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Simulating bimodal tall fescue growth with a degree-day-based process-oriented plant model

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Abstract
Plant growth simulation models have a temperature response function driving development, with a base temperature and an optimum temperature defined. Such models function well when plant development rate shows a continuous change throughout the growing season. This approach becomes more complex as it is extended to cool-season perennial grasses with a dormant period and bimodal growth curves. The objective of this study was to develop such a bimodal growth model for tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort) in the Midwest USA based on multiyear measurement trials. Functions for bimodal growth were incorporated into the ALMANAC model and applied to tall fescue using published tall fescue yields for a variety of sites and soils. Fields of cultivars "Kentucky 31" and "BarOptima Plus E34" were divided into paddocks and sampled weekly for dry-matter accumulation. These biomass estimates were used to derive weekly growth values by differences between sequential weekly samplings. The measured values were compared to a single tall fescue simulation each year on one soil. Using these results, the ALMANAC model was modified and tested against mean reported tall fescue yields for 11 sites, with one to three soils per site. When we introduced midsummer dormancy into ALMANAC, we assumed dormancy began on the longest day of the year and lasted until the photoperiod was 0.68 hr shorter than the longest. ALMANAC simulated previously reported tall fescue yields well across the range of sites. Thus, ALMANAC shows great promise to simulate bimodal growth in this common cool-season grass.

KEYWORDS
ALMANAC, bimodal growth model, cool-season fescue, growth curves, simulation modeling

1 | INTRODUCTION

Scientists often need to assess the value of plants in pastures and other ecosystems. Considerable investment is required to accurately make these assessments (Kallenbach, 2015). Plant growth simulation models predict plant responses in ecosystems and can be candidate tools to model how different factors affect plant responses in forage/livestock systems. Such modelling systems include PHYGROW (Angerer, 2012; Stuth, Angerer, Kaitho, Jama, & Marambii, 2005; Stuth, Schmitt, Rowan, Angerer, & Zander, 2003b; Stuth et al., 2003a), GPFARM-Range (Andales, Derner, Ahuja, & Hart, 2006; Andales et al., 2005), SAVANNA (Coughenor, 1993), the Sustainable Grazing Systems model (Doran-Browne, Bray, Johnson, O'Reagain, & Eckard, 2014; Johnson, Lodge, & White, 2003) and APEX (Kumar, Udawatta, Anderson, & Mudgal, 2011; Zilverberg et al., 2017).

Plant development models have long had a temperature response function driving development, with a base temperature and an optimum temperature defined. Thus, degree-days (also called heat units or growing degree-days) accumulate when daily temperatures exceed the base temperature in the spring and can slow down and stop as temperatures decrease late in the growing season. As high temperatures near mid-season exceed the optimum temperature, development rate does not continue to increase with increasing temperature and may even decrease. Daylength also affects development for photoperiod sensitive species, cultivars or ecotypes.

Such simulation models have often been shown to function well when plant development rate shows a continuous change throughout the growing season, gradually increasing throughout the increasing temperatures during the first half of the growing season and gradually decreasing thereafter. Such phenology of warm-season perennial grasses is relatively straightforward. Plants begin growth in the spring based on their base temperature, have an optimum temperature that describes growth in the hottest part of the year and have leaf area development based on a leaf area index development curve. Stresses such as drought or nutrient deficiencies reduce leaf area growth.

Dry-matter (DM) accumulation is often simulated with a radiation use efficiency (RUE) approach. Cumulative photosynthetically active radiation (PAR) intercepted by the plant canopy is converted to DM with the species-specific RUE value (Ruimy, Jarvis, Baldocchi, & Saugier, 1995; Runyon, Waring, Goward, & Welles, 1994; Stockle & Kiniry, 1990). Again, stresses such as drought and nutrient deficiencies can reduce DM increase below the potential (Ahanger, Mrad-Talab, Abd-Allah, Ahmad, & Hajiboland, 2016). This approach becomes more complex as it is extended to cool-season perennial grasses. In contrast to warm-season grass development, cool-season grasses, exemplified by tall fescue (Schedonorus arundinaceus (Schreb.) Dumort), have a lower base temperature and often show a bimodal growth pattern, with spring and early summer growth, a mid-season depression and dormancy period during the hottest parts of summer, followed by a smaller growth cycle during late summer and early fall (Kallenbach & Bishop-Hurley, 2002; Turgeon, 2005).

