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Switchgrass simulation by the ALMANAC model at diverse sites in the southern US

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Abstract

Simulation models for plant species important for biofuel such as switchgrass (*Panicum virgatum* L.) can be used to make management decisions related to biomass productivity and related to environmental impacts such as soil erosion and changes in surface and groundwater quality. The present study was designed to evaluate the accuracy of simulation of switchgrass biomass production by the ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria) model at sites in Texas, Arkansas, and Louisiana. We used multi-year field data for Alamo switchgrass yields at each of five sites to evaluate ALMANAC. The model realistically simulated mean switchgrass yields at each of the locations and the total variability of all the data pooled, but did not perform as well in accounting for the year-to-year variability within some locations. Sensitivity analysis showed that changes in runoff curve number (CN) and changes in maximum stomatal conductance (GSI) had variable impacts on simulated values among the sites. A 15% change in CN changed mean annual biomass yield from 0% to 16% depending on location. Changing GSI from 4 to 8 mm s^{-1} changed mean annual biomass from 1% to 31% depending on location. ALMANAC shows promise as a tool to realistically simulate mean biomass yields and variability around the mean for multi-year runs of switchgrass at

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these diverse sites. Further research, with more extensive measurements of soil parameters including soil nutrients is needed to determine why the model reasonably simulated individual years' yields at Stephenville, TX and Dallas, TX, but had difficulty at other sites.
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Keywords: Leaf area index; Radiation-use efficiency; Switchgrass; Modeling

1. Introduction

Switchgrass (*Panicum virgatum* L.) is an important herbaceous species for modern agriculture for a number of reasons. It can be planted for biofuel as an alternative crop on productive agricultural sites [1]. It has been recommended for stabilizing stream banks, preventing soil erosion and taking up excess nutrients from adjacent fields under cultivation with row crops [2]. Its capacity to take up large amounts of nutrients [3] also makes it valuable for areas below animal and municipal waste sites for reducing the movement of nitrogen and phosphorus into streams and rivers [4].

The capacity of process-based models to simulate key processes related to such uses of switchgrass becomes important as these models are used to assess environmental impacts due to soil erosion and water quality degradation downstream. Likewise, realistic simulation of biomass production on different soils and in different climatic zones will allow prediction of the capacity of geographical regions to supply switchgrass as a feedstock for production of fuels, chemicals, and power. Simulation in such environments requires a robust model for plant growth, the soil water balance, water runoff, soil erosion, and climatic impacts.

The ALMANAC (Agricultural Land Management Alternative with Numerical Assessment Criteria) model [5] has been demonstrated as a valuable tool to simulate cropping systems [6–8], rangelands [9], and monoculture plots of Alamo switchgrass [10]. Future applications of this model with switchgrass will benefit from its accurate simulation of grass biomass in diverse environments. While Kiniry et al. [10] validated the model with two years of switchgrass data at six sites in Texas, a more extensive study with more years and additional locations will better test how accurately the model can simulate biomass differences found across a wider range of soils, temperature zones, and rainfall zones.

The runoff curve number (CN) [11] is used to determine potential runoff of water from the soil surface. It is determined by the land use and treatment classes and the hydrologic soil group. The CN has been shown to be critical for crop yield simulation accuracy in water-limited sites [12]. Likewise, the maximum stomatal conductance for water vapor (GSI) was recently incorporated from the EPIC (Erosion Productivity Impact Calculator) model [13] and is important as a measurable plant parameter affecting plant water use.

The first objective of this paper was to test ALMANAC's simulation of biomass production of Alamo switchgrass with three years of data at two sites in Texas, one site in Arkansas and one site in Louisiana; and seven years of data at Stephenville, TX. The second objective was to describe the sensitivity of the model's simulation of biomass and water use with changing values of CN and GSI with multiple years of weather at the same five sites.

2. Materials and methods

2.1. Model description

To be useful in applications for a wide range of soils and with diverse climatic conditions, grassland models need sufficient detail to quantify differences among plant species, soils, and climate conditions without making the input requirements prohibitively large. Such models must complement the available soils data and the available validation data sets for grasses.

The ALMANAC model is a process-oriented simulator of plant communities with several competing species. It simulates growth of one plant species or several competing species in a general way, but with sufficient detail so that it can be easily transferred among regions without recalibration. ALMANAC includes subroutines and functions from the EPIC model [13] and has additional details for plant growth. Required climate and soil inputs are readily available. Parameters for many common grass and crop species are available with the model. ALMANAC is a robust model not requiring local calibration of plant parameters or hydrology components. Parameters descriptive of the growth of several grass species were derived from a field experiment at Temple, TX [14]. Likewise, parameters for additional plant species can often be easily derived from the literature.

