* is the % of intercepted light for a plant, *popfac* is the area of soil per plant, *ptsred* is a water stress reduction factor, *pnetcor* is a [CO₂] correction factor and 0.001 is to convert in grams. Because gross photosynthesis is modeled at the scale of the plant and the potential of

gross photosynthesis is per unit area of canopy, the % of intercepted light times the area of soil per plant represents the light intercepted by a plant (ILp). This percent of intercepted light is modeled only as a function of plant height (z) and the row spacing ($rowsp$). The area of soil per plant, in dm^2 , is calculated by multiplying the row spacing, in dm , by the plant spacing within the row ($pltsp$), in dm . So, from above, ILp can be expressed as:

$$ILp = 1.0756 \times z \times pltsp \quad (2)$$

and equation (1) becomes:

$$Pg = pstand \times (1,0756 \times z \times pltsp) \times ptsred \times pnetcor \times 0,01 \quad (3)$$

Thus ILp is a function only of plant height and plant spacing in the row. ILp does not take account of row spacing so GOSSYM models the same quantity of intercepted light for a varying row spacing from say 50 cm to a couple of meters! ILp will increase as plant spacing increases within the row (Note increasing plant spacing within the row decreases total plant density). The increase in ILp is monotonic and unbounded for both variables. This is especially troubling for the variable “ $pltsp$ ” (plant spacing).

Material and Methods

A New Light Interception Model. The new light interception model described below addresses the limitations described previously. This approach does not necessitate any additional input from the user. The objective was to replace the existing model in a transparent manner. This implies that if a user were to simulate past year’s crops he/she must obtain the same results (of course, only when using “traditional” row spacing). In the new model, “% of intercepted light” is defined in Thornley and Johnson (1990) as:

$$int_ = 1 - (Tg + Tc) \quad (4)$$

where Tg is the light transmitted to the ground without traversing the canopy and Tc is the light transmitted to the ground through the canopy. Tc is expressed as:

$$Tc = (1 - Tg)e^{-KL'} \quad (5)$$

where K is the light extinction coefficient within the canopy and L' is the effective leaf area index defined as the ratio of the LAI divided by $(1 - Tg)$. The transmitted light through the canopy gap is related to plant height (h) and the gap between rows (g) with the following equation:

$$Tg = \frac{\sqrt{h^2 + g^2} - h}{g} \quad (6)$$

The gap between row depends on row spacing ($rowsp$) and the maximum branch length ($pwidth$), which is

calculated from plant height (S . Thanisawanyangkura, unpublished data). The area of soil per plant is a function of the plant spacing ($pltsp$) and the plant width ($pwidth$). Then ILp can be expressed as a function of plant width, row spacing, plant spacing and effective LAI:

$$ILp = \left(1 - \frac{\sqrt{h^2 + (rowsp - pwidth)^2} - h}{rowsp - pwidth}\right) \times (1 - e^{-KL'}) \times pltsp \times pwidth \quad (7)$$

A New Photosynthesis Model. As described in the introduction, the gross photosynthesis in GOSSYM is calculated from the light intercepted by a plant and from a potential gross photosynthesis per unit area ($pstand$). This gross photosynthesis potential is a function of the incident radiation:

$$pstand = 2.39 + 1.37RI - 0.00054 RI^2 \quad (8)$$

where RI is the daily incident radiation (in W/m^2) above the canopy. The relationship in 8 was established by Baker *et al.* (1972) based on measurements made on closed canopies on a crop which was more than 100 days old. All studies show that cotton leaf net photosynthesis increases from the first day of unfolding until about 20 days later. After this period, net photosynthesis of the leaf decreases. However, net photosynthesis is the result of the gross photosynthesis minus growth respiration and dark respiration. Dark respiration is maximal at about 7 days after emergence (Constable and Rawson, 1980) and the peak of leaf expansion is very early, between 3 to 6 days after leaf unfolding. Thus growth respiration must be also maximal during this period. There are few studies on cotton gross photosynthesis and none focus on very early leaf stages. However, it can be inferred that leaf gross photosynthesis must be the highest, per unit leaf area, during the first days after leaf unfolding. GOSSYM will be systematically biased because the photosynthesis sub-model uses a potential gross photosynthesis. To remove this bias, the relation between leaf age and gross photosynthesis must be taken into account. Cotton leaf light interception may be affected by heliotropism (Lang, 1973). This can vary during the growing season with plants in a community tracking the sun less than isolated plants (Thanisawanyangkura *et al.*, 1997). Light penetration in the canopy is strongly related to the spatial distribution of the leaf area (Thanisawanyangkura *et al.*, 1998). In the case of isolated plants or during early growth stages, leaves can develop without competition from neighboring plants and can intercept direct solar beams from different sun angles. Young, plants also have a reduced number of leaves and with a 3/8 spiral of phyllotaxy, there is lower mutual leaf shading than at canopy closure. As LAI increases, the increase in net photosynthesis decreases (Monteith, 1965) or, if expressed per unit of covered ground, the net photosynthesis decreases (Mutsaers, 1982). These responses (higher gross photosynthesis, heliotropism,

