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MODELING ABOVEGROUND BIOMASS ACCUMULATION OF COTTON

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ABSTRACT

The objective of this study was to develop an improved model for describing the accumulation of aboveground cotton biomass. The model input was RTEP, which was the normalized product of thermal effectiveness and photosynthetically active radiation. The model was calibrated using data from field plots with five N rates and two cotton cultivars. Model validation was conducted using data from three independent cotton fields. Eight nonlinear functions described cotton growth well (R>0.0.894, SD<0.05). The parameters of the functions were then compared and the results indicated that the Richards function best fit the nonlinear relationships in a biologically meaningful way. The equation was as follows: relative aboveground biomass accumulation (RAGBA) = $1.024/(1+e^{6.646-10.115RTEP})^{1/1.417}$ (r = 0.981, s = 0.043). Validation results indicated that the root mean square error was 0.659 t hm^{-2}, the relative error was 5.337%, the coefficient of concordance was 0.988, and the coefficient of determination was 0.961. The second derivative of the optimized model showed that in cotton, the process of aboveground biomass accumulation could be divided into three phrases using two inflection points. When the accumulation rate of the aboveground biomass of cotton was at its maximum, the relative product of thermal effectiveness and PAR was 0.622, the maximum rate of the aboveground biomass accumulation was 2.299, and the aboveground biomass accumulation was 0.549. In conclusion, our study indicates that the product of thermal effectiveness and PAR is a valuable parameter for estimating aboveground biomass accumulation in cotton.

Key words: Cotton, Aboveground biomass accumulation, Product of thermal effectiveness and PAR (TEP), Normalization, Richards Model

INTRODUCTION

Plant development and biomass accumulation are complex and multifaceted processes (Arshadullah *et al*., 2009; Meade *et al*., 2013). An accurate model of biomass accumulation in plants could provide a much needed description of important aspects of plant development (Meade *et al*., 2013; Torrez *et al*., 2013). Such a model could describe and predict that which would be difficult to obtain experimentally. In addition, dynamic simulation models of plant growth would be an invaluable aid in the decision-making process of farmers.

A good model is flexible enough for use under a variety of environmental conditions and simple enough that it can be included in more complex models of whole plant growth (Meade *et al*., 2013). Many investigators have examined the link between climate and plant biomass accumulation, with the observed climate acting as a boundary forcing for the plant model (Osborne *et al*., 2007).

Several methods have been developed to estimate biomass accumulation of crops. Most of these use the segmented model approach, which combines multiple linear models to describe biomass accumulation (Meade *et al*., 2013). The use of segmented models, which assumes that each stage of growth is distinct from the next, is perhaps the simplest method for analyzing crop growth. However, segmented models cannot describe continuous biomass accumulation. Nonlinear functions are needed to model the continuous growth of crops.

Nonlinear functions that model crop biomass accumulation generally have a sigmoid shape (i.e., logistic, Weibull, or Gompertz). Nonlinear function models of plant growth have been developed for many crops (Thornley and France, 2007), including maize (Gambín *et al*., 2008; Meade *et al*., 2013), sorghum (Gambín *et al*., 2007), soybean (Board *et al*., 2005), rice (Qiao *et al*., 2013), wheat (Pepler *et al*., 2006) and safflower (Dordas *et al*., 2009). Recent studies have either used days after emergence (DAE) or growing degree days (GDD) as independent variables in models of biomass accumulation (Meade *et al*., 2013; Xue, *et al*., 2008; Yang *et al*., 2012). Although both inputs have been shown to be accurate predictors of biomass accumulation, models using GDD are generally considered to be more accurate than models using DAE for describing the entire growth process of crops (Meade *et al*., 2013). The GDD method, which utilizes thermal units, was developed to improve accuracy in estimating the physiological maturity of crops. However, the GDD method does not take into consideration the effect of photosynthetic active radiation (PAR) or global radiation (Q) on crop growth.

Cotton yield is generally determined by two factors: biomass accumulation and the proportion of biomass partitioned to the reproductive organs (Bange and Milroy, 2004; Saleem *et al*., 2010; Yang *et al*., 2011; Yang *et al*., 2012). The accumulation of aboveground biomass at different growth stages directly influences vegetative and reproductive growth. The accumulation rate varies among growth stages. For example, Yang *et al*., *(*2012) observed that nearly 65% of total cotton biomass accumulated between first bloom and peak bloom, regardless of N application rate. The authors referred to this time as the period of fast biomass accumulation (Yang *et al*., 2012).

In this paper, we used the abbreviation TEP to represent the product of thermal effectiveness and PAR The TEP value was calculated for each day during the cotton growing season and then normalized to obtain relative TEP (RTEP). The RTEP values were then used as independent variables in non-linear models describing aboveground biomass accumulation in cotton. Nitrogen uptake is a critical factor limiting the accumulation of aboveground cotton biomass. Cotton biomass generally increases as N fertilizer application increases. Therefore, the models were calibrated using data from cotton grown with five different N application rates. The specific objectives of this study were (i) to assess the relationship between aboveground cotton biomass and TEP, (ii) to select the best nonlinear function for modeling the accumulation of aboveground biomass in cotton, and (iii) to verify the models using data collected from three fields of high-yield cotton.

