Simulating Switchgrass Growth and Development under Potential and Water-Limiting Conditions

Patricio Grassini,* Eric Hunt, Robert B. Mitchell, and Albert Weiss

ABSTRACT
Anticipating a demand for switchgrass (Panicum virgatum L.) as a source for biofuel production, a crop simulation model of this crop can be a component of a biofuel decision support system. The objective of this effort was to develop and test a model for switchgrass, based on robust empirical relationships between plant behavior and the environment. The model simulates date of annual growth initiation (AGI), anthesis, aboveground biomass, leaf area index (LAI), and water balance components with a daily time step for crops grown under potential and water-limiting conditions. Daily weather data (solar radiation, maximum and minimum temperature, and rainfall), soil available water-holding capacity (AWHC), and the fraction of AWHC at the date of AGI (FAWHC-AGI) are required inputs. Two cultivar-specific parameters, the maximum rate of development at the optimum temperature ($R_{max}$) and maximum LAI (MAXLAI), synthesize differences in development and growth between cultivars. Tested against 10 independent data sets, the model generated good predictions of date of anthesis (root mean square error (RMSE) = 3 d) and aboveground biomass (RMSE = 1.5 Mg ha$^{-1}$).

As the price of petroleum increases, interest in alternative fuels, especially renewable biofuels, increases (Samson et al., 2005; Karp and Shield, 2008). Switchgrass, a perennial warm-season C$_4$ grass, is an important forage crop that also shows great potential as a renewable biofuel crop (Sanderson et al., 1996; Samson et al., 2005; Rosenberg, 2007; Mitchell et al., 2008). It is planted in early spring and AGI in subsequent years begins in the early spring (Vogel, 2004; Parrish and Fike, 2005). Under near-potential conditions, switchgrass produces about half of its biomass potential by the end of the establishment year and can be near full production by the end of the second growing season (Mitchell, personal communication, 2008). Harvesting switchgrass for biomass energy will likely occur near anthesis (Vogel et al., 2002) or after a killing frost (Adler et al., 2006). When switchgrass is harvested around anthesis, the regrowth after harvest provides autumn and winter wildlife habitat and livestock forage (Vogel, 2004; Parrish and Fike, 2005). While maximum aboveground dry matter production varies between 12 and 40 Mg ha$^{-1}$ under near-optimal conditions, depending on the location, cultivar, and season, on-farm switchgrass productivity is generally well below this range, as a result of abiotic and biotic stresses (Parrish and Fike, 2005; McLaughlin et al., 2006; Schmer et al., 2008).

Just as research encompasses a wide range of objectives, from applied (developmental) to basic, so does crop simulation modeling. Models analogous to applied or developmental research could be used to simulate switchgrass growth and development and to provide biomass estimates for biofuel production to decision makers ranging from growers to policymakers. Thus, the focus is to understand and synthesize known relationships in a well-defined structure with a minimum number of inputs (e.g., Pasioura, 1996).

No simulation model has been developed specifically for switchgrass. Several studies (Kiniry et al., 1996, 2005, 2008a, 2008b; Brown et al., 2000) have adapted switchgrass developmental, morphological, and physiological characteristics to the multi-species simulation models EPIC (Williams et al., 1989) and ALMANAC (Kiniry et al., 1992). Widespread use of these detailed models is limited by the large number of required soil, weather, and cultivar data inputs. Also, EPIC and ALMANAC do not simulate, at least in a direct way, the timing of switchgrass regrowth and use the thermal time approach to compute crop development, which has been challenged by Yin et al. (1995). No evaluation of models predictions of crop development has been reported for switchgrass.

The objective of this paper was to develop and evaluate a switchgrass model which simulates development and growth for use in biofuel production. The model was developed for potential and water-limiting conditions and based on conservative relationships to describe crop responses to the environment.

