



HAL
open science

Wheat Growth Process 3D Visualization Research Based on Growth Model

Hailong Liu, Shuqin Li, Yeping Zhu, Shengping Liu, Shijuan Li

► **To cite this version:**

Hailong Liu, Shuqin Li, Yeping Zhu, Shengping Liu, Shijuan Li. Wheat Growth Process 3D Visualization Research Based on Growth Model. 11th International Conference on Computer and Computing Technologies in Agriculture (CCTA), Aug 2017, Jilin, China. pp.217-231, 10.1007/978-3-030-06137-1_21 . hal-02124232

HAL Id: hal-02124232

<https://inria.hal.science/hal-02124232>

Submitted on 9 May 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Wheat Growth Process 3D Visualization Research Based on Growth Model

Hailong Liu¹, Shuqin Li², Yeping Zhu^{1(✉)}, Shengping Liu¹, and Shijuan Li¹

¹Institute of Agricultural Information, Chinese Academy of Agricultural Sciences/Key Laboratory of Agri-information Service Technology, Ministry of Agriculture, Beijing 100081, China;

{liuhailong, zhuyeping, liushengping, lishijuan}@caas.cn

²Information Center, North China University of Technology, Beijing 100144, China
lsq@ncut.edu.cn

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

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., 2016).

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, 2012; Kang et al., 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 et al. (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. (2004) 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 ($\text{NH}_3\text{-N}$) content of 9.2 mg kg^{-1} , a nitrate N ($\text{NO}_3\text{-N}$) 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), $75 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ and $90 \text{ kg K}_2\text{O ha}^{-1}$ were applied for all three treatments. Each plot is 25 m^2 ($5 \text{ m} \times 5 \text{ m}$), 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 IBM 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 *et al.*, 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:

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

where GDD is effective accumulated temperature, $^{\circ}\text{C} \cdot \text{d}$; $L_n(GDD)$ 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; L_n 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 equation (2); Lp_a and Lp_b are the model parameters, which is come from regression analysis.

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

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:

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

$$LGDD = \sum_{j=1}^n \Delta T \quad (4)$$

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., 2012). $LGDD$ 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:

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

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:

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

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:

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

where $W(GDD)$ is the plant height at different GDD s; W_{\max} 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.	
Hg35	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
		5	$W=1.6/(1+3.76 \times e^{-0.002t})$	0.905	47.363	0.001
	N2	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
		5	$W=1.6/(1+2.64 \times e^{-0.003t})$	0.971	165.689	0.000
	N3	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
		5	$W=1.3/(1+3.82 \times e^{-0.002t})$	0.981	255.975	0.000
	N1	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
		5	$W=1.5/(1+7.25 \times e^{-0.003t})$	0.94	110.382	0.000
Jm22	N2	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
		5	$W=1.5/(1+2.64 \times e^{-0.003t})$	0.857	23.961	0.008
	N3	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
		5	$W=1.2/(1+2.369 \times e^{-0.001t})$	0.965	167.45	0.000
	N1	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
		5	$W=1.4/(1+2.92 \times e^{-0.002t})$	0.982	274.097	0.000
H4399	N2	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
		5	$W=1.4/(1+3.45 \times e^{-0.002t})$	0.972	238.769	0.000
	N3	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.
		5	$H=15/(1+45.56 \times e^{-0.006t})$	0.888	47.609	0.000
	N1	6	$H=23/(1+15.59 \times e^{-0.006t})$	0.885	53.755	0.000
		7	$H=37/(1+37.26 \times e^{-0.009t})$	0.962	202.286	0.000
		5	$H=17/(1+130.42 \times e^{-0.006t})$	0.974	262.484	0.000
Hg35	N2	6	$H=25/(1+22.58 \times e^{-0.007t})$	0.954	125.491	0.000
		7	$H=38/(1+30.29 \times e^{-0.009t})$	0.994	1083.77	0.000
		5	$H=19/(1+34.9 \times e^{-0.005t})$	0.93	93.405	0.000
	N3	6	$H=28/(1+17.98 \times e^{-0.006t})$	0.969	283.65	0.000
		7	$H=43/(1+32.25 \times e^{-0.008t})$	0.982	447.178	0.000
		5	$H=16/(1+253.74 \times e^{-0.008t})$	0.978	224.614	0.000
	N1	6	$H=27/(1+25.68 \times e^{-0.006t})$	0.932	82.87	0.000
		7	$H=41/(1+42.48 \times e^{-0.01t})$	0.978	363.341	0.000
Jm22		5	$H=18/(1+24.21 \times e^{-0.005t})$	0.883	60.492	0.000
	N2	6	$H=29/(1+16.68 \times e^{-0.006t})$	0.968	243.55	0.000
		7	$H=47/(1+22.51 \times e^{-0.008t})$	0.985	524.658	0.000

H4399	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
	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 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 1-4, 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.

