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Modeling boll maturation period, seed growth, protein, and oil content of cotton (*Gossypium hirsutum* L.) in China

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ABSTRACT

The simulation of cottonseed (*Gossypium hirsutum* L.) growth is still an area of great uncertainty, especially in the process of cottonseed quality formation. A simple process-based model was developed to predict cotton boll maturation period and simulate cottonseed biomass accumulation, protein, and oil content. The cotton boll maturation period module took solar radiation and N nutrition factors into account in addition to temperature and variety maturity profile. Based on the hypothesis that the accumulation of biomass, oil, and protein are mainly sink-determined, the model was developed by considering parameters of cultivar characteristics, weather (temperature and solar radiation), and crop management variables (precisely N supply). The subtending leaf *N* concentration of cotton boll was simulated by a new semi-empirical model, and worked as the direct indicator of the N nutrition effect on cottonseed growth and development. The model was calibrated using data obtained in experiment conducted in Nanjing (the lower reaches of Yangtze River Valley) in 2005 and 2006. The model was then tested using two field experimental data sets. One was obtained in Nanjing, China in 2007, and the other in the Yellow River Valley (Xuzhou and Anyang) and the lower reaches of Yangtze River Valley (Huaian), China in 2005. The simulated values of boll maturation period by the model were very consistent with the observed values, with root mean square error (RMSE) lower than 3 days. The RMSE of cottonseed dry weight, protein content, and oil content predictions were 8.9 mg seed^{-1}, 2.19%, and 2.71%, respectively. The result showed that the model is sufficiently robust to predict the cotton boll maturation period, cottonseed dry weight, and quality in wide range of conditions. It is not only a necessary component of cotton growth model, but also provides a good platform for further study in modeling cottonseed protein and oil yield.

1. Introduction

Simulation models are increasingly used for the assessment of crop productivity and the impact on the environment that may result from given combinations of crop characteristics, weather, soil, and crop management. The study of crop growth model started from 1960s and cotton (*Gossypium hirsutum* L.) was one of the earliest crops studied. Since the model SIMCOT (Duncan, 1973), a lot of systemic cotton growth models had appeared. GOSSYM (Fye et al., 1984; Reddy and Baker, 1988, 1990; Boone et al., 1993) was one of the most famous models. It simulated the dynamics of development, growth, and yield production of cotton plants. Meanwhile, KUTUN developed by Mutsaers (1984) in Holland was also a more mechanistic model. The studies in Australia paid more attention to field management, such as SIRATAC (Hearn and daRoza, 1985) and OZCOT (Wells and Hearn, 1992; Hearn, 1994). With the development of eco-physiology studies in cotton, COTTAM (Jackson et al., 1988; Larson et al., 1996) was developed with more comprehensive inputs including climate condition, soil parameters, and management variables. Linking physiological and architectural models enhanced the cotton models in function, and the COTONS model developed in 1998 was a good example (Jallas et al., 2000; Hanan and Hearn, 2003). Moreover, many other models at that time showed their particular feature, such as COTCO2 (Wall et al., 1994), COTGROW (Pan et al., 1996), and the model developed by Reddy (1994). Now many researchers are still engaging in the area, with new advances made (Ko et al., 2005; Yang et al., 2008; Ravula et al., 2008).

Cotton is not only the most important fibre crop in the world but also the second best potential source for plant proteins after soybean, the fifth oil-producing plant after soybean, palm-tree, colza, and sunflower (Sawan et al., 1988; Ahmad et al., 2007). Therefore, there is a need to understand the accumulating

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processes of oil and protein in cottonseeds. Cotton modeling has been well studied, but studies on simulating cotton seed growth have so far remained limited. To our knowledge, there is no report or communication regarding the modeling of the formation of cottonseed protein and oil. Both linear (Thaker et al., 1989) and cubic polynomial (Rabadia et al., 1999) models could be used to delineate cottonseed biomass accumulation. The nitrogen accumulation and the change of oil content after flowering had also been quantified (King and Leffler, 1979) by simple equations. However, none of them could express the changes in the accumulation under diverse environment conditions, nor explain the physiological mechanisms involved.

Modelling of boll maturation period serves at the basis of the modelling of cottonseed growth and quality formation. Previous studies usually predicted crop development related to thermal time mainly determined by temperatures (Hearn and daRoza, 1985; Jamieson et al., 1998). Recently, Physiological Development Time (PDT) has been widely used in many crops such as wheat, rice, and cotton (Cao and Moss, 1997; Meng et al., 2003; Zhang et al., 2003), mainly taking into account variety maturity profile, temperature conditions, and photoperiod. With regard to cotton boll development, some studies have showed that the boll maturation period is also influenced by solar radiation and nitrogen nutrition (Chen and Yu, 2001; Reddy et al., 2004), in addition to genotype and temperature conditions. Abundant sunshine accelerates boll development as a subsidiary factor, especially when temperature conditions are sub-optimal (Chen and Yu, 2001; Ma et al., 2005). Excessive nitrogen nutrition has been found to delay cotton boll maturation (Tang et al., 2003; Reddy et al., 2004). So far, studies on modeling boll development have not integrated the factors of solar radiation and N nutrition.

