

A GENERAL, PROCESS-ORIENTED MODEL FOR TWO COMPETING PLANT SPECIES

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ABSTRACT

Simulation models for the interaction between weeds and crops generally are simple, empirical equations which lack generality across locations or species or are so complex and difficult to apply that their use by independent researchers is not feasible. The objective of this article is to describe and demonstrate a user-oriented model for weed-crop competition with enough detail to be general across locations and species but not so complex that independent users cannot apply it to their situations. The ALMANAC model described in this article contains the detailed functions for water balance, nutrient cycling, and plant growth as in the EPIC model, and additional detail for light competition, population density effects, and vapor pressure deficit effects which enable it to simulate the growth and seed yield of two competing plant species in a wide range of environments. It reasonably simulates the impact of infestations of johnsongrass, foxtail species, or cocklebur on yields of maize, soybean, and wheat. This model should be a useful tool for simulating management strategies related to weed control.

KEYWORDS. Corn, Wheat, Soybean, Weeds, Simulation.

INTRODUCTION

Simulation models for weeds alone or for weeds competing with crops have been developed for a number of applications. The level of complexity of such models is often related to the type of application expected and to the targeted user group. The acceptance of simulation models by users depends on the difficulty of adapting models to different locations, the difficulty in obtaining the required input parameters, and the generality of the model for different weed-crop combinations and for different locations.

Relatively simple, stand-alone models frequently simulate weed impacts on crop yields with one calibration for each weed-crop combination at a location. They are

intended for practical applications such as predicting the economic threshold for a weed density in a crop (e.g., Marra and Carlson, 1983; Auld and Tisdell, 1987). Often such models consist of a single equation for crop yield as a function of weed density (e.g., Cousens, 1985; Firbank and Watkinson, 1985; Hume, 1989; O'Donovan et al., 1989; Vleeshouwers et al., 1989).

Stochastic models simulate the population dynamics of a weed or a weed-crop combination. They may describe changes in plant communities (Debaeke and Sebillotte, 1988; Mortimer et al., 1989; Pacala and Silander, 1990; Swinton and King, 1990), predict weed seed production (Cousens et al., 1986), or simulate germination times within a weed population (Bridges et al., 1989).

Models which describe a process or a limited number of processes often increase the understanding of a system and can be incorporated into more comprehensive models of weed-crop communities. Examples of single process models are those which simulate the thermal response of germination (Wiese and Binning, 1987; Bridges et al., 1989), of seedling emergence (Benec Arnold et al., 1990), of leaf area development (Alm et al., 1988), and of flowering (Bridges and Chandler, 1989).

Process-oriented models for entire weed-crop communities (Orwick et al., 1978; Scott et al., 1978; Kropff, 1988; Graf et al., 1990; Wilkerson et al., 1990) frequently improve the basic understanding of such communities but are not appropriate for practical applications. The large number of inputs and the difficulty in obtaining the inputs may discourage others from using the model. Furthermore, when such models are developed for a specific crop-weed combination they may not be easily adapted to other, dissimilar crops and weeds.

The ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) model is unusual in that it is a process-oriented simulator of a weed-crop community intended for practical applications. This model simulates crop-weed competition in a general way and with sufficient detail so that it can be easily transferred to different regions and different plant species. The required weather and soil inputs are readily available, and parameters specific to the plant species can be easily derived from the literature. The objective of this article is to describe and demonstrate the ALMANAC model.

MATERIALS AND METHODS

The ALMANAC model simulates the water balance, the nutrient balance, and the interception of solar radiation for two competing plant species. This model includes subroutines and functions from the EPIC model (Williams

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et al., 1984) and adds details for plant growth. The model has a daily time step. It is designed to simulate weed impacts on crop yields and intercropping in a reasonable and easily implemented way.

MODEL FUNCTIONS

Competition for Light. ALMANAC simulates light interception by leaf canopies, using Beer's law (Monsi and Saeki, 1953), and the leaf area index (LAI) of the total canopy. The model divides the intercepted light between the two plant species using the system of Spitters and Aerts (1983). The total interception is calculated with the LAI of each species, weighted by their light extinction coefficients (k). The greater the value of k for a species, the more light that species will intercept at a given LAI value and the more effectively that species will compete for light.

The fraction of daily incoming solar radiation intercepted by the total leaf canopy is:

$$\text{Fraction} = 1.0 - \exp(-k_A \times \text{LAI}_A - k_B \times \text{LAI}_B) \quad (1)$$

where subscript A identifies the species currently being considered and subscript B identifies the other species. The variable k is a species' extinction coefficient (positive value) and LAI is the species' leaf area index.

The ratio (RATIO) of the solar radiation intercepted by species A to the solar radiation intercepted by species B is calculated as:

$$\text{RATIO} = \frac{\text{LAI}_A \times k_A \times \exp(-k_1 \times \text{LAIHF}_1)}{[\text{LAI}_B \times k_B \times \exp(-k_2 \times \text{LAIHF}_2)]} \quad (2)$$

This is the ratio of the LAI of each species, weighted by k for each species and by the fraction of light transmitted to half the height of the plant species [$\exp(-k_n \times \text{LAIHF}_n)$]. Light at this height was chosen by Spitters and Aerts (1983) to estimate, in a simple way, the average illuminance throughout the leaf canopy of a species. This weighting gives preference to taller species and species with more efficient canopies for light interception. The fraction of total intercepted solar radiation partitioned to species A is $\text{RATIO}/(\text{RATIO} + 1)$. The fraction for B is $1 - (\text{fraction for A})$. Variable k_1 is the estimated extinction coefficient of the combined leaf canopy above half the height of species A. Variable k_2 is the same, above half the height of species B.