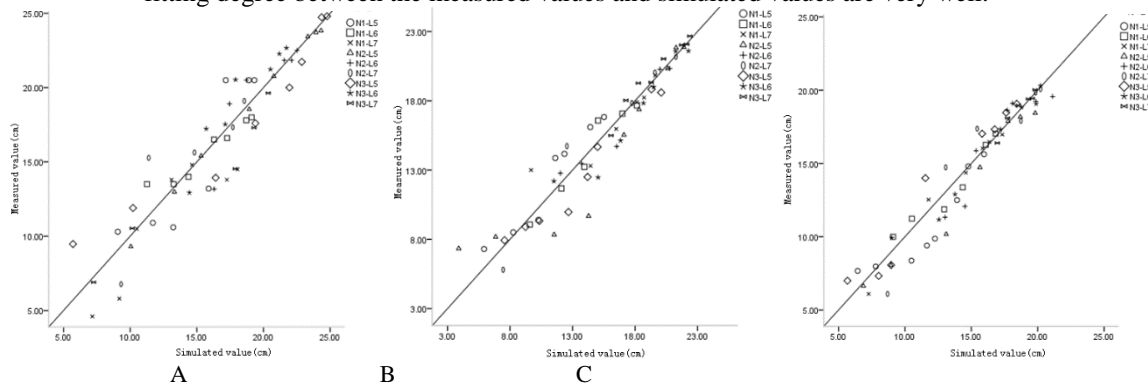


Fig.1. Comparison of different varieties wheat leaf length measured values and simulated values with different nitrogen treatment and different leaf position

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

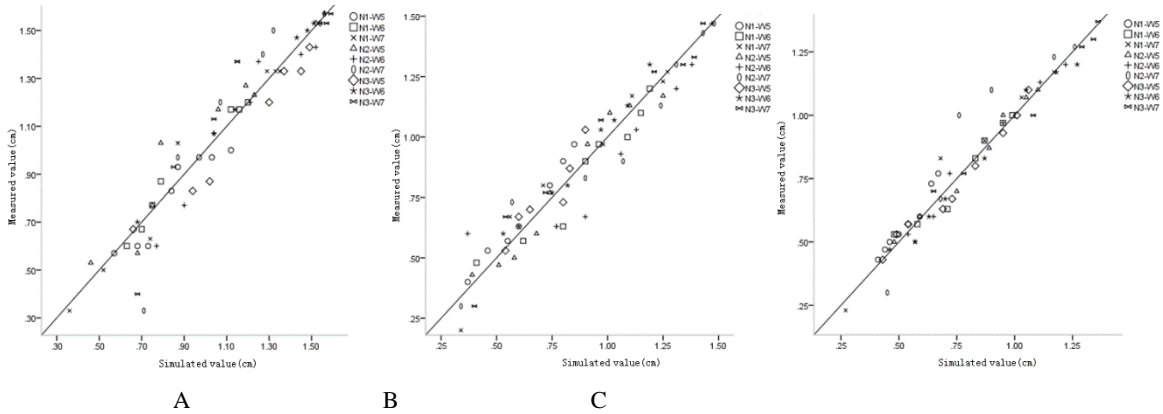


Fig.2. Comparison of different varieties wheat maximum leaf width measured values and simulated values with different nitrogen treatment and different leaf position

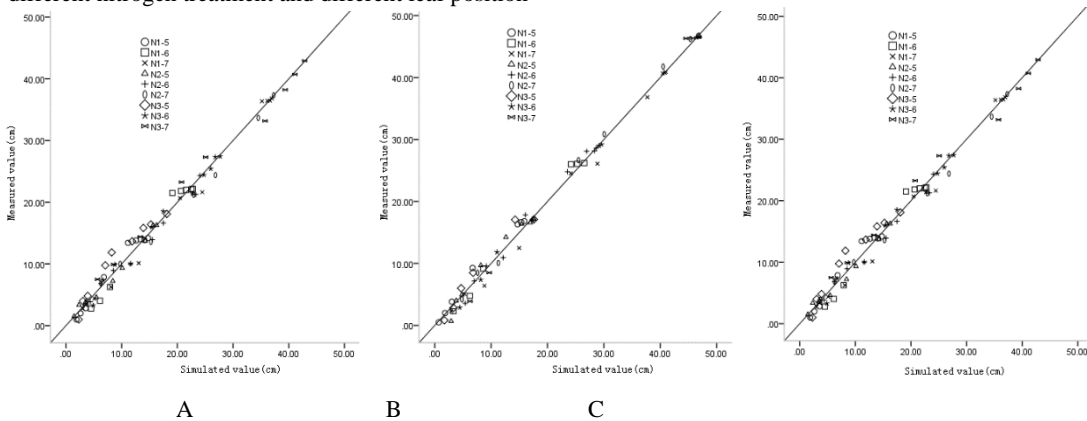


Fig.3. Comparison of different varieties wheat leaf height measured values and simulated values with different nitrogen treatment and different leaf position

