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Modeling morphological dynamics and color characteristics of rice panicle

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ABSTRACT

This paper was to develop the models for predicting the dynamics of panicle geometric morphology, panicle and branch curves and panicle color, and to visualize rice panicle in three dimensions (3D). Based on three experiments with different rice (*Oryza sativa* L.) cultivars, the time-course data were collected on the panicle geometric morphology, (including the number of branches and spikelets, the lengths of panicle and branches, and the diameter of panicle axis), the spatial coordinates of panicle axis and branches, and the RGB (red, green and blue) values of panicle color in rice. The dynamics of rice panicle morphology, panicle and branch curves, and RGB values of panicle color with thermal time (TT) were then characterized and simulated. The derived models were further used to visualize rice panicle in 3D. The results indicated that some appropriate functions (quadratic, logistic, exponential and Gaussian) could be chosen to describe the dynamics of the panicle geometric morphology and the RGB values of panicle color with time (growing process) and space (distributions of panicle organs) during panicle development. Combining the above models with the topological structure of rice panicle, rice panicle was visualized with Microsoft.Net and OpenGL (a graphics library). Validation of the models with the independent data indicated that all relative root mean square errors (RRMSEs) between the measured and simulated values were below 20%. Comparison of virtual and real panicles at different development stages showed that the virtual rice panicles were quite similar to real panicles. Overall, the present study could effectively simulate the dynamic changes of 3D morphology and color characteristics of rice panicle, and would provide a key technological support for fulfilling visualization of the whole rice plant.

1. Introduction

Virtual crop models, which simulate crop growth and development in three-dimensional (3D) space by computer, have wide application prospect in the fields of plant production, crop breeding, plant type design, teaching and virtual experiment, and have been an interesting theme of research in recent years (Birch et al., 2003; Vos et al., 2010). Significant progress has been made in modeling morphological structures and virtual representation of maize (Ivanov et al., 1995; Fournier and Andrieu, 1998; Guo et al., 2006), cotton (Hanan and Hearn, 2003), wheat (Fournier et al., 2003; Evers et al., 2007), rice (Watanabe et al., 2005) and other crops (Kaitaniemi et al., 2000; Dornbusch et al., 2007; Han et al., 2011).

Rice is a staple food crop and is of substantial importance for food security in many countries. Rice panicle is the vital organ for yield formation, and traits of panicle are key considerations in rice plant type and super high yield breeding (Feng et al., 2004; Hay and Spanswick, 2006; Kato and Katsura, 2010; Xu et al., 2010). Therefore, dynamic simulation and visual representation of panicle morphology is essential in digitalization and visualization of rice crop (Hay and Spanswick, 2006; Singh et al., 2009; Kato and Katsura, 2010; Mo et al., 2012). Previous studies have provided qualitative description on the distribution of panicle grains on primary and secondary branches, steady and unsteady traits in panicle structure, and the effect of different genotypes on panicle morphology (Zhou et al., 2003; Xu et al., 2004). The 3D visualization of panicle grain was realized by using the pictures of panicle grains (Ogawa et al., 2002), but the visualization of whole panicle was not performed yet. A panicle morphology model was initially built by L-system (Liu et al., 2002), but the simulation of the complicated structure of the panicle was restricted by regularity of L-system. The 3D visualization of panicle was realized by observation of panicle morphology (Yang et al., 2008; Sun et al., 2009), yet the panicle color was not simulated either. The 3D visualization of panicle was

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also realized by simulating panicle and branch curves using the second order Bessel curve, but Bessel curve is complicated such that its parameters were difficult to obtain (Wu et al., 2009). Based on calculation of bending deformation, visualization of panicle was conducted (Ding et al., 2010), but the parameters in the model of panicle morphology were difficult to determine, and the effects of different factors on panicle morphology could only be revealed with the experimental data. Besides, the morphology model of rice plant was constructed and 3D visualization of single plant was realized by L-studio (Watanabe et al., 2005), but the morphology of panicle was not quantitatively described in detail. In most of the previous studies, the morphological models of rice panicle were not supported by sufficient experimental data, and the spatial morphology of rice panicle was not completely quantified. In addition, the dynamics of panicle color were not systemically studied, and most of the color rendering for panicle was not based on experimental data either. All of these limitations made 3D morphological simulation of rice panicle inaccurate and 3D visualization insufficiently realistic.

Therefore, this study was undertaken to (1) develop a 3D panicle morphological model (including sub-models of the number of branches and spikelets, panicle elongation, branch length, the distribution of branches and spikelets, and panicle axis diameter), (2) construct dynamic models of panicle and branch curves, and panicle color based on RGB values, (3) realize the dynamic visualization of 3D panicle in rice. The expected results would provide the technological support for further development of functional-structural models and visualization of whole rice plants.

