Development and validation of SUCROS-Cotton: a potential crop growth simulation model for cotton

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Received 21 December 2007; accepted 26 July 2008

Abstract

A model for the development, growth and potential production of cotton (SUCROS-Cotton) was developed. Particular attention was given to the phenological development of the plant and the plasticity of fruit growth in response to temperature, radiation, daylength, variety traits, and management. The model is characterized by a comparatively simple code and transparent algorithms. The model was parameterized for Chinese cotton varieties and validated with extensive independent datasets on cotton growth and production from the Yellow River region and Xinjiang Province. The model validation showed that the phenology, growth and yield were simulated satisfactorily. The root mean square error (RMSE) for date of emergence, date of flowering, date of open boll stage and duration from sowing to boll opening was less than four calendar days, both for cotton grown in monoculture and cotton grown in a relay intercropping system with wheat. The RMSE of predicted total dry matter compared with observations was at most 6.6%, of lint yield 6.6%, and for number of harvestable bolls 10.0%. SUCROS-Cotton provides a tool to (1) assess production opportunities of cotton in various ecological zones in response to temperature, incoming radiation and management, (2) identify optimal cotton ideotypes for different agro-ecological conditions and for guiding breeding efforts, and (3) explore resource-use-efficient cropping systems, including intercropping options, and crop management practices such as plastic film mulching and sowing date.

Additional keywords: development, development time, growth, intercropping, lint yield, physiological day

Introduction

Simulation models of crop growth and production provide a widely accepted tool for assessing agricultural production opportunities in different agro-ecological zones in response to weather and management. Such models help to identify ideotypes that are well adapted to certain agro-ecological conditions, to understand interactions between genotypes, environment and management (Kropff & Goudriaan, 1994; Yin *et al.*, 2004), and to derive optimal management strategies under uncertain weather conditions and climate change (Meinke *et al.*, 2001).

Cotton (*Gossypium hirsutum* L.) is a major cash crop in China, with a total production area of about 4.8 million ha. There are three major cotton producing regions: (1) Xinjiang Province, (2) the Yangtze River basin and (3) the Yellow River basin (Hsu & Gale, 2001). Climatic conditions in these regions are different. The Xinjiang Province is in the northwest. Summers there are short, hot and arid, and major production constraints are low night temperatures in spring and autumn. Due to the short growing season, as defined by the occurrence of night frosts, the region is only suitable for early and mid-early maturing varieties, and plastic film mulching is used after sowing to increase soil temperature and accelerate the growth and development of the seedlings. All cotton in Xinjiang Province is irrigated. The Yangtze River basin is the most southern and warmest region of the three. Here, it is possible to grow a cotton crop and a wheat crop in sequence within a 12-month period, enabling two full crop harvests per year. Irrigation is generally not needed because there is sufficient rainfall. The Yellow River basin valley is further north and has lower temperatures than the Yangtze River basin, but higher spring and autumn temperatures than Xinjiang Province. Sixty percent of the cotton in this region is sown in a relay-intercropping system with wheat. In cotton–wheat intercropping systems the cotton is sown in strips of bare soil that are left unsown in the preceding fall when the wheat crop is grown. After the wheat is harvested, in June, the cotton can occupy the whole land. In a cotton–wheat relay-intercropping system, the seedling phase of cotton and the reproductive phase of wheat overlap over a period of approximately seven weeks. Immediately after the harvest of cotton, at the end of October, wheat is sown. Despite the lower wheat yield resulting from the open space in the canopy and the lower cotton yield resulting from the shading by the wheat during initial cotton growth, the aggregate yield in this relay-intercropping system significantly exceeds the yields of cotton and wheat monocrops, as shown by land equivalent ratios of up to 1.39 (Zhang *et al.*, 2007).

Plant densities vary widely among the three production regions: from 37,500 plants per ha in the Yangtze River basin to 60,000 plants per ha in the Yellow River basin and 225,000 plants per ha in Xinjiang Province. The low plant density in the Yangtze River basin is possible because of the vigorous growth of cotton under the hot humid conditions that are prevalent in this region. The high plant density in Xinjiang Province compensates for the shortness of the growing season.

Different varieties are used in the three regions. Early maturing varieties (CRI16, CRI36) and mid-early maturing varieties (CRI32, CRI35) are used in Xinjiang Province, mid-early maturing varieties (hybrid CRI29, CRI38, CRI41) and early maturing varieties (CRI27) in the Yellow River basin and mid-early maturing varieties (Simian2) in the Yangtze River basin. In the Yellow River basin, the terminal growing point of the main stem is removed at the end of July ('cut-out') to curtail further vegetative development and formation of additional flowers. This management practice directs assimilates to the growing bolls. In Xinjiang Province, the time of 'cut-out' is mid-July. Most cotton varieties used in China are bred by the China Cotton Research Institute (CRI) in Anyang, Henan Province, in the Yellow River basin.

