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Modeling Differential Growth in Switchgrass Cultivars Across the Central and Southern Great Plains

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Abstract Switchgrass (*Panicum virgatum L.*) has been recognized as a potential biofuel crop, because it is adapted to a wide range of environmental and climatic conditions. Zones of adaptation for many switchgrass cultivars are well documented and attributed to local adaptation to the temperature and photoperiod at the location of origin. The objective of this study is to develop cultivar-specific growth parameters for the Agricultural Land Management and Numerical Assessment Criteria (ALMANAC) model based on location of origin and use these parameters to predict the biomass production of two lowland cultivars (Alamo and Kanlow) and two upland cultivars (Blackwell and Cave-in-Rock) in the central and southern Great Plains (TX, AR, LA, OK, KS, and MO). The plant parameters adjusted for each cultivar's origin include average growing season temperature (22–27 °C), photoperiod at growth onset (11.46–13.12 h), maximum number of heat units (1,500–2,300), maximum leaf area index (6–12), and light extinction coefficient (0.33–0.50). The absolute difference between the average simulated and measured yields across all seven field locations for each cultivar is less than 0.5 Mg ha^{-1}. Performance of the cultivar-specific parameters varies by location, but the parameters do a reasonable job of estimating the average yield (less than 15 % difference) of each cultivar for a majority of field locations. In addition, regional simulations of the four cultivars each show realistic spatial variation in yield across the central and southern Great Plains. The parameters derived in this project for the ALMANAC model provide a tool for optimizing choice of switchgrass cultivar on different soils, in different climates, and with different management across large geographic regions.

Keywords Ecotypes · Photoperiod · ALMANAC model · *Panicum virgatum* · Local adaptation

Introduction

Switchgrass is a wide-ranging warm-season perennial grass that has gained considerable attention as a potential biofuel crop. It is capable of maintaining reasonably high biomass production on marginal and highly erodible soils and can withstand heat, cold, and drought [1–3]. The extensive environmental and climatic adaptation of switchgrass has been attributed to significant genetic and phenotypic variation of the two main switchgrass ecotypes. The zones of latitudinal adaptation for the lowland and upland ecotypes have been well documented [4–7]. The lowland ecotype is adapted to the southern portion of the range (south of 42° N latitude), and the upland ecotype is adapted to the northern portion of the range (north of 34° N latitude) [7]. Although, the zones of adaptation are not geographically distinct, lowland and upland ecotypes have unique phenotypes. Lowland plants are taller and have blue pigmentation, fewer and larger tillers, thicker stems, and flower later than upland plants [6, 8, 9].

Many studies have focused on identifying the factors governing the latitudinal adaptation of switchgrass cultivars [4, 10, 11]. Genetic variation for photoperiod and temperature at the latitude of origin has a pronounced effect on switchgrass productivity and survival when moved north or south more than one hardiness zone [4, 12]. Switchgrass cultivars show

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variation in photoperiod sensitivity prior to anthesis, similar to other warm-season grasses [13, 14]. In a greenhouse experiment, Van Esbroeck et al. determined that prolonged dormancy in the spring of northern cultivars (such as Cave-in-Rock) could be overcome by extending the day length [14]. This suggested that photoperiod sensitivity of northern populations is the factor limiting growth in the south where day lengths are shorter. Conversely, southern cultivars (such as Alamo) were not sensitive to photoperiod in the vegetative state. Photoperiod also affects floral initiation and anthesis, shortening the duration of growth for northern cultivars as they are moved south [15].

Process-oriented models of plant growth are being widely used to simulate biomass production potential of switchgrass and the potential range of environmental impacts [16–20]. There are different ways to incorporate ecotype or cultivar-specific variation of switchgrass growth into process-based simulation models. For example, Kiniry et al. used the Agricultural Land Management and Numerical Assessment Criteria (ALMANAC) model to simulate biomass of four switchgrass ecotypes at five locations [17]. Each ecotype was parameterized by adjusting the maximum leaf area index (based on the degree of local adaptation to the climate and environmental conditions) and the heat units required to reach maturity. The maximum potential leaf area index (LAI) was assumed to be larger in southern regions and largest for southern lowland cultivars. Likewise, the DAYCENT model was used to simulate six switchgrass cultivars at four locations in the Central Valley of CA [21]. The root-to-shoot ratio, baseline temperature, optimum temperature, and maximum temperature were adjusted for each cultivar. The upland cultivars were assumed to allocate more primary production to root biomass than lowland cultivars. The lowland cultivars were assumed to have higher optimum and maximum temperatures.