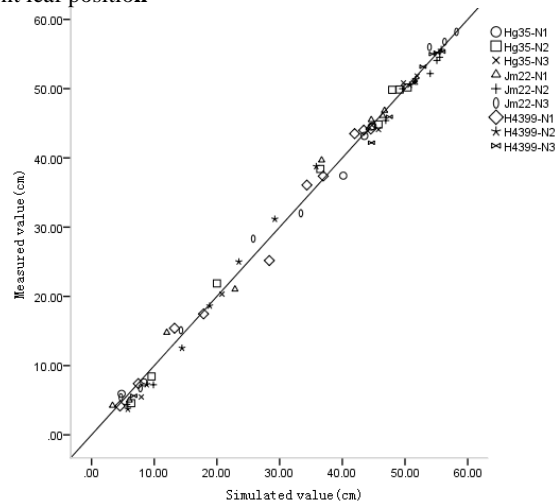


Fig.4. Comparison of different varieties wheat plant height measured values and simulated values with different nitrogen treatment

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 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 Fig. 5, 6, 7, separately, which showed different growth stage of the wheat had different morphologies.

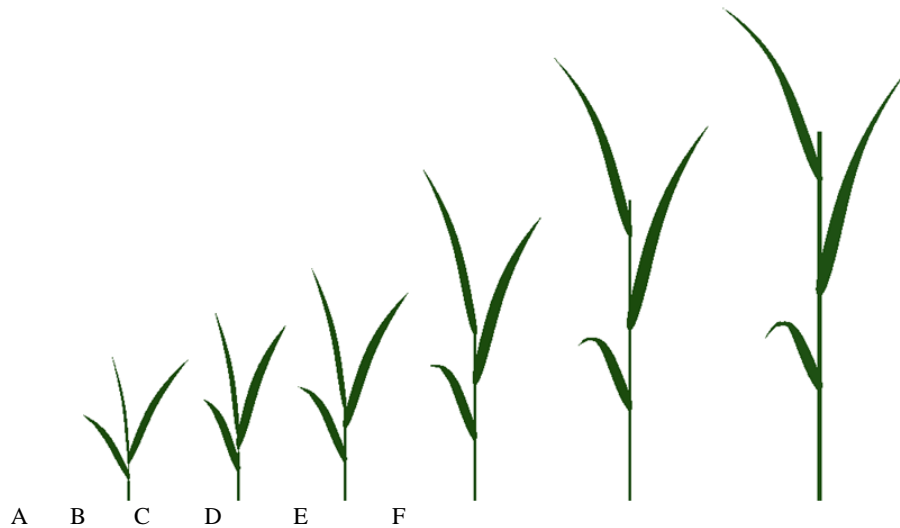


Fig. 5. Growth simulation of Hg35 wheat under N1 treatment

A: March 30, 2016; B: April 5, 2016; C: April 10, 2016; D: April 20, 2016; E: April 30, 2016; F: May 10, 2016. The same as below



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

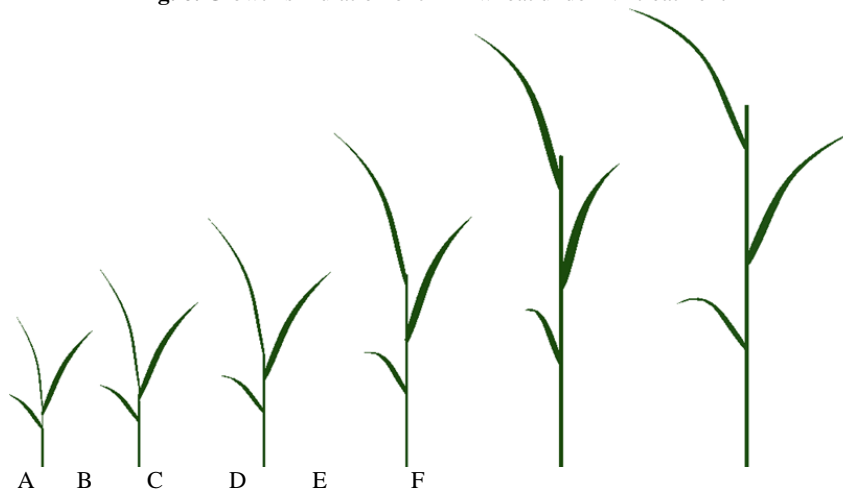


Fig. 7. Growth simulation of H4399 wheat under N1 treatment

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.

