Wheat Growth Process 3D Visualization Research Based on Growth Model

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Abstract. With the rapid development of computer virtual technology and agricultural information technology, crop Three-Dimensional (3D) visualization plays an increasingly important part in predicting crop growth dynamic, planting management, and crop breeding. Due to the complexity of wheat morphological structure, as well as big difference on morphological characteristics at different stages, it is a big challenge to build the wheat growth 3D visualization. In this study, the field experiments were carried out from 2015 to 2016 at Tianjin in China, including 3 wheat cultivars under 3 nitrogen application levels. Based on the field experiment, the wheat morphological data, such as length, width, bending angle of leaf, stem and leaf angle, stem diameter, etc., were collected periodically. Then, the quantitative relationship between wheat morphological data and effective accumulated temperature was analyzed, and the growth simulation models of leaf length, maximum leaf width, leaf height and plant height were built by logistic equation. Based the mode test, the logistic model could predicate the wheat leaf growth precisely. Based on the wheat morphological characteristic parameters and topology structure, we established construction algorithm of wheat leaf main vein control point using parameterized modeling method based on curve and curved surface. With the aid of Non-Uniform Rational B-Splines (NURBS) technology and OpenGL graphics library, the wheat organs geometric models were constructed, such as leaf, leaf sheath, stem etc. As a result, Wheat growth simulation model, which was constructed by the effective accumulated temperature, could better predict wheat growth status. Combined with wheat morphological structure model, growth visualization of different varieties wheat under different nitrogen levels was realized, and 3D visualization of wheat growth process was finally realized. The 3D visualization mode can provide wheat crop growth dynamic prediction, cultivation management control and crop plant type design, provide strong technical support for wheat crop ideal plant type screening, high yield, high efficiency, lodging resistance, etc.

Keywords: Wheat · Effective accumulated temperature
Growth simulation model · Morphological structure model · 3D visualization

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1 Introduction

With the combination of computer graphics and crop growth knowledge, the study of crop morphology structure and physiological function has entered into the stage of digitalization and visualization. It has become possible to simulate process of crop growth, to realize quantitative analysis, accurate description and visual expression of the crop morphological structure, to realize quantitative calculation, simulation and prediction of the state of each factor and crop growth process on the computer. Crop model includes Crop Growth Model (CGM) and Morphological Structure Model (MSM). The CGM can provide field management practice, production forecast and economic benefit analysis, and the MSM is a useful tool for ideal crop type selection, high yield, crop group design and optimization (Li et al. 2016a, b).

In the study of CGM, since DE WIT built the first maize growth model in 1965, some of famous CGMs were built in the world, such as Decision Support System for Agrotechnology Transfer (DSSAT) in the USA, School of de Wit in Northlands, Agricultural Production Systems Research Unit (APSRU) in Australian, and Wheat Cultivational Simulation-Optimization-Decision making System (WCSODS) in China (Cao et al. 2008, 2011; Kang 2012). In those CGMs, the wheat growth models play a very important roles to simulate wheat growth, moisture and nitrogen balance, dry matter accumulation, and climate change (Zhang et al. 2017). Thorp et al. (2010) used the CERES-Wheat to simulate soil water content under different planting density and nitrogen level, and the result showed that the CERES-Wheat could predict the soil water content underground 210 cm. CERES (Crop Environment Resource Synthesis system)-Wheat was integrated into the DSSAT to simulate wheat growth (Jones et al. 2003). Langensiepen et al. (2008) used the CERES-Wheat to simulate the effect of different nitrogen application level on wheat growth and development in the north German area, and the results showed the model could not run well and suggested that the relationships between water and soil, as well as water and nitrogen uptake, need be improved. WOFOST (WOrld FOod STudies) is a quantitative dynamic model of the growth and production of annual field crops for different climates and soil conditions, which was developed by the Center for World Food Studies (CWFS), the Wageningen University and Research, Department of Theoretical Production Ecology and the DLO-Center for Agrobiological Research and Soil Fertility, Wageningen, the Netherlands. In India, Mishra et al. (2013) used WOFOST to predict the growth and yield of different varieties of wheat, and showed that the WOFOST could be used to predicate the wheat yield in the western region of Indian. APSIM (Agricultural Production Systems sIMulator)-Wheat model was developed by APSIM Initiative, and then Agricultural Production Systems Research Unit (APSRU) developed it continually. Kouadio et al. (2015) used APSIM to study the impact of climate change on wheat yield in western Canada. In China, Wheat Cultivational Simulation-Optimization-Decision Making System (WCSODS) was built by Gao Liangzhi from Jiangsu Province Academy of Agricultural Sciences, which is a computer software system of wheat cultivation to make wheat cultivational decision for different years (Gao et al. 2000). Shi and Jin. (2003) simulated the wheat growth and yield change under waterlogging condition by

WCSODS, and then integrated the modules of effect of excessive soil water on photosynthesis, dry matter distribution, and leaf senescence into the WCSODS.

