

Sunflower simulation using the EPIC and ALMANAC models

J.R. Kiniry^a, R. Blanchet^b, J.R. Williams^c, V. Texier^b, C.A. Jones^c and M. Cabelguenne^c

^aU.S. Department of Agriculture, Agricultural Research Service, Grassland, Soil and Water Research Laboratory, Temple, TX, USA

^bInstitut National de la Recherche Agronomique, Toulouse, France
^cTexas Agricultural Experiment Station, Temple, TX, USA

ABSTRACT

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Modeling of sunflower (*Helianthus annuus* L.) is challenging because the crop species combines high yield potential with great adaptability. This paper surveys recent modeling-related research on sunflower phenology, growth, and yield. Simulations of sunflower by two closely related models, EPIC and ALMANAC, are described. Phenology was predicted with growing degree days with a 6°C base temperature (GDD₆) summed from sowing to maturity, assuming anthesis occurred when 0.62 of the total GDD₆ had accumulated. Growth simulation involved leaf area index (LAI) development, light interception, and radiation-use efficiency (RUE). Inclusion of a vapor pressure deficit (VPD) effect appeared to make RUE more general. A modified harvest index approach was used to simulate seed yields. The EPIC and ALMANAC models gave reasonable yield simulations over a wide range of environments and management options. The models should be valuable both for assessing the impacts of different management schemes and for identifying subject areas where additional basic research is needed.

INTRODUCTION

Sunflower adaptability

The adaptability of sunflower, which makes it suitable for production over a wide range of environments, also makes sunflower modeling difficult. Hybrid sunflower is a nontillering high-potential-yield crop which is unusually flexible in adapting to its environment. Maximum photosynthesis (Hesketh

Correspondence to: J.R. Kiniry, U.S. Department of Agriculture, Agricultural Research Service, Grassland, Soil and Water Research Laboratory, 808 East Blackland Road, Temple, TX 76502, USA.

and Moss, 1963; Warren-Wilson, 1966; Andreeva et al., 1980) and RUE (Kiniry et al., 1989) for sunflower approach those of a C₄ species. Under well-watered conditions, the harvest index (HI) can be 30 to 40% (English et al., 1979; Rawson and Turner, 1982; Connor et al., 1985; Guiducci, 1988). Because of its high photosynthetic capacity and relatively high harvest index, sunflower is a viable crop for high-yielding environments. It has been grown successfully on the deep soils of the midwestern USA, the USSR, and central Europe, where low to moderate humidity has reduced disease infestation (Sackston, 1978; Acimovic, 1988). Its ability to withstand drought (Turner, 1986; Blanchet et al., 1990; Piquemal et al., 1990; Planchon, 1990) makes it a desirable crop for subhumid areas with shallow soils, such as the calcareous zones of the Mediterranean Basin and Middle East. In these areas it can yield 2 to 3 t ha⁻¹ and thus compete with durum wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and sorghum (*Sorghum bicolor* (L.) Moench), with or without irrigation.

Sunflower models

Sunflower models should adequately quantify the water balance and growth responses to environment to predict yield over the wide range of conditions in which the crop is grown. However, most models for sunflower growth and yield are simple and simulate few processes. Yield has been regressed against weather variables to predict yield in some areas (Castrignano et al., 1988; Wendland and Glauber, 1989). A model developed in Australia (Pearson et al., 1985) predicts plant dry weight at floral initiation and maturity based on solar radiation, temperature, and nitrogen, assuming adequate soil moisture throughout the season. Two models which include simulation of the water balance were developed by Smith et al. (1978) and Sadras and Hall (1989). The former includes regression equations with temperature or solar radiation to predict total plant dry matter and seed weight. The latter model simulates development of leaf area, development of roots, and phenology in order to investigate soil water availability in Argentina.

EPIC and ALMANAC models

The EPIC (Erosion Productivity Impact Calculator) model simulates the water balance, nitrogen and phosphorus, plant growth, and harvestable yield of several crops including sunflower (Williams et al., 1984, 1989; Sharpley and Williams, 1990). The ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) model is nearly identical to EPIC, but has more detailed simulation of crop growth. Researchers at Toulouse, France have modified the EPIC model to simulate sunflower growth and development more accurately than the standard version of the model.

The objectives in the present paper are to describe in general terms sunflower growth, development, and production of grain yield and to describe the simulation of these processes in the EPIC and ALMANAC models. While the discussion will focus mainly on applications of these two models, the basic approach can be adapted to other modeling programs.

SUNFLOWER GROWTH AND DEVELOPMENT

Phenology

Accurate simulation of growth stage duration is critical for yield predictions. As discussed below, yield is most sensitive to stress near the anthesis date. Growth duration is important in determining the amount of water used and solar radiation intercepted by the leaf canopy. Phenological prediction is necessary to differentiate among maturity types such as for investigations concerning drought avoidance with early hybrids.

The two environmental variables reportedly having the greatest impact on the rate of sunflower development are temperature and photoperiod. It has been reported that short days can accelerate sunflower development (Dyer et al., 1959; Schuster and Boye, 1971; Doyle, 1975). While methods of simulating this short-day response have been described (Goyne et al., 1977; Goyne and Hammer, 1982; Hammer et al., 1982), photoperiod appears to be inconsequential when predicting development over a wide range of locations. Data from studies at several locations (Robinson et al., 1967; Goyne et al., 1989) demonstrated that photoperiod can be ignored when modeling sunflower development.

