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Simulating Alamo Switchgrass with the ALMANAC Model

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ABSTRACT

A model for forage yield with adequate details for leaf area, biomass, nutrients, and hydrology would be valuable for making management decisions. The objectives of this study were to develop Alamo switchgrass (*Panicum virgatum* L.) parameters for the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model and demonstrate its accuracy across a wide range of environments. Derived plant parameters included potential leaf area index (LAI), potential biomass growth per unit intercepted light, optimum nutrient concentrations, and growth responses to temperature. The model's simulated yields accounted for 79% of the variability in measured yields for one-cut and two-cut harvest systems from six diverse sites in Texas in 1993 and 1994. Simulated yields for three locations differed in sensitivity to potential LAI, heat units to maturity, radiation use efficiency (RUE), and soil depth. The ALMANAC model shows promise as a management tool for this important forage and bioenergy crop.

Forage models require details for LAI, water balance, and nutrient balance to simulate yields on various soils in drought-prone and nutrient-limiting conditions. Perennial forage development begins with germination of seeds and progresses through seedling emergence, leaf area development with associated light interception and carbon assimilation, anthesis, and leaf senescence. In subsequent production years, the primary phases of plant growth are vegetative and reproductive development.

A modeling approach that employs RUE (Kiniry et al., 1989) offers an easily applied technique for simulating crop biomass. Models based on RUE use a stable value for dry matter produced per unit of light intercepted, assuming adequate soil moisture, adequate soil nutrients, and moderate temperatures. Simulated daily biomass production decreases below potential if drought stress or N or P deficiency occurs. Simulated leaf area development begins when air temperature exceeds a base temperature and LAI approaches a maximum at a given sum of degree days. Beer's law (Monsi and Saeki, 1953) simulates light interception, assuming a random spatial arrangement of leaf area. This system simulates different type leaf canopies by changes in the light extinction coefficient. Stability of photosynthesis per unit leaf area among genotypes within several forage species (Sheehy and Cooper, 1973; Delaney and Dobrenz, 1974; Hoveland et al., 1974; Nelson et al., 1975) supports the stability of RUE within a species. Genotypic differences in forage production are more closely related to development of total leaf area and thus total light intercepted, than to productivity per unit leaf area. In addition, the same RUE value is often valid for different cultivars within a species. Differences in forage production among cultivars are mainly due to differences in potential LAI or in the rate of accumulation of LAI.

With this approach, the ALMANAC model (Kiniry et al., 1992b) can describe forage production across environments with different soils, rainfall, and temperatures. The model, with appropriate plant parameters, could help managers to (i) select genotypes for a location, (ii) predict changes in soil erosion and changes in water quantity and quality when row-cropped fields are converted to perennial herbage production, and (iii) predict changes in economic return when such fields are converted to perennial herbage production.

Switchgrass is an important forage and biomass energy crop attracting interest recently as an alternative crop (Sanderson et al., 1996). The first objective of this study was to develop ALMANAC parameters for Alamo switchgrass. We also investigated the ability of the model to predict switchgrass forage yields over a range of soil types and rainfall amounts. This model can provide a standard of comparison for forage models with more complex C assimilation and partitioning (McMurtrie and Wolf, 1983; Hanson and Skiles, 1987; Norman and Polley, 1989; Hunt et al., 1991).

MATERIALS AND METHODS

General Model Description

The ALMANAC model simulates the soil water balance, the soil and plant nutrient balance, and the interception of solar radiation. This model includes subroutines and functions from the Erosion-Productivity Impact Calculator (EPIC) model (Williams et al., 1984, 1989) with added details for plant growth. The model has a daily time step. It simulates plant growth for a wide range of species and is implemented easily.

Light Interception

ALMANAC simulates light interception by the leaf canopy with Beer's law (Monsi and Saeki, 1953) and the LAI. With greater extinction coefficient values (k), a given LAI intercepts more light.