In the research field of MSM, Deng et al. (2004) proposed a static leaf 3D model based on Cardinal spine and triangle faces, which has the advantage of using less control points to show more realities effect, but the details of the blade features cannot be showed accurately. By using the Non-Uniform Rational B-Splines (NURBS) free surface, Liu et al. (2004) built the leaf geometrical models of maize and rice. Zheng et al. (2004) used the B-splines to model the geometry of maize leaf canopy. Wu et al. (2009) used the NURBS to simulate leaf blade and sheath, and cylinder to simulate stem geometry, then the 3D morphology of organs were drawn based on OpenGL platform. EL-LATIF A (2011) proposed B-Spline-based leaves structure model to control the shape relationships by changing the marginal and venation of simple leaf or leaflet, and the model could give satisfied results for various shapes of leaf and compound leaves. By combination of growth models, morphological structure models, mathematic models and visualization models, Guo et al. (2007) developed the 3D process of canopy and morphological development of the maize cultivar NONGDA 108 with high sense of reality. Quan et al. (2006) developed a geometric modeling approach to rebuild he geometry of each leaf from multiple views based on images and 3D data. Based on knowledge of growth patterns for plant, using image segmentation and 3D reconstruction technology, Li et al. (2005) proposed a fast visual plant model upon images. Loch et al. (2004) collected the data points from leaf surfaces by employing the laser scanner to build the visually realistic model by triangle-based interpolate. Based on point cloud data after deleting the noise points, Sun et al. (2012) proposed surfaces reconstruction of plant leaves through Delaunay triangulation by optimizing algorithm to eliminate wrong edges.

Now, there are a lot research works on CGM and MSM, but the studies related to integration of wheat CGM and MSM were less reported. In this study, we tried to combine the MSM into CGM to realize the wheat dynamic wheat growth process based 3D visualization. To realize the wheat MSM visualization, Effective Accumulated Temperature (EAT) is an environmental factor to drive the wheat morphological structure changes. The objective of the study is to predict wheat dynamic growth, and provide some information for wheat planting management and wheat type design.

2 Materials and Methods

2.1 Field Experiment

The field experiment was implemented from October 2015 to June 2016 in Wuqing district, Tianjin, China. The soil type is heavy loam meadow soil, with an ammonium N (NH_3-N) content of 9.2 mg kg^{-1}, a nitrate N (NO_3-N) content of 37.5 mg kg^{-1}, available phosphorus concentration of 25.8 mg kg^{-1}, exchangeable potassium concentration of 426.8 mg kg^{-1}, and pH 8.66 within the 0-20 cm soil. This region is a typical warm continental monsoon climate with arid spring, hot rainy summer and cold dry winter.

The experiment included 3 wheat cultivars and 3 Nitrogen treatments, with three replication of each treatment. The wheat cultivars include Hengguan 35 (Hg35), Jimai 22 (Jm22), and Heng 4399 (H4399) with different morphologies, which are the dominance wheat cultivars in this area. The nitrogen treatments were 0 (N1), 225 (N2), 300 kg N ha^{-1} (N3), and the ratio of basal N to sidedress N was 1:3. To decrease the limitation of phosphorus (P_2O_5) and potassium (K_2O), 75 kg P_2O_5 ha-1 and 90 kg K_2O ha^{-1} were applied for all three treatments. Each plot is 25 m^2 (5 m × 5 m), and the plot management followed local standard practices for weed and pest control and irrigation for winter wheat cropping system.

2.2 Data Collection and Analysis

During the wheat growing season, wheat morphology data (leaf length, leaf width, leaf angle, leaf height, stem diameter, plant height, etc.), meteorological data, and texture images were collected for the wheat growth simulation model building and visualization research.

The data was processed by Microsoft Excel 2007, and then statistical analysis was carried out by IMB SPSS Statistics 22. The figures with 1:1 line were drawn to compare the fitting degree between measured values and simulation values.

2.3 3D Modelling Method

In this study, according to the winter wheat growth characters, the wheat growth periods are divided into three stages, including seedling stage (from October 15-November 30), wintering stage (December 1- February 29 on the next year), growth and development stage (March 1 to June 5) (Liu et al. 2008). In the Tianjin area, the wheat stops growing during the overwintering stages due to low temperature. After turning green stages, with weather warming, the wheat straw and leaf start rapid growth until the grain filling stage (Qiao and Yu 2002). This study is based measurement from field experiment, and the quantitative relationship between wheat plant morphological and effective accumulated temperature, namely, Growing Degree Days (GDD) are analyzed to develop the dynamic 3D growth model.