As we begin to assess the environmental impacts of broad-scale biofuel production of potential biofuel species, it is vital to consistently and accurately simulate cultivar-specific biomass production across large regions and latitudinal gradients to determine if biomass production is feasible and sustainable. Plant growth parameters and functions required for mechanistic simulations must be based on the actual processes controlling adaptation, not just empirical relationships if these model simulations are going to realistically capture changes in temperature conditions, rainfall, and soil properties across a large geographic extent. With all of this in mind, the objective of this study is to develop cultivar-specific growth parameters for the ALMANAC model based on the latitude of origin. After spatial parameterization and verification of these growth parameters, they are used to predict the biomass production of four switchgrass cultivars (Alamo, Blackwell, Cave-in-Rock, and Kanlow) in the central and southern Great Plains (TX, AR, LA, OK, KS, and MO).

Methods

General description of the ALMANAC model

The ALMANAC model is a process-oriented model of plant growth that simulates light interception, competition for water and nutrients, and biomass production and partitioning [22]. The model runs on a daily time step. Light interception by the canopy is estimated using Beer's law [23]. Nutrient, water, and temperature stress factors are calculated daily and can impede biomass production. Leaf area and biomass production is temperature dependent with growth initiated when the average daily temperature is above the baseline temperature. Temperature stress accumulates when the average daily temperature is greater than the optimum temperature. The plant reaches maturity when the maximum number of heat units is reached. Radiation use efficiency defines potential biomass increases each day based on photosynthetically active radiation captured by the leaf canopy. The inputs required to run the model are crop parameters, weather data, soil properties, and management schedules.

Locally adapted plant growth parameters

We develop cultivar-specific plant growth parameters for two lowland cultivars (Alamo and Kanlow) and two upland cultivars (Cave-in-Rock and Blackwell) by assuming that each cultivar is locally adapted to the location at which it originated. These cultivars originated as far south as Live Oak, TX, and as far north as Cave-in-Rock, IL (Table 1). We adjust five plant growth parameters for each cultivar's location of origin, including (1) the average growing season temperature (optimum temperature), (2) the photoperiod at growth onset, (3) the maximum number of heat units, (4) the maximum leaf area index, and (5) the light extinction coefficient. Growing season mean temperature at each cultivar's location of origin is calculated as the long-term (1950–2000) average monthly temperature from April to September [24]. We define growth onset as the day biomass consistently starts accumulating, and the photoperiod of growth onset is the corresponding hours of daylight for that date at the cultivar's location of origin. We use the ALMANAC model to estimate growth onset. Within the model simulations, plant growth is initiated when the average of the daily maximum and minimum temperatures is greater than the baseline temperature for at least 3 days in a row. The baseline temperature for switchgrass growth is assumed to be 12 °C for all cultivars [25, 26].

The maximum number of heat units (PHU) determines the length of the growing season from growth initiation in the spring to maturity for each cultivar. In this study, the maximum PHU for each cultivar is determined by summing the heat units required to reach the estimated date of maturity at each location of origin. Heat units accumulate when the average daily temperature is greater than the baseline temperature. The maximum PHU at the location of origin of each cultivar is assumed to be a developmental constraint. Therefore, moving a cultivar to a more southern location will not allow for greater heat unit accumulation with warmer temperatures and may decrease the duration of growth due to more rapid accumulation of heat units. However, moving a cultivar to a northern location may reduce the number of heat units that accumulate due to a shorter interval with temperature above the baseline.

Leaf area is accumulated throughout the growing season according to a sigmoid-shaped curve, and the maximum LAI is reached near the date of anthesis. The maximum LAI is an important crop parameter that specifies the leaf area available for light interception. The maximum LAI for each cultivar is determined from values reported in the literature [27] (Table 1). The light extinction coefficient is used to calculate the fraction of photosynthetically active radiation using Beer's law. The light extinction coefficient has been calculated for many switchgrass cultivars, and the values reported by Kiniry et al. [25] for Alamo, Kanlow, and Cave-in-Rock in TX, MO, and NE are used to approximate the location of origin (Table 1).