Numerous growth models exist for cotton (Duncan, 1972; McKinion *et al.*, 1975; Jones *et al.*, 1980; Baker *et al.*, 1983; Mutsaers, 1984; Hearn, 1994; Wall *et al.*, 1994; Lemmon & Chuk, 1997; Pan *et al.*, 1997; Jallas *et al.*, 2000; Hanan & Hearn, 2003). These models differ in their modelling objective, modelling concepts, and domain of applicability. The prediction quality of some of these models has been extensively assessed in experiments to justify their application. For instance, GOSSYM has been validated and applied in many locations (Reddy, 1988; McKinion & Baker, 1989; Boone *et al.*, 1993; Khorsandi & Whisler, 1996;). It was applied to analyse the effects of weather on yield (Reddy, 1990) and to evaluate economic strategies of growth regulator application (Watkins *et al.*, 1998). Based upon GOSSYM, the model COTGROW was developed (Pan *et al.*, 1997). This model was adapted to Chinese varieties, but it does not account for characteristic elements in Chinese cotton cultivation, such as relay intercropping with wheat or the use of plastic film mulching. GOSSYM and COTGROW are based on a complex and incompletely documented code. These models are therefore difficult to adjust and to further develop for exploration of options for cotton production in China. A concise and transparent new model for cotton under Chinese growing conditions is needed to enable studies – relevant to China – on land use, ideotyping, crop management, sustainability and consequences of global climate change.

The objectives of this paper are: (1) to describe the conceptual structure of SUCROS-Cotton, a model that meets the above-formulated requirements, (2) to evaluate the model, using extensive datasets on the phenology, growth and productivity under different combinations of genotype, environment, management, and cropping system.

Description of the model

SUCROS-Cotton simulates development and growth of cotton under the influence of temperature and radiation. It consists of modules for phenology, photosynthesis, morphogenesis, fruit formation and abscission, dry matter partitioning, yield, and management practices, and uses the physiological development time concept (Soltani *et al.*, 2006) to model development and calculate carbon allocation over plant organs. SUCROS-Cotton is based on concepts of the SUCROS class of crop growth simulation models characterized by a concise and transparent code, which have been extensively documented (Goudriaan & Van Laar, 1994). Compared with SUCROS (Goudriaan & Van Laar, 1994), SUCROS-Cotton includes new algorithms for quantifying effects of plastic film mulching, 'cut-out', and genetic traits, and implements the boxcar train approach (Goudriaan & Van Roermund, 1999) to simulate cotton fruit dynamics, fruit abscission, single boll weight and yield. SUCROS-Cotton includes the concept of an assimilate supply/demand ratio (Gutierrez *et al.*, 1984) to model fruit abscission and fruit filling. SUCROS-Cotton is programmed in the Fortran-based simulation language FST (Fortran Simulation Translator; Van Kraalingen *et al.*, 2003). FST allows the development of a concise and easily understood code, which can be ordered according to physiological principles and conceptual model structure, as FST has a sorting algorithm to arrange equations in calculation order. A listing and a complete list of variables are available at <http://www.cwe.wur.nl/UK/Downloads/>. A list of the symbols used in this paper is provided in Appendix 1.

Inputs needed to run the model are (1) latitude and longitude, (2) daily weather data: minimum and maximum temperature, incoming global radiation, (3) genetic parameters: earliness, maximum weight of a single boll, first node on the main stem producing a fruit bearing branch, and (4) management parameters: plant density, date of cut-out, film mulch and cultivation in monoculture or in relay with wheat.

Model structure

The state variables in SUCROS-Cotton are physiological development time (τ; days), leaf area index (L; m^2 leaf area per m^2 surface area), total biomass (B; g m^{-2}), carbohydrate reserve pool, and the biomasses of leaves, stems, fruits and roots. Development is computed on the basis of temperature, daylength and a variety coefficient. Photosynthesis, dry matter partitioning, and LAI are calculated as in SUCROS (Goudriaan & Van Laar, 1994). Potential fruit growth is simulated by calculating assimilate demand on the basis of fruit age, measured in calendar days, and genetic traits. The ratio of supply/demand for dry matter is computed to scale growth processes of fruits, which may be sink or source limited (Gutierrez *et al.*, 1984). Moreover, the supply/demand ratio affects fruit abscission. Lint yield is calculated from fruit mass, using allometric relationships.