2.3.1 Leaf Length Model

The wheat leaf growth is from slow to fast, then from fast to slow, which fits S curve (Chen et al. 2005). After the quantitative relationship between GDD and leaf length was analyzed after turning green stage of wheat growth, the Logistic equation was used to simulate the leaf length change, as follows:

$$L_n(GDD) = \frac{L_n\max}{1 + Lp_a \times e^{-Lp_b \times (GDD - IniGDD_n)}} \qquad L_m < n \leq L_n \tag{1}$$

where *GDD* is effective accumulated temperature, °C·d; $L_n(GDD)$ is the leaf length of the *n*th leaf on the stem with different *GDD,* cm; L_m is the leaf number before the turning green stage; *Ln* is the total leaf number, which is the wheat cultivar parameter; $L_n max$ is the last leaf length of the *n*th leaf; $IniGDD_n$ is the GDD when the *n*th leaf initial, which is computed from Eq. (2); Lp_a and Lp_b are the model parameters, which is come from regression analysis.

$$IniGDD_n = LGDD + \sum_{i=1}^{n} PHYLL_i \quad 1 \leq n \leq L_n \tag{2}$$

where $IniGDD_n$ is the GDD when the *n*th leaf initial; L_n is the total leaf number; $PHYLL_i$ is the thermal time (degree days) interval between sequential leaf tips, namely phylochron interval, which is the cultivar parameter; *LGDD* is the GDD from planting day to seedling emergence, and the calculation formula is shown below:

$$\Delta T = \begin{cases} T_j - T_0 & T_j \geq T_0 \\ T_0 & T_j < T_0 \end{cases} \quad j = (1, 2, 3\ldots\ldots \mathrm{n}) \tag{3}$$

$$LGDD = \sum_{j=1}^{n} \Delta T \tag{4}$$

Where n is the days from planting day to seedling emergence stage; T_j is the daily average temperature; T_0 is the critical temperature of wheat growth, and it is set as 0 in this study (Yu *et al.* 2002). *LGDD* is related to the wheat planting date and cultivar. Based on the field experiment, the *LGDD* were set as 130 °C·d, 135 °C·d, and 125 °C·d for Hg35, Jm22, and H4399, respectively.

2.3.2 Maximum Leaf Width Model

The wheat leaf growth includes the changes of leaf length and width. Based on regression analysis of field experiment data, the maximum leaf width of one leaf at different time change with the effective accumulated temperature in S curve, and fit the Logistic equation, as follows:

$$W_n(GDD) = \frac{W_n \mathrm{max}}{1 + Wp_a \times e^{-Wp_b \times (GDD - IniGDD_n)}} \quad L_m < n \leq L_n \tag{5}$$

Where the W_n *(GDD)* is the maximum width of the *n*th leaf at different *GDD*s, cm; $W_n max$ is the maximum width of *n*th at harvest stage; Wp_a and Wp_b are the parameters from regression analysis.

2.3.3 Leaf Height Model

In this study, the leaf height is the height from the ground to the bottom of this leaf sheath. Based on the data analysis, the Logistic equation is used to simulate the leaf height change with the effective accumulated temperature, as follows:

$$H_n(GDD) = \frac{H_n \mathrm{max}}{1 + Hp_a \times e^{-Hp_b \times (GDD - IniGDD_n)}} \quad H_m < n \leq H_n \tag{6}$$

Where $H_n(GDD)$ is the leaf height of *n*th at the different *GDD*s, cm; *Hm* is the total leaf number before turning green stage, and *Hn* is the total the leaf number from plant date to harvest; $H_n$max is the maximum of the *n*th leaf at the harvest stage. Hp_a and Hp_b are the parameters from regression analysis.

2.3.4 Plant Height Model

Plant height plays a very important role on wheat yield, and is a preferred traits in wheat breeding. The wheat plant height changes with the change of effective accumulated temperature, which is also fit the S type curve, as follows:

$$W(GDD) = \frac{W_{\max}}{1 + Wp_a \times e^{-Wp_b \times (GDD - IniGDD)}} \tag{7}$$

where *W(GDD)* is the plant height at different *GDD*s; *Wmax* is the final plant height at harvest stage, cm; Wp_a and Wp_b are the model parameters, come from regression analysis.

3 Result and Discussion

Based on the field experiment, the 2 replication data from 3 wheat cultivar (Hg35, Jm22, and H4399) with 3 nitrogen treatments (N1, N2, and N3) were used as regression analysis to build the Logistic model for dynamic 3D morphology simulation of wheat plant growth, and another replication data were used to validate the model.