Spatial model parameterization and verification

The yield data collected in 2010 and 2011 [28] and an additional year of field data collected in 2012 are used for cultivar-specific model calibration and validation. We analyze seven of the ten locations spanning TX, OK, AR, and MO to spatially parameterize the four cultivars (Table 2). Two sites, Weslaco and Kingsville in southern TX, are excluded from this analysis because of excessive weeds, and Booneville, AR, is excluded because it was established a year after all other sites. Field trials were initiated in spring of 2009 with all cultivars planted in a randomized complete block design with four replicates. Each year, 1 m^2 was harvested at least twice during the growing season and a final harvest in September or October. The average measured yield for each cultivar is the average maximum yield reported each year at every location (Table 2). For complete details on the experimental and sampling design, see [26]. Each field site is simulated as close to reality as possible using the appropriate site-specific soil type reported by Kiniry et al. [26], and climate data is from the National Oceanic and Atmospheric Administration (NOAA) for the closest daily weather station from 2009 to 2012 for daily maximum temperature, minimum temperature, and precipitation. The management schedule for parameterization and validation is simplified. All sites were planted on 10 April of 2009 and harvested 30 September of every subsequent year. In the field experiments, there was no visible nutrient stress; therefore, we assume that there is adequate N and P.

The maximum PHU and LAI are two parameters constrained not only by cultivar origin but also by the latitude of the simulation site. To parameterize and verify the cultivar-specific crop parameters at all seven field locations, these parameters must be adjusted. The maximum PHUs (or the maximum length of the growing season) for each cultivar is determined based on the temperature at the location of origin. However, when moving to a different location, the maximum may not always be reached, and the length of the growing season must be rescaled to fit the appropriate temperature regime. Therefore, the average number of growing degree days until maturity is reached was calculated for each location using data from the closest NOAA weather station. If the PHUs at a site are greater than the maximum for the cultivar, the PHUs were set to the cultivar maximum. For the two upland cultivars from higher latitudes, the PHUs are constant across all locations because the calculated PHUs are higher than the cultivar maximum at every location. However, the two lowland cultivars range from 2,300 in the TX to 1,200 in MO (Table 3).

Next, we change the maximum LAI and the fraction of intercepted solar radiation as a function of latitude. First, we regress mean yield of each cultivar as a function of latitude. Three of the four cultivars show a positive significant slope for this relationship with R^2 values ranging from 0.71 to 0.94 (Fig. 1). The aboveground biomass predicted from the linear relationship with latitude (pY) for each cultivar is used hereafter. This process is not done for Alamo because the

Table 1 Location of origin for four representative switchgrass cultivars and relevant environmental variables calculated at each origin. Growing season temperature is the long-term (1950–2000) average monthly temperature from April to September. The day of growth onset, corresponding day length, and maximum PHU were determined using the ALMANAC, assuming a baseline temperature of 12 °C. Maximum LAI and light extinction coefficient for cultivars are taken from the literature [25]

Cultivar name	Ecotype	County of origin	State of origin	Growing season temp (°C)	Day of growth onset	Day length of growth onset (h)	Max PHU	Max LAI	Light extinction
Alamo	Lowland	Live Oak	TX	27	13 February	11.46	2,300	12	0.33
Blackwell	Upland	Kay	OK	23	13 April	12.74	1,600	6	0.33
Cave-in-Rock	Upland	Hardin	IL	22	13 April	13.12	1,500	8.8	0.36
Kanlow	Lowland	Hughes	OK	23	13 March	12.23	2,300	6.8	0.50

Table 2 Average measured yields, simulated yields, and percent difference for all four switchgrass cultivars at seven field locations from 2010 to 2012

Field location Latitude	Temple, TX 31.9	Nacogdoches, TX 31.66	Fayetteville, AR 36.07	Stillwater, OK 36.12	Mt. Vernon, MO 37.1	Columbia, MO 38.95	Elsberry, MO 39.17	Average of all locations
Alamo								
Msrd yield (Mg ha^{-1})	26.7	25.6	13.1	11.7	17.0	19.7	22.3	19.4
Sim yield (Mg ha^{-1})	20.8	24.9	16.2	18.4	18.8	18.0	18.8	19.4
% Difference	−22.2	−2.5	23.9	57.5	10.7	−8.5	−15.6	
Blackwell								
Msrd yield (Mg ha^{-1})	5.7	4.6	7.7	7.7	9.4	10.0	13.0	8.3
Sim yield (Mg ha^{-1})	5.2	5.2	7.7	7.3	7.8	13.4	11.9	8.4
% Difference	−9.2	12.6	0.1	−6.0	−17.5	33.4	−8.4	
Cave-in Rock								
Msrd yield (Mg ha^{-1})	4.4	4.5	9.4	9.4	10.0	10.3	12.9	8.7
Sim yield (Mg ha^{-1})	4.3	4.3	8.4	8.2	10.1	13.9	14.5	9.1
% Difference	−3.3	−4.3	−11.2	−12.7	1.2	35.8	12.3	
Kanlow								
Msrd yield (Mg ha^{-1})	10.1	11.5	12.4	9.8	15.3	18.5	22.5	14.3
Sim yield (Mg ha^{-1})	9.3	8.2	12.8	15.3	16.5	16.0	18.9	13.8
% Difference	−8.1	−28.6	3.1	55.7	7.9	−13.7	−16.2	