The model simulates water balance, nutrient balance, and interception of solar radiation by competing plant species. It simulates daily plant growth through leaf area index (LAI), light interception, and a constant for converting intercepted light into biomass (radiation-use efficiency). Stresses such as nutrient deficiency, drought, or temperature extremes reduce LAI and biomass growth.

The ALMANAC model used herein is a recent version that has incorporated additional methods of calculating potential evapotranspiration including Penman-Monteith [15], Penman [16], Priestly Taylor [17], Hargreaves [18], and Baier-Robertson [19]. This version has improved sensitivity to stomatal conductance, and has the water table simulation components described for the EPIC 9200 version used for saltcedar (*Tamarix*) simulation [20].

In order to improve switchgrass simulation by ALMANAC, field data from switchgrass plots at Temple, TX were used to derive values for plant parameters. LAI development requires an input potential LAI for a species at high plant density, and representative values at two lower plant densities. Accurate prediction of light interception depends on realistic values of LAI for a given plant density. Values of LAI for switchgrass were obtained from measurements on plots in the field study at Temple, TX [14].

Field-derived values for the critical species-specific parameters were described previously [9,10]. The model simulates light interception by the leaf canopy with Beer's law [21] and the LAI. The greater the value of the extinction coefficient k, the more light will be intercepted at a given LAI. The fraction of incoming solar radiation intercepted by the leaf canopy is

$$\text{fraction} = 1.0 - \exp(-k \times \text{LAI}). \qquad (1)$$

The value of k was determined for Alamo switchgrass in the Temple study.

Simulation of light interception also requires accurate description of leaf area production and decline. The model simulates LAI development through the season with an S-curve through the origin. This curve describes how LAI can increase, under non-stress conditions, as a function of heat units.

Similarly, biomass growth is simulated with a radiation use efficiency approach [14]. Soil water and nutrients commonly limit grass growth in Texas. ALMANAC's water balance consists of transpiration calculations predicting potential plant water use if sufficient water is present in the plant's 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 root zone. Nutrient values for switchgrass were derived in the Temple study with adequate fertilizer on a deep Houston Black clay. Grass growth was reduced below potential at the sites as nutrients became limiting.

The maximum potential rooting depth defines the potential depth of a plant species in the absence of a root-restricting soil layer. Soil cores from the plots in the Temple study in 1994 indicated that switchgrass roots extended to at least 2 m. A value of 2.2 m was used for switchgrass, which is greater than the depths of all the soils in this study as described below.

Base temperature in ALMANAC is the same for all growth stages of a plant species. Base temperature constrains the initiation of leaf area expansion and thus dry matter accumulation early in the growing season. 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 the growing season. Base temperature for the warm season grasses is assumed to be 12 °C and optimum temperature is 25 °C [22]. The input heat unit sum to reach maturity each year is 2300 for all the sites.

2.2. Demonstration data sets

Model runs were made with climate and soil data from three Texas sites, one site in Louisiana and one in Arkansas (Tables 1 and 2). The data represent a greater than two-fold difference in mean annual rainfall for the measurement years. Data were from plots established in 1997 for the Clinton, LA; Hope, AR; Dallas TX; and College Station, TX sites. Data from Stephenville, TX included measured yields from plots established in 1997 as well as plots established in 1992. Simulations used Natural Resource Conservation Service runoff curve numbers based on each soil's hydrologic group and hydrologic condition [11]. Runoff curve numbers were 71 for College Station, 81 for Hope and Clinton, and 88 for Stephenville and Dallas. Plot biomass was cut at 0.10 m and this value was used for the model simulation harvests in mid October each year. In the model, the remaining above-ground biomass was burned in the field in January of each year and 120 kg N ha^{-1} and 50 kg P ha^{-1} applied on March 5 each year.

For the data of all the sites pooled and for the data of each site, we compared the means and standard deviations (SD) of simulated and measured yields. We also regressed measured annual yields on simulated yields to investigate how much of the year-to-year variability was accounted for by the model simulations for data of all the sites pooled and the data of each site.

3. Results and discussion

3.1. Demonstration data sets

The ALMANAC model realistically simulated the switchgrass yields for all the data pooled. The model's mean simulated yields were similar to the

Table 1
Soil characteristics for five switchgrass sites simulated by ALMANAC

Location	Soil type	Soil depth (m)	PAW[a] (mm)
Dallas, TX	Houston Black clay (Udic Haplusterts)	1.6	182
Stephenville, TX	Windthorst fine sandy loam (Udic Paleustalf)	1.5	190
College Station, TX	Weswood silt loam (Fluventic Ustochrepts)	1.5	215
Hope, AR	Bowie fine sandy loam (Plinthic Paleudults)	2.1	281
Clinton, LA	Dexter silt loam (Ultic Hapludalfs)	1.7	280

[a] Plant available water; difference between field capacity and wilting point in the profile.