Summer dormancy has been considered as a desirable trait for Mediterranean temperate perennial grasses survival under summer stress including heat stress and drought stress (Malinowski, Zuo, Kramp, Muir, & Pinchak, 2005; Ruyue, 2016; Volaire & Norton, 2006). Cool-season turf grasses like tall fescue often suffer from an extended period of high temperatures and drought. Drought and heat stresses result in declines in quality and productivity of tall fescue associated with reduction in root growth, leaf water potential and chlorophyll content (Carrow, 1996; Jiang & Huang, 2001; Malinowski et al., 2005; Nielsen-Gammon, Zhang, Odins, & Myoung, 2005). In addition, summer dormancy in tall fescue can be characterized as endo-dormancy in response to temperature and daylength (Salome, Xie, & McClung, 2008). Thus, cool-season tall fescue usually initiates growth early in the spring and then slows down or stops growth in early summer as days get sufficiently long. Growth resumes after this dormancy period ends, in late summer or early fall and continues until temperatures drop below the base temperature. The second growth interval following dormancy often has noticeably less biomass accumulation than the first interval (Burns & Chamblee, 1979). The high growth rate in the spring is prior to anthesis (Wolf, Brown, & Blaser, 1979), with rate declining thereafter. There is no tillering in midsummer due to high-temperature effects on auxin levels (Yeh, Matches, & Larson, 1976).

To accurately simulate such bimodal growth patterns, process-based simulation models must transform the basic approach of a single degree-day sum for the entire growing season, and instead use a degree-day sum approach with a mid-season dormancy period defined by daylength. As days approach the longest day of the year, a process-based model must be able to realistically simulate how such grasses become dormant. Likewise, as daylength decreases following the longest day of the year, such a model must realistically simulate when dormancy ends and plant growth resumes. Therefore, this study was designed to develop such a bimodal growth system for tall fescue in the Midwest USA based on multiyear measurement trials. The Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model is used as it has already been shown to realistically simulate coastal bermudagrass (*Cynodon dactylon* (L.) Pers.) and bahiagrass (*Paspalum notatum* Flueggé) (Kiniry et al., 2007). This model can simulate several representative native grasses in Texas (Kiniry et al., 2002), switchgrass (*Panicum virgatum* L.) over a diverse range of sites (Kiniry, Schmer, Vogel, & Mitchell, 2008; Kiniry et al., 1996), buffelgrass [*Pennisetum ciliare* (L.) Link] and "Old World Bluestems" (*Bothriochloa* Kuntze, *Capillipedium* Stapf and *Dichanthium* Willemet) (Kiniry, Johnson, Venuto, & Burson, 2014b), and several native grasses in the Intermountain west of the USA (Kiniry et al., 2014a). The model version developed in this study represents the first time ALMANAC has been applied to a grass with a bimodal growth pattern. In addition, by making this model realistic for this cool-season pasture/hay grass, it extends the model's usefulness for making management decisions common for producers' applications for similar cool-season grasses. The resulting improved model is subsequently tested against published United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) tall fescue yields (USDA NRCS [USDA Natural Resources Conservation Service], 2012) for a variety of sites and soils within the region of the USA where tall fescue is commonly grown. This project was designed to be an important first step towards simulating other similar cool-season perennial grasses that exhibit such bimodal growth patterns.

2 | MATERIALS AND METHODS

2.1 | Mt. Vernon, MO field data

We obtained plant growth calibration data from a grazing experiment at the University of Missouri Southwest Research Center, Mt. Vernon during the growing seasons of 2011–2013. Six 3.56-ha pasture units were each divided into eight equal-sized grazing cells for rotational stocking. Three pasture units were more than 20 years old, which established Kentucky 31 (>90% infected with the native endophyte Epichloë coenophiala), while the three remaining pasture units were BarOptima Plus E34 (>80% infected with a novel endophyte) seeded in September 2009 at 10.2 kg/ha raw seed. Hoberg

(101 g/kg sand, 662 g/kg silt, 236 g/kg clay, 9.8 g/kg organic matter, pH 5.7), Viraton (75 g/kg sand, 589 g/kg silt, 336 g/kg clay, 11.7 g/kg organic matter, pH 5.8) and Wilderness (171 g/kg sand, 556 g/kg silt, 273 g/kg clay, 10.8 g/kg organic matter, pH 5.6) soil series comprised 75% of the land area.

