PRINCIPLES AND APPLICATIONS OF SUNFLOWER CROP SIMULATION MODELS

Francisco J. Villalobos, Instituto de Agricultura Sostenible (CSIC) and Departamento de Agronomia, Universidad de Cordoba. Apartado 4084, 14080 Cordoba, Spain
Fax +34 957 499252; e-mail: AG1VIMAF@UCO.ES

Summary:

Crop simulation models are mathematical representations of crops which can be run on computers to quantify the effect of management, genotype and environment on crop performance. Several sunflower models have been developed although only a few are specific models of sunflower, like OILCROP-SUN, which is a sink-source daily time step model. In this model development is calculated as a function of temperature (thermal time approach) while biomass accumulation is the product of intercepted radiation and radiation-use efficiency. Crop models have been applied for different purposes such as genotype evaluation, but they may be very useful for solving other agronomic problems in combination with experimental work specially under variable environments or when complex interactions occur. Future work should be dedicated to improve submodels of dry matter partitioning which will probably require reducing the time step of the model, but also to the combination of crop models with models of pests and diseases and of seed quality.

INTRODUCTION

Crop models are mathematical representations of crops which are run on computers and usually take into account the effect of genotype, environment and management on crop performance. Dynamic models started in the 50's as a tool for analyzing complex systems in engineering (Forrester, 1961), where they have been quite successful. Later de Wit developed his quantitative analysis of photosynthesis which has led to a set of simulation models of plants and crops. In the early 70's USA goverment funds were dedicated to primitive crop simulation models which were supposed to be the tool required to predict yields in foreign (enemies or not) countries. Since then the scientific effort dedicated to crop models has been enormous and crop models have become a very useful tool in many areas of agricultural research.

Sunflower modelling has received comparatively less attention than the modelling of other crops such as wheat. Complete crop models of sunflower have been developed since the late 80's although only a few are specific models of sunflower (Steer et al., 1993; OILCROP-SUN, Villalobos et al., 1996) while others may be applied to any species (e.g. CROPSYST, Stockle et al., 1994) or to some species (Epicphase, Cabelguenne et al., 1999). In the case of specific models some have been developed for a single cultivar (Hysun-30; Steer et al., 1993) while others may be calibrated for any cultivar (OILCROP-SUN).

I will not attempt here to describe the models or compare their performance, but to emphasize some key characteristics of sunflower crop models and to discuss the applicability of sunflower models for different objectives. Finally I will try to point out the main avenues for improvement of sunflower models.

PHOTOSYNTHESIS VERSUS RADIATION-USE EFFICIENCY MODELS

Two main schools of thought on crop modelling may be distinguished: the first would be the Wageningen or C.T. de Wit's school, which has given special importance to photosynthesis modelling. In these models photosynthesis is the key proccess which determines crop growth via empirical partitioning coefficients. The effect of stress (e.g. water stress) occurs via photosyntesis. On the other hand we have a second school which we may call Ceres' or Ritchie's school that has produced a whole bunch of models (e.g. Ceres-Wheat) with a common input-output structure. In these models dry matter accumulation is calculated as the product of intercepted radiation and Radiation-Use Efficiency (RUE) following Monteith (1977). Growth rates are calculated firstly as a function of temperature and may be limited by carbohydrate supply and/or water or nutrient stress. de Wit's school models could be typified as source-driven (SD) models while Ritchie's type could be called sink-source (SS) models.

Source-driven models may lead to the right answer but they are essentially wrong in physiological terms. Let's focus for instance on the effect of water stress on crop growth: in SD models this effect would cause stomatal closure and thus, reduced assimilation which in turn, will mean less growth. On the contrary actual plants (and SS models) will respond to water stress firstly by reducing expansive growth without stomatal closure which requires a more severe water stress (Sadras et al., 1993). This allows for either carbohydrate storage or enhanced root growth which are key for plant acclimation to water stress.