MATERIALS AND METHODS

Experiment Design: Experiment 1 consisted of plot experiments at two locations near Shihezi, Xinjiang Uyghur Autonomous Region, China. The plots were at the National Agricultural Hi-tech Demonstration Park in 2010 and at the Shihezi University Agricultural Experiment Station in 2011. The soil at both sites is heavy loam. Selected soil properties at the two sites are shown in Table 1.

Cotton was sown by hand on April 20, 2010 and April 16, 2011. The cotton cultivars were ‘Xinluzao 43’ (XLZ 43) and ‘Xinluzao 48’ (XLZ 48). The plant density was 2.63×10^5 plant hm^{-2}. The study included five N fertilizer application rates: 0 kg hm^{-2} (N0), 120 kg hm^{-2} (N1), 240 kg hm^{-2} (N2), 360 kg hm^{-2} (N3), and 480 kg hm^{-2} (N4). The plots were arranged in a randomized complete block design with three replicates. The area of each plot was 46 m^2 (4.6 m × 10 m).

Each plot was completely covered by laying three sheets of plastic film (1.4 m wide × 10 m long) edge to edge. Each sheet of plastic film had four rows of cotton, with row spacings of 10 cm - 66 cm - 10 cm - 66 cm (Fig. 1a). There were 10 cm between each hill within a row. Two drip tapes were laid under each sheet of plastic film. The emitter discharge rate was 3.2 l h^{-1} and the emitter spacing was 0.30 m. After sowing, 600 m^3 ha^{-1} of water was immediately applied to each plot via drip irrigation to promote germination. A total of 5400 m^3 hm^{-2} of water was applied during the growing season. The water was divided evenly among 11 irrigation events. Waterproof membrane was buried to a depth of 60 cm around each plot to prevent water movement between plots.

The plots were fertilized at planting with 75 kg K_2O hm^{-2} as potassium chloride and 150 kg P_2O_5 hm^{-2} as calcium superphosphate. Nitrogen fertilizer (urea) was applied via drip irrigation, with 10% of the N applied at planting, 25% applied at budding, 45% applied at blooming, and 20% applied at full boll (Table 2). The remaining management practices were the same as those used by local farmers.

Experiment 2 was conducted in 2012 at fields belonging to the Agricultural Modernization of Xinjiang Production and Construction Corps (43°06'-45°20' N). Cotton cultivar ‘Xinluzao 45’ (XLZ 45) was grown on Field 9, Company 2, 105th Corp of the 6th Division. Cultivar ‘Biaoza A_1’ (BZ A_1) was grown on Field 3, Company 5, 149th Corp of the 8th Division. Cultivar ‘Shiza 2’ (SZ 2) was grown on Field 6, Company 19, 150th Corp of the 8th Division. The total area of each irrigated field was approximately 450 hm^2. The cotton in all three fields was sown on April 23, 2012. The plant density was 2.5×10^5 plants hm^{-2}. Two drip tapes were placed under the plastic film with an emitter discharge rate of 3.2 l h^{-1} and emitter spacings of 0.30 m. The total amount of irrigation water applied during the growing season was 5400 m^3 hm^{-2}. Fertilizer was applied at planting at the following rates: 375 kg N hm^{-2} as urea, 150 kg P_2O_5 hm^{-2} as calcium superphosphate, and 75 kg K_2O hm^{-2} as potassium chloride. All other aspects of crop management were the same as in experiment 1.

Measurement of Aboveground Biomass: In Experiment 1, nine similar plants were removed from each plot every 14 days from emergence to harvest during the 2010 and 2011 growing seasons. In Experiment 2, 30 similar plants were removed from each field every 14 days from emergence to harvest in 2012. The plants were separated into stems, leaves, buds, blooms and bolls, and open-bolls. Plant samples were dried for 30 min at 105 °C and then at 80 °C until reaching constant weight.

Climatological Information: Climatological data in Experiment 1 was obtained from an observation station belonging to the Shihezi Weather Bureau. Photosynthetically active radiation (PAR), global radiation (Q), and temperature (T) were automatically measured every hour during the growing season. In experiment 2, climatological data was obtained by weather stations belonging to each corp.

Calculation of Thermal Effectiveness: Thermal effectiveness (TE) is the ratio of crop growth for 1 d under real temperature conditions to crop growth for 1 d under ideal temperature conditions. The relationship between TE and temperature can be expressed each hour according to Equation (1):

$$TE = \begin{cases} 0, & T \le T_b \\ (T - T_b)/(T_o - T_b), & T_b < T < T_o \\ 1, & T = T_o \\ (T_m - T)/(T_m - T_o), & T_o < T < T_m \\ 0, & T \ge T_m \end{cases} \quad (1)$$

where T_o is the optimum growth temperature; T_b is the base temperature of growth; T_m is the maximum temperature of growth; and T is the mean temperature each hour. The values of T_b, T_o and T_m of cotton were set as follows: from sowing to emergence, T_b = 12 °C, T_o = 30 °C, and T_m = 45 °C; from emergence to boll opening, T_b = 12 °C, T_o = 30 °C, and T_m = 35 °C (Guan *et al*., 2013; Hawkins *et al*., 2012; Suleiman *et al*., 2013).