Table 2
Rainfall sums for the five switchgrass data sets

Location	Lat. (deg)	Elevation (m)	Annual rainfall (mm)	Runoff CN
Dallas, TX	32.75	134	346	88
Stephenville, TX	31.13	399	404	88
College Station, TX	30.67	94	456	71
Hope, AR	33.67	118	517	81
Clinton, LA	30.88	21	795	81

Rainfall values are the averages for the simulated years. Runoff CN is the runoff curve number.

mean measured yields for all the locations, with 15.34 ± 3.57 (mean ± SD) for simulated yields and 15.54 ± 3.45 for measured. The model accounted for 47% of the variability in measured yields and the fitted regression line was close to the 1:1 line throughout the range of measured data (Fig. 1).

The model realistically simulated the switchgrass yields at each of the five locations. The model's mean simulated yields were similar to the mean measured yields for all the locations, varying by less than 2% within any location (Table 3). Likewise, the (SD) values for the simulated yields were similar to the SD values for measured yields. Thus the model shows promise for predicting not only long-term means in these regions, but also reasonable variability around the means. The latter is important for long-term simulations used for environmental impact assessments.

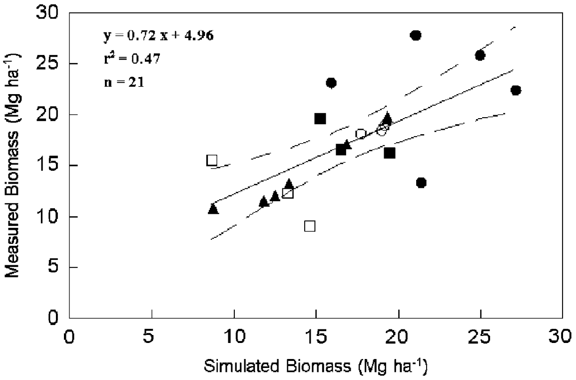

Fig. 1. Measured and simulated biomass yields for switchgrass at five locations for three to seven years at each location. Solid line is the regression line and dashed lines are the upper and lower 95% confidence limits. Symbols represent College Station, TX (●), Dallas, TX (○), Hope, AR (■), Clinton, LA (□), and Stephenville, TX (▲).

The model did not perform as well in accounting for the year-to-year variability in yields for most of the locations. In assessing how much of the variability in measured yields could be accounted for by simulated yields, only two of the five sites had positive regression slopes and r^2 values greater than 0.7 (Table 3). The Stephenville location, with seven years of data, showed the greatest similarity between measured and simulated yields over the years. The slope and r^2 were both >0.9. For the Dallas site, with only three years of data and a smaller range of measured yields, the model still had an r^2 >0.7. The closeness of the regression line to the 1:1 line within the range of measured data for both of these sites offers hope that the model can predict individual years reasonably in the future.

The lack of fit for the other three sites, as indicated by either negative regression slopes or low r^2 values, was investigated further by checking how annual rainfall related to measured yields. We wanted to see if year-to-year variability in measured yields may have been due to something besides differences in rainfall, and thus possibly something not simulated in the model.

The results of this analysis showed that Stephenville, with its close fit for measured and simulated yields, also showed one of the best fits for measured yield as a function of annual rainfall (Table 4). The r^2 was 0.36 and the slope was a positive 0.013. Results for the other locations were not as clear-cut. Dallas showed a high r^2 value for the rainfall regression, but the slope was negative. Clinton had an r^2 of 0.32 and the slope was 0.01.

Table 3
Measured and simulated switchgrass yields (Mg ha^{-1} y^{-1})

Location	*n*	Simulated Mean ± SD	Measured Mean ± SD	Slope	r^2
Clinton, LA	3	12.2 ± 2.6	12.3 ± 2.6	−0.98	0.90
Hope, AR	3	17.1 ± 1.8	17.4 ± 1.5	−0.68	0.62
College Station, TX	5	22.1 ± 3.8	22.5 ± 5.0	0.09	0.00
Stephenville, TX	7	14.6 ± 3.7	14.8 ± 3.6	0.94	0.96
Dallas, TX	3	18.6 ± 0.6	18.5 ± 0.4	0.49	0.77

Only the last two sites had positive, significant slopes. Slope and r^2 are for measured yield as a function of simulated yield.