Variables LAIHF_1 and LAIHF_2 are the values for combined LAI above half the height of each species. Values of k_1 and k_2 are weighted means of the extinction coefficients of both species. These weights are determined by the relative species composition of the LAI above half the height of each species.

Leaf Area Simulation. Accurate simulation of light interception depends on realistic values of leaf area for both plant species. This requires that the leaf area be sensitive to population density. Three variables are used in ALMANAC to simulate the potential LAI of each species at different population densities. The first is the potential LAI at high densities. The other two variables are data points used to fit an s-curve function for a zero-to-one

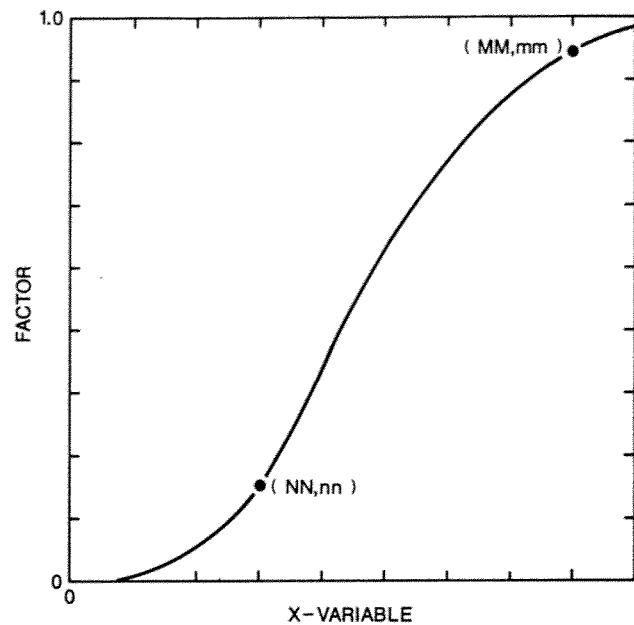


Figure 1—General function for simulating a zero-to-one factor as a function of a variable using an “s” curve. For the factor reducing potential maximum leaf area index in the season, the x-variable is plant population density. For the factor describing potential leaf area each day, the x-variable is fraction of heat units (PHU) which have accumulated between planting and maturity. For the factor reducing dry matter due to frost, the x-variable is the minimum daily temperature ($^{\circ}\text{C}$).

factor which reduces potential LAI at different population densities (fig. 1). The same general s-curve function simulates leaf area production as discussed below.

The model generates an s-curve that is forced through the origin and the two points, asymptotically approaching $y = 1.0$. The s-curve function takes the form:

$$F = X / [X + \exp(Y1 - Y2 \times X)] \quad (3)$$

where F is the factor for reducing potential LAI, X is the population density, and $Y1$ and $Y2$ are the s-curve coefficients generated by ALMANAC.

Simulation of light competition also requires an accurate description of leaf area production and decline. The model estimates leaf area production, up to the point of maximum leaf area for the growing season, by using a function similar to equation 3. In this case, two data points define an s-curve in which both the X and Y variables are on a zero-to-one scale. For each simulation day, the fraction of total heat units (PHU) that have accumulated is determined, denoted as SYP. The value for PHU is zero at planting and maximum at maturity. The s-curve simulates how LAI can increase, under nonstress conditions, as a function of SYP.

Loss of leaf area late in the season is described with the LAI decline factor (RLAD). This occurs after an input fraction (XDLAI) of PHU has accumulated. Three equations describe how leaf area (SLAI) declines late in the season:

$$XX = \log_{10} [(1.001 - \text{SYP}) / (1.0 - \text{XDLAI})] \quad (4)$$

$$\text{RTO} = \text{RLAD} \times XX \quad (5)$$

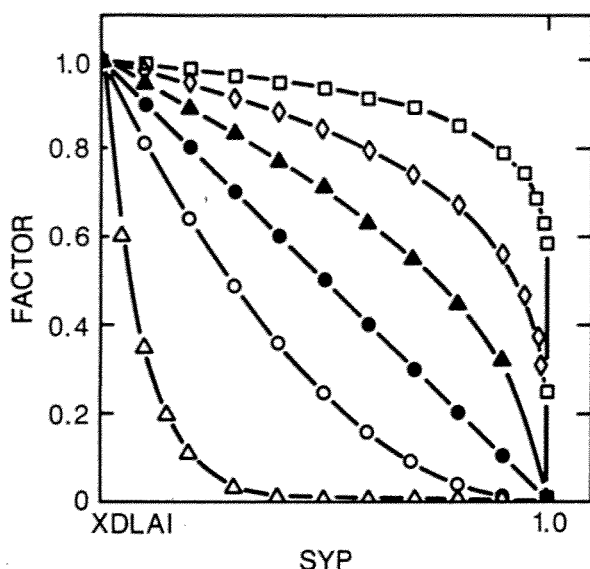


Figure 2—Factor for reducing radiation-use efficiency or leaf area index late in the season. Variable SYP is the fraction of the season from sowing to maturity. Variable XDLAI is the fraction of the season when radiation-use efficiency and leaf area index begin to decline. Lines represent declines due to input parameter values of 0.1 (\square), 0.25 (\diamond), 0.5 (\blacktriangle), 1.0 (\bullet), 2.0 (\circ), and 10.0 (\triangle).

where RTO is constrained to be greater than or equal to -10.0 , and:

$$SLAI_t = \text{Minimum of } (SLAI_{t-1} \text{ and } SLAIO \times 10^{RTO}) \quad (6)$$

where t is the current day, $t - 1$ is the previous day, and SLAIO is the SLAI on the day before leaf area begins to decrease. Thus as SYP goes from XDLAI to 1.0, XX goes from approximately 1.0 to almost zero (fig. 2). The value of RLAD determines the shape of this leaf area decline function.