A growing degree day equation with a base temperature of 6°C (GDD_6) is a reasonable compromise among the various techniques of simulating temperature effects on development. Studies report sunflower base temperatures of 6.6°C (Hammer et al., 1982), 7.2°C (Robinson, 1971) and 6.1°C (Unger, 1986). The summed GDD_6 from sowing to maturity for various locations include 1972 in Bushland, Texas, USA (Unger, 1986), 1411–1437 in Minnesota, USA (Robinson, 1971), 1448 at New South Wales, Australia (Anderson et al., 1978), 1514–1815, depending on cultivar, in Brazil (Sangoi and da Silva, 1988), 1480 in Emerald, Australia (Keefer et al., 1976), 1198–1873 for different cultivars in the USA (Robinson et al., 1967), and 1570 for early French hybrids and 1700 for late French hybrids (Merrien, 1986).

The fractions of the total GDD_6 from sowing to maturity which had accumulated at anthesis were similar for a wide range of locations. Fractions for data from Brazil (Sangoi and da Silva, 1986), Australia (Keefer et al., 1976; Anderson et al., 1978), Minnesota (Robinson, 1971), and Florida, USA (Green et al., 1982) ranged from 0.63 to 0.66. Other values included 0.59 in Kansas, USA (Hattendorf et al., 1988), 0.58 in France (Merrien, 1986), 0.56

TABLE 1

Maximum seasonal leaf area index values for sunflower from a wide range of locations. Underlined values were selected as representative, intermediate values

Source	Loc. (lat., long.)	plants m ⁻²	LAI
Anderson et al., 1978"	Armdale, Australia (30.31°S, 151.39°E)	3.2	1.8
Seiler, 1988 ^b	Bushland, TX, USA (35.11°N, 102.05°W)		1.8
Whitfield et al., 1989"	Tatura, Australia (36.26°S, 145.14°E)	4.4	2.5
Schmidt and da Silva, 1986"	Guaiba, Brazil (30.06°S, 51.19°W)	2.5	2.6
Pearson et al., 1985"	Camden, Australia	5.0	2.7
Gimenez and Fereres, 1986"	Cordoba, Spain (37.53°N, 4.46°W)	15.0	2.4
		5.6	3.2 for 66 to 91 days to flower, 7.9 for 111 days to flower
Sadras et al., 1989"	Buenos Aires, Argentina (34.35°S, 58.29°W)	2.0	3.2
Guiducci, 1988"	Central Italy (42.57°N)	5.1	<u>4.0</u>
Connor and Palta, 1985"	Australia	6.0	<u>3.5</u>
Blanchet et al., 1982"	Toulouse, France (43.36°N, 1.26°E)	-	<u>3.5</u>
Cox and Joliff, 1986"	Oregon St. Hyslop Lab	5.0	4.4 to 9.4
Blanchet and Merrien, 1982"	Toulouse, France (43.36°N, 1.26°E)	8.0	<u>5.0</u>
Rawson and Turner, 1982 ^a	Canberra, Australia (35.17°S, 149.08°E)	5.0	<u>5.4</u>
			5.6 to 10.1
Mean of underlined values			4.3

"Irrigated or had received adequate rain so that no drought stress occurred.

^bDryland.

in Bushland, Texas (Unger, 1986), and 0.55 in Brazil (Sangoi and da Silva, 1988). The overall mean value was 0.62.

Leaf area index

A survey of reported maximum LAI values for the season with well-watered conditions from a wide range of environments indicated that a reasonable value would be 4.3 (Table 1). Plant population seems to have little effect on LAI for a wide range of population densities. A model developed by Sadras and Hall (1989) predicted a maximum LAI at 6.25 plants m⁻² with LAI predictions greater than 90% of potential at populations from 4 to 9 plants m⁻².

Drought stress can severely limit leaf growth (Boyer, 1970). Leaf expansion is one of the most drought-sensitive growth processes. Models of plant growth should predict reduced leaf growth when water deficits begin. Similarly, nitrogen deficiency reduces leaf expansion and LAI and should be included in models (Radin and Boyer, 1982; Blanchet et al., 1987a).

Photosynthesis and biomass production

Sunflower has an unusually high photosynthetic rate for a C_3 plant. This is evidenced by CO_2 exchange rates similar to maize (*Zea mays* L.). Net photosynthesis of sunflower can be 90 to 140% of that of maize grown in the field (Hesketh and Moss, 1963; Warren-Wilson, 1966; Blanchet et al., 1982) and in growth chambers (Andreeva et al., 1980). The high photosynthetic rates may be related to a high content of ribulose biphosphate carboxylase in the leaves (Ranty et al., 1988).

Sunflower also has relatively large values for RUE. Values can be as large as the largest RUE of maize (Blanchet et al., 1987a; Kiniry et al., 1989) (Table 2). Sunflower RUE in Toulouse, France was 4.8 to 5.0 $g MJ^{-1}$ of intercepted photosynthetically active radiation.

The great within-species variability in RUE for well-watered conditions has recently been related to the vapor pressure deficit (VPD) for some crop species. Radiation-use efficiency of adequately watered sorghum in a greenhouse decreased from 2.9 to 2.3 $g MJ^{-1}$ with increased VPD (Hamdi et al., 1987). This response is probably due to decreased leaf conductance. Leaf conductance of sunflower can decrease by 72% as VPD increases from 1 kPa to 4 kPa (Hernandez et al., 1989). Likewise, estimated mean VPD during the growing season explained 50 to 76% of the variability in RUE of field-grown maize,

TABLE 2

Radiation-use efficiency (RUE) values for sunflower data sets with no drought stress

Source	Location	RUE ($g MJ^{-1}$)	VPD (kPa)
Guiducci, 1988	Central Italy	1.9	
Connor et al., 1985	Goulburn Valley, Australia	1.3 1.8	1.8 1.7
Kiniry et al., 1989	Temple, TX, USA	2.2	1.1
Warren-Wilson, 1967	Australia	2.6	
Whitfield et al., 1989	Tatura, Australia	2.7 ^a	
Cox and Joliff, 1986	Oregon, USA	2.8	1.1
		3.2	1.3
Blanchet et al., 1987a	Toulouse, France	4.8	0.9
		5.0	1.0

^aEstimated based on CO_2 exchange measurements.