2. Material and methods

2.1. Experiment design

Experiment 1. The field experiment was conducted in 2005 at the Experiment Station of Nanjing Agricultural University (118°50′E, 32°02′N), China. Two rice (*Oryza sativa* L.) cultivars with different panicle types, Wuxiangjing 14 (WXJ14) with erect panicle and Yangdao 6 (YD6) with bending-type panicle, were planted on 20 May, and transplanted on 20 June using one seedling per hill. The experiment was arranged in a randomized complete block design with three replications. The plot size was 4 m × 2.5 m with 16.6 cm × 20 cm spacing. The total nitrogen rate of 247 kg ha^{-1} was applied, with N distributed as 50% at pre-transplanting, 10% at tillering, 20% at jointing, and 20% at booting. For both cultivars, phosphorus (P_2O_5) and potassium (K_2O) were applied as basal dose at 82.5 kg ha^{-1} and 164.7 kg ha^{-1}, respectively. All the other management measures were applied according to the local cultural practices to allow potential productivity.

Experiment 2. The experiment was conducted in 2010 with two cultivars in cultivation barrels at Experiment Station of Nanjing Agriculture University (118°50′E, 32°02′N), China. The same two cultivars as in Experiment 1 were sown with the mode of direct seeding on 1 June. The cultivation barrel was 35 cm in diameter at the upper surface, 20 cm in diameter at the bottom surface, and 40 cm high. Two seedlings were planted per barrel for both cultivars. Nitrogen was applied at 3.6 g for each barrel, and in four splits as that in Experiment 1. Phosphorus and potassium were applied as basal dose at 0.8 g P_2O_5 and 1.53 g K_2O for each barrel. The other field managements followed local practices for rice high yield.

Experiment 3. The experiment was conducted in 2011. The same two cultivars as in Experiment 1 were planted on 26 May, and transplanted on 13 June at 28 cm × 20 cm spacing for YD6 and 20 cm × 15 cm for WXJ14 with one seedling per hill for each cultivar. The total nitrogen rate was 220 kg ha^{-1} for both cultivars. The other procedures of the experiment were the same as those in Experiment 1.

2.2. Data acquisition

Before panicle heading, eight erect and well-grown main stems and tillers for each cultivar were chosen to be labeled. The time points for the beginning and ending of panicle heading and of panicle curve bending as well as panicle maturity were recorded. When heading began, the elongation of labeled panicles was measured and recorded daily. After heading, spatial coordinate data of labeled panicle axis and branches were measured every other day by a 3D digitalization device (FastScan, Polhemus, USA).

After heading, five well-grown panicles were selected as samples every three days. Then, a ruler was used to measure the lengths of panicle, branches, and axis internodes. A pair of calipers was used to measure the panicle axis diameter. The number of primary and secondary branches on each axis node, panicle grains on each primary branch and secondary branch were counted and recorded. A scanner (EPSON Perfection 1200 PHOTO, EPSON, Japan) with the image size of 200 × 200 pixels, 24 bits color depth and default settings (contrast and brightness were zero), was utilized to scan whole rice panicles, panicle axis, branches and panicle grains of samples. Then, RGB values of panicle axis and grains from the basis to the distal end along panicle axis were extracted from the scanned pictures. Each panicle was equally divided into several segments along panicle axis, and the length of each segment was about 2 cm. RGB values of organs in each segment were the average RGB values in this segment. Finally, the RGB values were calibrated by a color correction method based on standard whiteboard (Cheng et al., 2007).

After panicle maturity, morphological data and RGB values of the labeled rice panicles were measured as described in the above steps.

2.3. Data analysis

Data from Experiment 1 were used to build panicle morphological models; those from Experiment 2 were used to build a panicle curve model based on Gaussian function and a color model based on RGB values; and data from Experiment 3 were used to validate the above models. Data fitting, variance analysis and geometry transformation were done by the softwares Excel 2007, MatlabR2009a, Visual Studio 2005 and CurveExpert 1.4. The fits between the simulated and observed values were calculated with the relative root mean square error (RRMSE) (Rinaldi et al., 2003).

2.4. Spatial topological structure of panicle

Rice panicle mainly consists of a panicle neck, a panicle neck node, a panicle axis, primary and secondary branches, pedicels and spikelet. The panicle axis length is the length from the panicle neck node to the degradation node at the distal end of panicle axis. Generally, there are eight to fifteen nodes on a panicle axis, in which the panicle neck node and the degradation node are the first and the last one, respectively. The branches include primary branches and secondary branches. Primary branches grow around the panicle axis with 2/5 opening, nearly opposite-shaped or whorled-shaped. There are about six spikelets on each primary branch, three on each secondary branch, and one at the distal end of each small branch (Xu and Xu, 1984), as displayed in Fig. 1.

3. Results

3.1. Simulation of panicle morphology

3.1.1. Number of primary branch, secondary branch and spikelet

The data analysis showed that the total number of primary branches (TNPB) and the total number of spikelets (TNS) of the