Acknowledgments:

The study was funded by the National Natural Science Foundation of China (Grant no. 41471285), the Agricultural Science and Technology Innovation Program (ASTIP) of Chinese Academy of Agricultural Sciences (CAAS-ASTIP-2016-AII), Fundamental Research Funds for Central Non-profit Scientific Institution (JBYW-AII-2017-34), and the National Key Research and Development Program of China (2016YFD0200601).

References

1. CAO H X, SHI C L, JIN Z Q. Advances in researches on plantmorphological structure simulation and visualization. *Scientia Agricultura Sinica*, 41(3): 669-677 (2008) (in Chinese)
2. CAO H X, ZHAO S L, GE D K, LIU Y X, LIU Y, SUN J Y, YUE Y B, ZHANG Z Y, CHEN Y L. Discussion on development of crop models. *Scientia Agricultura Sinica*, 44(17): 3520–3528 (2011)
3. CHEN G Q, ZHU Y, CAO W X. Modeling leaf growth dynamics in winter wheat. *Acta Agronomica Sinica*, 31(11): 1524-1527 (2005)(in Chinese)
4. CHEN Y L, YANG P, ZHANG W Y, ZHANG W X, ZHU Y P, LI S J, GONG F J, BI H B, YUE T, CAO H X. Aboveground architecture model based on biomass of winter wheat before overwintering. *Acta Agronomica Sinica*, 42(5): 743-750 (2016)(in Chinese)
5. DENG X Y, ZHOU S Q, GUO X Y, YUAN C Y. A static leaf model based on cardinal spline and triangle faces. *Computer Engineering and Applications*, 40(25): 199-204 (2004) (in Chinese)
6. EL-LATIF A. A new model for the structure of leaves. *Journal of Software*, 6(4): 670 -677 (2011)
7. GAO L Z, JIN Z Q, ZHENG G Q, FENG L P, ZHANG L Z, SHI C L, GE D K. Wheat Cultivational Simulation-Optimization-Decision Making System(WCSODS). *Jiangsu Journal of Agricultural Sciences*, 16(2): 65-72 (2000)(in Chinese)
8. GUO X Y, ZHAO C J, LIU Y, QIN X Y, DENG X Y, SUN G Y. Three-dimensional visualization of maize based on growth models. *Transactions of the Chinese Society of Agricultural Engineering*, 23(3): 121-125 (2007) (in Chinese)
9. JONES J W, HOOGENBOOM G, PORTER C H, BOOTE K J, BATCHELOR W D, HUNT L A, WILKENS P W, SINGH U, GIJSMAN A J, RITCHIE J T. The DSSAT cropping system model. *European Journal of Agronomy*, 18(3/4): 235-265 (2003)
10. KANG M Z. Review and perspectives on research about functional-structural plant models. *Journal of System Simulation*, 24(10): 2039–2048 (2012) (in Chinese)
11. KOUADIO L, NEWLANDS N, POTGIETER A, MCLEAN G, HILL H. Exploring the potential impacts of climate variability on spring wheat yield with the APSIM decision support tool. *Agricultural Sciences*, 6(07): 686-698 (2015)
12. LANGENSIEPEN M, HANUS H, SCHOOP P, GRASLE W. Validating CERES-wheat under North-German environmental conditions. *Agricultural Systems*, 97(1): 34-47 (2008)