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Abbreviations: ALMANAC, Agricultural Land Management Alternatives with Numerical Assessment Criteria; EPIC, Erosion-Productivity Impact Calculator; LAI, leaf area index; PAW, plant available water (the difference between field capacity and wilting point); PHU, heat units from planting to maturity; RTO, variable used as an exponential of 10 to decrease LAI late in the season; RUE, radiation use efficiency; SLAI, current value for simulated LAI; SLAI0, LAI value as LAI begins to decrease due to senescence late in the season; SYP, fraction of the heat units from planting to maturity or from initiation of spring growth until maturity.

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

$$\text{Fraction} = 1.0 - \exp(-k \times \text{LAI}) \qquad [1]$$

Simulated switchgrass k is 0.65, a value previously derived for maize (*Zea mays* L.), orchardgrass (*Dactylis glomerata* L.), barley (*Hordeum vulgare* L.), and rice (*Oryza sativa* L.) (Monteith, 1969).

Leaf Area Development

Accurate prediction of light interception depends on realistic description of leaf area. Input values for Eq. [2] for switchgrass LAI development are from plot measurements at Temple, TX (Kiniry, unpublished data). These plots were different from the ones from which the demonstration data were taken, as described below. While ALMANAC simulates decreases in LAI due to low plant density, for this application we assume adequate density to attain the potential LAI. The input potential LAI is 12.0. The model estimates leaf area production up to the point of maximum leaf area for the growing season using Eq. [2]. The sigmoid-curve function for potential LAI production takes the form:

$$F = \text{SYP}/[\text{SYP} + \exp(\text{Y1} - \text{Y2} \times \text{SYP})] \qquad [2]$$

where F is the factor for relative LAI, SYP is the fraction of heat units from planting to maturity, and Y1 and Y2 are the sigmoid-curve coefficients generated by ALMANAC. This curve passes through the origin and through two points, asymptotically approaching $F = 1.0$. The model calculates SYP each day. The sum of heat units is zero at planting in the establishment year and at tiller emergence in subsequent years, and is maximum at maturity. Switchgrass simulated LAI reaches 20% of potential at 10% of the heat units for the season and 95% of potential at 20% of the heat units (Fig. 1).

The model describes loss of switchgrass leaf area late in the season with the LAI decline factor set to 1.0. The LAI begins to decrease after 70% of heat units for the season have accumulated. Three equations describe how leaf area declines late in the season:

$$\text{RTO} = \log_{10}[(1.001 - \text{SYP})/0.3] \qquad [3]$$

where today's LAI is the minimum of yesterday's LAI and SLAIO $\times$ 10^{RTO}. SLAIO is the LAI on the day before leaf area begins to decrease. Thus, as SYP goes from 0.7 to 1.0, RTO goes from 1.0 to zero (Fig. 1). Simulated switchgrass leaf area declines linearly with accumulated heat units.

Biomass Production and Partitioning

The model simulates biomass with an RUE value for each plant species (Kiniry et al., 1989). Values for RUE have been derived for wheat (*Triticum aestivum* L.), rice, maize, and

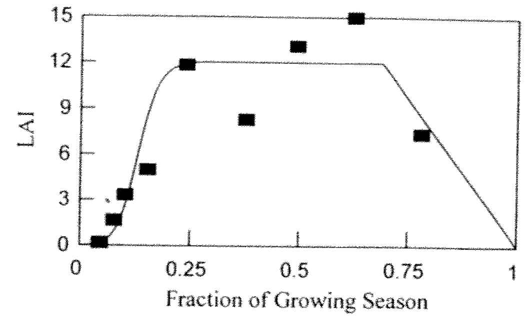

Fig. 1. Seasonal patterns of simulated (line) and measured (squares) Alamo switchgrass leaf area index (LAI). Measured values are from Temple, TX.

sorghum [*Sorghum bicolor* (L.) Moench] (Kiniry et al., 1989), for potato (*Solanum tuberosum* L.) (Manrique et al., 1991), and for sunflower (*Helianthus annuus* L.) (Kiniry et al., 1992a). For switchgrass, we used an RUE value greater than that of maize, 4.7 g MJ^{-1} of intercepted photosynthetically active radiation, with a decrease of 0.85 g MJ^{-1} for each 1 kPa increase in vapor pressure deficit above the threshold of 1 kPa (Stockle and Kiniry, 1990). The model partitions biomass to roots starting at 20% of daily growth at emergence and decreasing to 10% by anthesis.