Photosynthetic Active Radiation: There are two methods for measuring PAR. Radiation studies usually report PAR using the energy system (Q_{PAR}, w m^{-2}). Agricultural and ecological studies usually report PAR using the quantum system (U_{PAR}, μmol m^{-1} s^{-1}). We chose the latter method for calculating PAR in this study, using the following equation:

$$PAR = ¦_Q \times Q \quad (2)$$

where $¦_Q$ is the photosynthesis coefficient, i.e. the proportion of PAR in total solar radiation Q. The normative value is 0.5 (Wang *et al*., 2013).

Calculating the Product of TE and PAR: Ni *et al* (2009) developed a dynamic model describing the total accumulation of aboveground crop biomass. The model first multiplied hourly values of TE and PAR to obtain a value called HTEP (μmol m^{-2} h^{-1}) for each hour of every day during the growing season. The formula for calculating HTEP is as follows:

$$HTEP = \begin{cases} TE \times PAR \times 3600, & PAR > 0 \\ TE, PAR < 0 \end{cases} \quad (3)$$

where TE is a unitless estimate of thermal effectiveness ranging between 0 and 1, PAR is the average instantaneous photosynthesis active radiation (μmol m^{-2} s^{-1}), and 3600 is a constant for converting average instantaneous PAR into total PAR for one hour.

The HTEP values were summed over 24 h to obtain daily TEP (DTEP, μmol m^{-2} d^{-1}) according to the following equation:

$$DTEP = \sum_{i=1}^{24} (HTEP \times 10^{-6}) \quad (4)$$

The DTEP values within each growth stage were summed to obtain accumulated TEP during that stage.

$$TEP_{i+1} = TEP_i + DTEP_{i+1} \quad (i = 1,2,3,\ldots\ldots n) \quad (5)$$

where TEP_{i+1} is the TEP on Day *i*+1 (mol m^{-2}) of that growth stage; TEP_i is the TEP on Day *i* (mol m^{-2}); and $DTEP_{i+1}$ is the TEP on Day *i*+1 (mol m^{-2} d^{-1}). Total TEP was used as the independent variable in the model for predicting the accumulation of aboveground cotton biomass.

Normalization of Data: The biomass data were normalized by calculating the relative aboveground biomass accumulation at each growth stage (RAGBA). The following equation was used:

$$RAGBA_i = AGBA_i / AGBA_{total} \quad (0 \leqslant RAGB_i \leqslant 1) \quad (6)$$

where $RAGBA_i$ is the relative aboveground biomass accumulation within growth stage *i*; $AGBA_i$ is the measured accumulation of aboveground biomass accumulation within growth stage *i* (t hm^{-2}); and $AGBA_{total}$ is the total aboveground biomass accumulation within the growing season (t hm^{-2}).

The TEP values within a growth stage were normalized to obtain relative TEP (RTEP) using the following equation:

$$RTEP_i = TEP_i / TEP_{total} \quad (0 \leqslant TEP_i \leqslant 1) \quad (7)$$

where $RTEP_i$ is the RTEP at growth stage *i*; TEP_i is the TEP at growth stage *i* (mol m^{-2}); and TEP_{total} is total TEP during the growing season (mol m^{-2}).

Statistical Analysis and Model Verification: Correlation analysis between accumulated RTEP and RAGBA were performed using SPSS 17.0 software. Origin Pro 8.5 was used to prepare the figures. Curve Expert 1.4 was used for fitting the data. Sigma Plot 10.0 was used to draw 1:1 straight line graphics. Data collected from Experiment 1 was mainly used to calibrate the regression models. Data collected from three independent fields (Experiment 2) was subsequently used to validate the regression models under different management practices. The performance of the models was estimated by comparing the differences in coefficient of determination (R^2), root mean square error (RMSE), relative error (RE, %), and coefficient of concordance (CC). The precision and accuracy of the models increased as R^2 and CC increased and as RMSE and RE decreased. The values of RMSE, RE and CC were calculated using Eq.(8), Eq.(9) and Eq.(10), respectively:

$$RMSE = \sqrt{\frac{\sum_{n=1}^{n} (O_m - S_m)^2}{n}} \quad (8)$$

$$RE = \left(RMSE / \hat{O}_m\right) \times 100\% \quad (9)$$

$$CC = 1 - \left[\sum_{n=1}^{n} (O_m - S_m)^2 \Big/ \sum_{n=1}^{n} \left(\left|O_m - \hat{O}_m\right| + \left|S_m - \hat{O}_m\right| \right)^2 \right] \quad (10)$$

where O_m is the measured aboveground biomass, S_m is the predicted aboveground biomass, $\hat{O}_m$ is the mean of the measured values of relative aboveground biomass, and *n* is the number of samples.