13. LOCH B. Surface fitting for the modeling of plant leaves[D]. Brisbane: University of Queensland, 2004.
14. LI Q Y, NIAN L, LIU W D, LI L, ZHOU S M, YIN J. Effects of accumulated temperature before winter on growth and development of wheat in henan province. *Chinese Journal of Agrometeorolog*, 31(4): 563-569 (2010)(in Chinese)
15. LI S Q, LIU H L, ZHU Y P, LI S J, LIU S P, ZHANG H Y, LI Z Y. 3-D visualization of wheat leaves using measured data and NURBS surface. *Fujian Journal of Agricultural Sciences*, 31(7): 777-782 (2016b)(in Chinese)
16. LI S Q, ZHU Y P, LIU H L, LI S J, LIU D, ZHANG H Y, LI Z Y. Research and realization of wheat leaf three-dimensional visualization based on NURBS surface. *Journal of Agricultural Science and Technology*, 18(3): 89-95 (2016a) (in Chinese)
17. LI Y F, ZHU Q S, CAO Y K, HE X P. A fast visual modeling plant based on images. *Application Research of Computers*, 22(11): 253-257 (2005) (in Chinese)
18. LI Y, DENG Z, ZHAI G L, ZONG J, CAI J M, ZHANG W Z. Accumulated temperature model for crop coefficient of winter wheat. *Water Saving Irrigation*, (4): 36-40 (2015)(in Chinese)
19. LIU D, ZHU Y P, LIU H L, LI S J, XU J P. Research progress on 3d plant visualization. *Journal of Agricultural Science and Technology*, 17(1): 23-31 (2015) (in Chinese)
20. LIU Z D, DUAN A W, GAO Y, LIU H. Study on dynamic model of leaf Area index(LAI) for winter wheat in xinxiang area. *Journal of Triticeae Crops*, 28(4): 563-569 (2008)(in Chinese)
21. LIU X D, CAO Y F, LIU G R, HU Z. The modeling of rice leaf based on NURBS. *Microelectronics & Computer*, 21(9): 117-124 (2004) (in Chinese)
22. MISHRA S K, SHEKH A M, YADAV S B, ANILKUMAR, PATEL G G, PANDEY V, PATEL H R. Simulation of growth and yield of four wheat cultivars using WOFOST model under middle Gujarat region. *Journal of Agrometeorology*, 15(1): 43-50 (2013)
23. QIAO Y H, YU Z R. Dynamic changes and quantification of winter wheat leaf area. *Chinese Journal of Eco-Agriculture*, 10(2): 83-85 (2002)(in Chinese)
24. QUAN L, TAN P, ZENG G, YUAN L, WANG J D, KANG S B. Image-based plant modeling. *ACM Transactions on Graphics*, 25(3): 599-604 (2006)
25. SHI C L, JIN Z Q. A WCSODS- based Model for Simulating Wet Damage for Winter Wheat in the Middle and Lower Reaches of the Yangtse River. *Journal of Applied Meteorological Science*, 14(4): 462-468 (2003)(in Chinese)
26. SUN Z H, LU S L, GUO X Y, WEN W L. Surfaces reconstruction of plant leaves based on point cloud data. *Transactions of the Chinese Society of Agricultural Engineering*, 28(3): 184-190 (2012)
27. THORP K R, HUNSAKER D J, FRENCH A N, WHITE J W, CLARKE T R, PINTER JR P J. Evaluation of the CSM-CROPSIM-CERES-Wheat model as a tool for crop water management. *Transactions of the ASABE*, 53(1): 155-158 (2010)
28. WU Y L, CAO W X, TANG L, ZHU Y, LIU H. OpenGL-based visual technology for wheat morphology. *Transactions of the Chinese Society of Agricultural Engineering*, 25(1): 121-126 (2009)(in Chinese)
29. YANG H B, XU C Z, LI C G, LI F Y. Growth and Required accumulated temperature of winter wheat under different sowing time. *Chinese Journal of Agrometeorolog*, 30(2): 201-203 (2009)(in Chinese)
30. YU Z R, MAO Z Q, MA Y L. A simulation study on thermal requirement for growth of winter wheat and its leaves. *Journal of China Agricultural University*, 7(5): 20-25 (2002)(in Chinese)
31. ZHANG H Y, LI S J, ZHU Y P, LIU H L, LI S Q, LIU D. Research progress on wheat crop model. *Journal of Agricultural Science and Technology. Technol*, 19(1): 85-93 (2017)(in Chinese)
32. ZHENG W G, GUO X Y, ZHAO C J, WANG J H. Corn leaf geometric modelling study. *Transactions of the Chinese Society of Agricultural Engineering*, 20(1): 152-154 (2004)(in Chinese)
33. ZHAO C J, GUO X Y, LU S L. Virtual design and simulation of plant growth system in agriculture and forestry. *Beijing: Science Press*. 318-323 (2010)(in Chinese)

4 Preparation of Your Paper

4.1 Structuring Your Paper

Affiliations. The affiliated institutions are to be listed directly below the names of the authors. Multiple affiliations should be marked with superscript Arabic numbers, and they should each start on a new line as shown in this document. In addition to the name of your affiliation, we would ask you to give the town and the country in which it is situated. If you prefer to include the entire postal address, then please feel free to do so. E-mail addresses should start on a new line and should be grouped per affiliation.