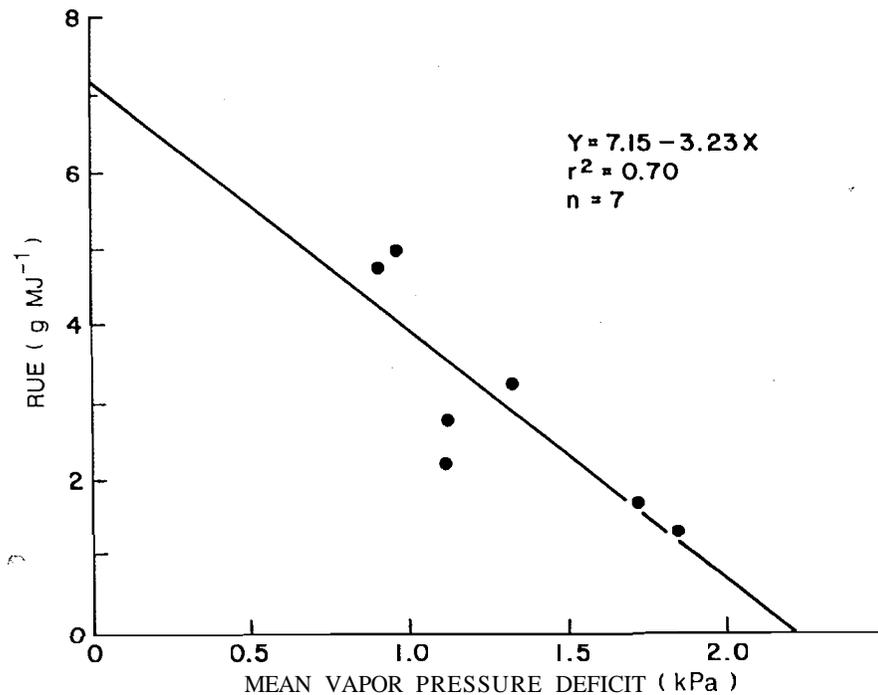


Fig. 1. Radiation-use efficiency as a function of mean vapor pressure deficit in well-watered conditions (see Table 2). An additional data point for northern Texas, USA (from D.F. Wanjura, 1984. Trans. ASAE, 17: 1734-1744) had VPD equal to 1.75 kPa and RUE equal to 1.53, similar to the expected value of 1.50.

sorghum, and potato (*Solanum tuberosum* L.) without drought stress (Stockle and Kiniry, 1990; Manrique et al., 1991).

A similar relationship between VPD and RUE can be shown with sunflower (Fig. 1), using data from diverse environments (Table 2). The r^2 value was similar to that reported for sorghum (Stockle and Kiniry, 1990) and the slope indicated greater sensitivity than maize, sorghum, or potato. The Goulburn Valley of Australia had the smallest mean RUE and Toulouse, France had the largest. The Goulburn Valley mean was 31% of the Toulouse mean. This difference is similar to the maximum difference in leaf conductance (Hernandez et al., 1989), with a minimum value which was 28% of the maximum.

Radiation-use efficiency of sunflower sometimes decreases after anthesis, but the generality of this phenomenon remains to be tested. Connor et al. (1985) reported decreased RUE after anthesis in the first year of their data, but such a decrease was not evident in the second year (Fig. 2). Likewise, Blanchet (pers. commun.) reported a 50% drop in RUE after anthesis. This could be explained by the greater energy costs for synthesis of oil in seeds

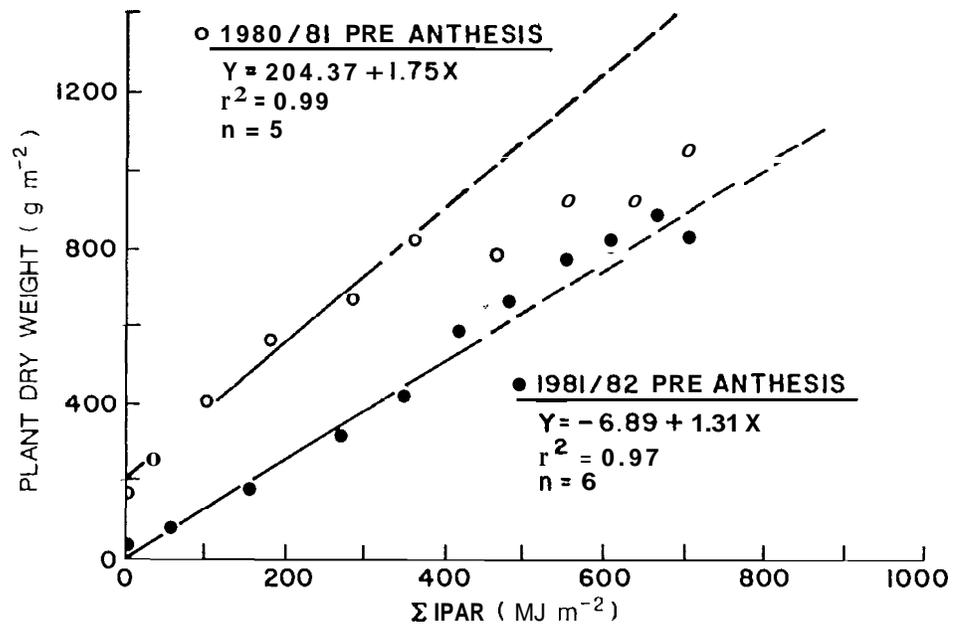


Fig. 2. Above-ground plant biomass and cumulative intercepted PAR (IPAR) for sunflower in Australia (from Connor et al., 1985). Regression lines were fit to the data prior to anthesis. Thus, the last four points were not used for either year.

relative to vegetative material (Penning de Vries et al., 1983). However, analysis of the data of irrigated sunflower in Oregon, USA (Cox and Joliff, 1986) indicated no such decrease during the grain filling period (Fig. 3). The 1981 data did show an apparent decrease in slope with the last harvest, but this was very late in grain filling. The 1980 results appeared to have the same slope throughout the season.

