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RESEARCH ARTICLE

Modeling curve dynamics and spatial geometry characteristics of rice leaves

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Abstract

The objective of this work was to develop a dynamic model for describing leaf curves and a detailed spatial geometry model of the rice leaf (including sub-models for unexpanded leaf blades, expanded leaf blades, and leaf sheaths), and to realize three-dimensional (3D) dynamic visualization of rice leaves by combining relevant models. Based on the experimental data of different cultivars and nitrogen (N) rates, the time-course spatial data of leaf curves on the main stem were collected during the rice development stage, then a dynamic model of the rice leaf curve was developed using quantitative modeling technology. Further, a detailed 3D geometric model of rice leaves was built based on the spatial geometry technique and the non-uniform rational B-spline (NURBS) method. Validating the rice leaf curve model with independent field experiment data showed that the average distances between observed and predicted curves were less than 0.89 and 1.20 cm at the tilling and jointing stages, respectively. The proposed leaf curve model and leaf spatial geometry model together with the relevant previous models were used to simulate the spatial morphology and the color dynamics of a single leaf and of leaves on the rice plant after different growing days by 3D visualization technology. The validation of the leaf curve model and the results of leaf 3D visualization indicated that our leaf curve model and leaf spatial geometry model could efficiently predict the dynamics of rice leaf spatial morphology during leaf development stages. These results provide a technical support for related research on virtual rice.

Keyword: rice, morphological models, leaf, geometry characteristics, virtual plant

1. Introduction

Virtual crop, which simulates crop growth and development in three-dimensional (3D) space, may find wide applications in the fields of high yield plant design, crop production and management, relevant teaching, crop breeding, and virtual experimentation, and has become an important research theme in recent years (Birch *et al*. 2003; Cao *et al*. 2008). Virtual crop might eventually permit the prediction of the growth of transformed genotypes or of combinations of alleles of genes of interest under arbitrary climate conditions (Tardieu 2003). Also, virtual crop is an intuitive tool to enhance our understanding of complex crop phenotypes, which will ultimately lead to new breeding approaches and improved crop cultivars (Xu *et al*. 2011).

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Significant progress has been made in the study of virtual crops of rice (Watanabe *et al*. 2005; Zhang *et al*. 2014a, b), maize (Fournier and Andrieu 1998; Guo *et al*. 2006), wheat (Fournier *et al*. 2003; Evers *et al*. 2007; Lei *et al*. 2011), cotton (Hanan and Hearn 2003), and other crops (Kaitaniemi *et al*. 2000; Dornbusch *et al*. 2007). Recently, virtual crop has been widely applied. For example, a 3D plant crown architecture model was developed and used to assess light capture and whole-plant carbon gain consequences of leaf display in understory plants (Pearcy and Yang 1996). A 3D architectural model was employed to specify rice plant types (Zheng *et al*. 2008). A 3D crop root architectural model was constructed to simulate root changes under various nutrient conditions (Fang *et al*. 2009). A virtual maize model of GreenLab was used to study both the stand and the individual plants in a field of maize with the aim of generating numerical representations of the crop at both stand and individual plant levels (Feng *et al*. 2014). Leaves are the most important crop organ for canopy light distribution and photosynthesis production. They are affected by development status and spatial distribution (Wang *et al*. 2007). Therefore, leaf spatial morphology and distribution is a vital part in virtual crops research.

Rice is one of the most important food crops in the world. Morphological modeling and 3D visualization of the rice leaf is vital for virtual rice. Lately, there have been many studies on morphological modeling and 3D visualization of rice leaf. Based on analysis of the rice leaf, a process model of the rice leaf curve was constructed to study its spatial development (Shi *et al*. 2006). Various curves, such as Hermite (Mi *et al*. 2003; Watanabe *et al*. 2005), Bezier and quadratic curves (Yang *et al*. 2006), cubic B-splines (Zheng *et al*. 2009), and parabolic curves (Liu *et al*. 2009a), were chosen to simulate the rice leaf curve or leaf edge curve for leaf visualization. Meanwhile, non-uniform rational B-spline (NURBS) surface method (Liu *et al*. 2004), approximation method (Meng *et al*. 2005), and Bezier curved surface (Ma *et al*. 2010) were used to simulate the geometric morphology of the rice leaf blade. Besides, the logistic function was utilized to simulate the leaf elongation process, and the value of the leaf's width-to-length ratio, thus the morphological modeling and 3D visualization of rice leaf were implemented by combining several sub-models (Watanabe *et al*. 2005). Geometric parameter models of the rice leaf blade were established based on leaf blade biomass (Liu *et al*. 2009b). A rice leaf shape model under different nitrogen and water statuses was constructed by Zhu *et al*. (2009).

Until recently, the morphological models of the rice leaf curve were not supported by sufficient experimental data, and these previous models are not dynamic. Under natural growth conditions, the leaf blade appear as a spiral at early leaf appearance time, and then leaf blade gradually expands and appears spatial curved surface from the tip to the base of leaf blade along the leaf length direction. However, most of the previous works just focused on the modeling of the expanded rice leaf blade, and lacked detailed investigation on spatial morphology changes of the unexpanded leaf blade. These deficiencies would affect the simulation of leaf blade spatial morphology and bring errors in application of the models.

Our work therefore concentrated on the following aims: (1) develop a dynamic simulation model of rice leaf curve on the main stem based on field experimental data of different rice cultivars under different nitrogen (N) rates; (2) construct a detailed 3D geometry morphology model (including sub-models of unexpanded leaf blade, expanded leaf blade, and leaf sheath) of the rice leaf; and (3) achieve 3D dynamic visualization of the rice leaf based on our relevant models. We expected that our results would provide the technology support for further development of virtual crop.

2. Material and methods

2.1. Experiment site and design

Two experiments were conducted in 2010–2011 at the Experiment Station of Nanjing Agricultural University (118°50´E, 32°02´N), Jiangsu Province, China. In Experiment 1, soil organic matter, total N, available phosphorous (P), and available potassium (K) were 14.5 g kg^{-1}, 1.15 g kg^{-1}, 41 mg kg^{-1}, and 79 mg kg^{-1}, respectively. The corresponding soil properties were 15.1 g kg^{-1}, 1.32 g kg^{-1}, 38 mg kg^{-1}, and 85 mg kg^{-1}, respectively for Experiment 2.

Experiment 1: This field experiment was conducted in 2010. *Oryza sativa* L. ssp. *japonica* Wuxiangjing 14 with upright leaves (W14) and *Oryza sativa* L. ssp. *indica* Yangdao 6 with drooping leaves (YD6) were planted on 26 May, and transplanted on 13 June. The plot size was 4 m×2.5 m with a plant spacing of 28 cm×20 cm for YD6 and 20 cm×15 cm for W14, with one seedling per hill for each cultivar. Three N rates of 0 (N1), 125 (N2), and 250 kg ha^{-1} (N3) were applied in four splits (50% at pre-transplanting, 10% at tillering, 20% at spikelet promotion, and 20% at spikelet protection stages) for all treatments. For both cultivars under different N rates, P_2O_5 and K_2O were applied as a basal dose at 82.5 and 164.7 kg ha^{-1}, respectively. Other field managements followed local practices for high yield rice.

Experiment 2: The experiment was conducted in barrels. Rice was direct seeding on 1 June 2011. The culture barrels were 35 cm in diameter at the upper underside, 20 cm at the lower underside, and were 40 cm in height. Two seedlings were planted per barrel for both cultivars on 1 June. The four N rates of 0 (N1), 1.5 (N2), 3.1 (N3), and 4.6 g (N4) for each barrel were applied in four splits (50%