Headings. Headings should be capitalized (i.e., nouns, verbs, and all other words except articles, prepositions, and conjunctions should be set with an initial capital) and should, with the exception of the title, be aligned to the left. Only the first two levels of section headings should be numbered, as shown in Table 1. The respective font sizes are also given in Table 1. Kindly refrain from using “0” when numbering your section headings.

Table 1. Font sizes of headings. Table captions should always be positioned *above* the tables.

Heading level	Example	Font size and style
Title (centered)	Lecture Notes	14 point, bold
1 st -level heading	1 Introduction	12 point, bold
2 nd -level heading	2.1 Printing Area	10 point, bold
3 rd -level heading	Run-in Heading in Bold. Text	10 point, bold
4 th -level heading	<i>Lowest Level Heading.</i> Text follows	10 point, italic

Words joined by a hyphen are subject to a special rule. If the first word can stand alone, the second word should be capitalized.

Here are some examples of headings: “Criteria to Disprove Context-Freeness of Collage Languages”, “On Correcting the Intrusion of Tracing Non-deterministic Programs by Software”, “A User-Friendly and Extendable Data Distribution System”, “Multi-flip Networks: Parallelizing GenSAT”, “Self-determinations of Man”.

Lemmas, Propositions, and Theorems. The numbers accorded to lemmas, propositions, and theorems, etc. should appear in consecutive order, starting with Lemma 1. Please do not include section counters in the numbering like “Theorem 1.1”.

4.2 Length of Papers

We only wish to publish papers of significant scientific content. Very short papers will be moved to the back matter, will not be made available for indexing, and will not be visible as individual papers on SpringerLink.

4.3 Page Numbering and Running Heads

There is no need to include page numbers or running heads; this will be done at our end. If your paper title is too long to serve as a running head, it will be shortened. Your suggestion as to how to shorten it would be most welcome.

4.4 Figures and Tables

It is essential that all illustrations are clear and legible. Vector graphics (rather than rasterized images) should be used for diagrams and schemas whenever possible. Please check that the lines in line drawings are not interrupted and have a constant width. Grids and details within the figures must be clearly legible and may not be written one on top of the other. Line drawings are to have a resolution of at least 800 dpi (preferably 1200 dpi). The lettering in figures should not use font sizes

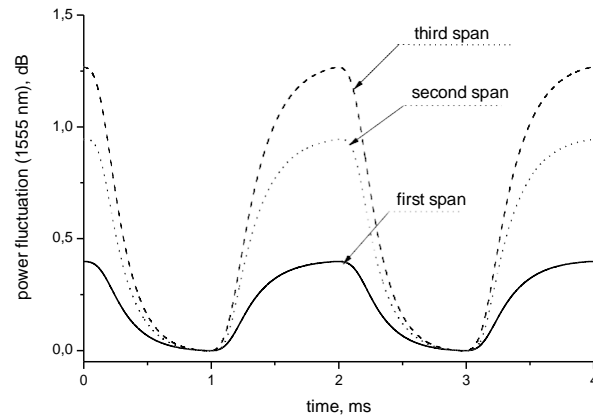


Fig. 1. Power distribution of channel at 1555 nm along the link of 383 km (Source: LNCS 5412, p. 323)

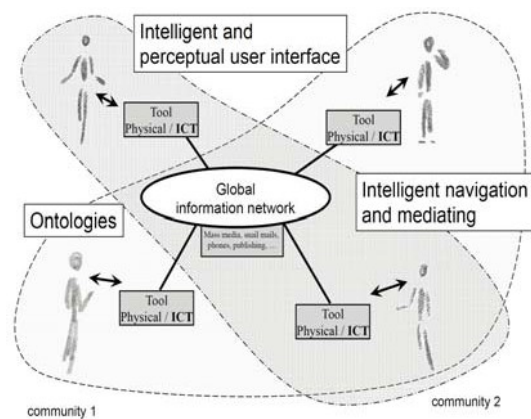


Fig. 2. Artifacts empowered by Artificial Intelligence (Source: LNCS 5640, p. 115)

smaller than 6 pt (~ 2 mm character height). Figures are to be numbered and to have a caption which should always be positioned *under* the figures, in contrast to the caption belonging to a table, which should always appear *above* the table.

Captions are set in 9-point type. If they are short, they are centered between the margins. Longer captions, covering more than one line, are justified (Fig. 1 and Fig. 2 show examples). Captions that do not constitute a full sentence, do not have a period.

Text fragments of fewer than four lines should not appear at the tops or bottoms of pages, following a table or figure. In such cases, it is better to set the figures right at the top or right at the bottom of the page.

If screenshots are necessary, please make sure that the essential content is clear to the reader.