ALMANAC describes declining RUE in later growth stages with an identical function to the one for the decrease in LAI. Just as for LAI, RUE of switchgrass decreases linearly after 70% of the heat units have accumulated.

The maximum rooting depth defines the potential depth without a root-restricting soil layer. Soil cores at Temple in 1994 showed that switchgrass roots extend to 2.2 m.

Harvest index is the dry weight of the seed divided by the dry weight of the total aboveground plant at maturity. The value we use for switchgrass is 0.01 to allow only minimal biomass partitioning to seeds.

Water and Nutrient Uptake

The model calculates potential transpiration from the LAI and daily climate data. Transpiration is reduced if demand exceeds the water present in the current rooting zone. The nutrient balance (N and P) also allows plants to acquire sufficient nutrients to meet the demands if adequate quantities are available in the current rooting zone. Nutrient values for switchgrass are from the standard pasture parameters of EPIC (Williams et al., 1984), with improvements in N concentration based on data collected at Stephenville during 5 yr (Sanderson, unpublished data) and Waller et al. (1972). Concentrations of N in the dry weight are 0.016 g g^{-1} in the seed, 0.035 in the young seedling, 0.015 near anthesis in the whole plant, and 0.0038 in the whole plant at maturity. Concentrations of P in

Table 1. Soil characteristics for the Texas switchgrass data sets simulated by ALMANAC. Soil nutrients and organic matter are initial means for the top 1.0 m, except for Dallas, where they are for the top 0.9 m.

Location	Soil type	Initial soil values			Soil depth	PAW†
		N	P	Organic matter		
		— mg kg^{-1} —		%	m	mm
Knox City	Windthorst fine sandy loam (Udic Paleustalfs)	1.6	3.0	1.17	1.5	193
Dallas	Houston Black clay (Udic Haplusterts)	2.4	28.6	2.46	1.6	182
Stephenville	Windthorst fine sandy loam	3.1	1.8	0.51	1.5	190
Temple	Houston Black clay	3.3	16.1	1.35	2.0	256
College Station	Weswood silt loam (Fluventic Ustochrepts)	3.6	55.2	0.76	2.0	266
Beeville	Parrita sandy clay loam (Petrocalcic Paleustolls)	1.6	3.0	1.17	1.0	110

† Plant available water; difference between field capacity and wilting point in the profile.

Table 2. Rainfall sums for the Texas switchgrass data sets.

Location	Lat.	Elevation	Annual rainfall 1993	Annual rainfall 1994
	°N	m	mm	
Knox City	32.83	445	565	–
Dallas	32.75	134	1079	1011
Stephenville	31.13	399	778	923
Temple	31.05	210	948	835
College Station	30.67	94	1210	1112
Beeville	28.40	67	953	921

the dry weight are 0.0022 g g^{-1} in the seed, 0.0014 in the young seedling, 0.0010 near anthesis in the whole plant, and 0.0007 in the whole plant at maturity.

Base Temperature, Optimum Temperature, and Total Degree Days

Base temperature in ALMANAC is constant for all growth stages. Base temperature constrains the initiation of leaf area growth and thus dry matter accumulation. Higher optimum temperature can allow increased plant development rate later in the season when temperatures are greater. The sum of heat units from sowing to maturity controls the duration of growth. Base temperature for Alamo switchgrass is 12°C and optimum temperature is 25 (Van Esbroeck, unpublished data). We allow 2300 heat units from planting to maturity. Heat units are reset to zero after maturity each year. Heat units are calculated from daily maximum and minimum temperatures, assuming the maximum equals 25°C if it exceeds 25°C.

Demonstration Data Sets

Model runs with data from six Texas locations (Sanderson et al., 1996) (Table 1) demonstrate how well the model functions with current inputs and are not independent validations. The data represent a range of rainfall and temperature regimes, soil types, and cutting treatments. Plots were established in the spring of 1992 and forage yields were measured in 1993 and 1994 except for Knox City. At Knox City, only 1993 data were collected. Soil cores were sampled at each site and characterized for texture and initial nutrients. Simulations used Soil Conservation Service runoff curve numbers of 78 at Knox City and Stephenville, and 81 at Dallas, Temple, College Station, and Beeville based on the soils' hydrologic group and hydrologic condition (SCS, 1972). We simulated a burn on 1 February of each year removing the biomass aboveground, except at College Station, where we input mowing operations, to be consistent with actual management practices. We compared simulated with measured yields and analyzed the results with regression.