The above reasoning does not imply that current SS models will perform correctly under water stress. Connor and Fereres (1999) have shown that the effects of water stress should be simulated at time intervals far shorter than the 1-day time interval typical of most current crop simulation models. The limiting factor for growth may be carbohydrate supply, temperature or shoot water potential all of which vary throughout the 24-hour period leading, for instance, to expansion growth occurring primarily during the night in a water stressed crop provided that temperature is not limiting.

THE MAIN CHARACTERISTICS OF A SUNFLOWER MODEL

Now I will review the main features of a sunflower model (OILCROP-SUN; Villalobos et al., 1996) which was developed by scientists of the Universities of Cordoba (Spain), Buenos Aires (Argentina) and Michigan State. The model is currently incorporated to the Decision Support System for Agrotechnology Transfer version 3 (DSSAT 3, Jones, 1999), a software package designed for crop simulation of several species. OILCROP-SUN may be classified as a Ceres-type model with the following characteristics:

1- Biomass accumulation is calculated as the product of RUE and intercepted radiation. This is particularly difficult for sunflower as RUE changes with ontogeny (Trapani et al., 1992) being low at the start, then increcasing until anthesis and then decreasing again. The low initial RUE may be due to light saturation of the photosynthetic system, while the post-anthesis reduction is clearly due to the onset of oil synthesis in the growing seeds. All these add up to an average seasonal RUE of only 1.6 g (MJ PAR)$^{-1}$ as compared to a maximum of 2.8 g (MJ PAR)$^{-1}$ just before anthesis. The radiation environment also affects sunflower RUE: shading increases sunflower RUE due to an increase in the fraction of diffuse radiation (Villalobos et al., 1992; Bange et al., 1997).

The second important difficulty in simulating sunflower biomass accumulation is radiation interception. Heliotropism is a well known feature of sunflower, although its effect on radiation interception has not been adequately quantified. In any case the extinction coefficient decreases with Leaf Area Index (LAI) as shown in Figure 1 for clear sky conditions in Cordoba. The data shown (Villalobos and Orgaz, unpublished) have been computed using a radiation interception model which incorporates heliotropism of the upper leaves. From the Figure it's also clear that the coefficient is higher in winter (day of year 350) than in summer (DOY 180), and the difference is maximum when LAI is low. These results contrast with the assumption of a constant extinction coefficient of some sunflower models (e.g. Steer et al., 1993).

The above variations in RUE and extinction coefficient were incorporated to OILCROP-SUN by including functions which relate the extinction coefficient and RUE to LAI.