Radiation-use Efficiency. Vapor pressure deficit (VPD) directly affects simulated radiation-use efficiency for biomass growth (RUE) and potential evapotranspiration. The functions for evapotranspiration are the same for all plant species (Williams et al., 1984). The response function for RUE is based on the work of Stockle and Kiniry (1990), Manrique et al. (1991), and Kiniry et al. (1992). Values of RUE are constant for a species at a VPD less than the threshold VPD. When VPD exceeds the threshold, RUE decreases linearly with increasing VPD. This form is easily implemented, with a typical value for the threshold 1.0 kPa and typical values for the slope -6.5 to -8.5 units of RUE/kPa increase in VPD for C_4 species (Stockle and Kiniry, 1990), -14.8 for potato (*Solanum tuberosum*, L.) (Manrique et al., 1991), and -32.3 for sunflower (*Helianthus annuus*, L.) (Kiniry et al., 1992).

The decline in RUE in later growth stages is simulated with the input variable RBMD (rate of biomass decline). This is similar to the decrease in LAI simulated with RLAD. Both RBMD and RLAD begin to have an effect after XDLAI is reached. The curve for rate of decline in RUE is identical to that for leaf area, with the value of RBMD determining its shape (fig. 2). A value of 1.0 for RBMD or RLAD results in a linear reduction to zero at

maturity. Greater values of RBMD or RLAD cause the function to approach the lines $X = XDLAI$ and $Y = 0.0$. Smaller values of these variables cause the function to approach the lines $Y = 1.0$ and $X = 1.0$.

Radiation use efficiency also responds to elevated CO_2 concentration. The value of RUE at the CO_2 concentration of 660 ppm is input as a plant species parameter.

Water and Nutrient Competition. The water balance consists of separate transpiration calculations for each species, with each using the water it needs if sufficient water is present in its current rooting zone. The nutrient balance (N and P) also allows each species to acquire sufficient nutrients to meet the demands if adequate quantities are available in its current rooting zone. The model requires a planting operation to establish each crop or weed species. Due to the model structure, when plant-available soil moisture in the current rooting zone is less than the potential evapotranspiration, the first-planted species is able to use the available water in its current rooting zone. Then the second-planted species is able to use the water left in its current rooting zone. A similar situation exists for uptake of N and P. Resulting problems should be negligible: initiation of drought stress or nutrient stress for a species will be altered, at most, by one day due to the order in which the two species were planted.

DERIVATION OF CONSTANTS FOR THE WEEDS

The weeds having the greatest impact on U.S. crop yields are pigweeds (*Amaranthus*), foxtails (*Setaria*), crabgrasses (*Digitaria*), cocklebur (*Xanthium*), and johnsongrass (*Sorghum halepense*, L., Pers.) (Brosten and Simmonds, 1989). We derived parameters for giant foxtail (*Setaria faberi*, Herrm.), green foxtail (*Setaria viridis*, L., Beauv.), cocklebur (*Xanthium pensylvanicum*, Wallr.), and johnsongrass. We also derived parameters for maize (*Zea mays*, L.), soybean (*Glycine max*, L., Merr.), and spring wheat (*Triticum aestivum*), using the values given for the EPIC model (Williams et al., 1989) and values derived from data not used in testing, unless noted below.

Model evaluation consisted of simulating values reported in the literature for yields of these crops in weed-free conditions and in competition with the two foxtail species, cocklebur, or johnsongrass. We used all available published data sets on these crop/weed combinations.

A number of parameters are either the same for all plant species or the same for all C_3 species and for all C_4 species (Table 1). In the following sections, we mainly describe parameters which had different values for the species investigated. Some parameters for weeds were estimated from values for similar crop species.

Base Temperature, Optimum Temperature, and Total Degree Days. The base temperature (TG) is important in a crop-weed competition model because the emergence date and rate of development early in the season are critical for simulating the interaction of the two species (Zimdahl, 1980). Base temperature is assumed to be the same for all growth stages. While seedling emergence is not directly simulated, base temperature constrains the initiation of leaf area growth and thus dry matter accumulation. Higher optimum temperature (TB) can increase competitiveness later in the season when temperatures are greater. The sum of degree days from

TABLE 1. Input parameters common for the C₃ species (wheat, soybean, cocklebur, foxtails), common for the C₄ species (maize, johnsongrass), or common for all species

	C ₃	C ₄	General Across Species	
DLAI	0.60	0.50	-	
DLAP (n, 1)	-	-	15.05	
FRST (n, 1)	-	-	5.01	(5.001)*
FRST (n, 2)	-	-	15.05	(15.01)
ALT	-	-	3.0	(2.00)
CAF	-	-	0.85	
GSI	-	-	0.007	
VPTH	-	-	1.0	
CVM	-	-	0.20	(0.03)
WSYF	-	-	0.01	
PST	-	-	0.95	
BN1	0.0524	0.0440	-	(0.60)
BN2	0.0265	0.0164	-	(0.231)
BN3	0.0258	0.0128	-	(0.0134)
BP3	0.0035	0.0023	-	(0.0019)

* Values in parentheses in this column represent parameter values for wheat when such values are unique to wheat.

sowing to maturity (PHU) controls how long the weed can compete and how late season stresses can affect seed yield.