Analyses were conducted using data from three locations to illustrate sensitivity of forage yield to four inputs. The three crop parameters examined were RUE, potential LAI, and heat units from planting to maturity. A physical input examined was the amount of plant-available water that can be stored in the soil profile. We altered plant-available water by changing the thickness of lower soil layers. The data sets used were the 1993 harvest at Knox City, the Stephenville A treatment in 1993 and 1994, and the one harvest treatment in 1993 and 1994 at Beeville. Annual rainfall amounts (Table 2) were least at Knox City and greatest at Beeville. All parameters were changed by similar relative amounts among locations and the simulated yield responses compared.

RESULTS

Demonstration with Measured Data at Six Sites

The model simulated yields with little bias due to year, cutting treatment, or type of environmental restriction on yield. Mean error of prediction (simulated minus measured) was 0.5 t ha^{-1} and the model accounts for 79% of the variability in measured yields (Table 3 and Fig. 2). ALMANAC overpredicted the 1993 data by an average of 0.4 t ha^{-1} and overpredicted the 1994 data by 0.8 t ha^{-1}. One-cut data had a mean overprediction of 0.1 t ha^{-1}. Two-cut data had a mean overprediction of

Table 3. Alamo switchgrass yields measured and simulated by ALMANAC. Days of stress are those simulated by ALMANAC.

Location	Year	Cuttings	Measured yield mean	SD	Simulated yield	Difference	Drought stress	N stress
		no.	t ha^{-1}				d	
Knox City	1993	1	7.4	2.3	6.3	−1.1	78	114
Dallas†	1993	1	6.6	1.2	7.2	0.6	22	114
	1994	1	6.1	1.0	5.5	−0.6	24	63
Stephenville A‡	1993	1	8.7	2.9	8.9	0.1	79	30
	1994	1	19.5	0.9	17.9	−1.6	65	76
Stephenville B	1994	1	16.3	2.9	19.5	3.2	108	60
Stephenville C	1994	1	14.5	2.5	14.2	−0.2	72	72
Temple	1993	1	11.4	0.0	14.6	3.2	52	136
	1994	1	17.7	1.9	14.8	−2.9	47	97
Temple	1993	2	10.8	0.0	10.0	−0.8	67	88
	1994	2	14.3	1.9	17.1	2.8	89	89
College Station	1993	1	18.8	3.7	18.8	−0.1	20	214
	1994	1	20.1	4.2	17.7	−2.4	38	204
College Station	1993	2	13.4	5.9	14.0	0.6	69	104
	1994	2	19.2	5.2	23.2	4.0	39	144
Beeville	1993	1	13.6	3.4	11.3	−2.3	41	234
	1994	1	12.3	0.3	17.5	5.2	78	168
Beeville	1993	2	9.8	0.0	10.4	0.6	36	195

† First cutting in June, only. After June, rodent damage reduced measured yields.
‡ Stephenville A was established in 1992. Stephenville B and C were established in 1993. Stephenville B received 134 kg N ha^{-1} in the spring of 1994, while Stephenville C received 78 kg ha^{-1}.

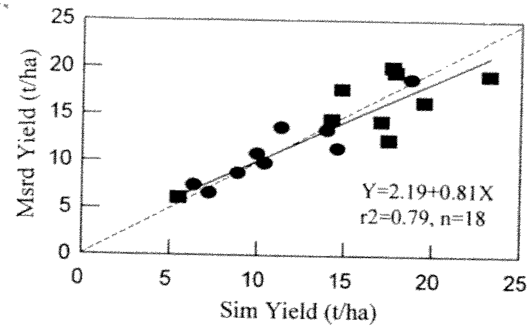

Fig. 2. Measured and ALMANAC-simulated switchgrass forage yields for six locations in Texas with one and two cuttings per season. The solid line is the fitted regression line and the dashed line is the 1:1 fit. Circles: 1993; squares, 1994.