relationship was not significant, and the LAI is assumed to be equal to the maximum LAI of 12 at all locations. Second, the maximum seasonal fraction of light intercepted, *Fmax*, at the highest yielding location is calculated using Beer's law [23]:

$$Fmax_c = 1 - \exp(-k_c \times mLAI_c) \quad (1)$$

where k is the light extinction coefficient, and *mLAI* is the maximum LAI for each cultivar, c. Third, the seasonal fraction of light intercepted, F, for each latitude, l, and cultivar, c, is reduced using the proportional decrease in predicted yield, pY, from the highest predicted yielding site, $pYmax$, for each cultivar, c.

$$F_{l,c} = Fmax_c\left(pY_{l,c}/pYmax_c\right) \quad (2)$$

Lastly, Beer's law was used again to calculate the *LAI* for each latitude, l, and cultivar, c, as follows:

$$LAI_{l,c} = 1\text{n}\left(1 - F_{l,c}\right)/-k_c \quad (3)$$

The LAI values calculated for each location and cultivar are presented in Table 3. Model verification is performed by comparing the average measured yield from (2010–2012) to the ALMANAC simulated yield parameterized using the cultivar-specific parameters derived from the location of origin and the site-specific parameters (PHU and LAI).

Geographic model predictions

One goal of this study is to develop cultivar-specific spatially continuous yield predictions for six states in the central and

Table 3 The PHU and LAI calculated for each cultivar and location

City, state	Latitude	Alamo		Blackwell		Cave-in-Rock		Kanlow	
		PHU	LAI	PHU	LAI	PHU	LAI	PHU	LAI
Temple, TX	31.9	2,300	12	1,600	1.33	1,500	1.29	2,300	0.89
Nacogdoches, TX	31.66	2,300	13.91	1,600	1.26	1,500	1.21	2,300	0.83
Fayetteville, AR	36.07	2,000	5.02	1,600	2.89	1,500	3.43	2,000	2.47
Stillwater, OK	36.12	2,000	4.99	1,600	2.92	1,500	3.46	2,000	2.49
Mt. Vernon, MO	37.1	1,800	4.42	1,600	3.44	1,500	4.35	1,800	3.16
Columbia, MO	38.95	1,200	3.56	1,600	4.79	1,500	7.83	1,200	5.93
Elsberry, MO	39.17	1,200	3.48	1,600	5.00	1,500	8.80	1,200	6.80