Harvest index

In models that simulate total plant biomass growth, the simplest way of predicting grain yield is to assume a stable harvest index (HI). Variability of HI across environments and cultivars becomes a major factor in the accuracy of grain yield predictions.

Harvest index was reasonably stable among several studies and, on average, was only slightly altered by severe drought. The mean value with adequate soil water was 0.29 (Table 3). Most of these values were between 0.29 and 0.33. Drought treatments sufficiently severe to reduce grain yield to 30–58% of well-watered yields had a mean HI of 0.30. The mean change in HI for these studies, relative to the well-watered values, was -0.03 .

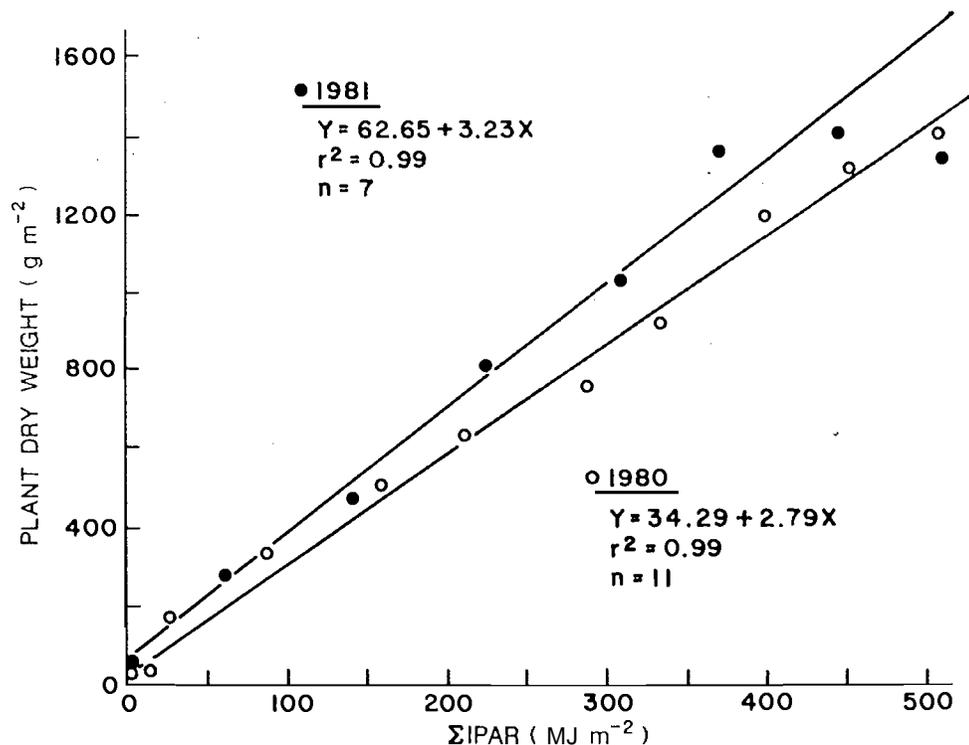


Fig. 3. Above-ground plant biomass and cumulative intercepted PAR (IPAR) for sunflower in Oregon (from Cox and Joliff, 1986). Anthesis occurred at approximately 320 MJ m^{-2} in both years. All data points were used to fit the regression lines except the last point for 1981.

Drought acclimation

A possible source of error in models such as EPIC and ALMANAC is the inability to predict the effects of drought acclimation. In these models, all genotypes are assumed to respond similarly to drought and drought acclimation is not included. In reality, osmotic adjustment can make plants less susceptible after one or more drought cycles (Turner, 1986; Conroy et al., 1988). Osmotic adjustment can preserve stomatal conductance, and photosystem activity can be maintained despite stress (Planchon, 1990). Drought adaptation can occur until about 35% of the total GDD for maturity has elapsed, with the photosynthesis/transpiration ratio being increased by this adaptation (Blanchet et al., 1990). Without drought acclimation, models may underpredict growth and yield in environments with repeated drying cycles.

Water-use efficiency

Water-use efficiency (WUE) is a common expression of plant productivity. It may represent the ratio of total above-ground dry biomass or dry seed weight to the seasonal evapotranspiration (ET). With this approach, different cultural practices can be assessed to determine optimum use of limited

TABLE 3

Harvest index values for sunflower

Source	Location	Mean harvest index	
		Well watered	Drought stressed
Hattendorf et al., 1988	Kansas, USA	0.21	
Sangoi and da Silva, 1988	Brazil	0.25	
Fercres et al., 1986	Spain	0.24 ^a	–
Gimenez and Fereres, 1986	Spain	0.29	0.25 ^b
Rollier, 1975	France	0.29	–
Guiducci, 1988	Italy	0.29	0.37 ^b
Rawson and Turner, 1982	Australia	0.30	0.26 ^b
English et al., 1979	Australia	0.33	–
Connor et al., 1985	Australia	0.45	0.32 ^c
Mean		0.29	0.30

^aMean for dryland in the highest-yielding year.

^bNo irrigation after planting. Grain yield was 51% (Spain), 38% (Italy) and 30% (Australia) of the well-irrigated yields.