RESULTS

Accumulation of Aboveground Biomass: Aboveground biomass of both cotton cultivars increased as TEP increased in all five N treatments. The increase generally followed an S-shaped pattern (Fig. 2). Significant differences in aboveground biomass were observed among the N treatments. In both 2010 and 2011, aboveground biomass increased as the N rate increased when TEP was less than about 1720 mol m^{-2}. However, when TEP was greater than about 1720 mol m^{-2}, N3 had the highest aboveground biomass accumulation followed by the N4, N2, N1, and then N0 treatments. These results were somewhat different than we expected. We observed that boll weight was lower in the N4 treatment than in the N3 treatment (data not shown). This suggests that excess N delayed cotton maturity and inhibited boll development, and that this had significant influence on the accumulation of total aboveground biomass. Plants in the N0 treatment were N deficient during the entire growing season. As a result, aboveground biomass accumulation was lowest in the N0 treatment. These results show that reasonable application of N fertilizer is a key factor for increasing the biomass accumulation and yield of cotton.

Relationship between RAGBA and RTEP: In experiment 1, two cotton cultivars were grown with five N rates. The values RAGBA and RTEP were obtained by normalization of AGBA and TEP from emergence to boll-opening. The relationship between RAGBA and RTEP was then established. Data were fitted using eight nonlinear functions (i.e., Rational, Polynomial, Growth, Morgan-Mercer-Flodin (MMF), Weibull, Gompertz, Logistic and Richards (Table-3). The fitted curves of all eight functions described biomass accumulation well, with the lowest R value belonging to the rational function (0.894, P<0.05). The eight functions were compared to determine which function was most appropriate for describing cotton growth. To be included in the comparison, each function had to meet three requirements, i.e. RTEP equals 0, 1, and positive infinity (Table-3). The following Richards equation was the best nonlinear function:

$$y = a/(1+e^{b-cx})^{1/d} \quad (11)$$

where y is the dependent variable, representing RAGBA; x is an independent variable, representing RTEP; a is the relative maximum growth; b is the initial value of the parameter; c is the relative growth rate parameter; and d is the curve shaping parameter.

The best fit function of the Richards equation produced a sigmoid curve (Figure-3). The parameters of a, b, c, and d are given separately in Table-4 (R^2>0.902). Parameter ‘a’ approached 1 in each model (Table-4). This indicates that the parameter has biological significance and that the model should be able to describe the accumulation of aboveground cotton biomass throughout the growing season. The best fit equation of the Richards function is as follows:

$$RAGBA = \frac{1.024}{\left(1+e^{6.646-10.115RTEP}\right)^{\frac{1}{1.417}}} \quad (12)$$

Verification of the Optimized Model: Data from experiment 2 were used to verify the best fit equation of the Richards function. The RTEP at any given time was substituted into equation (12) to obtain its corresponding RAGBA value. The RAGBA value was then multiplied by $AGBA_{total}$ to determine the AGBA value at any time. There was good agreement between the simulated and observed values at the three independent sites (Fig. 4). The statistical characteristics of the model were as follows: RMSE, 0.659 t hm^{-2}; RE, 5.337%; CC, 0.988; and R, 0.961.

Stage Division of Normalization Model: The accumulation rate of aboveground biomass can be obtained from the first derivative of Equation (11) as shown in Equation (13).

$$dy/dx = a \times c \times e^{(b-cx)} \Big/ \left[d\left(1+e^{(b-cx)}\right)^{(d+1)/d} \right] \quad (13)$$

The second derivative of Equation (11) was then solved. And assuming that the second derivative Equation was equal to 0, and then the RTEP values of two reflection points, $RTEP_1$ and $RTEP_2$, were obtained.

$$RTEP_1 = x_1 = -\ln\left(\frac{d^2+3d+d\sqrt{d^2+6d+5}}{2e^b}\right) \Big/ c \quad (14)$$

$$RTEP_2 = x_2 = -\ln\left(\frac{d^2+3d-d\sqrt{d^2+6d+5}}{2e^b}\right) \Big/ c \quad (15)$$

The values of a, b, c, and d were substituted into Equations (14) - (15) to obtain $RTEP_1$ = 0.381 and $RTEP_2$ = 0.719. Therefore, the process of aboveground biomass accumulation in cotton was divided into three stages. The ranges in the RTEP values were as follows: 0-0.3805 for the early stage of cotton growth, 0.38-0.719 for the intermediate stage of cotton growth, and 0.719-1.00 for the late stage of cotton growth.

Biomass accumulation ceases when plants reach 95% of physiological maturity (Sala *et al*., 2007). Therefore, our model was adjusted so that the growth of cotton stopped when AGBA reached 95% of its maximum. The corresponding $RTEP_3$ was expressed by the following equation:

$$RTEP_3 = x_3 = -\ln\left[\frac{(100 \times a/95)d - 1}{e^b}\right] \Big/ c \quad (16)$$

The parameter values of a, b, c and d were substituted into Equation (16) to obtain $RTEP_3$ = 0.9103. Thus, the third stage of the aboveground biomass accumulation was divided into 0.719-0.910.