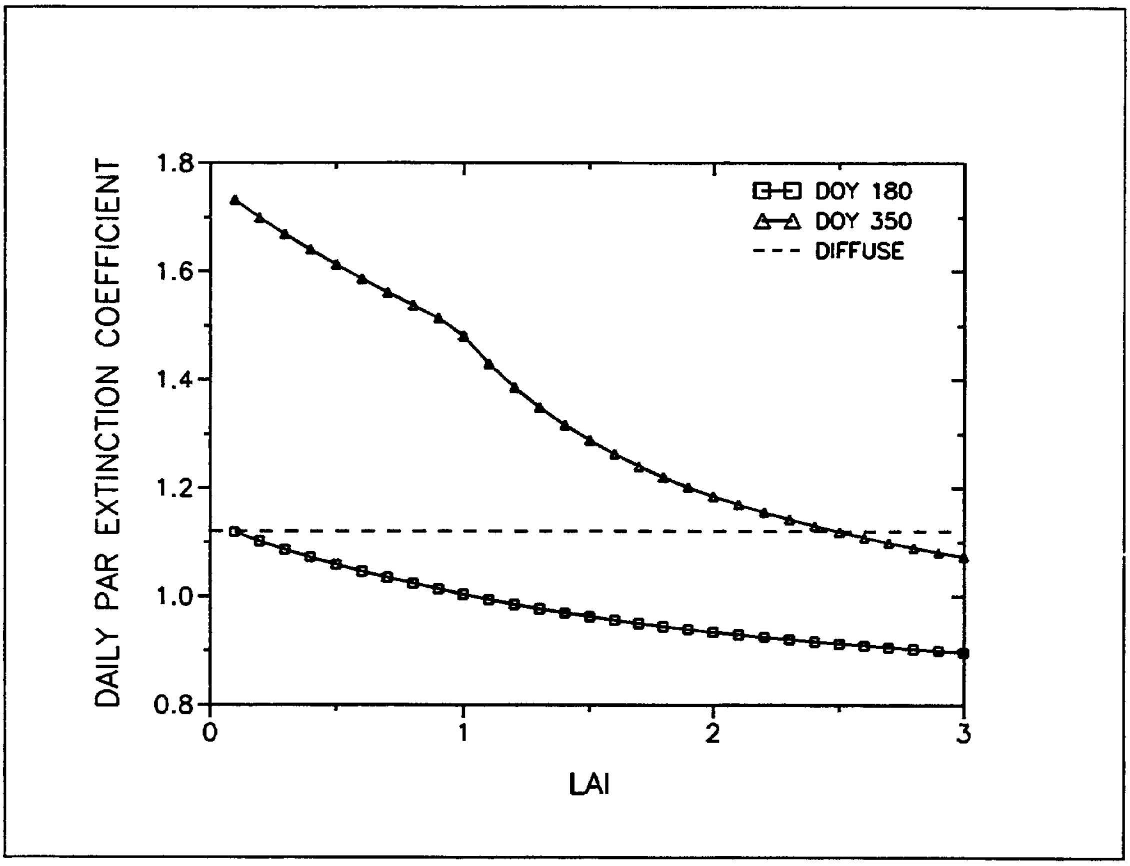

Fig. 1. Extinction coefficient for photosynthetically-active radiation of sunflower as a function of Leaf Area Index (LAI) at 38°N latitude (Cordoba, Spain) for sunny days in summer (DOY 180) and winter (DOY 350) and cloudy days (diffuse).

2- Main features of ontogeny

Sunflower phasic development is mostly dependent on temperature with an additional effect of photoperiod in the emergence-flower initiation (FI) phase. We have proposed the existence of a juvenile phase characterized by opposite leaves after which the plant responds to photoperiod (long day response) until the occurrence of flower initiation. That marks the end of leaf initiation. Therefore an evidence of photoperiod sensitivity would be a decrease in final leaf number for late spring plantings as compared to winter plantings.

After FI we have used a fixed thermal time (base 4°C; Villalobos and Ritchie, 1992) to predict the date of first anthesis and then a fixed thermal time to reach physiological maturity.

UTILITY OF SUNFLOWER SIMULATION MODELS

The various sunflower models developed so far have been used for different objectives like genotype evaluation (Aguera et al., 1997), irrigation management (Debaeke et al., 1998), etc. Aguera et al. (1997) calibrated OILCROP-SUN for sunflower populations differing in early vigour and then applied the model to quantify differences in evapotranspiration, growth and yield among those populations when grown in rainfed conditions in southern Spain. The authors concluded that the main advantage of early vigour is reduced soil evaporation and enhanced radiation-use efficiency, although season length has to be fitted to environmental conditions to avoid reductions in harvest index which may be caused by severe stress late in the season.

Simulation models will be specially useful under given circumstances. I have done a simulation experiment to illustrate them by considering a situation not too rare in the irrigated areas of southern Spain: deficit irrigation or irrigating with a limited amount. In this case we will try to investigate the optimum irrigation date of a short-season sunflower hybrid (Arbung E353) if we only apply a single irrigation of 100 mm. The soil is medium texture (160 mm water/m soil) but rather shallow (0.9 m depth). I have simulated crop performance for 24 years in Cordoba with different dates of irrigation starting at sowing date. Simulated yields are shown in Fig. 2. It's clear that an optimum date (around DOY 170: 19 June) exists and it's very close to the average first anthesis date (DOY 162: 11 June) which agrees with several previous experiments (e.g. Debaeke et al., 1998). However we would expect that the main advantage of irrigating close to anthesis should be the improvement in Harvest Index with no major effect in biomass production. That's not the case: in Fig. 2 we see that biomass accumulation increases as the irrigation is delayed until DOY 150 (30 May) thus part of the positive response of irrigating late is due to enhanced growth.