and better light penetration) can be termed Young Age Effects (YAE). The YAE are evidently linked to the structure of the plant during juvenile growth and can be empirically modeled as a first approach with the following function:

$$YAE = 1 + ae^{-b \times popfac} \quad (9)$$

where *popfac* is the area of soil per plant (function of plant spacing *–pltsp–* and plant width *–pwidth–*), and *a* and *b* are two variety-dependent parameters. As plants grow, the covered ground area and the LAI increase and the Young Age Effects are reduced. From equations (1), (7) and (9) the new gross photosynthesis model can be expressed:

$$ILP = \left(1 - \frac{\sqrt{h^2 + (rowsp - pwidth)^2} - h}{rowsp - pwidth}\right) \times (1 - e^{-KL'}) \times pltsp \times pwidth \times (1 + ae^{-b(pltspxpwidth)}) \times ptsred \times pnetcor \times 0.001 \quad (10)$$

Model Validation. The first step was to compare the results of the two models were run using the same conditions used to validate the original model. (Kharche, 1984; Landivar, 1987). The second step consisted of testing the model with the previous simulation conditions but changing the density parameters, plant and row spacing. These spatial arrangements were tested over a range of values.

Results and Discussion

Comparison of New Versus Original Models. Given the nature of the problem with GOSSYM, the new model was expected to provide similar results to those of GOSSYM when using traditional practices improved results when deviating from traditional conditions. The new model with improved light interception and photosynthesis sub-models was compared with the original model for two years, 1981 and 1983 and two cultivars, early-season and full-season. 1981 and 1983 were selected to represent the original model since data from these years were used in its development. The cultivar settings were chosen as “early-season” in 1981 and “full-season” in 1983 because they represent the two extremes of growth types in commercial production. Results showed that with traditional row spacing of 0.97 m, simulation results were similar. Simulations of light interception with the original and new models tracked each other closely. There were slight deviations in June, July, late October and November for both simulations. Deviations were never more 5% of the original, explained by the improvements made to the light interception model and follow the same pattern for both cultivars because the new model is independent of cultivar. Trends in LAI for the simulation sets tracked each other closely, deviating slightly during canopy closure from July to LAI=3. This non-

significant deviation of less than 5% of the original was due to changes in the photosynthetic response, since the response of the model before and after canopy closure varied due to “young age effects”. Simulated daily photosynthesis had similar responses to changes in temperature and solar radiation.

Verification of Plant Density Effects. The spatial arrangements used for the simulations tested were beyond those that would make agronomic sense. This was to study the model’s response at extremes, especially for variables whose behaviour was cause for concern, i.e, responses to changes in spatial arrangements and plant densities. Yield responses for both models increase as row spacing increases, reaching a maximum for the new model at ca. 150 cm between rows and for the original model at ca. 100 cm for the same within row spacing. After reaching their peaks, both models predict rapid declines in yield, the new model predicting a more rapid decrease. The yield levels depend on the set of simulation conditions and could differ with other sets of conditions. The trends are most important in comparing models. The low yields simulated by both models for narrow row spacing express the depressive effect of a very high plant density. The falling trend after models reach their peak expresses the effect of very wide row spacing. If both models show the same trend, the new model accentuates the high-density and wide spacing effects. This is more in accordance with reality and the new model again shows better ability to reproduce plant light competition and is a general trend over the range of the simulated plant spacing. The main differences between plant spacing responses are the row spacing where the response reaches its peak. As plant spacing increases the value of row spacing for maximum yield decreases except at the peak where both yield predictions are approximately equal, the new model predicting lower yields than the original model. The new model predicts yields consistently below the predictions of the original model with similar trends to those observed before. Disparity between the models appears mainly when row spacing is above than 1 m. The new model is more sensitive to row spacing variation and its response is more realistic.

Conclusion

The new model has an increased sensitivity to plant and row spacing variations. Both models give similar responses in the traditional range of plant spacing and row spacing but the trends from the new model are more in accordance with cotton plant response. Nevertheless, whereas the trends are correct, the yield predictions seem too low with narrow row spacing and wide plant spacing large or too high when plant spacing is very low and row spacing is very high. The reason is certainly in the nature of the soil model and the calculation of water and nitrogen stress. In the model, these factors are affected by row spacing only. There is no adjustment in water and N availability as within row plant spacing changes. Adjustments to these soil factors will be necessary to enhance the model. Nevertheless, the limitations to model behavior inherent in photosynthesis and light interception have been removed and the range of model applicability has been increased. This model correctly simulates yield responses over the range of spatial distributions used in commercial agriculture except for ultra narrow rows. The new light interception and photosynthesis sub-models take account of plant and crop structures, paving the way for a "plant population" model (Jallas, 1998) as an alternative to the "average plant" model approach.

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