Fields were fertilized annually with 56 kg N ha^{-1} applied in spring each year. Within a pasture unit, four of the eight paddocks received spring N on 4 March, 1 March and 8 March in 2011–2013 respectively. The others received N on 19 May, 9 May and 28 May in 2011–2013 respectively. The deferred N application promoted summer regrowth for grazing and occurred after excess forage had been removed as hay. All paddocks received 84 kg N ha^{-1} on 17, 14 and 21 August, 2011–2013 respectively. All paddocks received 103 kg P_2O_5 ha^{-1} on 17 August 2011. In the spring of 2016, soil phosphorus in Pasture 6 was 25.8 kg P ha^{-1}, as compared to an average of 53.2 kg P ha^{-1} in the other pastures. Thus, Pasture 6 received an additional 214 kg P_2O_5 ha^{-1} on 14 August 2012.

Rotational stocking occurred on pasture units with five fall-calving, Angus/Simmental beef cows (stocking rate 1.4 cows ha^{-1}). Cow–calf pairs commenced grazing on approximately 1 April each of 3 years. Autumn-born calves departed the pasture units at weaning in late May. Grazing ended between mid-November and early December for timed artificial insemination each of 3 years. Cattle rotationally grazed pastures were measured weekly with an ultrasonic sensor (Senix Corp, Hinesburg, VT) mounted to the front of an ATV. The height data guided pasture management decisions. Animal groups moved to a new paddock when forage height reached the target residual of 75 ± 5 mm. If forage growth could not meet animal demand in a pasture unit, animals received silage made from paddocks during periods of excess growth.

We calibrated the ultrasonic sensor to forage mass four to six times per year. To calibrate, we measured a 5-m (±2 m) strip of forage twice with the ultrasonic sensor. Then, we cut a 0.82-m-wide strip, centered over that same area, to a 3 cm height with a flail-type harvester. We harvested approximately 25 (±3) such strips from paddocks for all calibration events, representing a range of forage masses.

All paddocks were sampled weekly with biomass estimated from pasture cover/height readings by an ultrasonic sensor (Senix Corp, Hinesburg, VT) mounted to the front of an ATV. Biomass was calibrated to ultrasonic sensor measurements every 6 weeks. These biomass estimates were used to derive weekly growth rate values by differences between sequential weekly samplings. Growth rates were calculated on paddocks during times that they were not grazed. The general form of the weekly growth curves was compared to the expected form based on the report of Kallenbach and Bishop-Hurley (2002).

2.2 | Adaptation of the ALMANAC model to simulate mid-season dormancy

Growth rate data for Mt. Vernon, MO, were derived from weekly measurements of plant DM per unit ground area in paddocks where no grazing ever occurred between the measurement dates. The growth rate was calculated for each of the two cultivars by subtracting each date's measured DM value from the previous date's value and then dividing by number of days between the two measurements. These growth rates of the two cultivars were plotted against measured dates during 2011, 2012 and 2013. All statistical analyses have been performed using Statistical Analysis Software version 9.3. To compare growth rates between two cultivars within each year, a Wilcoxon rank-sum test was performed. Average growth rates of two cultivars observed in each year were also plotted against measured dates, and significant differences in average growth rates between years were also tested by a Wilcoxon rank-sum test.

The tall fescue growth model was designed based on growth patterns observed for the two cultivars. The decrease in growth

TABLE 1 The dominant soil type, average annual rainfall in mm from 1994 to 2013 and NRCS published yields and yields simulated by the ALMANAC model for the different sites used for the yield simulations

County, State	Dominant soil type	Avg. rain (mm)	NRCS (t/ha)	Sim. yields (t/ha)
Lawrence, MO	Gerald silt loam	1,139	7.33	7.44
Cooper, MO	Menfro silt loam eroded	1,059	6.68	6.90
	Pershing eroded	1,059	8.29	7.50
Laclede, MO	Viraton silt loam	1,164	4.98	4.63
	Moniteau silt loam	1,164	8.14	7.65
Yell, AR	Cane loam	1,203	6.67	6.99
	Barling silt loam	1,203	8.31	8.11
Logan, AR	Enders silt loam, eroded, occ. flooded	1,262	4.10	5.22
	Barling silt loam, occ. flooded	1,262	8.31	8.60
Wilson, TN	Norene silt loam, rarely flooded	1,364	6.67	7.61
	Waynesboro loam	1,364	7.70	7.96
Williamson, TN	Mimosa silt loam eroded	1,370	3.20	3.74
	Captina silt loam	1,370	8.21	8.27
Limestone, AL	Lindside silt loam	1,328	8.21	9.43
Madison, AL	Talbott silty clay loam, eroded, undulating	1,389	4.62	5.01
	Melvin silty clay loam	1,389	10.26	9.28
Guilford, NC	Iredell fine sandy loam	1,072	2.91	3.50
	Clifford sandy loam	1,072	4.79	4.82
	Nathalie sandy loam	1,072	5.43	5.64
Richland, SC	Toccoa Loam	1,182	6.67	6.58
	Congaree loam	1,182	9.80	9.49
			p-value	.63