^cTotal irrigation and rain was 257 mm prior to anthesis and 198 mm from anthesis to maturity. Grain yield was 58% of the control.

irrigation water. While EPIC and ALMANAC do not predict biomass or yield based on WUE, their simulation of the water balance and the biomass and grain yield can be used to estimate the WUE.

Sunflower WUE for total above-ground biomass (WUE_b) can vary by a factor of two. Values in Australia ranged from 10.9 to 18.3 kg ha⁻¹ mm⁻¹ (Connor et al., 1985). In Spain, values from trials with different planting dates ranged from 14 to 25 kg ha⁻¹ mm⁻¹ (Gimeno et al., 1989). The mean value from a study in Kansas was 20.5 kg ha⁻¹ mm⁻¹, with all values differing less than 1 kg ha⁻¹ mm⁻¹ from the overall mean (Hattendorf et al., 1988).

Water-use efficiency for seed weight (WUE_s) is more variable than WUE_b due to the greater variability in seed weight. The WUE_s is the product of WUE_b and HI. In France, WUE_s ranged from 5.8 to 10.2 kg ha⁻¹ mm⁻¹ (Blanchet et al., 1990). Values from 0.9 to 2.7 kg ha⁻¹ mm⁻¹ have been reported by Unger (1978) in Texas. In Kansas, WUE_s ranged from 3.6 to 4.7 kg ha⁻¹ mm⁻¹ (Hattendorf et al., 1988).

THE EPIC AND ALMANAC SUNFLOWER GROWTH MODELS

Description of the EPIC and ALMANAC models

The EPIC model was developed to determine the relationship between soil erosion and soil productivity in the USA (Williams et al., 1984). EPIC is composed of physically based components for simulating erosion, plant growth,

and related processes. It also includes economic components for assessing the cost of erosion and determining optimal management strategies. The physical processes involved are simulated simultaneously and realistically using readily-available inputs.

The model is generally applicable, computationally efficient, and capable of computing the effects of management decisions. Model components include weather simulation, hydrology, erosion-sedimentation, nutrient cycling, crop growth, tillage, soil temperature, economics, and plant environment control. Several of these components have been described in the literature (Jones et al., 1984; Williams et al., 1984, 1989).

The model is sensitive to crop characteristics, weather, soil fertility, and other soil properties. The processes simulated include: interception of solar radiation; conversion of intercepted light to biomass; division of biomass into roots, above-ground biomass, and economic yield; root growth; water use; and nutrient uptake. Potential plant growth is simulated daily and can be reduced by stress involving water, nitrogen, phosphorus, temperature, or aeration. Root growth can be reduced by soil strength, temperature, or aluminum toxicity.

EPIC simulates several crops with a general crop growth model using unique parameter values for each crop species. EPIC is capable of simulating crop growth for annual and perennial plants. Annual crops grow from planting to harvest date or until the accumulated growing degree days equal the potential growing degree days for the crop.

The EPIC and ALMANAC models simulate potential plant biomass by predicting leaf area index (LAI) and using incoming solar radiation. Beer's law (Monsi and Saeki, 1953), with an appropriate value for extinction coefficient, is used to predict the fraction of incoming solar radiation intercepted at a given LAI. The sunflower extinction coefficient is assumed to be 0.90 (Monteith, 1969). Predicting potential plant growth requires an assumed value of RUE for a crop species in the absence of drought, nutrient, and temperature stress. Daily accounting for such stresses with nutrient models and water balance models can then reduce predicted leaf and biomass growth.

The EPIC and ALMANAC models use a one dimensional rooting system with root depth normally approaching the input maximum as flowering is approached. Cultivar differences in potential rooting depth, which have been related to drought tolerance (Fereris et al., 1983; Terbea and Vranceanu, 1988), can be simulated by entering different values for maximum rooting depth. Root restrictive soil layers can be input which prevent root penetration and prevent further downward growth of roots.

The soil profile is divided into layers for computation of water, nitrogen, and root dynamics. As soon as the roots enter a layer, all the available water and nitrogen in that layer are assumed to be available to the plant.

Both EPIC and ALMANAC use a HI approach with important modifications.

The value for HI begins at 0 at flowering, increasing to the maximum at physiological maturity. Stress near the date of anthesis can reduce the HI. Seed yield has been shown to be most sensitive to drought in the 40 days approximately centered around anthesis (Robelin, 1967). These models assume temperatures below 6 °C stop growth prior to maturity and reduce the HI.

The plant growth component of ALMANAC is identical to that in the EPIC model, as described by Williams et al. (1989) with a few exceptions. In ALMANAC, RUE is assumed to be 4.6 g MJ⁻¹ for mean daily VPD less than 0.8 kPa. When VPD exceeds 0.8 kPa, RUE decreases 3.2 g MJ⁻¹ kPa⁻¹. Vapor pressure deficit is not allowed to decrease RUE below 1.8 g MJ⁻¹ as this was the smallest RUE value in the high VPD conditions of Connor et al. (1985) in Australia. Leaf area index is a function of population density. Values for LAI are predicted with an exponential S-curve where a population of 2 plants m⁻² has 63% of the potential LAI and 6 plants m⁻² has 99%. Temperate locations are assumed to have an LAI of 4.3 at high plant populations based on the values from several data sets described above. Model testing in Brazil, as discussed below, assumed a maximum LAI of 2.9 as this was intermediate between the values reported for Brazil (Schmidt and da Silva, 1986) and Argentina (Sadras et al., 1989).