Base temperature values for all species but wheat range from 8° to 11° C (Table 2). This temperature for winter and spring wheat is 0° C (Kiniry et al., 1991). We use 8° C for maize (Kiniry and Bonhomme, 1991) and 10° C for soybean (Kiniry et al., 1991).

Cocklebur and the two foxtail species are simulated with a base temperature of 10° C, while 11° C is used for johnsongrass. Cocklebur has been reported to emerge the same date as soybean and thus must have a similar base temperature (Stoller and Woolley, 1985). For foxtails, extrapolating the function of 1/(days to 50% emergence) to zero results in a value of 10° C (Vanden Born, 1971; Weaver et al., 1988). Similar analysis with johnsongrass for 1/(days to flowering) (Bridges and Chandler, 1989) and

1/(days to emergence) (Ingle and Rogers, 1961) indicated a base temperature greater than 10° C.

Values for optimum temperature are 25° C, with two exceptions. Wheat, a cool season species, is simulated with 15° C. Johnsongrass is tolerant of high temperatures and is simulated with 30° C.

The sums of degree days from sowing to maturity for the various species are determined by making model runs and estimating dates of maturity based on reported dates of leaf senescence or of cessation of seed growth (Tables 3 and 4). Values for degree day sums are stable across data set locations for giant foxtail and cocklebur. Maize values are 925 in Canada and 1550 at the other locations. Values for soybean range from 1250 to 1850. Values for green foxtail in Canada are much less than that for giant foxtail.

Plant Height. Potential height (HMX) of the canopy is important for simulating the competition for light. Plant types with a flowering structure extending much above the leaf canopy have a HMX value 0.20 to 0.30 m less than the reported plant heights. Realistic values for the different species are easily obtained from the literature. However, maturity-type differences and differences between locations in the height of a plant species must be recognized. The values given here should be reasonable for most applications, but a correction may be needed if the value for a weed or crop in a data set is known to differ substantially from these reported ones.

Values for HMX of all the species considered in this article range from 0.8 to 2.0 m. Values are 2.0 m for maize, 0.8 m for soybean, and 1.2 m for wheat. With the exception of green foxtail, all simulated weed heights are 1.0 m. Johnsongrass biotypes have been reported as being 1.0 to 1.2 m tall (Wedderspoon and Burt, 1974; McWhorter and Jordan, 1976; and Massion and Lindow, 1989). Some johnsongrass biotypes, especially in the northern part of each range, can be as tall as 2.8 m (McWhorter, 1971; Warwick et al., 1984). Cocklebur heights have been

TABLE 2. Input parameter values which differ among species

CROP:	Cocklebur	Giant Foxtail	Green Foxtail	Johnsongrass	Maize	Soybean	Wheat
Parameter							
WA	33.0	37.0	37.0	35.0	39.0	25.0	35.0
HI	0.40	0.10	0.10	0.15	0.60	0.31	0.42
TB	25.0	25.0	25.0	30.0	25.0	25.0	15.0
TG	10.0	10.0	10.0	11.0	8.0	10.0	0.0
DMLA	5.0	3.8	3.3	5.0	7.0	7.0	5.0
DLAP (n, 2)	50.95	54.95	54.95	57.95	50.95	50.95	50.95
PPL (n, 1)	1.35	30.30	30.30	1.10	4.57	30.43	125.60
PPL (n, 2)	3.95	75.75	75.75	10.95	8.86	50.71	250.95
RLAD	0.50	2.00	1.00	1.00	0.10	0.10	1.00
RBMD	1.00	1.00	1.00	1.00	0.10	0.10	10.00
WAC2	660.45	660.43	660.43	660.35	660.45	660.34	660.46
VPD2	-32.30	-6.50	-6.50	-8.50	-6.50	-6.50	0.0
HMX	1.00	1.00	0.70	1.00	2.00	0.80	0.90
RDMX	2.00	2.00	2.00	2.00	2.00	1.70	2.00
CNY	0.065	0.065	0.065	0.020	0.0175	0.065	0.0234
CPY	0.0091	0.0091	0.0091	0.0028	0.0025	0.0091	0.0033
BP1	0.0074	0.0074	0.0074	0.0060	0.0062	0.0074	0.0084
BP2	0.0037	0.0037	0.0037	0.0022	0.0023	0.0037	0.0032
COSD*	0.01	0.01	0.01	0.01	2.51	0.33	0.18
PRY*	0.01	0.01	0.01	0.01	100.00	400.00	120.0
EXT	0.90	0.65	0.65	0.65	0.65	0.45	0.65

* Cost of seed (dollars / ac) and price for yield (\$ / metric ton) are region-specific and year-specific. Users interested in the economic output should supply appropriate values.