Measured and simulated yields were statistically compared using *t* test at $\alpha = 0.05$.

rate near mid-season and the resumption of growth following dormancy were compared to daylengths to determine how to adapt the model for these simulations. Thus, the model code was changed so that no heat units accumulated (development and growth were zero) during this mid-season dormancy period. A new crop category, IDC 9, was created to specify plants with bimodal growth. Tall fescue parameters are as follows: WA, 32; DLMA, 5; DLAI, 0.50; DLAP1, 10.20; DLAP2, 20.95; and DORMNT, 0.677. WA is the potential growth rate per unit of intercepted PAR. DLMA is the maximum potential leaf area index. DLAI is the fraction of growing season when leaf area starts to decline. These values for DLAP1 and DLAP2 indicate that when 10% of the total heat units to maturity have accumulated, 20% of the final LAI is present and when 20% of the heat units have accumulated, 95% of the final LAI is present. LAP1 and LAP2 are the first and second points on an optimal leaf area development curve. DORMNT is daylength when dormancy begins. Management for all simulations consisted of the following: fertilizing on 1 April, planting on 10 April in the initial year, assuming 2,800 potential heat units from greenup to maturity each year, 50 seedlings/m^2, harvesting 90% of aboveground DM on 1 July, fertilizing again on 17 August and harvesting 90% of aboveground DM on 1 November.

2.3 | Validating the improved ALMANAC model with the Mt. Vernon field data

The growth rate was calculated by subtracting each month's simulated DM value (not included root biomass) from the previous month's value and then dividing by 30. The monthly growth rates of 2004–2013 and monthly growth rates averaged over 10 years were plotted against month. To evaluate the plant parameters and test ALMANAC's ability to accurately simulate tall fescue biomass across four sites, simulated biomass values in 2011, 2012 and 2013 were compared with the measured biomass values that came from the field measurements. Relative ratio between simulated and measured fall biomass productions was calculated in each year.

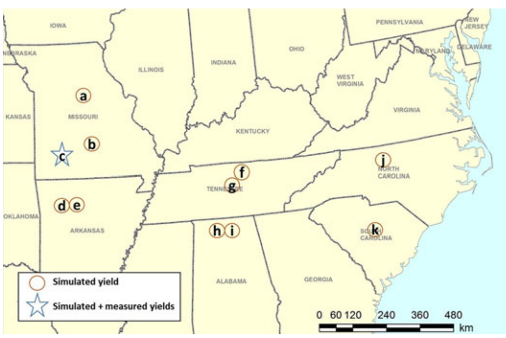

FIGURE 1 Simulated and measured sites conducted in this study. Star symbol represents both simulated and measured sites, while circle symbol represents only simulated site. a, Cooper; b, Laclede; c, Lawrence; d, Logan; e, Yell; f, Wilson; g, Williamson; h, Limestone; i, Madison; j, Guilford; k, Richland counties

2.4 | NRCS published yield data for model testing

We used reported USDA-NRCS tall fescue yields to test our adapted ALMANAC model. We selected simulation sites representative of the various areas and soils across the tall fescue-growing region of the USA (Burns & Chamblee, 1979) (Table 1; Figure 1). There are three weather station sites in Missouri (counting Mt. Vernon), two in Arkansas, two in Tennessee, two in Alabama, one in North Carolina