How can we explain this behaviour if water stress would likely decrease leaf growth and thus radiation interception and biomass accumulation? The explanation may be the one shown in Fig. 3 where soil N loss is shown to decrease when the irrigation is delayed until DOY 150 (30 May): thus irrigating early usually causes a reduction in N availability to the crop and therefore biomass production is reduced. On the other hand as irrigation is delayed the N availability improves (N leaching is reduced) which improves biomass and finally yield.

This example will serve to illustrate some of the situations where crop models are specially useful:

a) analyzing complex interactions: the interaction water-nitrogen found in the above example was not expected and indicates that the answer to the problem (when to irrigate) would also depend on N availability.

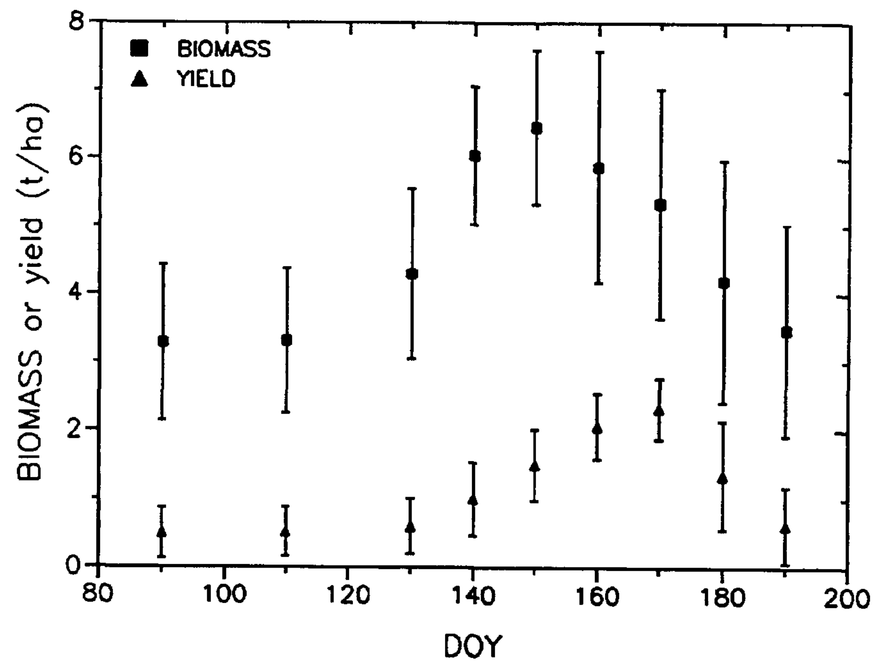

Fig. 2. Aerial biomass and yield as a function of the date when a single irrigation of 100 mm is applied. Sunflower cv. "Arbung E353". Cordoba, Spain.

b) dealing with variability: one of the major drawbacks of experiments in agronomy is the interannual variability in environmental conditions leading to different experimental results in different years. That means that answers to many agronomic questions require performing the experiment during different years. That's clear in the example of limited irrigation where yield is quite variable as indicated by the large standard deviation typically around 500 kg/ha for yield (Fig. 2).