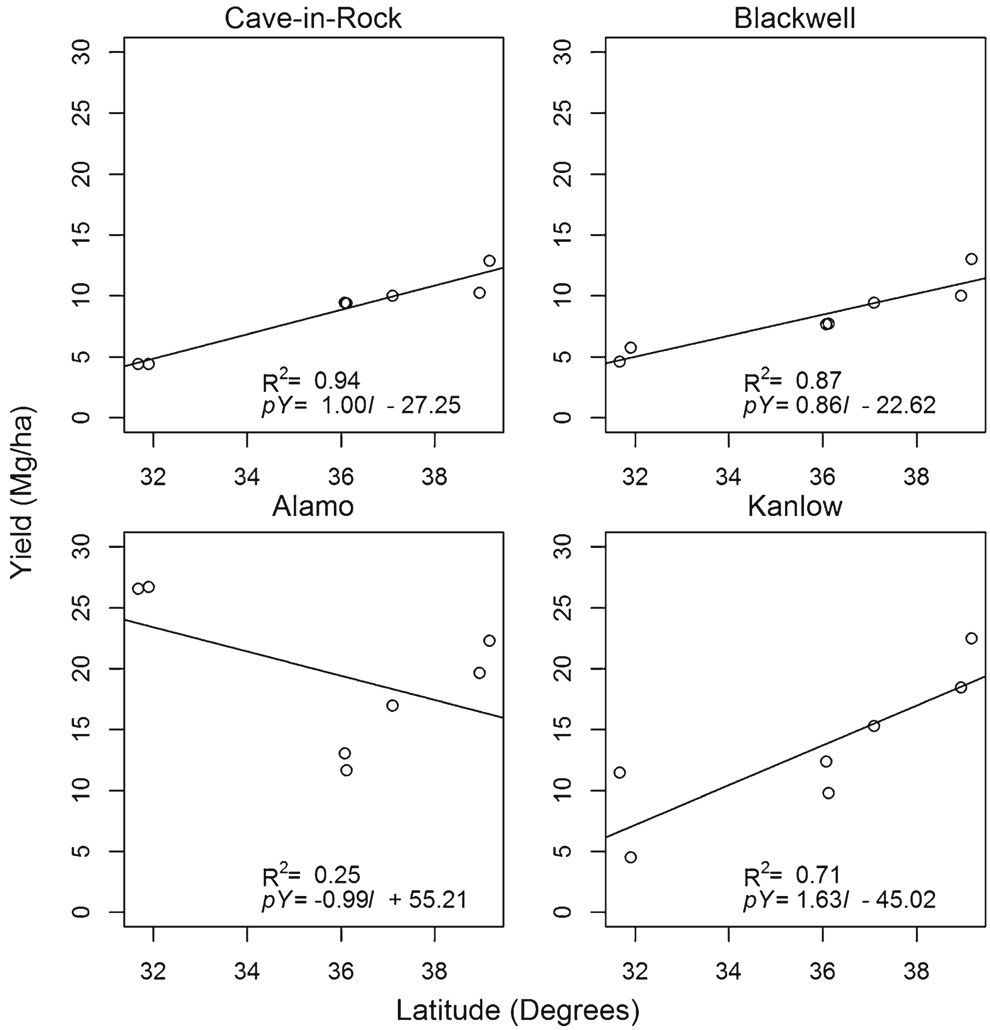

Fig. 1 Scatterplot and linear regression of biomass vs. latitude of seven field evaluation sites for measured yield from 2009 to 2012 for four switchgrass cultivars (Alamo, Blackwell, Cave-in-Rock, and Kanlow)

southern Great Plains (TX, OK, AR, LA, MO, and KS). This geographic region is divided into 14,887 0.1° grid cells. An ALMANAC simulation model is run using the dominant soil component at each cell centroid. The soil properties necessary to run the ALMANAC are extracted from the USDA-NRCS Soil Survey Geographic database. Daily weather data is simulated by the ALMANAC using a built-in database of average climate conditions from 1986 to 1996 for 975 weather and wind stations in the USA (containing 158 weather and 182 wind variables). A unified management schedule is applied to emphasize the difference in environment across space. Switchgrass is planted the first year on 10 February and harvested every subsequent year on 30 September. We assume that plants are not nutrient limited, and adequate N and P fertilizer is applied. Simulations are run for 23 continuous years, and the averages of the post-establishment yields are reported as the average of the last 20 years.

In the above section, we parameterize five cultivar-specific model parameters based on the location of origin that do not change depending on the location grown and two cultivar-specific model parameters (LAI and PHUs) that depend on the field location. Therefore, LAI and PHU must be calculated for each new simulation location. Equations (1), (2), and (3) are directly used to calculate LAI for each cultivar as a function of latitude for all simulation locations. Above, the PHUs at each field location are calculated using the ALMANAC model and weather station data. The PHUs do not vary by location for the two upland ecotypes, Blackwell and Cave-in-Rock; therefore, these are set respectively to 1,600 and 1,500 for all locations (Table 3). The PHUs for the two lowland ecotypes, Alamo and Kanlow, do vary by latitude. The PHUs are reduced as the latitude increased because there are fewer days with temperatures greater than the baseline temperature. To quantify this relationship, we regress latitude, l, on PHU at the seven field locations and find a significant linear relationship between the two ($PHU = -141.05l + 6885.53$, $R^2 = 0.85$). The regression equation is then used to predict the PHUs based on latitude for any new field location.