Remark 1. In the printed volumes, illustrations are generally black and white (half-tones), and only in exceptional cases, and if the author or the conference organization is prepared to cover the extra costs involved, are colored pictures accepted. Colored pictures are welcome in the electronic version free of charge. If you send colored figures that are to be printed in black and white, please make sure that they really are also legible in black and white. Some colors show up very poorly when printed in black and white.

4.5 Formulas

Displayed equations or formulas are centered and set on a separate line (with an extra line or half line space above and below). Displayed expressions should be numbered for reference. The numbers should be consecutive within the contribution, with numbers enclosed in parentheses and set on the right margin. Please do not include section counters in the numbering.

$$x + y = z \tag{1}$$

Equations should be punctuated in the same way as ordinary text but with a small space before the end punctuation mark.

4.6 Footnotes

The superscript numeral used to refer to a footnote appears in the text either directly after the word to be discussed or – in relation to a phrase or a sentence – following the punctuation mark (comma, semicolon, or period).¹

For remarks pertaining to the title or the authors' names, in the header of a paper, symbols should be used instead of a number (see first page of this document). Please note that no footnotes may be included in the abstract.

¹ The footnote numeral is set flush left and the text follows with the usual word spacing.

4.7 Program Code

Program listings or program commands in the text are normally set in typewriter font:

```

program Inflation (Output)
  {Assuming annual inflation rates of 7%, 8%, and
  10%,...  years};
  const  MaxYears = 10;
  var    Year: 0..MaxYears;
         Factor1, Factor2, Factor3: Real;
begin
  Year := 0;
  Factor1 := 1.0; Factor2 := 1.0; Factor3 := 1.0;
  WriteLn('Year 7% 8% 10%'); WriteLn;
  repeat
    Year := Year + 1;
    Factor1 := Factor1 * 1.07;
    Factor2 := Factor2 * 1.08;
    Factor3 := Factor3 * 1.10;
    WriteLn(Year:5,Factor1:7:3,Factor2:7:3,
            Factor3:7:3)
  until Year = MaxYears
end.

```

[Example of a computer program from Jensen K., Wirth N.: Pascal User Manual and Report. Springer, New York (1991)]

4.8 Citations and Bibliography

For citations in the text, please use square brackets and consecutive numbers. We would write [1,2,3,4,5] for consecutive numbers and [1], [3], [5] for non-consecutive numbers. The numbers in the bibliography section are without square brackets. We prefer numbered references to other styles of references, such as those with abbreviated names and years.

Please write all references using the Latin alphabet. If the title of the book you are referring to is, e.g., in Russian or Chinese, then please write (in Russian) or (in Chinese) at the end of the transcript or translation of the title.

In order to permit cross referencing within SpringerLink, and eventually between different publishers and their online databases, Springer standardizes the format of the references. This feature aims to increase the visibility of publications and facilitate academic research. Please base your references on the examples given in the references section of these instructions. References that do not adhere to this style will be reformatted at our end.

We would like to draw your attention to the fact that references to LNCS proceedings papers are particularly often reformatted due to missing editor names or incomplete publisher information. This adjustment may result in the final papers as pub-

lished by Springer having more pages than the original versions as submitted by the authors. Here is an example:

Reference as formatted in author's original version:

Assemblal, H.E., Tschumperlé, D., Brun, L.: Efficient Computation of PDF-Based Characteristics from Diffusion MR Signal. In: MICCAI. Volume 5242. (2008) 70–78

Reference after reformatting by Springer:

Assemblal, H.E., Tschumperlé, D., Brun, L.: Efficient Computation of PDF-Based Characteristics from Diffusion MR Signal. In: Metaxas, D., Axel, L., Fichtinger, G., Székely, G. (eds.) MICCAI 2008, Part II. LNCS, vol. 5242, pp. 70–78. Springer, Heidelberg (2008)

One more line is needed for this reference, as a result of Springer's adjustment.

Please make sure that all your sources are correctly listed in the reference section.

Do not include references to pieces of work that are not connected with your paper.

The references section at the end of this paper shows a sample reference list with entries for journal articles [1], an LNCS chapter [2], a book [3], proceedings without editors [4] and [5], as well as a URL [6]. Please note that Springer proceedings are cited with their publication acronyms and volume numbers.

4.9 Plagiarism

Springer takes plagiarism seriously. If an author has copied from another author or has used parts of another author's work (text, tables, figures, etc.), without his or her permission and a reference, then the paper on SpringerLink will be given a "retracted" stamp, and an erratum explaining the reasons for the retraction will be included. In addition, the volume editors and the author's academic supervisors will be informed that plagiarism has been committed. Please note that a retracted paper remains visible, with its "retracted" stamp. It does not simply disappear.