3.1 Regression Analysis for Leaf and Plant Height

For the leaf length 3D growth simulation, the measured maximum leaf length at the harvest stage was set as the leaf length upper bound. The regression equations were built by regression analysis for dynamic wheat leaf length growth (Table 1). The R^2 values of regression equation are between 0.772–0.983, which showed the model had high fit degree for simulating the leaf length changes, and the F value are between 10.153 and 340.191, sig.<0.05, which showed the equations were significant. Using the same method, the models of the maximum leaf width model (Table 2), Wheat leaf height (Table 3) and Wheat plant height (Table 4) were built for different wheat cultivars under N1, N2, N3 treatments.

Table 1. Wheat leaf length regression equation of Hg35, Jm22, and H4399

Variety	Treatment	Leaf position	Regression equation	R^2	F	Sig.
H35	N1	5	$L = 20/(1 + 3.4 \times e^{-0.005t})$	0.861	30.911	0.003
		6	$L = 20/(1 + 1.24 \times e^{-0.004t})$	0.907	48.759	0.001
		7	$L = 20/(1 + 2 \times e^{-0.004t})$	0.887	39.305	0.002
	N2	5	$L = 25/(1 + 4.2 \times e^{-0.005t})$	0.983	340.191	0.000
		6	$L = 25/(1 + 0.675 \times e^{-0.002t})$	0.813	17.372	0.014
		7	$L = 25/(1 + 1.775 \times e^{-0.002t})$	0.772	10.153	0.045
	N3	5	$L = 25/(1 + 17.83 \times e^{-0.008t})$	0.916	65.700	0.000
		6	$L = 25/(1 + 0.925 \times e^{-0.002t})$	0.919	57.042	0.001
		7	$L = 25/(1 + 2.65 \times e^{-0.003t})$	0.950	57.049	0.005
Jm22	N1	5	$L = 20/(1 + 4.36 \times e^{-0.003t})$	0.936	72.888	0.000
		6	$L = 20/(1 + 1.5 \times e^{-0.003t})$	0.916	43.621	0.003
		7	$L = 20/(1 + 2.74 \times e^{-0.008t})$	0.889	31.932	0.005
	N2	5	$L = 22/(1 + 19.18 \times e^{-0.007t})$	0.896	60.302	0.000
		6	$L = 22/(1 + 1.144 \times e^{-0.003t})$	0.947	53.385	0.005
		7	$L = 22/(1 + 2.178 \times e^{-0.009t})$	0.966	84.13	0.003
	N3	5	$L = 23/(1 + 3.749 \times e^{-0.003t})$	0.961	146.57	0.000
		6	$L = 23/(1 + 2.898 \times e^{-0.005t})$	0.924	60.828	0.001
		7	$L = 23/(1 + 0.69 \times e^{-0.004t})$	0.963	156.414	0.000
H4399	N1	5	$L = 18/(1 + 3.366 \times e^{-0.003t})$	0.876	42.460	0.001
		6	$L = 18/(1 + 1.404 \times e^{-0.003t})$	0.948	72.912	0.001
		7	$L = 18/(1 + 1.8 \times e^{-0.006t})$	0.964	105.860	0.001
	N2	5	$L = 21/(1 + 19.18 \times e^{-0.007t})$	0.946	87.82	0.000
		6	$L = 21/(1 + 1.144 \times e^{-0.003t})$	0.826	23.744	0.005
		7	$L = 21/(1 + 2.178 \times e^{-0.009t})$	0.917	44.233	0.003
	N3	5	$L = 21/(1 + 5.06 \times e^{-0.003t})$	0.968	182.453	0.000
		6	$L = 21/(1 + 2.163 \times e^{-0.004t})$	0.959	115.499	0.000
		7	$L = 21/(1 + 0.315 \times e^{-0.002t})$	0.932	54.559	0.002

Table 2. Wheat maximum leaf width regression equation of Hg35, Jm22 and H4399

Variety	Treatment	Leaf position	Regression equation	R^2	F	Sig.
Hg35	N1	5	$W = 1.4/(1 + 2.23 \times e^{-0.002t})$	0.868	39.559	0.001
		6	$W = 1.4/(1 + 1.56 \times e^{-0.002t})$	0.98	240.758	0.000
		7	$W = 1.4/(1 + 3.26 \times e^{-0.005t})$	0.959	117.673	0.000
	N2	5	$W = 1.6/(1 + 3.76 \times e^{-0.002t})$	0.905	47.363	0.001
		6	$W = 1.6/(1 + 1.52 \times e^{-0.003t})$	0.853	29.116	0.003
		7	$W = 1.6/(1 + 1.41 \times e^{-0.004t})$	0.864	38.040	0.001
	N3	5	$W = 1.6/(1 + 2.64 \times e^{-0.003t})$	0.971	165.689	0.000
		6	$W = 1.6/(1 + 2.17 \times e^{-0.004t})$	0.999	4359.236	0.000
		7	$W = 1.6/(1 + 1.5 \times e^{-0.004t})$	0.853	17.371	0.025