Application of the Characteristic Parameters of the Model: Based on the second derivative of Equation (11), and assuming that the second derivative Equation was equal to 0, the accumulated RTEP was obtained when the maximum aboveground biomass accumulation rate was reached. This value was substituted into the first derivative of Equation (11) to obtain the maximum accumulation rate of aboveground biomass. After determining the maximum accumulation rate of aboveground biomass, RTEP was substituted into Equation (11) to determine RAGBA. The equations for the above mentioned parameters are as follows:

$$RG_{ave} = \frac{1}{a}\int_0^a \frac{dy}{dx}dx = \frac{a \times c}{2(d+2)} \quad (17)$$

$$ARTEP = (b - \ln d)/c \quad (18)$$

$$AR_{\max} = \frac{a \times c}{(1+d)^{(d+1)/d}} \quad (19)$$

$$ARAGBA = \frac{a}{(1+d)^{1/d}} \quad (20)$$

where RG_{ave} is the relative average growth rate of aboveground biomass accumulation of cotton, ARTEP is the relative product of thermal effectiveness and PAR after determination of the maximum accumulation rate of aboveground biomass accumulation, AR_{max} is the maximum accumulation rate of aboveground biomass, and ARAGBA is the relative aboveground biomass accumulation after determination of the maximum accumulation rate. The parameter values of a, b, c, and d were substituted into Equations (17) - (20) to obtain RG_{ave}=1.516, ARTEP=0.622, AR_{max}=2.299, and ARAGBA=0.549. Therefore, when the accumulation rate of the aboveground biomass of cotton was at its maximum, the relative product of thermal effectiveness and PAR was 0.622 and the value of aboveground biomass accumulation was 0.549. The latter value was approximately 60% of the total aboveground biomass.

Table-1: Selected soil properties at the experimental fields

Year	Location	Organic matter ($mg\ kg^{-1}$)	Alkaline-N ($mg\ kg^{-1}$)	Olsen-P ($mg\ kg^{-1}$)	Available K ($mg\ kg^{-1}$)	pH Value
2010	Demonstration zone	29.63±1.02	69.72±2.32	19.83±3.24	518.25±50.31	7.8±0.27
2011	Test station	16.29±0.97	52.35±1.49	35.80±1.26	219.02±34.25	7.1±0.21

Table-2: Fertilizer application rates in the plot experiments

Treat-ment	Total fertilizer ($kg\ ha^{-2}$)			Amount applied at planting ($kg\ ha^{-2}$)			Amount of N fertilizer applied as topdressing ($kg\ ha^{-2}$)		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	Bud stage	Bloom stage	Full boll stage
	Distribution ratio			10%	100%	100%	25%	45%	20%
N0	0	150	75	0	150	75	0	0	0
N1	120	150	75	12	150	75	30	54	24
N2	240	150	75	24	150	75	60	108	48
N3	360	150	75	36	150	75	90	162	72
N4	480	150	75	48	150	75	120	216	96

Table-3: Dynamic models of relative aboveground biomass accumulation in cotton

Model	Fitted equation	Parameter a	b	c	d	R	SD	y value X→∞	x = 0	x = 1
Richards	$Y=a/(1+e^{b-cx})^{1/d}$	1.024	6.645	10.115	1.417	0.983**	0.042	a	0.009	1.002
Logistic	$Y=a/(1+be^{-cx})$	1.043	182.489	8.575		0.981**	0.046	a	0.005	1.008
Gompterz	$Y=a(e^{-e})^{b-cx}$	1.195	3.309	5.093		0.974**	0.049	a	0	1.049
Weibull	$Y=a-b(e^{-cx})^d$	0.974	0.882	8.210	5.837	0.953**	0.047	a-b	0.009	0.973
MMF	$Y=(ab+cx^d)/(b+cx^d)$	0.112	0.033	1.026	8.258	0.941**	0.042	c	0.011	0.994
Growth	$Y=a(b-e^{-cx})$	7.149	0.915	0.270		0.917**	0.046	a*b	0.054	1.079
Polynomial	$Y=a+bx+cx^2+dx^3$	1.725	-10.149	19.096	-9.713	0.901**	0.043	∞	1.382	0.958
Rational	$Y=(a+bx)/(1+cx+dx^2)$	-0.041	0.218	-2.036	1.223	0.894**	0.048	0	0.002	0.948

Note: x and y in the model represent RTEP and RADBA, respectively, ** indicates significant difference at P<0.01; Among the parameters, a denotes the relative maximum change; b denotes the initial value of the parameter; c denotes the growth rate parameter; d denotes the curve shaping parameter. The same abbreviations will be used in the following tables.

Table-4: Parameters of the optimal model for relative aboveground biomass accumulation of cotton grown with different N rates