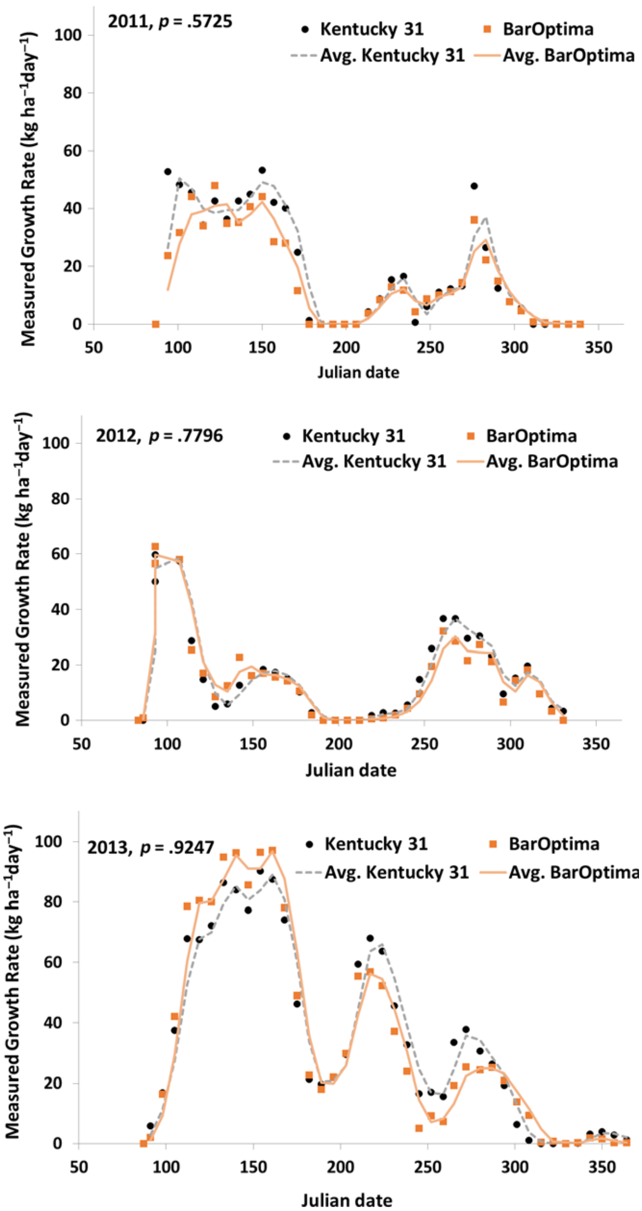

FIGURE 2 Measured plant growth rates (kg ha^{-1} day^{-1}) for "Kentucky 31" and "BarOptima" tall fescue in 2011, 2012 and 2013 at Mt. Vernon, MO. The Wilcoxon rank-sum test was performed to compare "BarOptima" and "Kentucky 31" growth rates within each year at α = 0.05 and measured plant growth rates (kg ha^{-1} day^{-1}) averaged over "Kentucky 31" and "BarOptima" tall fescue within 2011, 2012 and 2013 at Mt. Vernon, MO. The Wilcoxon rank-sum test was performed to compare average growth rates between years at α = 0.05