Abbreviations: AGI, annual growth initiation; AWHC, soil available water-holding capacity; ds, crop developmental stage; FAWHC, fraction of soil available water-holding capacity; LAI, leaf area index; MAXLAI, cultivar-specific maximum leaf area index; PARENT, intercepted photosynthetically active radiation; $r$, daily developmental rate; $R_{max}$, cultivar-specific maximum developmental rate at the optimum temperature; RMSE, root mean square error; RUE, radiation use efficiency for aboveground biomass.
MODEL DEVELOPMENT

Overview

The model simulates date of AGI, anthesis, aboveground biomass, LAI, and water balance components for switchgrass grown under potential and water-limiting conditions (van Itersum and Rabbinge, 1997). Crop growth was assumed to be driven by solar radiation and temperature under potential conditions. Under water-limiting conditions, crop growth was driven by solar radiation, temperature, and the degree of water stress. For these two growing conditions, it was assumed that nutrients were nonlimiting and biotic stresses (i.e., pathogens, weeds, and arthropods) were effectively controlled. The model runs on a daily time step and contains five interacting modules: crop development, LAI expansion, crop growth, soil water balance, and the effect of soil water deficit and temperature on LAI expansion and radiation use efficiency (RUE). The interacting modules were largely based on previous research on crop simulation for other species (e.g., Amir and Sinclair, 1991; Wang and Engel, 1998). The model requires three sets of input data related to: (i) weather (daily maximum and minimum temperatures [°C], solar radiation [SR, MJ m⁻² d⁻¹], and rainfall [mm]); (ii) soil (AWHC [the difference in the volumetric water content between field capacity and the wilting point, v/v] and the soil available water at the date of AGI, expressed as a fraction of AWHC [FAWHC-AGI]); and (iii) cultivar-specific parameters (maximum developmental rate at the optimum temperature [R_max, d⁻¹] and maximum leaf area index [MAX-LAI]). This model applies to fully-established switchgrass (i.e., stands greater than 2-yr old that have achieved maximum root depth at an optimum plant density).

Crop Development

The model simulates switchgrass development based on temperature-driven phases; from 1 January to the date of AGI and from the date of AGI to anthesis. The period from anthesis to seed maturity is not simulated by the model. Year-to-year variation in the date of AGI is usually not reported in the literature on switchgrass. Therefore, AGI was assumed to occur when the 15-d running average of mean daily air temperature was ≥13°C, a value assumed to be the base temperature for switchgrass development based on Balasko and Smith (1971), Van Esbroeck et al. (1997), Volenec and Nelson (2003), and Moore et al. (2004). The second phase begins at the date of AGI and ends at anthesis (50% of the tillers with exposed anthers). The duration of this phase was assumed to be temperature driven, where 0 and 1 represent AGI and anthesis, respectively. The daily developmental rate (r) was calculated as:

\[ r = R_{max}f(T) \]  

where \( R_{max} \) was the cultivar-specific maximum developmental rate at the optimum temperature (d⁻¹) and \( f(T) \) was the temperature response function (0–1), based on the \( \beta \) function (Wang and Engel, 1998). This temperature response function was given as:

\[ f(T) = [2 \times (T - T_{min})^{2\alpha} / (T_{opt} - T_{min})^{2\alpha}] \times \left( 1 - (T - T_{min})^{2\alpha} / (T_{opt} - T_{min})^{2\alpha} \right) \text{if } T_{min} < T < T_{max} \]  

\[ f(T) = 0 \text{ if } T \geq T_{max} \text{ or } T \leq T_{min} \]

where \( T \) was the mean daily temperature (°C), \( T_{max} (42°C) \) was the temperature above which no development occurs, \( T_{min} (13°C) \) was the temperature below which no development occurs, and \( \alpha \) was the \( \beta \) function shape factor. These cardinal temperatures were based on data given in Balasko and Smith (1971), Van Esbroeck et al. (1997), Van Esbroeck et al. (1997, 2003), and Moore et al. (2004). Values of \( R_{max} \) (Table 1) were derived from reported development data for switchgrass stands grown under non-water-limiting conditions in Iowa and Texas (cultivar Alamo), Iowa, Missouri, and South Dakota (cultivars Blackwell, Pathfinder, and Sunburst), and Iowa, Missouri, Nebraska, and Texas (cultivar Cave-in-Rock). The data were collected during the 1992–1993 (Nebraska), 1995 (Iowa and Texas), and 2005 (Iowa, Missouri, and South Dakota) seasons and were not used for validation of the model. The simulated developmental stages (ds) were calculated from the accumulated daily development rates (i.e., \( \Sigma \tau \)) from the date of AGI.