TABLE 3. Measured and simulated maize and soybean yields with and without foxtail competition. Heat units for the season (PHU) are 1400 for giant foxtail, 1500 for wheat, and 1250 for all soybeans except in Maryland where the value was 1500. Maize has 1550 for PHU in all locations except Guelph where the value is 925. Green foxtail has 750 in Guelph and 550 in Regina

Location	Years	Crop	Grain Yield (Mg / ha)					
			Without Competition		With Competition			
			Measured	Simulated	Measured		Simulated	
Giant foxtail								
Urbana, IL*†‡	61-65	Maize	8.47	7.87	7.42	(88)§	6.49	(83)
Champaign, IL #	85-86	Maize	10.76	9.97	9.42	(88)	8.80	(88)
Urbana, IL*†	61-65	Soybeans	2.20	2.43	1.27	(62)	1.21	(50)
Queensland, MD***††	81-83	Soybeans	3.04	3.36	2.17	(71)	2.36	(70)
Urbana, IL‡‡	82-83	Soybeans	2.60	2.33	1.90	(73)	1.42	(61)
Green foxtail								
Guelph, Ont.§§	76-77	Maize	4.37	4.72	3.64	(83)	4.02	(85)
Regina, Sask. ##	81-86	Wheat	2.49	2.43	2.37	(95)	2.18	(90)

* Knake and Slife (1965).

† Knake and Slife (1969).

‡ Harvest index (HI) set to 0.50 to better describe the older maize hybrids.

§ Percentage of the yield in weed-free conditions.

|| Beckett et al. (1988).

Maximum height values (HMAX) are input as 2.2 m for maize and 1.5 m for giant foxtail as these were the reported values.

** Harris and Ritter (1987).

†† HI set to 0.40 to better simulate the weed-free yield.

‡‡ Harrison et al. (1985).

§§ Sibuga and Bandeen (1980).

|| Hume (1989).

The simulations assume that green foxtail is the only weed; whereas, actually only 79% of the weeds were green foxtail. The measured yield with weeds given here takes into account only the impact due to the presence of green foxtail. The mean measured yield when all weeds were present was 93% of the yield in weed-free conditions.

reported to be at least 0.30 m taller than soybeans (Stoller and Woolley, 1985). The height in Fayetteville, Arkansas, was 1.8 m (Monks et al., 1988). Other values reported were 1.2 m (Waldrep and McLaughlin, 1969) and 0.8 m (Nussbaum et al., 1985). Giant foxtail height can be 1.3 m (Santelmann et al., 1963; Knake, 1972). Thus we assume the flowering structure is 0.30 m above the leaf canopy

when we use a value of 1.0 m for HMX. Green foxtail has a height of 0.65 to 0.95 m (Schreiber and Orwick, 1978; Lee and Cavers, 1981; Bubar and Morrison, 1984). We use an HMX value of 0.70 m.

Leaf Area Index at Different Population Densities. The potential leaf area index in ALMANAC at high plant populations in the absence of competition with other

TABLE 4. Measured and simulated maize and soybean yields with and without cocklebur or johnsongrass competition. Heat units for the season (PHU) are 1450 for cocklebur, 1400 for johnsongrass, 1550 for maize, and 1250, 1800, 1600, 1850, and 1500 for the five soybean data sets in the order they appear in the table

Location	Years	Crop	Grain Yield (Mg / ha)					
			Without Competition		With Competition			
			Measured	Simulated	Measured		Simulated	
Cocklebur								
Champaign, IL*†	85-86	Maize	12.09	9.97	10.15	(84)‡	8.80	(88)
Urbana, IL§	74-75	Soybeans	2.85	2.47	1.04	(36)	0.77	(31)
Stoneville, MS	71	Soybeans	2.08	2.84	1.14	(45)	1.47	(52)
Fayetteville, AR#	75-76	Soybeans	1.24	1.57	0.66	(52)	0.85	(54)
Clayton, NC***††	85-86	Soybeans	4.95	3.71	3.68	(74)	3.15	(85)
Johnsongrass								
Jackson, TN‡‡	80-81	Soybeans	2.3	2.22	1.7	(75)	1.71	(77)

* Beckett et al. (1988).

† Maximum values for height (HMAX) are input as 2.4 m for maize and 1.8 m for cocklebur as these were the reported values.

‡ Percentage of the yield in weed-free conditions.

§ Bloomberg et al. (1982).

|| Barrentine (1974).

Geddes et al. (1979).

** Mortensen and Coble (1989).

†† HI set to 0.40 to better simulate the weed-free yield.

‡‡ Williams and Hayes (1984).

species is 7.0 for maize and soybean and 5.0 for spring wheat. Reasonable values for LAI of these crops at two common population densities are then used to estimate the potential LAI at any density. Potential LAI of maize in ALMANAC is 4 at 4 plants/m² and 6 at 8 plants/m². Potential LAI of soybean is assumed to be 3 at 30 plants/m² and 5 at 50 plants/m². Finally, potential LAI of wheat is 3 at 125 plants/m² and 4.75 at 250 plants/m².

Measurements of isolated johnsongrass plants at Temple, Texas (Kiniry, unpub., 1990) indicated a mean leaf area of about 0.50 m²/plant. We assume the maximum LAI at about 10 plants/m² approaches 5.0. Thus johnsongrass has 10% of this value at 1 plant/m² and has 95% of this value at 10 plants/m². Cocklebur can have an LAI as great as 4.8 at 3.2 plants/m² (Barrentine and Oliver, 1977). The simulated potential LAI of cocklebur is 5.0. From the same study, cocklebur at 1.1 plants/m² had an LAI of 2.0 and at 2.1 plants had an LAI of 3.5. Thus we assume cocklebur can have 35% of the potential LAI at 1 plant/m² and 95% of the potential at 3 plants/m².