Year	Cultivar	N rates	Parameter a	Parameter b	Parameter c	Parameter d	R	SD
2010	XLZ 48	N0	1.010	11.983	14.468	3.764	0.907**	0.009
		N1	1.000	6.695	9.750	1.790	0.913**	0.026
		N2	0.999	7.941	12.501	1.934	0.942**	0.019
		N3	0.999	3.677	7.208	0.774	0.967**	0.022
		N4	1.000	3.735	7.607	0.722	0.935*	0.021
	XLZ 43	N0	1.000	13.394	16.048	3.094	0.902**	0.014
		N1	0.993	2.2051	5.589	0.392	0.924**	0.017
		N2	0.995	1.916	5.669	0.343	0.955**	0.023
		N3	1.000	4.108	7.855	0.840	0.979**	0.020
		N4	0.999	4.038	8.076	0.768	0.964**	0.026
2011	XLZ 48	N0	0.999	8.934	11.510	3.740	0.904**	0.011
		N1	1.000	19.397	26.251	1.185	0.943**	0.030
		N2	1.000	11.326	16.506	1.508	0.952**	0.020
		N3	1.000	11.755	17.074	1.572	0.985**	0.027
		N4	0.999	10.529	15.231	1.539	0.953**	0.042
	XLZ 43	N0	1.000	11.710	14.719	3.259	0.965**	0.037
		N1	1.000	21.980	29.975	1.975	0.960**	0.041
		N2	1.000	12.844	18.353	1.799	0.984**	0.024
		N3	1.000	13.804	19.845	1.838	0.978**	0.034
		N4	0.999	12.385	17.723	1.949	0.961**	0.041

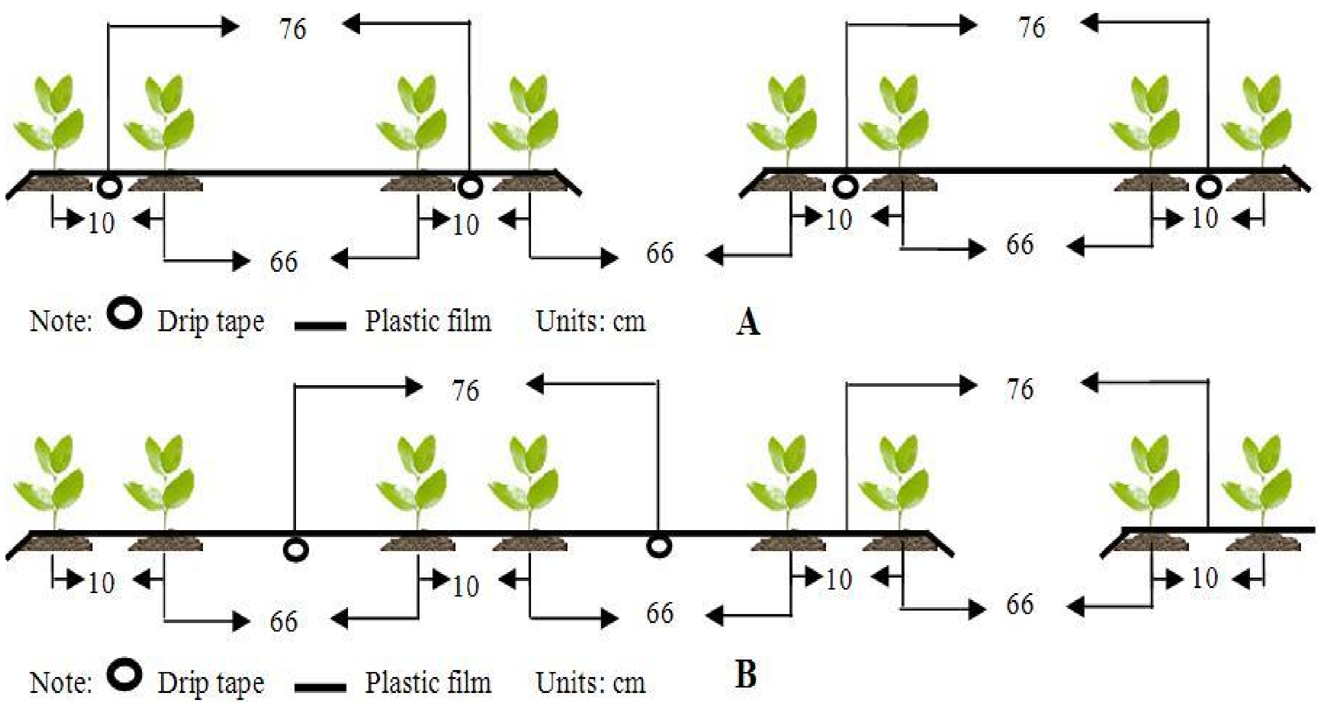

Figure-1: Diagram of the planting pattern in the cotton plots.