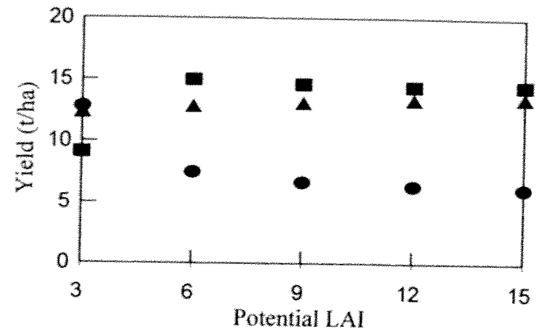

Fig. 4. Sensitivity of simulated annual forage yields to potential leaf area index (LAI) for one cutting system at three locations in Texas (squares, Beeville; triangles, Stephenville; circles, Knox City).

1.4 t ha^{-1}. The regression line of measured on simulated yields was close to the 1:1 line.

Sensitivity Analyses at Three Sites

Increasing the potential productivity by changing crop parameters can cause little or no increase in forage yields if soil water and soil nutrients are limiting. Increased biomass production in the establishment year (1992) can cause greater deficiency of soil water or soil nutrients the next 1 or 2 yr. With these sensitivity analyses, yields at Beeville and Stephenville represented mean yields in the 2 yr after establishment. The yield at Knox City was for the first year after establishment.

A 67% increase in RUE caused greater yield at Beeville and only negligible changes in yield at Stephenville and Knox City (Fig. 3). Such an increase in RUE increased yield 25% at Beeville, increased yield 4% at Stephenville, and decreased yield 7% at Knox City. Knox City, with the lowest rainfall amounts, had greater water and nutrient depletion the first year with increased potential forage production.

Increasing the potential LAI from 3 to 15 had variable effects on yields depending on the rainfall for the sites (Fig. 4). Beeville had a 64% increase as LAI increased from 3 to 6, with only negligible change in yield as LAI increased to 15. Stephenville yield increased gradually, with a 9% change in yield as the LAI increased from 3 to 15. Knox City yield decreased 42% as LAI increased from 3 to 6, with an 18% decrease in yield as LAI increased further to 15. This showed that switchgrass cultivars with lower LAI may, through reduced water use, be more productive than Alamo at low rainfall sites.

Increasing the heat units to maturity increased yield at Stephenville and Knox City, while Beeville had an optimum at 2300 heat units (Fig. 5). Beeville yield increased 55% as heat units increase from 1900 to 2300. Yield at this location decreased 15% as heat units increased from 2300 to 2900. At Stephenville, yield increased 26% as heat units reached 2500. Yield decreased slightly above 2500 heat units. At Knox City, yield increased 32% as heat units increased from 2100 to 2900. When heat units decreased from 2100 to 1900, yield decreased 75%.

The increases in potential for stored soil water as soil depth changed, increased yield at Stephenville and Knox City, while Beeville showed an optimum at 1.2 m (Fig. 6). As soil depth changed from 0.6 to 2.2 m, potential stored soil water increased from 76 to 282 mm at Stephenville and Knox City, and from 67 to 233 mm at Beeville. Correspondingly, yields increased 47% at Stephenville and 79% at Knox City. At Beeville, yield increased 34% as soil depth increased from 0.6 to 1.2 m. This was due to the increase in soil water storage, which reduced the number of simulated days of drought in 1993 from 50 to 17. Yield dropped drastically at Beeville with greater soil depths. This was due to increased depletion of soil N with the increase in soil water storage capacity, causing 42 to 52 more days of simulated N stress for soil depths greater than 1.2 m.

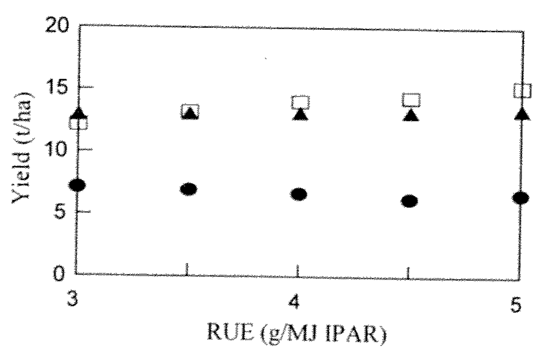

Fig. 3. Sensitivity of simulated annual forage yields to radiation-use efficiency (RUE) (g dry matter MJ^{-1} of intercepted photosynthetically active radiation) for one cutting system at three locations in Texas (squares, Beeville; triangles, Stephenville; circles, Knox City).