Simulation of development

The development of cotton depends on temperature, photoperiod and genetic traits (Robertson, 1968; Cao & Moss, 1997). Developmental stage is characterized by a development index, τ, which is calculated by accumulating daily development increments, expressed as a fraction of the daily development increment that would have been attained under optimal conditions. This index for physiological time further takes into account daylength and variety effects and is computed as:

$$\tau = \int f(T) \bullet g(D) \bullet h(V) \bullet \mathrm{d}t \qquad (1)$$

where $f(T)$ represents the influence of temperature, $g(D)$ the influence of daylength, and $h(V)$ the influence of variety. The terms $f(T)$ and $g(D)$ are time-varying functions, whereas $h(V)$ is a variety-specific constant. Early maturing varieties have a high value for $h(V)$ and the value $h(V)$ of the reference variety, CRI27, is 1. Development is completed when τ equals 60 days, being the minimum number of days needed by variety CRI27 to reach 50% open bolls under optimal conditions. The value of τ expresses how far the crop has progressed towards the stage of 50% of the plants having at least one open boll. Indicative values of τ for subsequent development stages are 2.5 at emergence, 17.5 at squaring, 27.5 at flowering, and 60 at open boll. The crop has reached a given stage when 50% of the plants have reached that stage.

Influence of temperature

The temperature effect on cotton development, $f(T)$, is calculated as:

$$\mathrm{f(T)} = \begin{cases} 0 & \text{if} \quad T<T_b \\ \dfrac{T-T_b}{T_o-T_b} & \text{if} \quad T_b \leq T<T_o \\ \dfrac{T_m-T}{T_m-T_o} & \text{if} \quad T_o \leq T \leq T_m \\ 0 & \text{if} \quad T>T_m \end{cases} \tag{2}$$

where T is the soil temperature at 5 cm depth until emergence ($\tau = 2.5$) and the air temperature, as measured in a Stevenson screen, thereafter. T_b is the biological base temperature, T_o the optimum temperature and T_m the maximum temperature for development. T_b was set at 15 °C until emergence, and at 12 °C thereafter, T_o was set at 30 °C and T_m at 35 °C for both air and soil temperature (Anon., 1982; Baker *et al.*, 1983; Zhao *et al.*, 2005). The temperature threshold for germination is based on data indicating that radicle elongation does not occur at temperatures below 15 °C and that cotyledons do not start expanding until soil temperature exceeds 16 °C (Xu & Xu, 1989).

The physiological time concept should ideally operate on an hourly time scale. As it must be possible to run the model with meteorological variables that are commonly measured at a weather station, like the daily minimum and maximum temperatures, an approximation is applied. As suggested by Goudriaan & Van Laar (1994), a daily value for $f(T)$ is calculated by determining the function value at the daily minimum temperature, at the average temperature, and at the maximum temperature, and calculating a weighted average function value according to respective weights of 0.25, 0.50 and 0.25.

Influence of daylength

As cotton is generally considered daylength-neutral (Anon., 1982), daylength effects are often not included in cotton models. However, daylength sensitivity exists when datasets originate from areas with large differences in latitude. In SUCROS-Cotton, the following empirical relationship (Goudriaan & Van Laar, 1994) is used to describe the response of development rate to daylength:

$$g(D) = \begin{cases} 1 & \text{if} \quad D \leq D_{\mathrm{b}} \\ \dfrac{D_m-D}{D_m-D_b} & \text{if} \quad D_b < D \leq D_m \\ 0 & \text{if} \quad D > D_{max} \end{cases} \tag{3}$$

where D is the actual daylength, D_b the base daylength below which development is most rapid, and D_m the maximum daylength, above which there is no development.

The following parameter values are used: D_b = 14 hours per day and D_m = 16 hours per day (Anon., 1982).

Influence of variety

The variety coefficient $h(V)$ was calculated from observations as the ratio between the sum of $f(T)$ at 50% open boll for a reference variety (i.c. CRI27) and the accumulation of $f(T)$ for the variety under consideration:

$$h(V) = \sum_{t=0}^{t=t_{50}(\text{ref})} f(T) \Bigg/ \sum_{t=0}^{t=t_{50}(\text{var})} f(T) \tag{4}$$

Here t_{50}(ref) and t_{50}(var) are the times of 50% open bolls for two varieties, where the first one is the reference variety. Late maturing varieties are characterized by a low value of $h(V)$.