Leaf Area Index Expansion

It was assumed under optimal conditions that LAI, as a function of ds, followed a Gompertz curve until anthesis (Fig. 1). The relationship was given by:

\[ y = y_{max} \cdot e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e^{-[e{-}]}]}]}}\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\}\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\}\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\}\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\}\]\}\]\}\}\]\}\}\]\]\}\}\]\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\]\]\]\]\]\]\]\]\]\}\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\}\]\]\]\]\]\]\]\]\]\]\]\]\]\]\]\}\]\]\]\}\]\]\]\]\]\]\]\]\]\]\}\]\}\]\}\}\}\}\}\}\]\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}\}
To deal with the large variation of MAXLAI among cultivars (range: 7.5–17.7; Mitchell et al., 1998, Kiniry et al., 1999, Heaton et al., 2008), Eq. [3] has two components. The part of the function between the braces has values ranging from 0 to 1 in the interval between ds = 0, that is, date of AGI, and 1, that is, date of anthesis (Fig. 1). The function is then scaled by MAXLAI. Coefficients of the function were developed from 2 yr of data collected at Temple, TX, under near-potential growth conditions by Kiniry et al. (1999), and fitted using CurveExpert 1.3 (Hyams, 2005). The coefficients of Eq. [3] were determined based on the assumption that LAI = 0 at the date of AGI (i.e., ds = 0). An important assumption was that leaf area growth was not source limited. Preanthesis leaf senescence was not accounted by this algorithm.

**Crop Growth**

Crop growth was assumed to start when plant development begins, that is, ds > 0, and to cease on anthesis, that is, ds = 1 (Parrish and Fike, 2005, Rosenberg, 2007). The initial biomass was set equal to zero. The daily increment in aboveground biomass was driven by the intercepted photosynthetically active radiation (PARINT, MJ m⁻² d⁻¹) and its conversion into biomass using RUE (g aboveground dry matter intercepted MJ⁻¹ PAR). The PARINT was calculated as follows:

\[
\text{PARINT} = SR \times 0.45 \times [1 - \exp(-k \times \text{LAI})]
\]  

where 0.45 represents the fraction of photosynthetically active radiation to the measured total incoming solar radiation (SR, MJ m⁻² d⁻¹) at the top of the canopy (Kiniry et al., 1999), k, the extinction coefficient, was equal to 0.65 based on measured data reported by Kiniry et al. (1996) and Madakadze et al. (1998). The PARINT was converted into aboveground biomass using a RUE of 4.7, the latter obtained from crops grown under near-potential conditions (Kiniry et al., 1999). The model only simulates aboveground biomass accumulation, thus the value of RUE does not include biomass partitioning to the roots.

**Soil Water Balance**

The soil water balance was computed using an approach similar to that reported by Sinclair (1986) and Sinclair et al. (2007) for soybean (Glycine max L.), Amir and Sinclair (1991) for wheat (Triticum aestivum L.), Muchow and Sinclair (1991) for maize (Zea mays L.), and Hammer and Muchow (1991) for sorghum (Sorghum bicolorum L. Moench). Maximum root depth (m) was set at 2 m based on Kiniry et al. (1999) and divided into an upper (SL1, 0–0.15 m) and lower layer (SL2, 0.15–2.0 m). The water balance components modeled were: rainfall interception by the crop canopy, surface runoff, soil evaporation, transpiration, and moisture storage in the soil.

It was assumed that part of the rainfall was intercepted by the canopy foliage and evaporated without entering the soil. Canopy rainfall interception (mm d⁻¹) was simulated following the Campbell and Diaz (1988) approach with an equation similar to Eq. [4] with a maximum value of intercepted rainfall equal to 1 mm.