EPIC calibration and modification

The EPIC model was adapted and refined by several Institut National de la Recherche Agronomique (INRA) scientists at Toulouse. The model changes were based on much of the literature discussed above, as well as experimental data obtained during several years near Toulouse in large weighing lysimeters (Blanchet et al., 1987a,b, 1990). These model modifications have been described by Quinones-Pedroza (1989) and Quinones-Pedroza et al. (1990): They are briefly summarized below:

1. For latitudes from 43° to 46°N and with 1700 GDD₆ from sowing to maturity, RUE was 4.0 g MJ⁻¹, dropping to 2.0 g MJ⁻¹ after 1000 GDD₆, to account for grain filling and oil synthesis. For higher latitudes, with 1500 GDD₆ required for maturity, RUE values were 4.5 prior to grain filling and 2.3 during grain filling.
2. Potential LAI, based on results in France (Blanchet and Merrien, 1982; Blanchet et al., 1982), was assumed to be 7 for a plant population of 10 plants m⁻², and 5.5 at 6 plants m⁻².
3. The root system was assumed to be well developed in deep soils. Thus there was no reduction in simulated root density with depth in the soil profile.
4. If water stress stopped plant growth for 7 days prior to accumulation of 35% of the total GDD₆ for the season, potential transpiration was decreased by 50% and RUE was increased by 50% for the remainder of the season. If a 3- to 7-day drought occurred, transpiration was reduced and the RUE increase was not as large. These attempts at quantifying drought acclimation

were based on results of Turner (1986), Conroy et al. (1988), Blanchet et al. (1990) and Piquemal et al. (1990). The functions have been adjusted, based on experimental data from Toulouse with a wide range of environmental conditions (Table 4). The results of this calibration indicated that the inclusion of such drought adaptation greatly improved simulation accuracy (Quinones-Pedroza et al., 1990).

5. Simulated HI was allowed to vary from 0.18 to 0.45 depending on the timing of stress. The normal HI was assumed to be 0.33 to 0.35, depending on cultivar. Drought stress prior to the accumulation of 35% of the total GDD_6 increased simulated HI by as much as 0.10. Early nitrogen stress, prior to bud appearance, can reduce the number of florets initiated and the number of seeds, resulting in reduced HI (Steer et al., 1984; Blanchet et al., 1987a). Water stress during anthesis and grain filling decreased simulated HI by as much as 0.15. Nitrogen stress prior to floral initiation, at 22% of the total GDD_6 , decreased HI by as much as 0.05.

These changes in the model improved the fit of the experimental data (Table 4; Quinones-Pedroza et al., 1990) and improved the model sufficiently to allow it to be used to diagnose when water stress occurred. Modeled and measured LAI were compared to make such a determination.

Testing the calibrated and modified EPIC model

The calibrated model was tested with data from various experiments conducted by the Centre Technique Interprofessionnel des Oleagineux Metro-

TABLE 4

Accuracy of EPIC simulations in Toulouse, France compared to the measured values for total dry matter (TDM) and grain yield (Yield), with several refinements of the model^a

Refinements introduced in the EPIC model	Correlation coefficient for the measured vs. simulated values		Root mean squared error ($g\ m^{-2}$)	
	TDM	Yield	TDM	Yield
Standard EPIC model	0.78	0.78	382	165
+drought adaptation + reduced RUE after anthesis	0.66	0.62	201	72
+root syst. geometry+ reduced RUE after anthesis	0.84	0.92	199	73
+root syst. geometry+ drought adaptation	0.89	0.93	128	40
+all refinements	0.90	0.93	82	24

^aExperimental data from 16 lysimeters with different depths and different irrigation treatments. The measured seed weight ranged from 175 to 400 $g\ m^{-2}$. The measured harvest index ranged from 0.29 to 0.34.

litains (CETIOM) in 1988 and 1989 (Table 5). Each year there were 4 or 5 treatments with different amounts and dates of irrigation, with three replications. Measurements included phenology, LAI on different dates, and seed yield. The plant population was 6 to 7 plants m^{-2} with no diseases or noticeable signs of nutrient deficiency. Three data sets in Table 5 had shallow soils with underlying rock layers. While roots can penetrate the cracks in the rocks, the decreased water-holding capacity along with the limited rainfall can cause plant water deficits in the spring and result in convenient conditions for studying drought adaptation. The first soil also had low water-holding capacity due to a high content of pebbles. Only recently has sunflower been grown on these drought-prone soils in France. Sunflowers have been found to be the best adapted summer crop to these conditions, with maize frequently failing to produce any appreciable yield.

The measured and simulated yields were very similar (Fig. 4). The mean square error of prediction (Wallach and Goffinet, 1987) was 0.078, representing an absolute root mean squared error of 10% ($0.28 t ha^{-1}$).

Data set C-Medium (Table 5) caused problems in the simulated results. There was uncertainty as to the amount of water which could be taken up due to the unknown percentage of rock in the soil. In addition, simulated ET may have been too low for this data set. When the crop was allowed to remove soil water below 1.6 MPa, the simulations were more realistic. Cox and Jollif (1986) reported that sunflower can extract more soil water than soybeans. Harvest index was set to a value between 0.33 to 0.35, depending on cultivar. With these adjustments, which are included in Fig. 4, the simulated model results agreed more closely with the measured data.

TABLE 5

Main characteristics of the French data sets used for validation of the refined EPIC model in Toulouse

Data set name	Location/Year	Lat. ($^{\circ}N$)	Soil depth (mm)	Potential soil water avail. (mm)	ETP ^a (mm)	Rainfall ^b (mm)	Irrigation (mm)		GDD ₆
							min.	max.	
B-Shallow	Beziers/1989 ^c	43	800	80	685	23	115	165	1700
B-Medium	Baziege/1989 ^c	43	900	135	715	68	0	105	1600
B-Deep	Baziege/1988 ^c	43	1600	240	630	227	0	105	1700
S. Shallow	Surgeres/1989 ^d	46	400	148	575	102	0	280	1700
C-Medium	Chateaudun/1988 ^d	48	600	177	620	205	0	80	1520
C-shallow	Chateaudun/1989 ^d	48	500	95	670	140	0	120	1515

^aPotential evapotranspiration from sowing to maturity estimated by EPIC.