Giant foxtail is simulated with potential LAI equal to 5.0 and the potential of green foxtail is assumed to be 70% as large. Giant foxtail has 0.040 to 0.060 m² of leaf area/plant and green foxtail had 0.018 to 0.053 m² of leaf area/plant with adequate N fertility (Schreiber and Orwick, 1978; and Nadeau and Morrison, 1986). Using the mean giant foxtail value of 0.050 m²/plant, 100 plants/m² would have a potential LAI of 5.0. The mean for green foxtail is 70% as great, and potential LAI is 3.5. For both foxtail species, LAI is 30% of the potential at 30 plants/m² and 75% of potential at 75 plants/m².

Declines in LAI and in Radiation-use Efficiency Late in the Season. The competitiveness and productivity of plants late in the season are dependent on the rate of decline in leaf area (RLAD), rate of decline in biomass production (RBMD), and the elapsed portion of the growing season when these declines begin (XDLAI), as discussed above. Maize and soybean are simulated with slow rates of both decline in leaf area and decrease in RUE. Thus, values for RLAD and RBMD are assumed to be 0.1. Leaf photosynthesis of both of these species has been reported to remain high late in the grainfilling period. By the dent stage of maize (about 80% of the time from silking to maturity) the photosynthetic rate was 87% of the value at blister (about 20% of the time from silking to maturity) (Vieter et al., 1977). The CO₂ uptake rate of soybeans reportedly decreases linearly during the last 20% of the season (Boon-Long et al., 1983).

For consistency in this initial application of ALMANAC, all weed species are assumed to have rapid leaf senescence and rapid decline in RUE. The value of RBMD is 1.0 for all weeds. The values of RLAD are 1.0 for green foxtail and johnsongrass, 2.0 for giant foxtail, and 0.5 for cocklebur. The value of XDLAI is 0.5 for C₄ species and 0.6 for C₃ species.

Radiation-use Efficiency and its Response to Vapor Pressure Deficit and CO₂ Concentration. The values for RUE are based on values for sorghum and maize (Stockle and Kiniry, 1990), soybean (Williams et al., 1989), and wheat (Kiniry et al., 1989). Maize produces 39 kg/ha of biomass for each 1.0 MJ/m² of intercepted photosynthetically active radiation (PAR) when the vapor

pressure deficit (VPD) is less than 1.0. Maize RUE decreases by 6.5 units for every 1 kPa increase in VPD above 1.0. Soybean has a RUE value of 25 and wheat has a value of 35. In ALMANAC, vapor pressure deficit decreases RUE of soybean by 6.5 units/kPa and does not affect RUE of wheat. Johnsongrass has simulated values identical to sorghum (*Sorghum bicolor*, L., Moench), with RUE equal to 35 and a rate of decrease equal to -8.5 units of RUE/kPa. The mean photosynthetic rate and net assimilation rate of cocklebur are 31 to 32% greater than for soybeans (Monks et al., 1988; Regnier et al., 1988). Thus, we assume RUE of cocklebur is 33. A linear regression fit for green foxtail dry weight as a function of cumulative intercepted PAR resulted in a RUE value of 37. The data was from a study by Lee and Cavers (1981) and we assumed clear day radiation values. This value is used for both foxtail species. The simulated values for the RUE response to VPD of cocklebur and foxtail are assumed to be equal to that of maize.

While not used in any of the analyses in this study, the increased RUE in response to increased atmospheric CO₂ concentration can be used to simulate changes in competition in response to changes in CO₂ concentration. Various measurements of plant productivity have been used to quantify the response of plants to elevated CO₂. These include RUE, rate of photosynthesis, and rate of biomass accumulation.

The factors from a number of studies are used to adjust RUE for CO₂ increases in ALMANAC. Relative changes in RUE are greater for C₃ species than for C₄ species. Soybean RUE increased by 37% as CO₂ increased from 330 to 660 ppm. (Imai and Murata, 1979; Charles-Edwards, 1982; Cure and Acock, 1986). The RUE of wheat increased by 31% (Cure and Acock, 1986) over this range. The median of values for foxtail species (Patterson and Flint, 1990) had a 16% increase. We assume cocklebur has the same percentage increase in RUE as that of soybean. Johnsongrass had no increase with increased CO₂ (Carter and Peterson, 1983; Patterson et al., 1984) and maize had a 15% increase (Imai and Murata, 1979; Charles-Edwards, 1982; Cure and Acock, 1986). Thus RUE at 660 ppm CO₂ for each of these species is the original RUE value multiplied by the appropriate factor.

Maximum Rooting Depth. The maximum rooting depth defines the potential depth in the absence of a root-restricting soil layer. The value for cocklebur has been reported to be over 2.0 m (Davis et al., 1967; Monks et al., 1988). Sorghum has a rooting depth of almost 2 m by maturity (Davis et al., 1967). Soybean roots are not as deep, with the depth about 80% of that for cocklebur (Monks et al., 1988). Maximum rooting depths for soybeans ranged from 1.6 m to 1.9 m in an Iowa field in August (Kaspar et al., 1984). For the simulations, all the weeds and all the crops except soybean have depth values of 2.0 m. The value for soybean, based on the field measurements in Iowa, are assumed to be 1.7 m. Further applications of the model, especially in moisture-limited conditions, may require more accurate values for this depth.