Surface runoff (RUNOFF, mm d⁻¹) was simulated using the Stewart et al. (1976) approach:

\[
\text{RUNOFF} = (\text{RAIN} - 200s)^2/[(\text{RAIN} + 800s)^2]
\]

where RAIN was daily rainfall (mm) after discounting canopy interception and s was the surface storage condition set in 0.1 m.

Potential and actual soil evaporation (PSE and ASE, respectively, mm d⁻¹) take place only in SL1 and were simulated using a modified version of the two-stage (I and II) model initially proposed by Ritchie (1972), and modified by Amir and Sinclair (1991), as follows:

\[
\text{PSE} = E_T \exp(-K \times \text{LAI})
\]  

\[
\text{ASE}_I = \text{PSE}
\]  

\[
\text{ASE}_II = \text{PSE} \times \left(0.5 - (t - 1)^{0.5}\right)
\]

where \(E_T\) was the daily reference evapotranspiration (mm) calculated by the Priestley and Taylor (1972) equation, \(K\) was the extinction coefficient for total incoming solar radiation (0.48), and \(t\) was time since the start of stage II (days). The first stage of soil evaporation (\(\text{ASE}_I\)) was assumed to proceed until available water in SL1 was equal to 0.5. The second stage of soil evaporation (\(\text{ASE}_II\)) was proportional to the square root of time since Stage II commenced, multiplied by PSE.

Transpiration (TRANS, mm d⁻¹) was calculated as follows:

\[
\text{TRANS} = \Delta B \times (7.44/\text{VPD}^{0.42})^{-1}
\]

where \(\Delta B\) was the daily increment in aboveground biomass (g d⁻¹) and the denominator represents the transpiration efficiency (g aboveground biomass per unit of millimeters transpired water) as a function of the daytime vapor pressure deficit (VPD, kPa). This latter relationship was based on a function developed from maize data by Stöckle et al. (2007). Daytime VPD was assumed to be 0.75 of the difference between saturated vapor pressures calculated from daily maximum and minimum temperatures (Tanner and Sinclair, 1983).

The simulation of the water balance begins at the date of AGI in spring. Water from rainfall or irrigation enters into SL1, after discounting losses through canopy interception and surface runoff. After a heavy rainfall or irrigation, both soil layers were allowed to retain up to an additional 10% of their AWHC. Thus, if the fraction of soil available water-holding capacity (FAWHC) in SL1 > 1.1, the excess water drains into SL2. Likewise, if FAWHC in SL2 > 1.1, the excess water drains below the root zone. In addition to soil evaporation, water can be removed by transpiration. To account for transpirational water loss from both layers, it was assumed that water was removed first from SL1, and that the relative rate of transpirational water loss was defined by Eq. [8b] (see below). Consequently, as the water available for transpiration (i.e., FAWHC) in SL1 decreases, the contribution of water of SL2 to transpiration increases. Root density was assumed not to limit water uptake which is a reasonable assumption for fibrous rooted perennial grasses under normal growth conditions (van Keulen, 1975).
Effect of Soil Water Deficit and Temperature on Leaf Area Index Expansion and Radiation Use Efficiency

Daily LAI expansion and RUE were sensitive to soil water deficit. These sensitivities were taken into account by relationships between water stress factors (WSF<sub>LAI</sub> and WSF<sub>RUE</sub>), constrained between 0 and 1 (where 1 is equivalent to the maximum daily LAI expansion or RUE) and FAWHC. The functions reported by Muchow and Sinclair (1991) for maize, similar to those reported for sorghum by Hammer and Muchow (1991), were used:

$$WSF_{LAI} = \frac{1}{1 + 270 \exp (-32.2 \text{FAWHC}_{AVG})} \quad [8a]$$

$$WSF_{RUE} = \frac{1}{1 + 9 \exp (-15.3 \text{FAWHC}_{AVG})} \quad [8b]$$

where the average FAWHC for the entire root depth ($\text{FAWHC}_{AVG}$) was calculated by $[(0.075 \text{FAWHC-SL1} + 0.925 \text{FAWHC-SL2})/2]$, where 0.075 and 0.925 are the relative thickness of SL1 and SL2 with respect to the total root depth (2 m).