Results

Spatial model parameter validation

The average simulated yield from 2010 to 2012 for each cultivar and field location was compared to the average measured yields from 2010 to 2012 for each cultivar and field location. The cultivar-specific crop parameters did a good job of estimating the average yield of each cultivar across all locations (Table 2). The absolute difference between the average simulated and measured yields across all field locations for each cultivar was less than 0.5 Mg ha^{-1}. The average difference between simulated and measured yields across all field locations was positive for Blackwell (0.1 Mg ha^{-1}) and Cave-in-Rock (0.4 Mg ha^{-1}), indicating that the simulated yields tend to slightly overpredict yield for the upland ecotype. There was no difference between average simulated and measured yield across all locations for Alamo, and the difference was negative for Kanlow (−0.5 Mg ha^{-1}), indicating that the simulated yields tend to be fairly accurate or slightly underpredict yield for the lowland ecotype.

Model performance by cultivar and location does vary. The two lowland cultivars, Alamo and Kanlow, have the largest percent error in Stillwater, OK, with a difference of 57.5 and 55.7 %, respectively. The two upland cultivars, Blackwell and Cave-in-Rock, have the largest percent error in Columbia, MO, with Blackwell overpredicting by 33.5 % and Cave-in-Rock overpredicting by 35.8 %. The crop parameters for Blackwell and Cave-in-Rock consistently predicted yields with less than a 20 % difference except at Columbia, MO. Kanlow has two sites (Nacogdoches, TX, and Stillwater, OK) with a percent error greater than 20 %, and Alamo has three sites (Temple, TX; Fayetteville, AR; and Stillwater, OK).

Simulated plant growth over time

We analyzed the simulated aboveground biomass accumulation over time for each cultivar to ensure that the growth patterns simulated were consistent with those observed for different ecotypes (Fig. 2). In our simulations, Alamo initiates growth approximately 50 days earlier than all other cultivars in the south (Temple, TX, and Nacogdoches, TX). This is consistent with an observation of more northern-adapted varieties being sensitive to longer photoperiods for growth initiation [31]. Furthermore, once Alamo starts growing in the south, the other varieties never catch up. In the north (Columbia, MO, and Elsberry, MO), Alamo starts growing around the same time as Kanlow and about 40 days before Cave-in-Rock, but all three cultivars have similar biomass in the middle of the growing season between day of year 160 and 180. Cave-in-Rock, the most northern-adapted cultivar, produces less than half as much biomass in the south as the north. Alamo, the most southern-adapted cultivar, produces the most biomass at the two southern locations in TX.

Predicted yield for the central and southern Great Plains

The four switchgrass cultivars each show spatial variation in yield across the central and southern Great Plains (Fig. 3). All cultivars have an east-to-west gradient in yield that is likely the result of variation in precipitation. Kanlow, Cave-in-Rock, and Blackwell also have a pronounced north-to-south yield gradient due to variation in temperature and photoperiod sensitivity. Alamo is the most productive along the Gulf Coast with more than 28 Mg ha^{-1} of biomass produced each year. The highest yielding locations for Blackwell (12–14 Mg ha^{-1}), Cave-in-Rock (16–18 Mg ha^{-1}), and Kanlow (greater than 28 Mg ha^{-1}) are in MO. Alamo and Kanlow have similar simulated biomass in MO and KS, close to where Kanlow originated.

Discussion

To accurately estimate switchgrass biomass production across a large geographic area, it is important to capture the differential production potential for a variety of climatic condition and soil types. However, simulating the production potential of switchgrass is complicated by the genetic diversity of many cultivated accessions and gene by environment interactions [29, 30]. Inevitably local land managers will target the most suitable and productive cultivar for their location. In this study, we emphasize that models of production potential must incorporate this notion of genetic diversity and include the key process controlling plant productivity.

The simulated differential growth of switchgrass cultivars is based on sensitivity to photoperiod and temperature at the location of origin. The difference in yield within the two upland (Blackwell and Cave-in-Rock) and two lowland cultivars (Alamo and Kanlow) is more pronounced between the two lowland varieties that originated further apart. Kanlow from Hughes, OK, originated where day length for growth onset is 0.77 h longer and growing season temperature is 4 °C lower than Alamo from Live Oak, TX. These differences make the highest yields for Kanlow in KS and MO and the lowest yields in TX and LA. There are substantial differences between model predictions within an ecotype, suggesting that these cultivar-specific parameters should not be used for more general simulation of an entire ecotype.