Harvest Index. Harvest index (HI) is the dry weight of the seed divided by the dry weight of the total above-ground plant at maturity. Values for the crops are assumed

to be the same as those in the EPIC model (Williams et al., 1989) with one exception: maize data sets after 1970 are assumed to have higher yielding hybrids, and the simulated HI value is 0.60.

Weed HI values were derived from the literature and from measurements of field grown plants from Temple, Texas (Kiniry, unpub. data, 1990). Giant foxtail has HI values from 0.092 to 0.101 (Knake, 1972). We use a value of 0.10 for both foxtail species. The flowering structure of johnsongrass consists of 29% of the total above-ground dry weight (Warwick et al., 1984). We assume that half of the flowering structure weight is seeds and that the simulated HI value is 0.15. Our unpublished measurements of cocklebur indicate HI can vary from 0.34 to 0.47 and the mean is 0.40.

Light Extinction Coefficient. As previously discussed, light interception by the leaf canopy is based on the leaf area index (LAI) at the given plant spacings and the light extinction coefficient (k) of the plant species. Maize, wheat, and rice have k values of 0.65, soybean has a k value of 0.45, and sunflower has a k value of 0.90 (Monteith, 1969). Cocklebur has leaf geometry similar to that of sunflower and thus we assume it has the same value for k . We use 0.65 for johnsongrass and the foxtail species.

RESULTS

The results described in this section are not an independent validation of ALMANAC. While the model was not "fit" to the data, changes in the model input parameters are not entirely independent of model simulations for these data sets. These demonstrations of model performance indicate how the model works over a range of environments. The input parameters used in these demonstrations provided realistic simulations for the plant species examined.

The simulated yields of three crops without weeds are similar to the measured yields (Tables 3 and 4). The mean measured maize yield over all data sets is 8.9 Mg/ha. The mean simulated maize yield is 8.1 Mg/ha. The mean simulated yield of soybeans is 2.6 Mg/ha and the mean measured yield is 2.7 Mg/ha. The one data set for wheat has a simulated yield 2% different from the measured value.

The ALMANAC model simulates the impact of two foxtail species reasonably for maize, soybean, and wheat. For maize, both simulated and measured mean yields with weeds are 86% of the weed-free yields. For soybeans, the mean measured yield with weeds is 69% of the mean weed-free yield. The mean simulated yield with weeds is 60% of the mean weed-free yield. The measured and simulated impacts of weeds on wheat yields differ by 5%.

Simulations of the impact of cocklebur on maize yield are similar to measured impacts, although the simulated weed-free yield is noticeably less than the measured value. The percentage impact of weeds differs by 4% between the simulated and measured values.

Mean values of the impact of cocklebur on soybean yields are similar for the measured and simulated results. The mean measured yield with cocklebur is 52% of the weed-free yield. The mean simulated value is 56%. The model predicts that the high yielding soybeans from

Clayton, North Carolina, have the smallest decrease in yield due to cocklebur competition in agreement with the measured results.

The ALMANAC model closely simulates both the weed-free soybean yield and the soybean yield with johnsongrass in Tennessee. The weed-free simulated yield is 3% different from the weed-free measured yield. Percentage weed impact for the simulated yields is 2% different from that for measured values.

One application of a weed-crop interaction model is to simulate the impact of differing weed densities on crop yield. Data from Champaign, Illinois (Beckett et al., 1988) were used to test the ability of ALMANAC to simulate maize yield with different population densities of giant foxtail and cocklebur.

The model adequately simulates the shape of the response for both weed species, while best simulating the individual values for giant foxtail infestations (figs. 3 and 4). For giant foxtail, the two lowest weed densities have simulated impacts close to the measured values. The simulated drop in yield between the two greatest densities is similar to the drop in measured yields at these densities. For cocklebur, the model overestimates the impact of the weeds at all densities. Simulated values do, however, show a plateau in yield response above 2 plants/m², similar to that in measured values.

The final model test demonstrates the dynamic nature of ALMANAC. Giant foxtail was removed from maize or soybean on different dates and the resulting yields were measured (Knake and Slife, 1969). The model closely simulates the maize yield reduction in response to delayed giant foxtail removal (fig. 5). The values for soybean yield with giant foxtail removed on different dates are presented with different data points for the two years (fig. 6). The model adequately simulates the plateau in yield with the

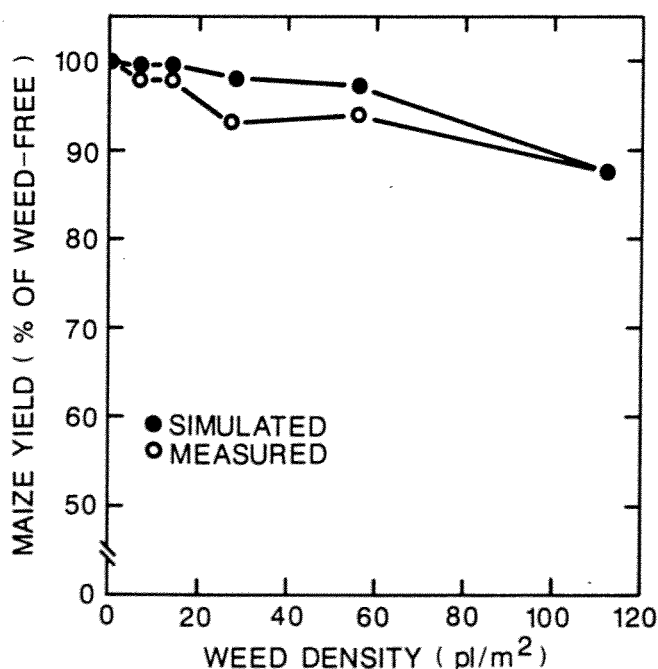


Figure 3—Simulated and measured maize yields with different densities of giant foxtail in Champaign, Illinois. Data are from Beckett et al. (1988).