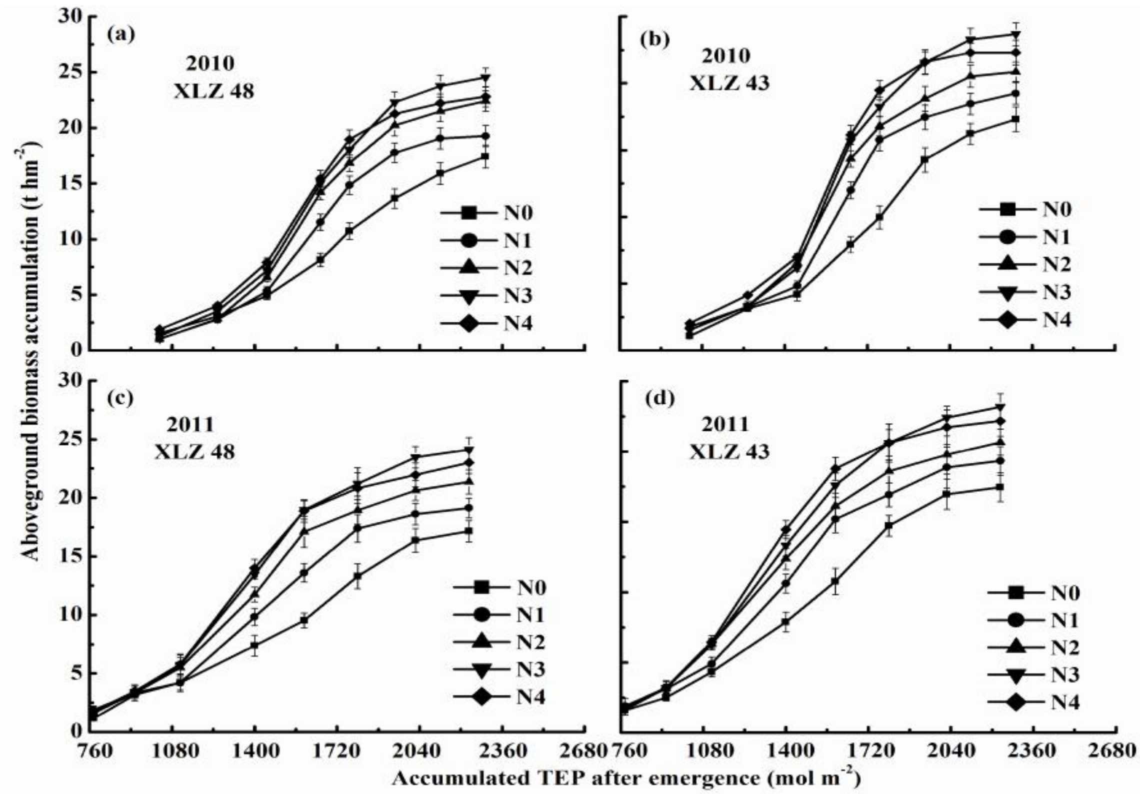

Figure-2: Changes in accumulated aboveground biomass with accumulated TEP. (a) and (c) show the results for cotton cultivar 'Xinluzao 48' (XLZ 48) in 2010 and 2011 respectively. (b) and (d) show the results for cultivar 'Xinluzao 43' (XLZ 43) in 2010 and 2011 respectively. The N fertilizer rates were 0 kg hm^{-2} (N0), 120 kg hm^{-2} (N1), 240 kg hm^{-2} (N2), 360 kg hm^{-2} (N3), or 480 kg hm^{-2} (N4).

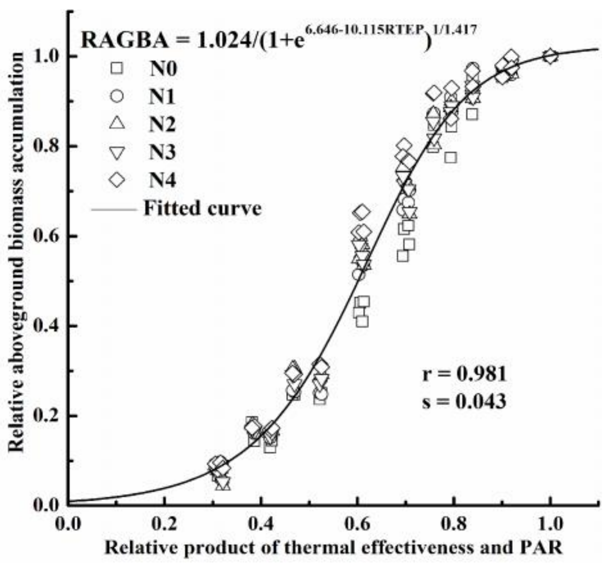

Figure-3: Richards model showing the relationship between the normalized values of aboveground biomass accumulation (RAGBA) and the normalized values of the product of thermal effectiveness and photosynthetically active radiation (RTEP).

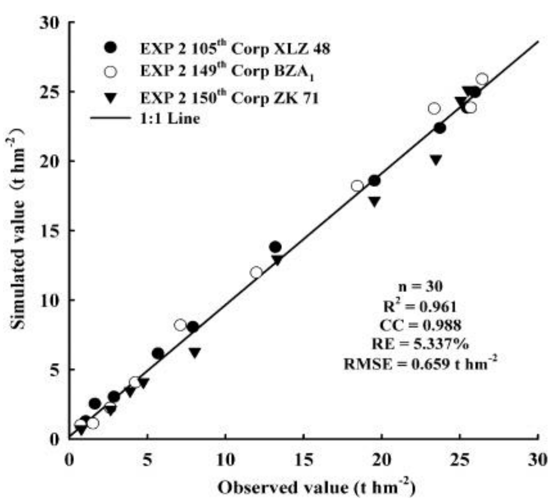

Figure-4: Comparison between the simulated and observed values for the accumulation of aboveground cotton biomass. The data were for three sites, each with a different cotton cultivar. Abbreviations: Exp 2, Experiment 2; 105 XLZ 48, Variety XLZ 48 planted at the 150th Corp; 149-BZ A_1, Variety BZ A_1 planted at the 149th Corp; 150 ZK71, Variety ZK 71 planted at the 150th Corp.