While there is a lot of supporting evidence showing that sensitivity to photoperiod and temperature at the location of origin impacts production potential, these are not the only factors [4, 11, 14, 31, 32]. Other factors associated with productivity gradients are freezing temperatures in the early spring and differential biomass allocation to roots [33].

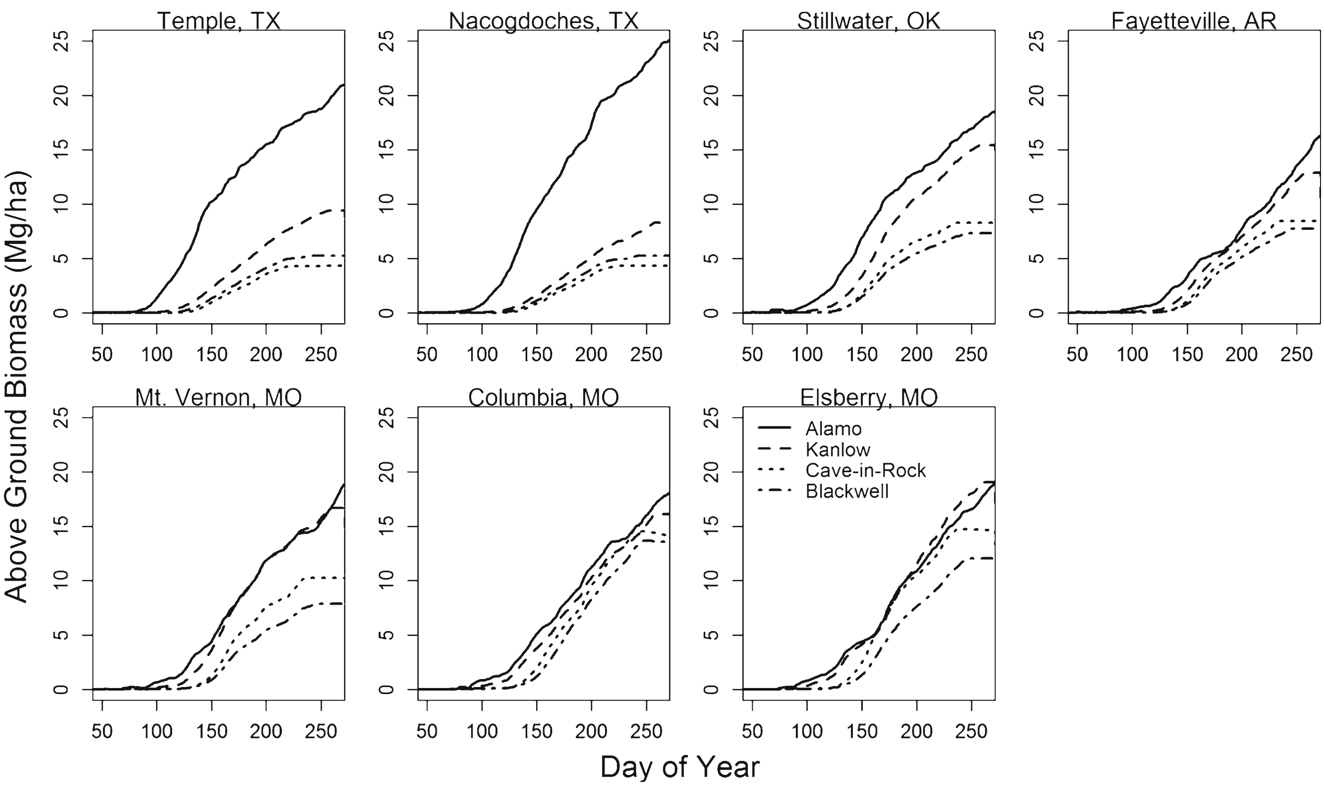

Fig. 2 The aboveground biomass accumulation by each day of year simulated using the ALMANAC model for Alamo (*solid line*), Blackwell (*dashed line*), Cave-in-Rock (*dotted line*), and Kanlow (*dashed-dotted line*) at each of the seven field locations

Southern lowland varieties are susceptible to early spring winter kill in the north due to a lack of photoperiod sensitivity that prevents the onset of growth [4]. This may be an important factor when moving southern lowland cultivars north of Hardiness Zone 6. While this factor has not been suggested to play an important role in our study region, care