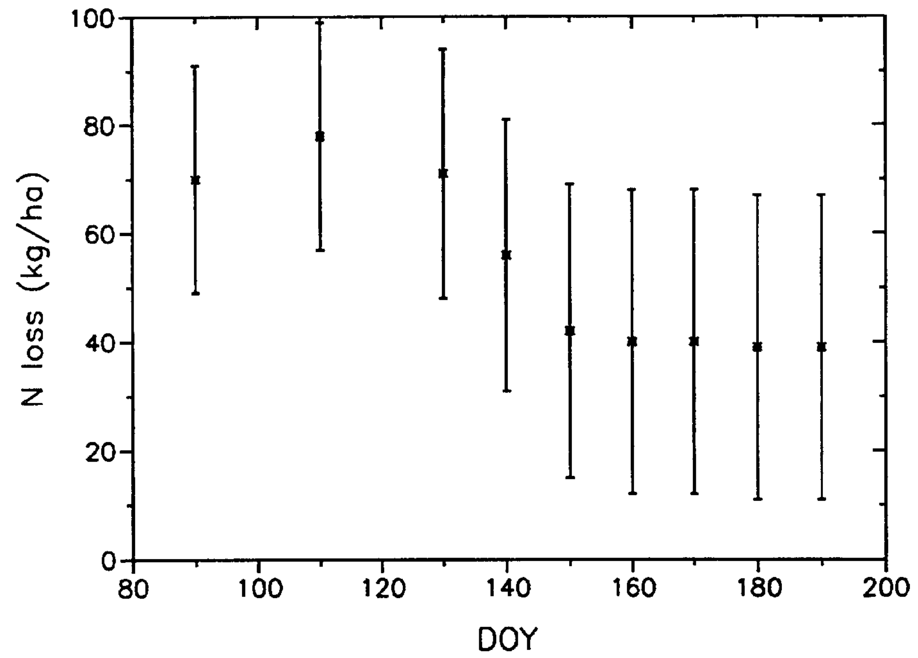

Fig. 3. Nitrogen loss during the growing season as a function of the date when a single irrigation of 100 mm is applied. Sunflower cv. "Arbung E353". Cordoba, Spain.

c) time and cost reduction: the amount of time and money that would have been needed to respond to the question (when to apply the 100-mm irrigation) would have been enormous (25 years x 9 treatments x say 4 repetitions = 900 combinations). Using the computer model this analysis requires no more than 10 minutes time and could be extended to other soil types, sunflower varieties, climates, etc. Of course I'm not claiming that the sunflower model can be applied to solve any agronomic question in any place of the world without experimental work. Even if we had perfect crop simulation models we would need some experimental work to calibrate (quantify parameters) the model for new varieties or soils. But we have to be realistic about the quality of crop simulation models. The high complexity of biological systems make it impossible to formulate completely mechanistic models of crops and we have to be happy with something which lies between the nechanistic and the empirical. Therefore the models will not work correctly under many situations and we will have to improve them to tackle with new problems. This improvement will usually require specific experiments. In summary crop simulation models along with adequate experiments will be a very useful tool for solving agronomic problems in variable environments or when complex interactions are present with a minimum cost.

I take here the opportunity to emphasize that a crop simulation model is a tool and not the objective of research by itself. The validity of a model should not be judged by trying to demonstrate that it is universally applicable which is obviously impossible but by the ability to solve specific problems.

NEEDS FOR THE FUTURE

Changes in agricultural policies, environmental problems and industrial uses of sunflower dictate the main improvements that should be incorporated to sunflower models:

a) partitioning of dry matter: in the best cases crop models use partitioning rules based on priorities that change along the crop cycle. For instance in OILCROP-SUN leaves have the maximum priority for carbon allocation after emergence (Trapani et al., 1994). After flower initiation stems become the main sink. Although this scheme has proved to work fine I feel that the key role of partitioning in crop performance can not be based in semi-empirical rules and should incorporate a more mechanistic basis which will require using a much shorter time step for simulation as suggested by Connor and Fereres (1999).

b) seed/oil quality submodels: previous attempts to developing empirical models of oil composition have mostly failed and we have only a qualitative knowledge of the relations between oil composition and the environment, mostly air temperature (Harris et al., 1978). I'm sure that incorporating an oil quality submodel to a crop model will lead to better predictions of oil quality as the crop model will provide most of the information needed (carbohydrate availability, water stress, N concentration, seed temperature).

c) coupling with pests and diseases models: the effect of some pests or diseases causing defoliation or nechrosis of leaves may be easily coupled to the crop model. However very little has been done so far apart from the work of Debaeke and Chabanis (1999) with phomopsis.

ACKOWLEDGEMENTS. I greatly appreciate the invitation of the organizers of the Int. Sunflower Conference and Drs. E. Fereres and F. Orgaz for their comments on the manuscript.