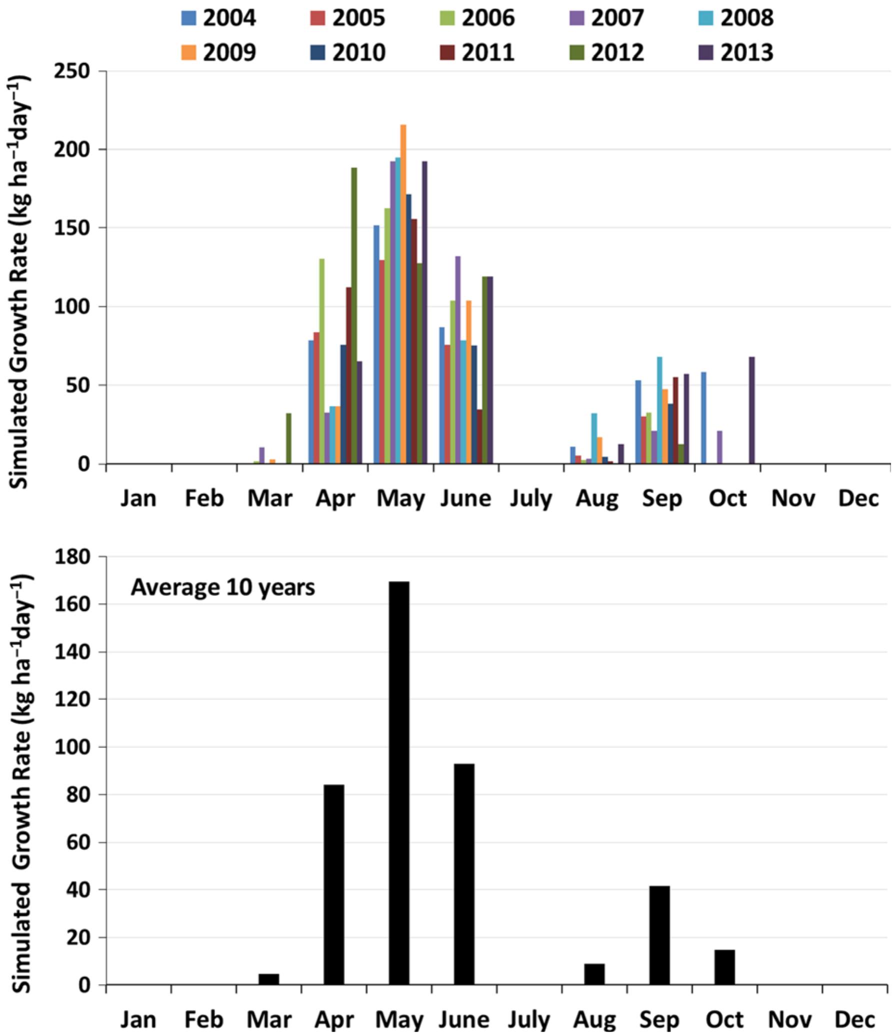

FIGURE 3 Simulated growth rate (above- and belowground biomass, kg ha^{-1} day^{-1}) of 2004–2013 and average simulated growth rate (above- and belowground biomass, kg ha^{-1} day^{-1}) over 10 years at Mt. Vernon, MO

TABLE 2 Measured and simulated yields per year of tall fescue in 2011, 2012 and 2013 at Mt. Vernon, MO

	Measured yield (t/ha)			Simulated	Measured/
Year	Kentucky 31	BarOptima	Mean	yield (t/ha)	simulated
2011	7.72	6.57	7.15	8.69	0.82
2012	7.60	7.55	7.58	6.97	1.09
2013	11.92	11.57	11.75	11.97	0.98

and one in South Carolina. With the exception of the Mt. Vernon site and one of the Alabama sites, all weather station sites have two or three contrasting soils simulated. These soils were chosen based on prominence in the area and reported yield of tall fescue. These sites were designed to determine whether the model developed from field growth data at one Missouri site was applicable across the region. The simulations include high- and low-yielding soils across the region.

We used the mean reported tall fescue yields for the 11 sites, with one to three soils per site (Table 1; Figure 1). These data are available at Natural Resources Conservation Service, United States Dept. of Agric. 2017. Web Soil Survey. Available online: http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx (accessed on 6 January 2017). The recorded yields were found by outlining the area of interest to include the site, accessing the "soil map" tab to identify the soils, and then accessing the "soil data explorer" tab. Users then accessed "vegetative productivity" and "yields of non-irrigated crops (component)" and specified "tall fescue." The conversion factor for these yield values to t/ha, taking into account unit differences and per cent moisture in tall fescue hay, is 1.005. This factor assumes 2,000 lbs per US ton, 0.454 kg/lb., 0.001 Mg/kg, 2.47 acres per ha. and 55.2% moisture (44.8% dry matter) in fescue hay (Pope, 2011).

Weather data were obtained from National Dept. of Commerce, National Oceanic and Atmospheric Administration. 2017. Climate Data Online Search. Available online: http://www.ncdc.noaa.gov/cdo-web/search) (accessed on 6 January 2017). Twenty years of recent weather data were used to make 20-year runs for each site. The last 10 years of simulations validated the model while 10 preliminary years of simulations allowed the model to stabilize. In these simulations, N was applied annually in direct relation to the reported NRCS values. Based on some of the initial runs at Mt. Vernon, the applied N was calculated as expected tall fescue yield (t/ha) times a 13.2 factor. This calculated value was the kg N applied per ha per year.