Table 4
Value of r^2 are for switchgrass measured yield as a function of annual rainfall (mm)

Location	n	r^2	Slope
Clinton, LA	3	0.32	0.01
Hope, AR	3	0.00	8.41
College Station, TX	5	0.02	0.00
Stephenville, TX	7	0.36	0.0134
Dallas, TX	3	0.70	−0.0002

Both Hope and College Station had r^2 values near zero.

3.2. *Responses to runoff curve number and maximum stomatal conductance*

Changes in runoff CN showed variable impacts on simulated values among the sites. Input values for CN were varied in an attempt to find how important it is to have accurate values for it when simulating switchgrass. In the present study, using ten years of weather data for the sites, varying CN from 65 to 90 resulted in a 16% decrease in mean yield at College Station, a 0% change at Dallas, a 2% increase at Hope, a 2% decrease at Clinton, and a 13% decrease at Stephenville (Fig. 2). Results with total evapotranspiration (ET) and plant transpiration (EP) with these changes (data not shown) showed a 9% and 11% decrease at College Station, 4% and 1% decreases at Dallas, no change and 2% increase at Clinton, and 13% and 16% decreases at Stephenville.

Greater values for maximum stomatal conductance (GSI) caused more moisture loss and thus greater impact of drought on yields. In all the simulations above, we assumed a value of 0.005 for GSI. Similar to CN, changes in GSI showed variable response among the locations (Fig. 3). College Station showed the greatest decreases in simulated yield with increasing GSI. Yield there decreased 31% as GSI increased from 0.004 to 0.008. Yield changes for the other sites were a 21% decrease for Dallas, a 7% increase for Hope, a 1% decrease for Clinton, and a 13% decrease for Stephenville. Values for ET and EP with this change in GSI resulted in 9% and 12% increases at College Station, 17% and 30% increases at Dallas, 25% and 44% increases at Hope, 18% and 35% increases at Clinton, and 6% and 9% increases at Stephenville (data not shown).

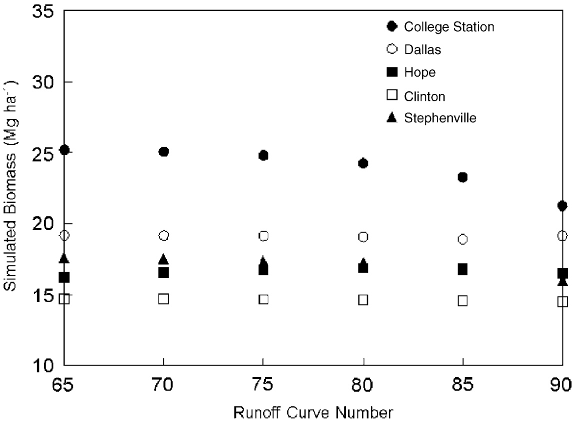

Fig. 2. Responses of simulated switchgrass yields to runoff curve number for five sites, with ten years of simulations.

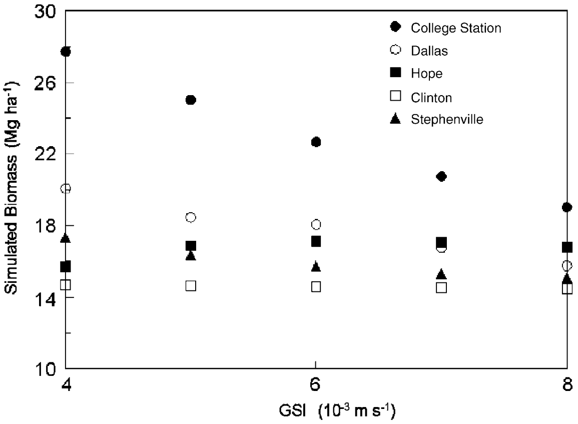

Fig. 3. Responses of simulated switchgrass yields to maximum stomatal conductance (GSI) for five sites, with ten years of simulations.

4. Conclusions

The ALMANAC model shows promise as a tool to realistically simulate mean biomass yields and variability around the mean for multiyear runs of switchgrass at these diverse sites in Texas, Arkansas, and Louisiana. The model can also reasonably simulate individual years' yields at sites like

Stephenville and Dallas, but may have difficulty at other sites. Future investigation into yield limiting factors at these sites and similar sites, with more than three years of data, may gain better insight into how such a model can better simulate yields for individual years.

Accurate values for CN and GSI are critical for realistic switchgrass simulation, especially in areas where soil moisture is limiting. Varying CN and GSI can have different effects on biomass yield, ET, and EP, depending on the rainfall and soil of a site.

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