^bTotal precipitation from sowing to maturity.

^cThe soil was a **mesic**, Udic **Haplustalf** soil of alluvial origin. The soil for the first data set had **pebbles**.

^dThe soil was shallow, developed on hard calcareous cracked rocks, with cracks in the rocks allowing roots to penetrate to a depth of at least 1 m.

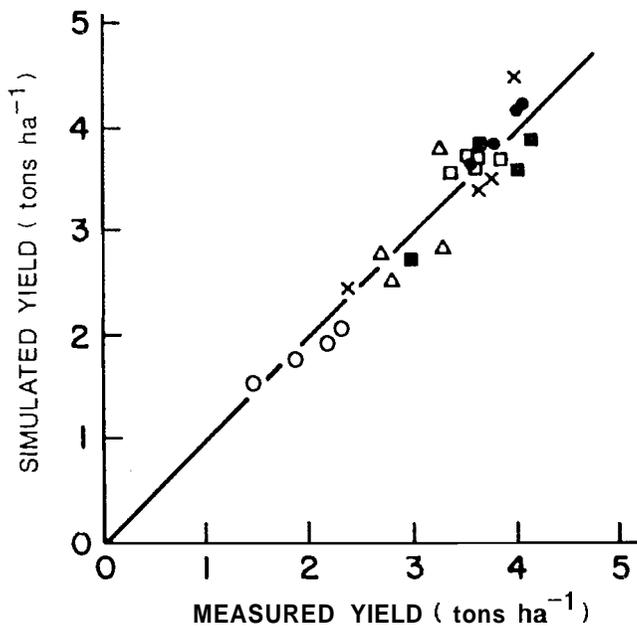


Fig. 4. Comparison of simulated and measured yields in France. The line is the 1:1 line. Data sets consisted of B-Shallow (Δ), B-Medium (\circ), B-Deep (\bullet), S-Shallow (\times), C-Medium (\square), and C-Shallow (\blacksquare) (R. Blanchet, unpublished, 1990).

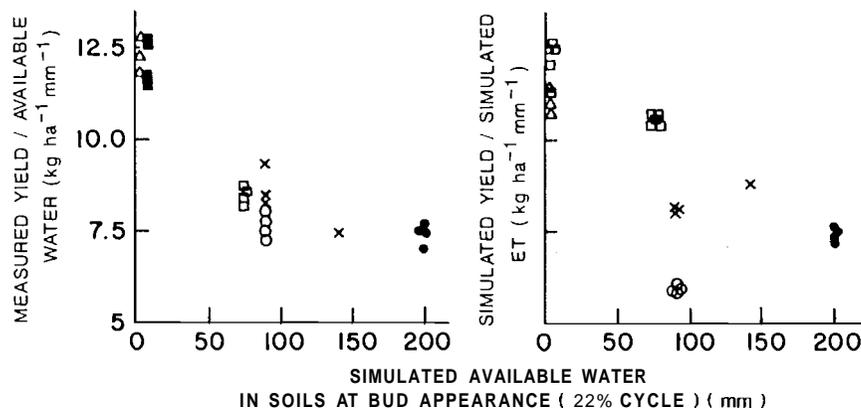


Fig. 5. Measured and simulated water-use efficiency in France, plotted as function of the simulated available water in soils at bud appearance (22% of the GDD_6 of the total from sowing to maturity). Data sets consisted of B-Shallow (Δ), B-Medium (\circ), B-Deep (\bullet), S-Shallow (\times), C-Medium (\square), and C-Shallow (\blacksquare) (R. Blanchet, unpublished, 1990).

The responses of WUE to available water at bud appearance were similar for simulated and measured data (Fig. 5). The experimental WUE was calculated as the measured yield divided by the sum of soil water, rainfall, and

irrigation. The simulated WUE was calculated as simulated yield divided by simulated ET. Both are plotted against the simulated amounts of available soil water at bud appearance ("star stage", 22% of the total GDD_6 from sowing to maturity). The simulation of soil water status at this phenological stage is generally quite good (Quinones-Pedroza, 1989). Water-use efficiency appears to be little influenced by irrigation under such conditions. There are differences between the experimental and simulated results for data sets B-Medium and C-Medium. The problem with data set C-Medium has been previously discussed, while data set B-Medium had low yields due to severe stress during anthesis and grain filling. However, it appears that knowledge of the soil water status at bud appearance could be a valuable indicator of approximate WUE and subsequent crop water requirement. This could aid in irrigation scheduling. High WUE and moderate water needs appear probable with dry soil at bud appearance and low WUE and high water needs appear probable if the soil has adequate soil water at this stage.

In conclusion, this calibration and adaptation of EPIC using varied French environments appeared reasonable and suggested interesting prospects for prediction of yield for different soils, climates, and cultural practices, such as irrigation scheduling. The model helped analyze growth processes and yield production in 5 or 6 environments where the response of sunflower to available soil water was sometimes difficult to predict and interpret (Merrien and Grandin, 1990).

Testing the ALMANAC model

Like EPIC, the ALMANAC model can be adapted for different geographic regions by changing the weather data and parameters related to the crop and the soil. Required inputs include the appropriate GDD_6 requirements for the season and values for soil water-holding capacity at different depths. Below are results from three locations with various planting dates, irrigation treatments, and planting densities, to demonstrate the utility of the model's yield simulations.

Location 1. Mandan, North Dakota, USA (Alessi et al., 1977), 46.50°N, 100.54°W, representing the major sunflower region in the USA.

Location 2. Bushland, Texas, USA (Unger, 1978), 35.11°N 102.05°W, representing a sunflower-producing area with high evaporative demand.

