

A DYNAMIC SIMULATION MODEL FOR DRYLAND SUNFLOWER

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SUMMARY

The structure of a simple, dynamic model for sunflower (QSUN) and its interaction with the environment are outlined. The model incorporates several recent approaches to simulation of crop growth in dryland conditions.

Using a daily time-step, QSUN estimates growth, development and yield of a sunflower crop. Daily temperature, radiation and rainfall drive the various sub-models. The phenology sub-model predicts stages of emergence, bud visible, anthesis and maturity. The growth sub-model estimates leaf area production and senescence and soil water extraction. Biomass production is calculated from the amount of intercepted radiation or from the amount of water accessible in the root zone, depending on whether radiation or water is limiting crop growth. Seed yield is calculated from the allocation of biomass to the grain following anthesis. Using independent data, the model predicted leaf area index, total biomass and grain yield well.

INTRODUCTION

Crop models can be developed at various levels of complexity. The level of complexity required depends on the objective of the modelling exercise. The "top down" approach to model design (Hammer et al., 1989; Shorter et al., 1991) is appropriate for models aimed at yield prediction. In this approach, complexity is kept to a minimum by commencing with a simple framework and only incorporating additional phenomena or processes if they improve predictive ability of the model. We adopted this method and developed QSUN, a dynamic sunflower model suitable for climatic risk analysis and the development of decision support data bases.

In dryland cropping, degree of water limitation is a major factor affecting productivity. Demand for water can be defined in terms of potential crop biomass production. Potential crop growth is the product of amount of intercepted radiation and the efficiency (e) with which it is converted to biomass (Charles-Edwards, 1982). Demand can be derived by dividing potential crop growth by the transpiration efficiency of the crop (q) for the day and vapour pressure deficit (Tanner and Sinclair, 1983). Under dryland conditions, however, crop growth is frequently limited by soil water uptake or supply. A framework on water extraction developed by Passioura (1983) and Monteith (1986) was used by Meinke et al. (1992b) to quantify potential soil water extraction on a range of soils. On any day, the actual transpiration of the crop can then be defined as the minimum of the demand or the supply for that day.

The calculation of balance between demand for and supply of water can be used to determine whether the environment is energy-limited (supply > demand) or water-limited (demand > supply) (Monteith, 1988). This switch provides a simple means to calculate biomass production by considering either radiation intercepted and radiation use efficiency in the energy-limited situation or transpiration and transpiration efficiency in the water-limited situation. Radiation use efficiency and transpiration efficiency coefficients are conservative across environments (Monteith, 1988).

Specifically, QSUN can be used to develop improved management strategies for areas for which long term daily climate records are available (e.g. Meinke et al., 1992a; Meinke and Stone, 1992). Opportunities to improve yields of dryland sunflower are generally associated with crucial decisions made at planting time. These decisions include management options such as the choice of cultivar in relation to available soil water and expected environmental conditions (particularly rainfall). QSUN has been designed to consider the contributions of genotypic and environmental effects on yield.

MODEL DEVELOPMENT

Construction of QSUN required five interacting modules: grain yield, biomass accumulation, crop leaf area, phenology and water balance. Details of all model functions are presented by Chapman et al. (1992a).

Grain yield

During grain filling, grain biomass may be considered as the product of total biomass and harvest index (HI). Grain growth can then be defined as a function of the date of onset of the increase in HI and the rate of HI increase (DHI). This approach inherently combines the contribution of current and stored assimilate to grain. The calculated rate of increase in HI was 0.011 d^{-1} , similar to that for other C3 plants.

Using data from Dubbelde (1990) we calculated a minimum value for HI of 0.16. This minimum value represents stem reserves which can be translocated even in the absence of any soil water to support assimilation during the grain filling period.

Muchow (1989) found that under conditions of severe water limitation during grain fill, HI ceased to increase. In the model, when the potential supply of water from the soil (T_s) falls below 0.8 mm d^{-1} , daily grain growth is limited to the amount of crop growth (C) on that day.

Crop Growth

Total above-ground biomass is calculated from the accumulation of daily crop growth (C). The maximum value of C is calculated from the product of the quantity of incident short wave solar radiation (S), the fraction of radiation intercepted by the simulated leaf area (I) and the efficiency with which this intercepted radiation is used (e).

For sunflower, the value of e was 1.05 g MJ^{-1} of intercepted short wave solar radiation (Kiniry et al., 1989) while the extinction coefficient for the canopy (k) is calculated as a function of leaf area index. The value of e is reduced after anthesis to account for nitrogen export from leaves.

The crop demand for water (T_d) on any day is calculated by multiplying C by the atmospheric saturation vapour pressure deficit (D in kPa) and dividing by the transpiration efficiency coefficient for above-ground biomass (TE_c in $g\ m^{-2}\ mm^{-1}\ kPa$). The daylight-averaged value of D is estimated from daily maximum and minimum temperature (Tanner and Sinclair, 1983). We found that TE_c ($n=8$) was similar to that quoted elsewhere for a wide range of C3 species: $4.5\ g\ m^{-2}\ mm^{-1}\ kPa$ (Monteith, 1988). This value was used for all simulations.