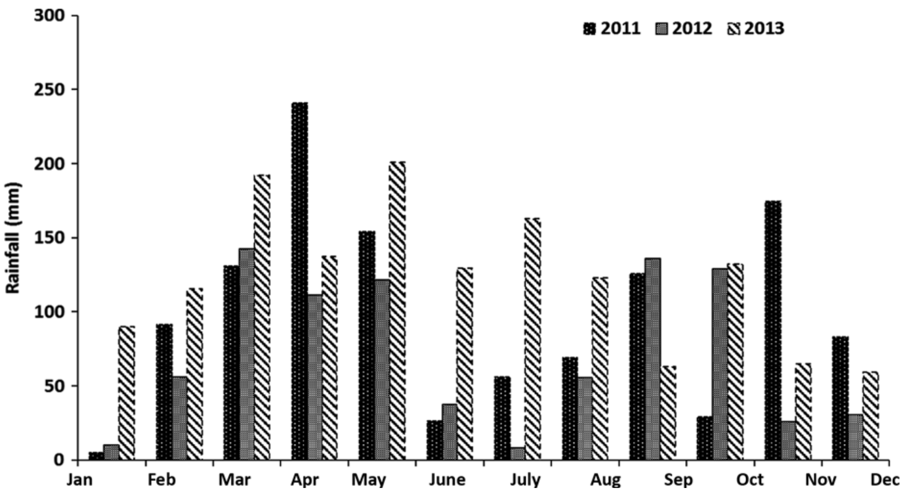

FIGURE 4 Monthly rainfall (mm) observed at Mt. Vernon, MO in 2011, 2012 and 2013

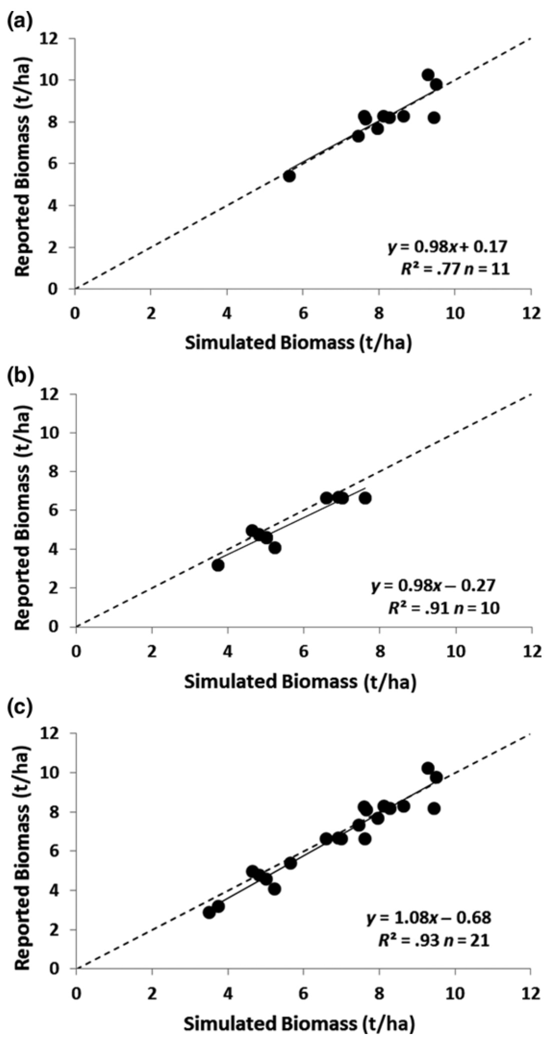

FIGURE 5 Reported (USDA-NRCS) and simulated tall fescue yields for (a) high-yielding soils, (b) low-yielding soils and (c) high- and low-yielding soils at diverse sites in the USA

The average measured yield at this site was divided by the annual applied N to get the 13.2 factor. This total annual amount in the simulations was split, with 40% applied 4 March and 60% applied on 17 August for each year. A paired t test was used to statistically compare mean annual simulated yields for all the soils combined and the NRCS values for annual tall fescue yields at $\alpha = 0.05$. In addition, the correlation and linear regression between simulated and measured tall fescue yields were estimated. This was performed for the high-yielding soils, for the lower yielding soils, and for all the soils combined.