To account for the sensitivity of RUE to low temperature, a temperature stress factor, (TSF<sub>RUE</sub>, 0–1) was used. This relationship was based on a linear-plateau function adapted from data reported for maize by Andrade et al. (1993) and Louarn et al. (2008):

$$TSF_{RUE} = 0 \quad \text{if} \ T \leq 6.4°C \quad [9a]$$

$$TSF_{RUE} = -0.42 + 0.067T \quad \text{if} \ 6.4°C < T < 21°C \quad [9b]$$

$$TSF_{RUE} = 1 \quad \text{if} \ T \geq 21°C \quad [9c]$$

Many factors can simultaneously limit crop growth (Sinclair and Park, 1993). Thus, a multiplicative stress approach (Eq. [8b] times Eq. [9]) was used to estimate the integrated water and low temperature impact on RUE. Finally, daily actual simulated LAI expansion and RUE were calculated as the product between their maximum daily values and their corresponding stress factors.

MODEL EVALUATION

Date of Annual Growth Initiation

Since this model was based on a mature crop, it was important to determine when AGI occurred each season. Long-term (1984–2003) simulations of the date of AGI were performed at two locations: Mead, NE, and Temple, TX. Mean simulated date of AGI differed markedly between these locations: 1 May (range: 7 April–20 May) at Mead, NE, and 4 March (range: 25 January–5 April) at Temple, TX (Fig. 2). The range of observed dates of AGI reported near Mead, NE [McCarty, 1986 (1958–1973 seasons); Mitchell, unpublished data, 2008 (2004–2007)] and Temple, TX [Sanderson and Wolf, 1995 (1989–1993), Sanderson et al., 1997 (1994–1995), Van Esbroeck et al., 1997 (1994–1995)] showed good agreement with the simulated patterns (Fig. 2).

For model runs, published data on values of field capacity and wilting point reported for the dominant soil series at each site were used to estimate AWHC. The FAWHC-AGI was based on measured data (provided by the High-Plains Regional Climate Center) or estimated from the rainfall pattern from 1 October of the previous year to the simulated date of AGI. Values of R<sub>max</sub> for each cultivar were given in Table 1. The MAXLAI was set equal to values reported for independent measurements (17.7 and 7.5 for cultivars Alamo and Cave-in-Rock, respectively, from Kiniry et al., 1999 and Heaton et al., 2008).

Simulated date of anthesis and aboveground biomass were compared against observed values using the RMSE calculated as

$$RMSE = \left\{ \frac{\sum (S - O)^2}{n} \right\}^{0.5} \quad [10]$$

Fig. 2. Twenty-year cumulative probability of simulated date for annual growth initiation (AGI) at Mead, NE, and Temple, TX (thick dashed and solid lines, respectively). Horizontal lines indicate the range of observed date of AGI near Mead, NE (thin dashed line, n = 19), and Temple, TX (thin solid line, n = 9), from data reported in the literature.

Date of Anthesis and Aboveground Biomass

Data for model evaluation came from published (Kiniry et al., 1999; Vogel et al., 2002) and unpublished (Mitchell, unpublished data, 2008) sources. Model predictions of date of anthesis and aboveground biomass were compared against independent sites × year data sets (n = 6 and 10, respectively). Established switchgrass stands, >3-yr old, were grown at Ames, IA (cultivar Cave-in-Rock, 1994 and 1995 seasons), Mead, NE (cultivar Cave-in-Rock, 1994, 1995, 2004, 2005, 2006, and 2007), and Temple, TX (cultivar Alamo, 1996 and 1997). Plot size ranged from 75 to 375 m<sup>2</sup>. No irrigation water was applied, so switchgrass relied on the stored soil water and seasonal rainfall. Crops were well supplied with nutrients and were kept free from pests, diseases, and weeds. Daily weather data were recorded on-site. Switchgrass development was recorded every 7 d during the 1994 and 1995 growing seasons at Mead, NE and Ames, IA (Vogel et al., 2002). At Temple, TX, date of anthesis was derived from seasonal LAI and aboveground biomass dynamics (Kiniry et al., 1999). Aboveground biomass was mechanically (Mead, NE and Ames, IA) or manually (Temple, TX) harvested from the center of each plot (harvested area: 0.07–6 m<sup>2</sup>) around the date of anthesis. Samples were oven-dried to constant weight at 70°C and aboveground biomass reported on an oven dry matter basis.