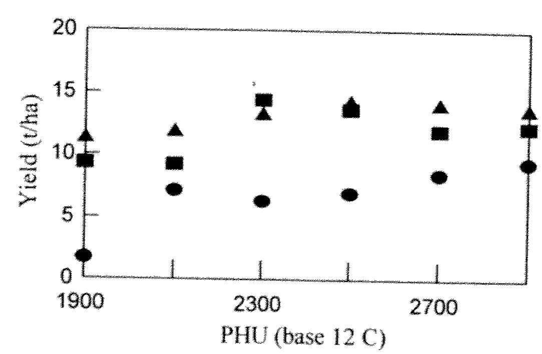

Fig. 5. Sensitivity of simulated annual forage yields to seasonal heat units to maturity (PHU) for one cutting system at three locations in Texas (squares, Beeville; triangles, Stephenville; circles, Knox City).

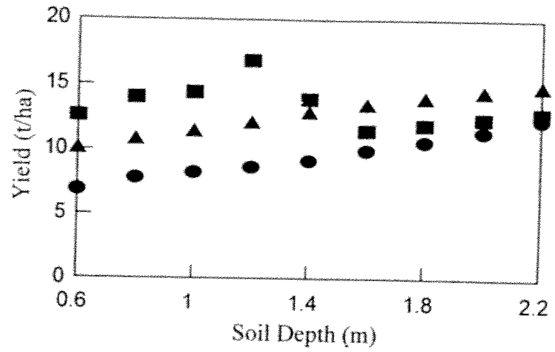

Fig. 6. Sensitivity of simulated annual forage yields to soil depth for one cutting system at three locations in Texas (squares, Beeville; triangles, Stephenville; circles, Knox City).

DISCUSSION

Sensitivity analyses pointed out how insensitive forage yields can be to some plant parameters when the major limitations to yield are environmental. The relatively level responses over much of the tested ranges of RUE, potential LAI, and duration of growth suggest that these factors can be unimportant for cultivar optimization in some environments. The most drastic reduction in LAI caused yield at the lowest rainfall site to increase, suggesting that the optimum cultivar for this site may have reduced potential LAI.

The analysis with different soil depths for the three sites showed the importance of accurate soil profile description for production sites with this deep-rooted grass. The actual potential rooting depth and water extraction of this species should be better defined at depths greater than 2 m. If switchgrass can extract water below 2 m, soils may need to be characterized deeper.

The parameters for switchgrass, a C_4 species, are closer to those of maize than for the C_3 grasses crested wheatgrass [*Agropyron cristatum* (L.) Gaertner], western wheatgrass [*Pascopyrum smithii* (Rydb.) Gould], or meadow bromegrass (*Bromus biebersteinii* Roemer & Schultes) (Kiniry et al., 1995). Maize has a higher base temperature than these C_3 grasses, 8°C instead of 6°C while switchgrass base is 12°C. Maize LAI reaches 15% of potential at 5% of the seasonal heat unit sum, while the other three species reach only 1% by that time. Thus, switchgrass is similar to maize, with 20% of potential LAI by 10% of the heat units. The switchgrass potential LAI of 12.0 is closest to the maize value of 6.5, with the wheatgrass species having 5.0 and meadow bromegrass having 3.0. Our input RUE of switchgrass as discussed above is greater than what we use for maize, with 3.9 g MJ^{-1} of intercepted photosynthetically active radiation for maize and 4.7 for switchgrass. The other three species are simulated with 3.5 g MJ^{-1}.

The ALMANAC model quantified much of the yield response to drought and limited N at sites with measured yields of six to 20 t ha^{-1} yr^{-1}. The model shows promise as a forage management tool in a wide range of environments.

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