(*continued*)

Table 2. (*continued*)

Variety	Treatment	Leaf position	Regression equation	R^2	F	Sig.
Jm22	N1	5	$W = 1.3/(1 + 3.82 \times e^{-0.002t})$	0.981	255.975	0.000
		6	$W = 1.3/(1 + 3.3 \times e^{-0.004t})$	0.935	85.754	0.000
		7	$W = 1.3/(1 + 3.04 \times e^{-0.007t})$	0.951	97.294	0.000
	N2	5	$W = 1.5/(1 + 7.25 \times e^{-0.003t})$	0.94	110.382	0.000
		6	$W = 1.5/(1 + 5.22 \times e^{-0.005t})$	0.916	65.433	0.000
		7	$W = 1.5/(1 + 3.74 \times e^{-0.007t})$	0.972	209.044	0.000
	N3	5	$W = 1.5/(1 + 2.64 \times e^{-0.003t})$	0.857	23.961	0.008
		6	$W = 1.5/(1 + 2.17 \times e^{-0.004t})$	0.969	187.458	0.000
		7	$W = 1.5/(1 + 1.5 \times e^{-0.004t})$	0.918	67.341	0.000
H4399	N1	5	$W = 1.2/(1 + 2.369 \times e^{-0.001t})$	0.965	167.45	0.000
		6	$W = 1.2/(1 + 1.932 \times e^{-0.002t})$	0.962	125.327	0.000
		7	$W = 1.2/(1 + 4.15 \times e^{-0.005t})$	0.973	145.139	0.000
	N2	5	$W = 1.4/(1 + 2.92 \times e^{-0.002t})$	0.982	274.097	0.000
		6	$W = 1.4/(1 + 2.26 \times e^{-0.003t})$	0.984	240.924	0.000
		7	$W = 1.4/(1 + 2.33 \times e^{-0.003t})$	0.880	29.216	0.006
	N3	5	$W = 1.4/(1 + 3.45 \times e^{-0.002t})$	0.972	238.769	0.000
		6	$W = 1.4/(1 + 2.92 \times e^{-0.003t})$	0.969	189.404	0.000
		7	$W = 1.4/(1 + 3.92 \times e^{-0.006t})$	0.967	118.842	0.000

Table 3. Wheat leaf height regression equation of Hg35, Jm22 and H4399

Variety	Treatment	Leaf position	Regression equation	R^2	F	Sig.
Hg35	N1	5	$H = 15/(1 + 45.56{*}e^{-0.006t})$	0.888	47.609	0.000
		6	$H = 23/(1 + 15.59{*}e^{-0.006t})$	0.885	53.755	0.000
		7	$H = 37/(1 + 37.26{*}e^{-0.009t})$	0.962	202.286	0.000
	N2	5	$H = 17/(1 + 130.42{*}e^{-0.006t})$	0.974	262.484	0.000
		6	$H = 25/(1 + 22.58{*}e^{-0.007t})$	0.954	125.491	0.000
		7	$H = 38/(1 + 30.29{*}e^{-0.009t})$	0.994	1083.77	0.000
	N3	5	$H = 19/(1 + 34.9{*}e^{-0.005t})$	0.93	93.405	0.000
		6	$H = 28/(1 + 17.98{*}e^{-0.006t})$	0.969	283.65	0.000
		7	$H = 43/(1 + 32.25{*}e^{-0.008t})$	0.982	447.178	0.000
Jm22	N1	5	$H = 16/(1 + 253.74{*}e^{-0.008t})$	0.978	224.614	0.000
		6	$H = 27/(1 + 25.68{*}e^{-0.006t})$	0.932	82.87	0.000
		7	$H = 41/(1 + 42.48{*}e^{-0.01t})$	0.978	363.341	0.000
	N2	5	$H = 18/(1 + 24.21{*}e^{-0.005t})$	0.883	60.492	0.000
		6	$H = 29/(1 + 16.68{*}e^{-0.006t})$	0.968	243.55	0.000
		7	$H = 47/(1 + 22.51{*}e^{-0.008t})$	0.985	524.658	0.000
	N3	5	$H = 18/(1 + 60.57{*}e^{-0.006t})$	0.865	25.658	0.007
		6	$H = 30/(1 + 20.61{*}e^{-0.006t})$	0.916	54.271	0.001
		7	$H = 47/(1 + 16.78{*}e^{-0.008t})$	0.898	70.488	0.000

(*continued*)

Table 3. (*continued*)