REFERENCES

- Aguera, F., Villalobos, F.J. and Orgaz, F. 1997. Evaluation of sunflower (Helianthus annuus L.) genotypes differing in early vigour using a simulation model. European Journal of Agronomy, 7:109-118.
- Bange, M.P., Hammer, G.L., and Rickert, K.G. 1997. effects of radiation environment on radiation use efficiency and growth of sunflower. Crop Science, 37: 1208-1214.
- Cabelguenne, M., Debaeke, P. and Bouniols, A. 1999. EPICphase, a version of the EPIC model simulating the effects of water and nitrogen stress on biomass and yield, taking into account of developmental stages: validation on maize, sunflower, sorghum, soybean and winter wheat. Agricultural Systems, 60:175-196.
- Connor, D.J. and Fereres, E. 1999. A dynamic model of crop growth and partitioning of biomass. Field Crops Res., 63:139-157.
- Debaeke, P., Cabelguenne,, M., Hilaire, A. and Raffaillac, D. 1998. crop management systems for rainfed and irrigated sunflower (Helianthus annuus) in south-western France. Journal of Agricultural Science, 131:171-185.
- Debaeke, P., and Chabanis, J. 1999. An integrated simulation model of yield loss by a fungal pathogen; stem canker (Phomopsis helianthi) in sunflower. In: Donatelli, M., Stockie, C.O., Villalobos, F.J. and Villar Mir, J.M. (Eds.): Proceedings Internatinal Symposium Modelling Cropping Systems, ESA-Univ. LLeida. pp. 73-74.
- Forrester, J.W. 1961. Industrial Dynamics. MIT Press, New York, 1961.
- Harris, H.C., McWilliam, J.R. and Mason, W.K. 1978. Influence of temperature on oil content and composition of sunflower seed. Australian Journal of Agricultural Research, 29: 1203-1212.
- Jones, J.W. 1999. ICASA: Advancing cooperative development and application of system analysis tools and crop models. In: Donatelli, M., Stockle, C.O., Villalobos, F.J. and Villar Mir, J.M. (Eds.): Proceedings Internatinal Symposium Modelling Cropping Systems, ESA-Univ. LLeida. pp. 25-29.
- Monteith, J.L. 1977. Climate and the efficiency of crop production in Britain. Phil Trans. R. Soc. London B., 281:277-294.
- Sadras, V.O. and Villalobos, F.J. 1993. Floral initiation, leaf initiation and leaf appearance in sunflower. Field Crops Research, 33:449-457.
- Sadras, V.O., Villalobos, F.J. y E. Fereres. 1993. Leaf expansion in field-grown sunflower in response to soil and leaf water status. Agronomy Journal,85:564-570.
- Steer, B.T., Milroy, S.P. and Kamona, R.M. 1993. A model to simulate the development, growth and yield of irrigated sunflower. Field Crops research, 32:83-99.
- Stockle, C.O., Martin, S. and campbell, G.S. 1994. Cropsyst, a cropping systems model: water/nitrogen budgets and crop yield. Agricultural Systems, 46:335-359.
- Trapani, N., Hall, A.J., Sadras, V.O. and Vilella, F. 1992. Ontogenetic changes in radiation use efficiency of sunflower (helianthus annuus L.) crops. Field Crops research, 29:301-316.
- Trapani, N., Hall, A.J. y F.J. Villalobos. 1994. Pre-anthesis partitioning of dry matter in sunflower (Helianthus annuus L.) crops. Field Crops Research, 37:235-246.
- Villalobos F.J. and Ritchie, J.T.. 1992. The effect of temperature on leaf emergence rates of sunflower genotypes. Field Crops Research 29:37-46.
- Villalobos, F.J., Soriano, A. and Fereres, E.. 1992. Effects of shading on dry matter partitioning and yield of field-grown sunflower. European Journal of Agronomy, 1(2):109-115.
- Villalobos, F.J., Hall, A.J., Ritchie, J.T. and Orgaz, F.. 1996. OILCROP-SUN: A development, growth and yield model of the sunflower crop. Agronomy Journal, 88:403-415.