DISCUSSION

The results showed that cotton has a sigmoid growth pattern that can be best explained using nonlinear growth models with RTEP as the independent variable in the model (Figure-3). We compared the ability of eight nonlinear functions to describe cotton growth in a biologically meaningful way. All eight functions met the three basic requirements for interpreting the accumulation of aboveground cotton biomass in a biologically meaningful way. However, when RTEP was positive infinity, parameter a in the Weibull, MMF, Growth, Polynomial, and Rational functions did not approach “1” (Table-3). This means that the RAGBA value predicted by the functions did not equal the total aboveground cotton biomass. Therefore, these five functions were excluded from further consideration. The remaining three models were tested using RTEP values of “0” (minimum) and “1” (maximum). When RTEP = 0, the RAGBA value of Gompterz was 0 (Table-3). This had no biological meaning; therefore, this model was also excluded from further consideration.

The Richards model and the Logistic model both did a good job of describing cotton growth. The Logistic model has been commonly used to describe the process of biomass accumulation in cotton (Yang *et al*., 2011, Yang *et al*., 2012) and in other food crops (Melchiori and Caviglia, 2008; Overman and Scholtz, 2011; Pepler *et al*., 2006). The Logistic model easily converges when placed within a statistical model as a regression covariate. However, Logistic functions have limitations. For example, they force a symmetric curve, which may not be biologically relevant (Overman and Scholtz, 2013). In addition, symmetry assumes that the acceleration of growth after the lag phase occurs at the same rate as the slowing of growth as maturity approaches (Overman and Scholtz, 2013). Overall, the Logistic function does not perform as well as the Richards model.

Our results clearly indicate that a Richards function can accurately estimate the accumulation of aboveground cotton biomass. Furthermore, RTEP, which reflects both the thermal and light conditions that cotton is growing under, is valuable as an input into the Richard’s model. The Richards function has been widely used to describe the growth of many crops (Meade *et al*., 2013), thus demonstrating its flexibility (Overman and Scholtz, 2013). In our study, the parameters of the Richards model were related to cotton growth in both 2010 and 2011 in a biologically meaningful way (Table-4). The results need to be validated under different growing conditions and at different sites. The close relationships between the observed and simulated values illustrates that the Richards model showed good goodness of fit for experiment 2. The highest R^2 values were obtained from the verification model (Figure-4). We concluded that the Richards function can accurately model cotton growth.

For convenience, we chose to normalize the observed values of AGBA and TEP at each cotton growth stage. The resulting values, RAGBA and RTEP, were used in the calibration of the nonlinear models. The normalized method enables researchers to obtain beneficial information. Normalization can not only overcome changes in model parameters caused by different cultivation techniques and cultivars but it can also improve the versatility of the model. This Richards model had relatively small parameters and straightforward biological interpretation. The credibility and universality of the model was enhanced. Future work is needed to improve the analytical method.

Analytical solutions can be found from nonlinear differential equations that are based on key fundamental processes (Overman and Scholtz, 2011). The first derivative (dy/dx) can be used to assess the relative characteristic values in the Richards model (i.e. AR_{max}, ARTEP, ARAGBA and RG_{ave}). Using the second derivative of the Richards model, the process of aboveground biomass accumulation in cotton was split into three stages using two inflection points. During the initial (lag) stage, there is little biomass accumulation (Meade *et al*., 2013; Sala *et al*., 2007a). In contrast, there is rapid, nearly linear accumulation in aboveground biomass during the next stage, which is between $RTEP_1$ and $RTEP_2$ (Figure-3). During this period, biomass accumulation reached approximately 60% of the total aboveground biomass accumulation during the growing season. Cotton biomass accumulated most rapidly between first bloom and peak bloom in each N treatment. This agreed with a previous report by Yang *et al* (2012).This period of fast growth was considered to be the key period (or sensitive period) for aboveground biomass accumulation of cotton. Soil fertility must be carefully managed during this period to ensure maximum yield (Boquet, 2005; Clawson *et al*., 2008; Kumbhar *et al*., 2008; Yang *et al*., 2012). During the final stage, cotton growth slows until a maximum weight is reached. At some point in the final stage, the cotton reaches physiological maturity and ceases to accumulate aboveground biomass (Meade *et al*., 2013; Sala *et al*., 2007a). Overall, the second stage in the process of aboveground biomass accumulation process was most important for cotton growth and yield formation. It is especially important to provide for the N needs of the cotton crop during this time (McConnell and Mozaffari, 2005; Yang *et al*., 2012).

Conclusions: This paper describes the selection of an optimized mathematical model for describing the accumulation of aboveground cotton biomass. Eight nonlinear functions were evaluated, with TEP (i.e., the product of thermal effectiveness and photosynthetically active radiation) as the input. Statistical procedures for the comparison of nonlinear regression models were described as well as methods for incorporating the function into a crop growth model. The new model, which uses Richards equation, is significantly better than previous models in describing the accumulation of aboveground cotton biomass. The new model is a useful tool for monitoring the growth and N needs of cotton. Such information is important for maximizing cotton yield and quality.

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