For model runs, published data on values of field capacity and wilting point reported for the dominant soil series at each site were used to estimate AWHC. The FAWHC-AGI was based on measured data (provided by the High-Plains Regional Climate Center) or estimated from the rainfall pattern from 1 October of the previous year to the simulated date of AGI. Values of R<sub>max</sub> for each cultivar were given in Table 1. The MAXLAI was set equal to values reported for independent measurements (17.7 and 7.5 for cultivars Alamo and Cave-in-Rock, respectively, from Kiniry et al., 1999 and Heaton et al., 2008).

Simulated date of anthesis and aboveground biomass were compared against observed values using the RMSE calculated as

$$RMSE = \left\{ \frac{\sum (S - O)^2}{n} \right\}^{0.5} \quad [10]$$

Fig. 2. Twenty-year cumulative probability of simulated date for annual growth initiation (AGI) at Mead, NE, and Temple, TX (thick dashed and solid lines, respectively). Horizontal lines indicate the range of observed date of AGI near Mead, NE (thin dashed line, n = 19), and Temple, TX (thin solid line, n = 9), from data reported in the literature.
where $S = $ simulated data, $O = $ observed data, and $n = $ number of pairs of simulated and observed data.

The independent dataset used for model validations covered a wide range of radiation, temperature, and rainfall conditions (Table 2). Model predictions of dates of anthesis and aboveground biomass for the independent data set were satisfactory over the range of observed values: simulated dates of anthesis and aboveground biomass were within ± 5 d and ± 15% of measured values, respectively, in all but two cases (Fig. 3). The RMSE was 3 d and 1.5 Mg ha$^{-1}$ for date of anthesis and aboveground biomass, respectively. When the largest observed aboveground biomass value (39.3 Mg ha$^{-1}$) was excluded from the analysis, the RMSE did not change and the difference between simulated and observed values as a function of observed values did not show any trend.

**Sensitivity Analysis**

A sensitivity analysis of the model was performed for date of anthesis and aboveground biomass using 20 yr of weather data (1988–2007) from Mead, NE, under two scenarios: potential and rainfed (i.e., water availability determined by the stored soil water and rainfall during the crop growth cycle). Selected variables (with corresponding default values) were $R_{\text{max}}$ (0.043 d$^{-1}$), MAXLAI (7.5), and RUE (4.7 g MJ$^{-1}$ PAR), assuming a root depth and FAWHC-AGI of 2 m and 0.70, respectively. These default values represent genotypic and typical environmental features of cultivar Cave-in-rock growing at Mead, NE. The changes in each of the selected variables were 0, ± 5, ± 10, ± 15, and ± 20% of the default values. Switchgrass is typically grown in marginal rainfed lands with large variations in soil depth and stored soil moisture at the timing of AGI (due to high spatial and temporal rainfall variability). Thus, in addition to the above sensitivity analyses, the model was also evaluated to simulate aboveground biomass for 0, –15, –30, –45, –60, and –75% changes in root depth and FAWHC-AGI with respect to the default values mentioned above (2 m and 0.7, respectively) using the same weather database and default values for $R_{\text{max}}$, MAXLAI, and RUE. The absolute and relative change in the simulated date of anthesis ($\Delta_{\text{ANTHESIS}}$, days) and aboveground biomass ($\Delta_{\text{BIOMASS}}$, %), respectively, was calculated as follows:

$$\Delta_{\text{ANTHESIS}} = S_i - S_i = 0\%$$ \hspace{1cm} [11a]

$$\Delta_{\text{BIOMASS}} = \left(\frac{S_i - S_i = 0\%}{S_i = 0\%}\right) \times 100$$ \hspace{1cm} [11b]

where $S_i$ is the 20-yr mean simulated date of anthesis or aboveground biomass obtained for a given $i$th change in the default value ($i = 0, \pm 5, \pm 10, \pm 15,$ and $\pm 20\%$ for $R_{\text{max}}$, MAXLAI, and RUE and 0, –15, –30, –45, –60, and –75% for root depth and FAWHC-AGI). Finally, to investigate the year-to-year variability in the sensitivity of aboveground biomass to the selected variables, the standard error for the magnitude of difference in

---

**Table 2. Average (±SE) daily maximum ($T_{\text{max}}$) and minimum ($T_{\text{min}}$) temperatures, incident solar radiation, total rainfall, and total reference evapotranspiration ($ET_o$) for the period between the simulated date of annual growth initiation and anthesis for the dataset used in the model evaluation.**

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>$T_{\text{max}}$</th>
<th>$T_{\text{min}}$</th>
<th>Radiation</th>
<th>Rainfall</th>
<th>$ET_o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ames, IA</td>
<td>1994</td>
<td>24.3 ± 0.7</td>
<td>12.8 ± 0.6</td>
<td>17.1 ± 0.7</td>
<td>243</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>1995</td>
<td>25.2 ± 0.6</td>
<td>15.3 ± 0.5</td>
<td>14.7 ± 0.6</td>
<td>150</td>
<td>191</td>
</tr>
<tr>
<td>Mead, NE</td>
<td>1994</td>
<td>25.2 ± 0.9</td>
<td>12.7 ± 0.7</td>
<td>23.2 ± 1.0</td>
<td>308</td>
<td>316</td>
</tr>
<tr>
<td></td>
<td>1995</td>
<td>26.9 ± 0.8</td>
<td>14.2 ± 0.7</td>
<td>19.9 ± 0.8</td>
<td>111</td>
<td>249</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>25.4 ± 0.6</td>
<td>12.9 ± 0.6</td>
<td>19.5 ± 0.8</td>
<td>246</td>
<td>289</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>24.3 ± 0.8</td>
<td>11.3 ± 0.7</td>
<td>20.8 ± 0.8</td>
<td>225</td>
<td>314</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>25.7 ± 0.6</td>
<td>11.7 ± 0.6</td>
<td>20.6 ± 0.8</td>
<td>119</td>
<td>294</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>25.8 ± 0.5</td>
<td>12.9 ± 0.5</td>
<td>20.0 ± 0.7</td>
<td>283</td>
<td>302</td>
</tr>
<tr>
<td>Temple, TX</td>
<td>1996</td>
<td>27.3 ± 0.7</td>
<td>13.9 ± 0.7</td>
<td>19.9 ± 0.6</td>
<td>287</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>23.6 ± 0.6</td>
<td>14.1 ± 0.5</td>
<td>17.4 ± 0.7</td>
<td>674</td>
<td>510</td>
</tr>
</tbody>
</table>

---

**Fig. 3.** Observed vs. simulated (a) dates of anthesis and (b) aboveground biomass for an independent data set of switchgrass grown at three locations in the U.S. Great Plains. Observed data were taken from Kiniry et al. (1999), Vogel et al. (2002), and Mitchell (unpublished data, 2007). Cultivars were Cave-in-Rock (open symbols) and Alamo (solid symbols). The dotted lines: (a) ±5 d and (b) ±15% deviation from the 1:1 line (diagonal solid line). The root mean square errors (RMSE) for each plot are shown. The vertical bars indicate selected ±SE of the mean of the aboveground biomass.
aboveground biomass, for each of the changes in the variables over the 20 yr of weather data was calculated.