This paper presents the results of a first integrated model on cottonseed growth and development encompassing: (1) a module of cotton boll maturation period model taking into account the effects of cultivar characteristic, weather conditions, and crop management variables (precisely N supply); (2) module of cottonseed growth model dealing with cottonseed biomass accumulation in daily step; (3) module of cottonseed protein content and cottonseed oil content model based respectively on *N* accumulation and fat synthesis.

2. Materials and methods

2.1. Field data

2.1.1. Experiments for boll maturation period model module

Field experiments were conducted at Jiangsu Agricultural Sciences Academy, Nanjing, Jiangsu, China (32°02′N, 118°50′E) in 2006 and 2007. The soil at the experimental site was a yellow-brown loam with 25 mg kg^{-1} organic matter, 12 g kg^{-1} total N, 85.1 mg kg^{-1} available N, 13.0 mg kg^{-1} available P, and 91.6 mg kg^{-1} available K contained in 20 cm depth of the soil profile. Two cultivars, Kemian 1(The growth period is 135 days) and NuCOTN 33B (The growth period is 120 days), were planted in 2006; Three cultivars, Kemian 1, NuCOTN 33B and Dexia 1(The growth period is 100 days), were planted in 2007. Based on the research result that 240 kg ha^{-1} is the optimum *N* rate in Nanjing (Xue et al., 2006), three *N* rates (0, 240, and 480 kg ha^{-1}) were applied in two equal amounts, before transplanting and at initial flowering stage. Cotton seeds were planted on 25 April in 2006 and 2007. When the seedlings had three true leaves, individual healthy and uniform plants were transplanted to the field at row spacing 0.9 m and plant spacing 0.3 m. The experiments were designed as randomized complete blocks with three replicates. Each plot was 6.3 m wide and 8.4 m long. In the experiments the boll flowering dates, opening dates, and boll position were recorded.

2.1.2. Experiments for cottonseed growth and quality formation model modules

To study the cottonseed biomass accumulation, protein and oil content, a series of field experiments were carried out in Nanjing (32°02′N, 118°50′E), Huaian (33°18′N, 119°05′E), and Xuzhou (34°12′N, 117°36′E) in Jiangsu Province, and Anyang (36°04′N, 114°13′E) in Henan Province, China in 2005. The soil type and soil nutrient contents were listed out in Table 1. Two cultivars, Kemian 1 and NuCOTN 33B, were planted on 25 April and 25 May, at row spacing 0.9 m and plant spacing 0.3 m. Three *N* rates (0, 240, and 480 kg ha^{-1}) were applied in two equal amounts, before transplanting and at the initial flowering stage. The experiments were designed as randomized complete blocks with three replicates in Nanjing and four replicates in other locations. Crop management was in line with local cultivation practices followed for upland cotton production in the region.

The white flowers at the first and second nodes of cotton plants were tagged on 15 July, 25 July, 10 August, 25 August, and 10 September. 10–15 pairs of boll tagged and its subtending leaf were picked each time at the 5th, 10th, 17th, 24th, 31th, 38th, 45th, and 52th day after flowering. The shells, seeds, and fiber were separated and then dried. The oil contents of cottonseeds were measured with Soxhlet extraction (Luque De Castro and Garcia-Ayuso, 1998), and the *N* concentrations of cottonseeds and subtending leaves were measured with Kjeldahl method (Feil et al., 2005). Cottonseed protein content = 6.25 × *N* concentration.

2.2. Statistical analysis

Field data collected in Nanjing in 2005 and 2006 were used to develop model and calibrate model parameters. The model was tested using independent field data collected in Nanjing in 2007 and in Xuzhou, Huaian and Anyang in 2005. Simulated values were compared with the observed values using the root mean square error (RMSE) calculated as:

$$RMSE = \left[\sum_{j=1}^{n}\frac{(Y_j - X_j)^2}{n}\right]^{0.5}$$

where Y_j = simulated value on the ith day, X_j = observed value on the ith day, n = number of pairs of simulated and observed value.

Table 1
Soil types and soil nutrient contents at the experimental sites in 2005.

Site	Soil type	Total N content (g kg^{-1})	Available N content (mg kg^{-1})	Available P content (mg kg^{-1})	Available K content (mg kg^{-1})
Nanjing	Yellow brown Loam	10.3	40.13	28.95	79.17
Xuzhou	Alluvial soil	11.7	47.83	29.00	77.54
Huaian	Alluvial soil	9.7	41.33	27.7	75.7
Anyang	Sand loam	9.4	39.28	23.57	71.19