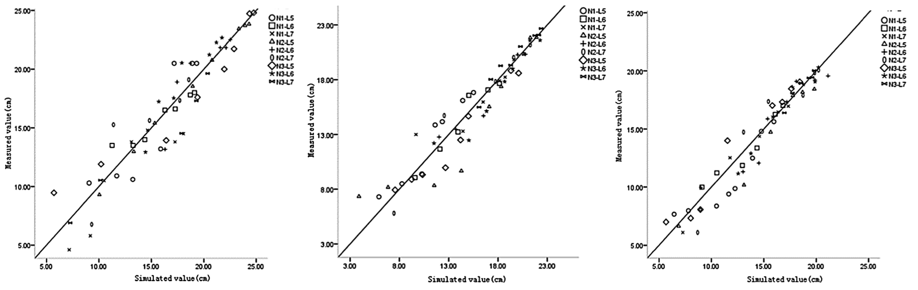
Variety	Treatment	Leaf position	Regression equation	R^2	*F*	Sig.
H4399	N1	5	$H = 12/(1 + 250.14{*}e^{-0.009t})$	0.94	93.968	0.000
		6	$H = 21/(1 + 63.735{*}e^{-0.009t})$	0.96	143.755	0.000
		7	$H = 35/(1 + 50.61{*}e^{-0.01t})$	0.917	66.543	0.000
	N2	5	$H = 18/(1 + 55.836{*}e^{-0.005t})$	0.909	70.347	0.000
		6	$H = 27/(1 + 14.418{*}e^{-0.005t})$	0.936	116.267	0.000
		7	$H = 41/(1 + 16.89{*}e^{-0.006t})$	0.882	67.248	0.000
	N3	5	$H = 15/(1 + 17.325{*}e^{-0.004t})$	0.859	36.588	0.001
		6	$H = 24/(1 + 16.368{*}e^{-0.005t})$	0.965	165.49	0.000
		7	$H = 41/(1 + 16.2{*}e^{-0.006t})$	0.932	54.559	0.002

Table 4. Wheat plant height regression equation of Hg35, Jm22 and H4399

Variety	Treatment	Regression equation	R^2	*F*	Sig.
Hg35	N1	$Y = 45/(1 + 530.36{*}e^{-0.008x})$	0.981	462.432	0.000
	N2	$Y = 51/(1 + 157.39{*}e^{-0.006x})$	0.959	211.479	0.000
	N3	$Y = 52/(1 + 208.57{*}e^{-0.007x})$	0.969	277.546	0.000
Jm22	N1	$Y = 47/(1 + 791.39{*}e^{-0.008x})$	0.969	252.704	0.000
	N2	$Y = 56/(1 + 543.48{*}e^{-0.008x})$	0.986	715.084	0.000
	N3	$Y = 59/(1 + 421.14{*}e^{-0.007x})$	0.958	207.281	0.000
H4399	N1	$Y = 45/(1 + 345.96{*}e^{-0.007x})$	0.972	279.667	0.000
	N2	$Y = 52/(1 + 183.92{*}e^{-0.006x})$	0.942	146.376	0.000
	N3	$Y = 56/(1 + 283.86{*}e^{-0.007x})$	0.942	147.018	0.000

3.2 Model Evaluation

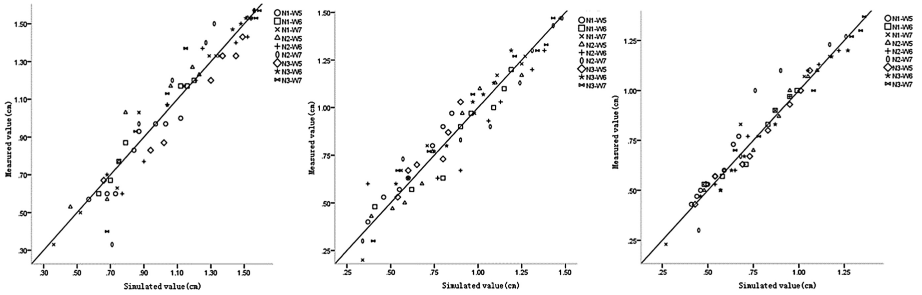
The field data of the third replications from the different wheat cultivars under different nitrogen treatment were used to evaluate regression model of the leaf and plant height growth. The measured values were selected from different GDDs to compare the simulated values from model, and 1:1 line graphs were plotted to compare the measured values and simulated values of leaf length (Fig. 1), maximum leaf width (Fig. 2), leaf height (Fig. 3), and plant height (Fig. 4). Based on the Figs. 1, 2, 3 and 4, it can be seen that the all of data are close to 1:1 line, which indicates that the fitting degree between the measured values and simulated values are very well.