3 | RESULTS

3.1 | Mt. Vernon, MO field data

No difference was found between two tall fescue varieties, "Kentucky 31" and "BarOptima" in the growth rates within each year ($p = .5725$ for 2011; $p = .7796$ for 2012; $p = 0.9247$ for 2013) (Figure 2). Both tall fescue varieties showed bimodal growth patterns shown as the growth reduction or dormancy interval begins near the longest day of the year (20 June) and lasts about 5 weeks. Growth resumed thereafter. The growth curves for the two varieties show similar dormancy (reduced growth) between 2011 and 2012 ($p = .9647$) (Figure 3). The similar growth curve observed in 2011 and 2012 resulted in similar annual production (Table 2). However, in 2013, the growth curves for the two varieties showed a shorter dormancy period and less growth reduction ($p = .0004$ for 2012 vs. 2013; $p = .0007$ for 2013 vs. 2011) (Figure 2). The maximum growth rates in the spring and fall 2013 were much higher than in 2011 and 2012 (Figure 2), which resulted in the highest annual production yield (Table 2).

3.2 | Adaptation of the ALMANAC model to simulate mid-season dormancy

When we introduced midsummer dormancy in ALMANAC, we assumed dormancy began on the longest day of the year and lasted until the photoperiod was 0.68 hr shorter than the longest. When simulating tall fescue DM with 10 years of weather at Mt. Vernon, MO, we show similar monthly growth reductions to the measured trends (Figure 3). The model appears to realistically simulate the bimodal pattern expected (Figure 3).

3.3 | Validating the improved ALMANAC model with the Mt. Vernon field data

The simulated annual yield production agreed well with the average measured yields of two tall fescue varieties for all 3 years (Table 2). Like the measured growth curve (Figure 2), the simulated maximum growth rate in the fall 2013 was much higher than 2011 and 2012 (Figure 3), which resulted in a higher annual DM production value of 11.97 t/ha. The higher measured and simulated yields in fall may be due to greater rainfall during summer in 2013 (Figure 4).

3.4 | NRCS published yield data for model testing

The model shows very similar growth patterns at all the simulation sites as at the Mt. Vernon site (data not shown). The ALMANAC model does an excellent job simulating reported tall fescue yields across the range of sites (Table 1; Figure 5). Simulated yields were not significantly different from NRCS values for all selected sites (p = .63). Simulated yields account for 77% of the variability in measured yields for the group of high-yielding sites (Figure 5a). The fitted regression line for this group of sites is close to the 1:1 line with zero intercept. For the low-yielding sites (Figure 5b), again the model does an excellent job compared to reported yields. The simulated yields account for 91% of the variability in measured yields. Similar to the high-yielding site results, the fitted regression is close to the 1:1 line with zero intercept. Finally, for all the data pooled (Figure 5c), the model also does an excellent job compared to the reported yields. Simulated yields account for 93% of the variability in measured yields. The fitted regression again is similar to the 1:1 line with zero intercept.

4 | DISCUSSION

The bimodal growth in the Mount Vernon field data agrees with previous reports (Burns & Chamblee, 1979; Kallenbach & Bishop-Hurley, 2002). When we introduced dormancy into the ALMANAC model, the model realistically simulated the bimodal pattern expected. In addition, the resulting simulated annual yield production agreed well with the average measured yields of two tall fescue varieties at Mount Vernon for all 3 years. The higher measured and simulated yields in fall of 2013 at Mount Vernon may be due to greater rainfall during summer in 2013. High summer rainfall can shorten the duration of summer dormancy, potentially resulting in less growth reduction and higher accumulated yield in fall. Similar results have been observed by Bates, Denton, and Beeler (2009) who reported that during July, rainfall increased more than 250% above the average rainfall, resulting in increased tall fescue yields. Finally, the accurate simulations when ALMANAC was applied to a wide range of sites and soils across the main region for tall fescue support that the model changes are realistic.

5 | CONCLUSION

Results from this study show great promise for the ALMANAC model's ability to simulate bimodal growth in a common cool-season grass, tall fescue. Using frequent estimates of tall fescue growth for two varieties over 3 years at a Missouri site, the pattern of plant dormancy response to photoperiod was determined. Tall fescue began dormancy near the longest day of the year (June 20th) and remained dormant approximately 5 weeks. Introducing this responsiveness into the ALMANAC model resulted in similar simulated growth patterns at the Missouri site. Subsequent simulations at a wide range of sites showed similar simulated growth patterns. In addition, when the model was applied to this wide range of sites in the tall fescue-growing region of the USA, the model realistically simulated annual reported yields. Thus, the ALMANAC model, with these modifications, is a realistic tool for pasture management of this important forage. Similarly, work with other cool-season forages would allow extension of this model into other pasture systems in other regions.

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