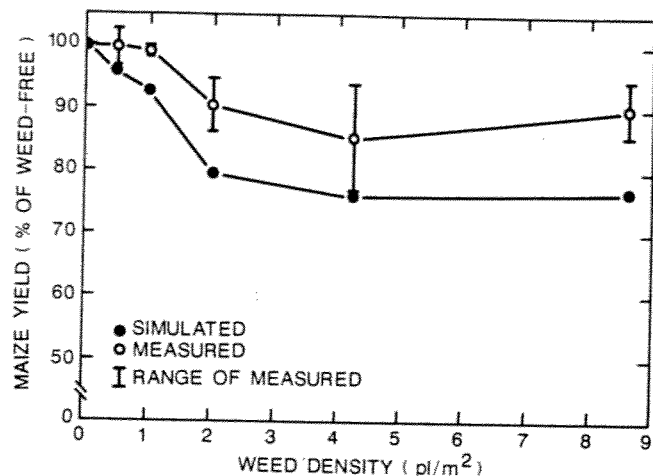


Figure 4—Simulated and measured maize yields with different densities of cocklebur in Champaign, Illinois. Data are from Beckett et al. (1988).

3 and 6 week removal treatments. The simulated values are below measured values for the 9 and 12 week treatments. The simulated yields for the 16 week treatment (weeds present throughout the season) are between the two measured values.

In conclusion, the ALMANAC model is a versatile tool which reasonably simulates the impacts of foxtail species, cocklebur, and johnsongrass on yields of maize, soybeans, and wheat. The model has sufficient generality to simulate a weed over a wide range of environmental conditions and has enough detail to account for differences in type of leaf canopy, in plant height, in rooting depth, and in population density. Because of its process-oriented approach, it should also be useful for simulating intercropping, brush and grass competition, and the effects of climate change on interspecies competition.

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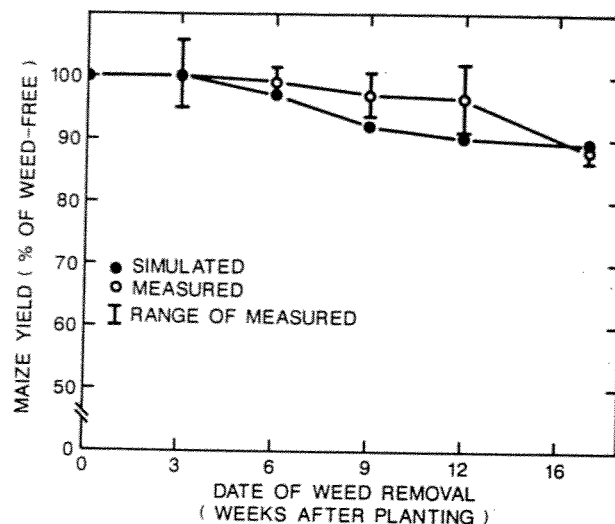


Figure 5—Simulated and measured maize yields with giant foxtail removed on different dates in Urbana, Illinois. Data are from Knake and Slife (1969).

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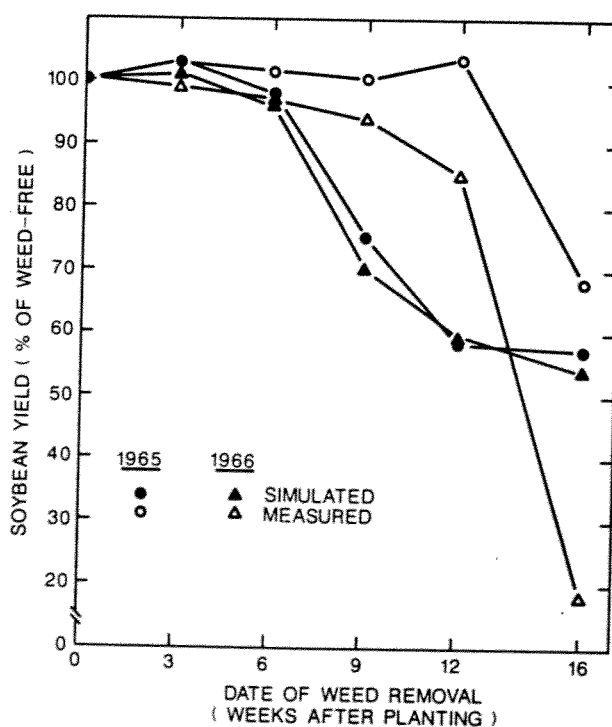


Figure 6—Simulated and measured soybean yields with giant foxtail removed on different dates in Urbana, Illinois. Data are from Knake and Slife (1969).

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