A B C

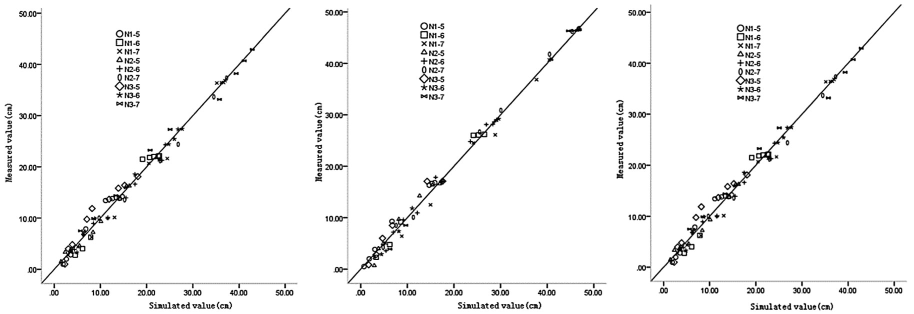
Fig. 1. Comparison of different varieties wheat leaf length measured values and simulated values with different nitrogen treatment and different leaf position

A. Hg35; B.Jm22; C.H4399. The same as below.



A B C

Fig. 2. Comparison of different varieties wheat maximum leaf width measured values and simulated values with different nitrogen treatment and different leaf position



A B C

Fig. 3. Comparison of different varieties wheat leaf height measured values and simulated values with different nitrogen treatment and different leaf position

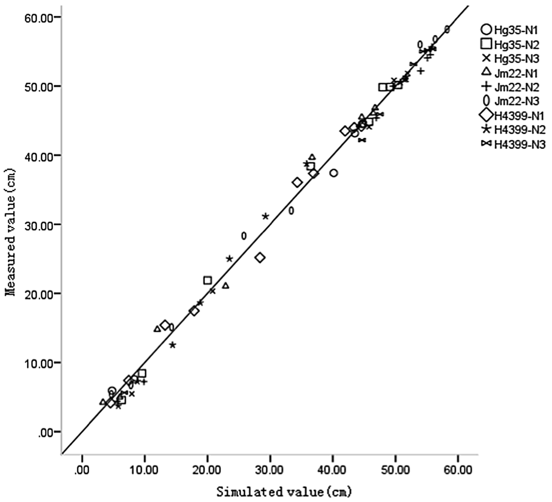


Fig. 4. Comparison of different varieties wheat plant height measured values and simulated values with different nitrogen treatment

3.3 Wheat 3D Shape Simulation

After the wheat leaf and plant height models were built and evaluated, the models could simulated the leaf and plant height changes daily. And then, based our previous researches (Li *et al*. 2016a, b), with the help of object-oriented programming