Simulated date of anthesis was sensitive to changes in R\textsubscript{max} (Fig. 4a): changes of ±20% in R\textsubscript{max} caused a −7 to +10 d variation in the date of anthesis. Under the potential and rainfed scenarios, simulated aboveground biomass was mainly sensitive to changes in RUE and R\textsubscript{max} (Fig. 4b, c). Under the potential scenario (Fig. 4b), the variation in aboveground biomass was proportional to changes in RUE value, that is, changes of ±20% in RUE caused a ±20% variation in aboveground biomass. Likewise, aboveground biomass was very sensitive to changes in R\textsubscript{max} value: changes of ±20% in the latter caused a −13 to +18% variation in aboveground biomass. Under the rainfed scenario (Fig. 4c), aboveground biomass was sensitive to RUE and R\textsubscript{max} but not to the same extent as in the potential scenario: changes of ±20% in RUE and R\textsubscript{max} caused a +8 to −12% and −10 to +7% variation in aboveground biomass, respectively. The standard errors of the difference in aboveground biomass for each of the changes in R\textsubscript{max}, MAXLAI, and RUE were relatively stable for the 20 yr of weather data in the two scenarios (<1.5% for all the changes). This result indicates that year-to-year variation in weather had little impact on the sensitivity of aboveground biomass to these variables.

Finally, aboveground biomass was sensitive to changes in the root depth and FAWHC-AGI: changes of −75% in the latter two variables caused a ≈−40% variation in aboveground biomass (Fig. 4d). As expected, the standard errors for the magnitude of difference in aboveground biomass for each of the changes in root depth and FAWHC-AGI were higher (1–5% for all the changes). The response of aboveground biomass to variations in root depth and FAWHC-AGI depends on the particular weather conditions in a given year.

**DISCUSSION**

It was not the goal of this modeling effort to develop a mechanistic model that simulates the whole spectrum of switchgrass responses to environmental factors. The goal of this effort was to develop a simple, but robust model of switchgrass growth and development that can be used as a tool by farmers, consultants, and policymakers in biofuel-oriented programs, under potential and water-limiting conditions.

This goal was accomplished: the satisfactory simulation of crop development and aboveground biomass, under potential and water limited conditions, while limiting the number of
inputs (Fig. 3). The model represents a further advance with respect to previous attempts to simulate switchgrass because:

(i) it only requires a small, readily available, number of weather, soil, and cultivar data inputs, (ii) the simulation of the date of AGI and anthesis is performed separately, (iii) the differences in crop development and growth between cultivars are simulated, (iv) the simulated dates of anthesis and aboveground biomass have been compared against independent datasets, which includes contrasting cultivars and environments, and (v) the errors associated with the predictions of date of anthesis and aboveground biomass were relatively small (3 d and 1.5 Mg ha\(^{-1}\), respectively).

Accurate prediction of crop development was crucial for biomass predictions as shown in the sensitivity analysis (Fig. 4). The value of \( R_{\text{max}} \) was therefore a key variable for the accurate biomass predictions as shown in the sensitivity analysis (Fig. 4). The University of Nebraska-Lincoln supplied the weather and soil data (University of Nebraska-Lincoln provided helpful comments on a suggestions at different stages of this study. Dr. Kenneth Cassman supplied the weather and soil data used in this study. The senior author wishes also to acknowledge financial support from the Fulbright Program for his graduate assistantship and the Agricultural Research Division of the Institute of Agriculture and Natural Resources at the University of Nebraska-Lincoln.

**ACKNOWLEDGMENTS**

Dr. James R. Kiniry (USDA-ARS, Temple, TX) supplied valuable suggestions at different stages of this study. Dr. Kenneth Cassman (University of Nebraska-Lincoln) provided helpful comments on a version of this manuscript. The High Plains Regional Climate Center (University of Nebraska-Lincoln) supplied the weather and soil data used in this study. The senior author wishes also to acknowledge financial support from the Fulbright Program for his graduate assistantship and the Agricultural Research Division of the Institute of Agriculture and Natural Resources at the University of Nebraska-Lincoln.

**REFERENCES**