Location 3. Guaiba, Brazil (Sangoi and da Silva, 1988), 30.15°S, 51.12°W, representing a humid, tropical location. Available soil water at planting is specified only in the publications for the first two locations. Fortunately, drought stress was not a limitation at the location in Brazil. Total GDD_6 from sowing to maturity were 1360–1500 for North Dakota, 1800 for Texas, and 1740 for Brazil. The input HI was 0.30 for North Dakota and Texas and 0.22 for Brazil.

The ALMANAC model simulated sunflower yields reasonably well in North

Dakota (Table 6). With the common plant population of 5 plants m^{-2} , predictions were within 11% of measured yields for the May plantings. In 1973, predicted yields for later plantings at this population were within 15% of measured yields. Greater errors occurred in 1974 for later plantings at 5 plants m^{-2} . The model simulates little or no response to plant population above 5

TABLE 6

Simulations of sunflower yield ($t\ ha^{-1}$) by ALMANAC at Mandan, North Dakota, USA at four populations, three sowing dates, in two years^a

Sowing date	Population (plants m^{-2})	1973		1974	
		Measured	Simulated	Measured	Simulated
21-23 May	2.5	1.2	1.0 (0.79) ^b	1.9	1.6 (0.81) ^b
	5.0	1.1	0.9 (0.89)	1.7	1.7 (0.97)
	7.5	0.7	0.9 (1.34)	0.8	1.7 (1.95)
	10.0	0.5	0.9 (2.00)	1.2	1.7 (1.41)
5-10 June	2.5	1.3	1.3 (0.93)	1.9	1.4 (0.69)
	5.0	1.1	1.1 (1.03)	1.7	1.3 (0.77)
	7.5	0.8	1.1 (1.35)	1.5	1.4 (0.87)
	10.0	0.7	1.1 (1.56)	1.1	1.3 (1.13)
26-27 June	2.5	1.2	1.0 (0.87)	0.9	1.4 (1.55)
	5.0	1.2	1.0 (0.85)	1.0	1.5 (1.46)
	7.5	1.4	1.0 (0.69)	0.7	1.5 (1.91)
	10.0	1.1	1.0 (0.89)	0.7	1.5 (1.96)

^aSource: Alessi et al., 1977.

^bSimulated yield divided by measured yield. Calculations made before rounding of yields.

TABLE 7

Simulations of sunflower yield ($t\ ha^{-1}$) by ALMANAC at Bushland, TX, USA under different irrigation levels for three years^a

Year	Total irrigation (mm)	Measured ^b yields	Simulated ^b yields
1975	236	3.3	3.3 (1.01) ^c
	66-79	2.7	2.6 (0.99)
	0	1.6	2.4 (1.53)
1976	305	2.3	2.4 (1.03)
	229	2.1	2.0 (0.95)
	152	1.4	1.6 (1.13)
	76	0.8	1.2 (1.51)
1977	278	3.0	2.6 (0.87)
	187-192	2.7	2.1 (0.78)
	101-104	2.2	2.0 (0.89)
	0	1.7	1.7 (1.01)

^aSource: Unger, 1978.

^bMeans for more than one irrigation treatment in some cases.

^cSimulated yield divided by measured yield. Calculations made before rounding of yields.

TABLE 8

Simulations of sunflower yield ($t\ ha^{-1}$) by ALMANAC in Guaiba, Brazil at three planting dates^a

Planting date	Measured yields	Simulated yields
5 September	3.6	3.2 (0.89) ^b
14 October	1.8	2.2 (1.26)
12 December	1.0	1.5 (1.45)

^aSource: Sangoi and da Silva, 1988.^bSimulated yield divided by measured yield. Calculations made before rounding of yields.

plants m^{-2} . Population is accounted for only in LAI prediction. As discussed above, the model assumes that 99 to 100% of the potential LAI can be reached for populations of 6 plants m^{-2} or greater. Thus, the reduction in measured yield as population increased from 5 to 10 plants m^{-2} was not predicted by the model.

The model adequately predicted the response of yield to reducing population density from 5 to 2.5 plants m^{-2} (Table 6). In 1973, measured changes in yield for 2.5 plants m^{-2} compared to 5 were similar to simulated changes. In four of the six sowings, the changes in simulated yields in response to reduced population density were in the right direction and of reasonable magnitude.

The ALMANAC model simulated yields reasonably well at Bushland, Texas for all irrigation treatments except the most extreme stress treatments in the first two years (Table 7). The simulated yields of the high irrigation treatments in 1975 and 1976 were within 3% of the measured yields. Excluding the most severe stress treatment of these years, simulated yields were within 13% of measured yields in all cases. The model overpredicted yield considerably for the most severe drought treatment in the first two years. The relatively stable HI approach of this model may have been responsible for this overprediction. In 1977, yields were underpredicted for all but the driest treatment.

In Brazil, ALMANAC predicted the highest yield within 11% of measured and simulated the yield reduction with later sowings (Table 8). However, the model overestimated yield in the later sowings. Thus ALMANAC can be used for predicting the yield of crops in high-humidity, warm locations if the sowing is near the optimum, but it may not adequately predict the impact of delays in sowing.

CONCLUSIONS

EPIC and ALMANAC provided reasonable sunflower yield predictions over a wide range of environments, soils, and management schemes. Adequate values of parameters can be estimated easily (Cabelguenne et al., 1988). For

intensive use of these models for crop management decisions in a given area, more carefully derived input environmental and crop parameters, such as described in the French version of the model, may be desirable. Such parameters relate to drought and temperature adaptation.

Potential areas for progress in sunflower modeling in the future include: N–water interactions on LAI, growth, and seed production; drought adaptation; and grain filling with translocation and remobilization from leaves, stems, and roots. In addition, more accurate simulation of high plant population may be valuable to some applications.

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