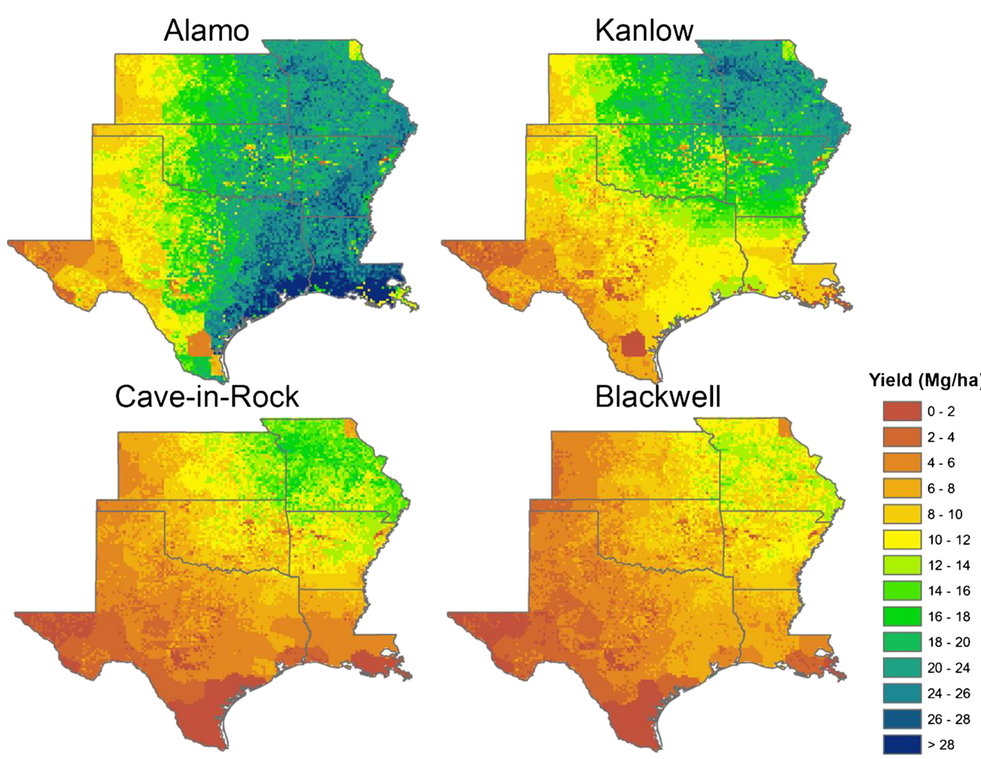

Fig. 3 Spatially continuous yield estimates simulated using the ALMANAC model for four switchgrass cultivars (Alamo, Blackwell, Cave-in-Rock, and Kanlow) in the central and southern Great Plains

should be taken when moving these cultivar-specific crop parameters to higher latitude locations.

In this study, we assume that the maximum depth of root growth is 2.2 m, and at growth onset, 40 % of biomass is portioned to root growth, and this decreases to 20 % at maturity for all cultivars. These assumptions are consistent with empirical measurements of switchgrass growth [33, 34]. There is some evidence that upland switchgrass cultivars may be more drought tolerant and allocate more biomass to root growth [33] However, these findings are also dependent on soil type. Currently, there is not enough data collected at several field sites on rooting depth and root-to-shoot allocation to develop cultivar-specific parameters. Future data collection may be used to refine these cultivar-specific switchgrass crop parameters and improve the accuracy of model predictions.

The cultivar-specific parameters, derived in this study for the ALMANAC model, provide a strong tool for many robust analyses beyond those of a purely statistical modeling framework. Because the ALMANAC is a process-based model, these results may be expanded to allow for identification of the most productive switchgrass cultivar and best possible management practices on many soil types and in different climate conditions. In addition, mechanistic models using similar crop growth parameter inputs (i.e., EPIC, SWAT, and APEX) make it possible to analyze an entire suite of cultivar-specific environmental impacts, which include changes in soil organic carbon, greenhouse gas emissions, nutrient losses and run off, soil erosion, and water use [35–38]. As such, these growth parameters will be valuable for future studies of switchgrass production for biofuel and its associated long-term environmental impacts.

Finally, the methodology described here is not specific to switchgrass and can be directly transferable to other biofuel crops of interest that are locally adapted to their location of origin. Deriving key parameters for the processes controlling productivity at different latitudes will depend on mechanisms identified. Crop growth parameters developed in this fashion will enable transfer between many different types of models and allow for a more consistent and comprehensive study of the feasibility and potential impacts of biofuel production.

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