On any day, biomass production depends on the balance of T_d and T_s (the amount of water that the roots can supply). When water is not limiting ($T_d < T_s$), biomass production is determined by the amount of radiation intercepted and radiation use efficiency. When water is limiting ($T_d \geq T_s$), biomass production depends on the amount of water available and transpiration efficiency.

Leaf area

Accurate prediction of leaf area is required to estimate interception of radiation. Green leaf area per plant is calculated as the difference between total plant leaf area and senesced plant leaf area which are calculated as functions of thermal time and total leaf number (Hammer et al., 1987). Functions developed for sunflower are presented by Chapman et al. (1992b).

The ratio of supply of water to demand for water (T_s / T_d) is used as an index of the effect of water deficit on the relative growth of leaf area. As T_s / T_d decreases from 1.5 to 0.5, the value of the water deficit multiplier decreases from 1 to 0. The basis of this effect is the assumption that leaf growth is more sensitive to water deficit than is transpiration (e.g. Rosenthal et al., 1989).

Phenology

Phenological stages may be input directly or may be predicted by the phenology sub-model that is based on functions of temperature and photoperiod.

The effect of frost at flowering (Lovett et al., 1979) is included in the phenology routine. If the daily minimum temperature drops to $0^\circ C$ or below when the value of STAGE is between 2.5 and 3.2 (i.e. immediately before and after 50% anthesis), then the model halts at that point. This function indicates planting times at which frost risk is substantial rather than quantify the effect.

Soil water balance.

Monitoring of soil water balance is essential to estimate T_s . The model for soil water balance employs any number of layers. Values of available water content, maximum available water content, and maximum rate of water extraction ($1/\tau$) are input for each layer.

Precipitation, runoff, percolation and drainage. A runoff curve number approach is used to determine how much rainfall and irrigation is able to infiltrate the soil profile (Knisel, 1980). Infiltrating water fills each layer successively until the amount of rain or irrigation entering the profile is exhausted or until all layers are full. Any remaining water is considered to be drainage.

Evaporation. Soil evaporation from the top 0.2 m layer is a slightly modified Ritchie two-stage evaporation model (Ritchie, 1972). During stage 1, water is freely evaporated (Penman, 1948). After a soil type specific amount of water has evaporated, stage 2 begins. During stage 2, soil evaporation is dependent on the square root of the number of days since the beginning of the stage.

Transpiration. Transpiration is based on a modified version of water extraction proposed by Passioura (1983) and Monteith (1986). In the model, transpiration is calculated as a function of the rate of descent of the extraction front into the soil, and the rate at which water is removed from a soil of a particular type at any depth (Meinke et al., 1992b).

As the extraction front reaches successive layers, the potential amount of water extracted from the layer (T_{ei}) on a particular day is derived from the exponential decrease of water content (θ) with time. As the profile is re-wetted the values of θ and t are reset appropriately. The value of $1/\tau$ is effectively the product of root length density and the hydraulic conductivity of the soil, and can be determined by monitoring water extraction. In uniform soils, the value of $1/\tau$ tends to be constant down to a depth of about 1 m, thereafter declining: the typical range of $1/\tau$ is 0.05 to 0.08 d^{-1} , which is equivalent to τ values of between 20 and 12.5 days (Meinke et al., 1992b).

By summing T_{ei} for all layers we obtain the potential supply of water from the roots for a particular day (T_e). This potential supply of water may be completely removed if water is limiting, i.e. canopy demand is greater than or equal to supply ($T_d \geq T_e$). Conversely, if not all of T_e is required for transpiration, only the relative fraction required (T_d / T_e) is removed from each layer.

MODEL TESTING AND ANALYSIS

Data sets from several locations were used to test the capability of the model to simulate crop growth and water use under dryland and irrigated conditions. We examined changes in variables during a simulation, and actual versus simulated data for a number of sites.

As the model does not account for the effect of water deficit on leaf senescence, leaf area index (LAI) after 45 DAS was over predicted for some experiment. However, across 21 experiments, LAI was reasonably well predicted with a regression slope of slightly less than one. Total biomass in 13 experiments was not significantly different from the 1:1 line.

Grain yield at maturity was simulated well for all experiments, with the slope and intercept of the regression not significantly different from the 1:1 line.

CONCLUSIONS

This simple and mechanistic crop simulation model provides a robust framework to simulate sunflower development and yield for a wide range of environmental conditions. Many potential applications for such models exist: QSUN has been used, for instance, for the development of decision support data bases in Northern Australia (Jamieson et al., 1992) and to quantifying production risk and improve management strategies (Meinke and Stone, 1992).

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