Acknowledgements. This should always be a run-in heading and not a section or subsection heading. It should not be assigned a number. The acknowledgements may include reference to grants or supports received in relation to the work presented in the paper.

5 Additional Information Required from Authors

5.1 Copyright Form

There are different copyright forms in place for the different Springer Computer Science proceedings book series. A prefilled copyright form is usually available from the conference website. Please send your signed copyright form to your conference publication contact, either as a scanned PDF or by fax or by courier. One author may sign

on behalf of all of the other authors of a particular paper. In this case, the author signs for and accepts responsibility for releasing this material on behalf of any and all co-authors. Digital signatures are not acceptable.

5.2 Contact Author Information

Kindly assure that, when you submit the final version of your paper, you also provide the name and e-mail address of the contact author for your paper. These details are used to compile a list of contact authors for our typesetting partners SPS in India. The contact author must be available to check the paper roughly seven weeks before the start of the conference, or before the book is due to leave the printing office, in the case of post-conference proceedings. Please also mark the corresponding author in the header of the paper, preferably with a small envelope. If this is not done by you, it will be carried out by our typesetters.

5.3 Correct Representation of Author Names

Authors' names should be written out in full at the tops of the papers. They are shortened by us to "initials surname" in the running heads and take the form "surname, given name" in the author index. If you or any of your co-authors have more than one family name, it should be made quite clear how your name is to be displayed in the running heads and the author index. Chinese authors should write their given names in front of their surnames at the tops of their papers. If you only have one (main) name, please make sure that this name is written out in full in the running heads, when you check your final PDF. Names and affiliations cannot be changed once a paper has been published.

6 Typesetting of Your Paper at Springer

Please make sure that the paper you submit is final and complete, that any copyright issues have been resolved, that the authors listed at the top of the chapter really are the final authors, and that you have not omitted any references. Following publication, it is not possible to alter or withdraw your paper on SpringerLink. Kindly note that we prefer the use of American English.

6.1 What Will Be Done with Your Paper

If the instructions have been followed closely, then only very minor alterations will be made to your paper. The production team at SPS checks the format of the paper, and if, for example, vertical spacing has been inserted or removed, then this is remedied. In addition, running-heads, final page numbers, and a copyright line are inserted, and the capitalization of the headings is checked and corrected if need be. Finally, the refer-

ence section is attuned to our specifications (see also Section 2.7). Light technical copyediting may also be performed.

6.2 Proof Reading Stage

Once the files have been worked upon, SPS sends a copy of the final PDF of each paper to its contact author. The contact author is asked to check through the final PDF to make sure that no errors have crept in during the transfer or preparation of the files. This should not be seen as an opportunity to update or copyedit the paper, which is not possible due to time constraints. Only errors introduced during the preparation of the files will be corrected. Particular attention should be paid to the references section. If SPS does not receive a reply from a particular contact author, within the timeframe given (usually 72 hours), then it is presumed that the author has found no errors in the paper. The tight publication schedule of our proceedings series does not allow SPS to send reminders or search for alternative e-mail addresses on the Internet.

In some cases, it is the contact volume editor or the publication chair who checks all of the PDFs. In such cases, the authors are not involved in the checking phase.

The purpose of the proof is to check for typesetting or conversion errors and the completeness and accuracy of the text, tables, and figures. Substantial changes in content, e.g., new results, corrected values, title and authorship, are not possible and cannot be processed.

References

1. Smith, T.F., Waterman, M.S.: Identification of Common Molecular Subsequences. *J. Mol. Biol.* 147, 195–197 (1981)
2. May, P., Ehrlich, H.C., Steinke, T.: ZIB Structure Prediction Pipeline: Composing a Complex Biological Workflow through Web Services. In: Nagel, W.E., Walter, W.V., Lehner, W. (eds.) *Euro-Par 2006. LNCS*, vol. 4128, pp. 1148–1158. Springer, Heidelberg (2006)
3. Foster, I., Kesselman, C.: *The Grid: Blueprint for a New Computing Infrastructure*. Morgan Kaufmann, San Francisco (1999)

4. Czajkowski, K., Fitzgerald, S., Foster, I., Kesselman, C.: Grid Information Services for Distributed Resource Sharing. In: 10th IEEE International Symposium on High Performance Distributed Computing, pp. 181–184. IEEE Press, New York (2001)
5. Foster, I., Kesselman, C., Nick, J., Tuecke, S.: The Physiology of the Grid: an Open Grid Services Architecture for Distributed Systems Integration. Technical report, Global Grid Forum (2002)
- 6.
- 7.
8.