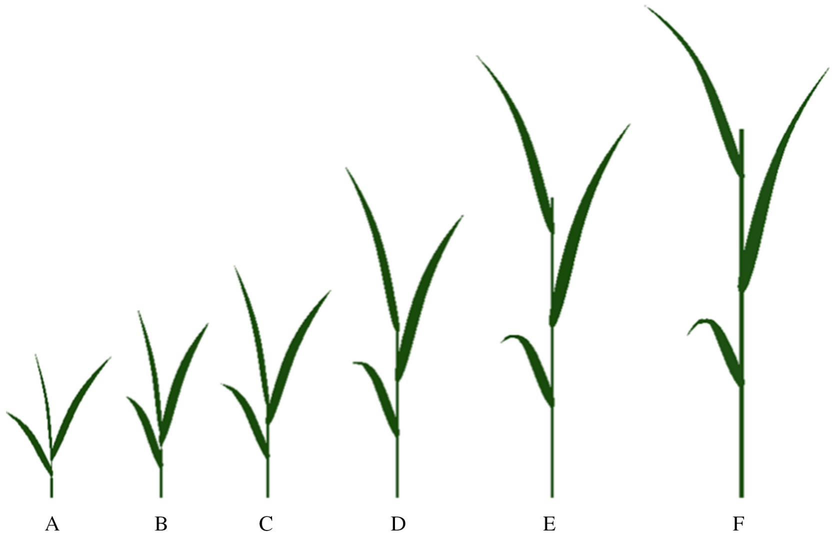


Fig. 5. Growth simulation of Hg35 wheat under N1 treatment

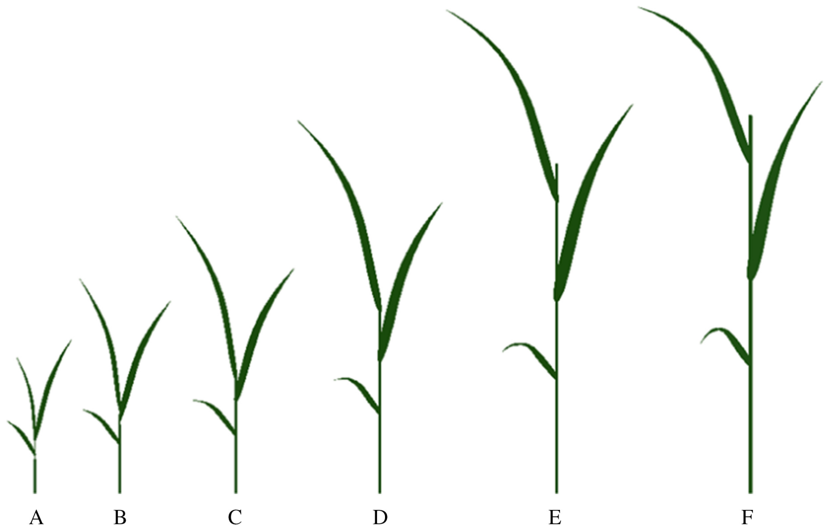


Fig. 6. Growth simulation of Jm22 wheat under N1 treatment

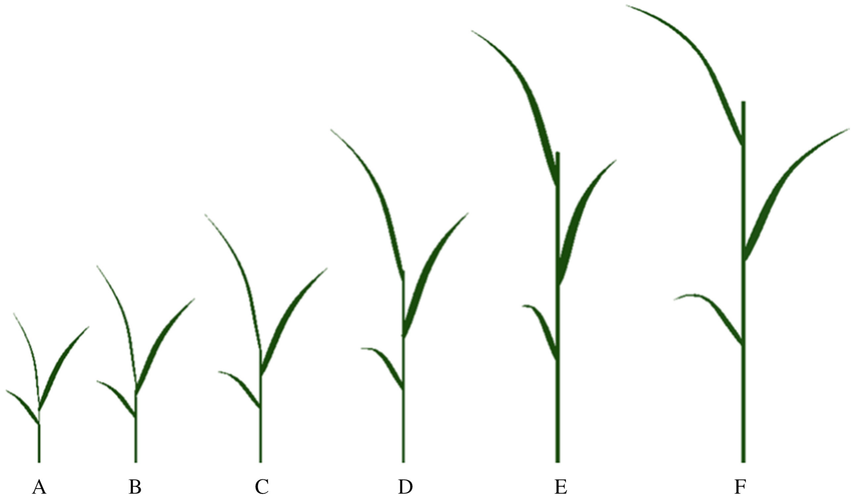


Fig. 7. Growth simulation of H4399 wheat under N1 treatment

technology, OpenGL and NURBS surface modeling technology, the dynamic 3D visualization system of wheat growth was built to simulate the wheat 3D growth after turning green stage. The 3 wheat cultivars (Hg35, Jm22, H4399) morphological graphs under N1 treatment were shown on Figs. 5, 6, 7, separately, which showed different growth stage of the wheat had different morphologies.

3.4 Discussion

By analyzing the quantitative relationship between various varieties of winter wheat morphology data and effective accumulated temperature, this study established the dynamic 3D simulation model of winter wheat after turning green stage, including leaf length, maximum leaf width, leaf height, and plant height, and the model could simulated the wheat 3D growth under different growing stages and different nitrogen treatments precisely.

Based on the simulation results, the *LGDD* and *PHYLL* had important effects on wheat 3D growth. Li *et al.* (2010) suggested the *LGDD* (>0 °C) of wheat was 110–120 °C·d, and *PHYLL* (>0 °C) was 72.8–89.3 °C·d in the Henan province of China. Yang *et al.* (2009) study showed that the *LGDD* (>0 °C) of wheat was 118.5–169.5 °C·d, and *PHYLL* (> 0 °C) was 34.1–78 °C·d in the Jining region of Shandong province, China. In this study, in the Tianjin region of China, the *LGDD* (>0 °C) for Hg35, Jm22, and H4399 was 125–135 °C·d, and *PHYLL* (>0 °C) was 88–95 °C·d. Therefore, the *LGDD* and *PHYLL* are different with the changes of wheat cultivar, region, and planting date.

Based on the platform of OpenGL, Wu et al. (2009) built the 3D morphology of organs and developed the rendering models of color, texture and light. In this paper, the dynamic 3D morphology model were developed to simulate the plant growth of different wheat cultivars under different nitrogen treatment based on quantitative relationship between various varieties of winter wheat morphology data and effective accumulated temperature.

4 Conclusions

The morphological structure are very important on wheat high yield, high quality, and stable yield, and the integration of wheat growth model and morphological model are quantitative expression of wheat growth and development as well as morphological structure (Chen et al. 2016; Liu et al. 2015; Zhao et al. 2010). In the present study, based on the field experiment, the dynamic 3D morphological model system was developed to simulate the 3D shape of winter wheat after turning green stage based on effective accumulated temperature, which could predict wheat leaf growth, leaf height, and plant height of different wheat cultivars under different nitrogen treatment, and realized the combination of wheat growth model and shape model.

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