Effect of plastic film mulching on development

Temperatures above the soil underneath a film cover are calculated from temperatures measured in a Stevenson screen, using empirical regression relationships. A temperature increment ΔT is calculated as:

$$\Delta T = c(T_{sf} - T_s)\,\frac{T - T_b}{T_s - T_b} \tag{5}$$

where T_s is the soil temperature at 5 cm depth without mulching, which is calculated from a linear regression with air temperature ($T_s = 0.890 + 1.017 \times T$; $R_2 = 0.975$; Zhang *et al.*, 2003), T_{sf} is the soil temperature at 5 cm depth under film mulch, which is also obtained from a linear regression with air temperature: $T_{sf} = 7.5725 + 0.8303 \times T$; $R_2 = 0.805$ (Zhao *et al.*, 1996), T_b is the base temperature for cotton development, and c is a coefficient representing the increase in soil temperature resulting from a 1 °C increase in air temperature (Anon., 1988; Zhang *et al.*, 2003). This coefficient is 0.51 from emergence to squaring, 0.22 from squaring to flowering, and 0 after flowering, because the film cover will be removed or is heavily shaded.

Morphogenesis

The young cotton plant first develops a stem and two cotyledons. Next, monopodials appear, the branches of which are initially dormant. Typically, there are 4 to 9 monopodial nodes on the main stem, depending on genetic earliness. Fruit nodes are located on sympodial branches. Squares are formed at the fruit nodes. The rate at which new organs such as main-stem leaves, fruit branches and fruit nodes are computed in the model is by the use of linear regressions against $f(T)$, based on experimental data. The functions are variety independent. Plant height is modelled as a linear function of $f(T)$ until growth is terminated by removal of the top bud (‘cut-out’).

Leaf area

The calculation of intercepted photosynthetically active radiation (PAR) is based on the leaf area index (L). In the model, leaf area index is computed by source-limited growth (Goudriaan & Van Laar, 1994), i.e., the availability of assimilates determines the formation and growth of new leaves. SUCROS-Cotton uses a developmental-stage dependent specific leaf area (SLA), which is linearly interpolated between values of 16.4 m^2 per kg dry matter (DM) at the 3-leaf stage, 22.0 m^2 per kg DM at 50% squaring, and 13.6 m^2 per kg DM at the 50% open boll (L. Zhang; unpublished data).

Radiation interception and photosynthesis

The calculation of radiative climate and canopy photosynthesis in SUCROS-Cotton is based on algorithms in SUCROS, as described by Thornley & Johnson (1990) and Goudriaan & Van Laar (1994). Five-point Gaussian integration is used to integrate the PAR interception over the vertical canopy profile. Daily PAR interception is calculated using 3-point Gaussian integration.

Respiration

Respiration is divided into two parts: growth respiration and maintenance respiration. SUCROS-Cotton uses algorithms for calculating plant respiration, as described by Goudriaan & Van Laar (1994).

Dry matter partitioning

Dry matter partitioning is fully determined by the developmental stage (Van Heemst, 1988). It is assumed that 70% of the daily produced assimilates is directly available for growth whereas 30% is allocated to a storage pool. When daily photosynthesis does not satisfy the demand of maintenance and growth respiration, dry matter is reallocated from the storage pool. If the daily net photosynthesis rate is 0 or negative, the relative reallocation rate from the reserve pool is 0.2 d^{-1}; otherwise it is 0.1 d^{-1} based on the assumption of the storage pool (Pan *et al.*, 1997). The daily available dry matter therefore consists of one component from current photosynthesis and a second one from the long-term storage pool. Dry matter partitioning to root and shoot differs among development stages. Stage-dependent partitioning coefficients were based on a review of crop model parameters by Van Heemst (1988). The partitioning to leaves is 0.65 at $\tau = 2.5$, 0.10 at $\tau = 17.5$, 0.05 at $\tau = 40$ and zero at $\tau = 60$; partitioning to stems is 0.35 at $\tau = 2.5$, 0.10 at $\tau = 17.5$, 0.05 at $\tau = 40$ and zero at $\tau = 60$; whereas partitioning to fruits is 0.0 at $\tau = 2.5$, 0.8 at $\tau = 17.5$, 0.9 at $\tau = 40$ and 1.0 from $\tau = 60$ onwards.

Fruit development and abscission

Formation of reproductive organs proceeds from squaring to flowering, boll filling and boll opening. All development stages of the reproductive structure will be referred to as fruits. The fixed boxcar train method (Goudriaan & Van Roermund, 1999) is used to simulate the dynamics of fruit development and abscission caused by assimilate stress, pest injury and extreme temperatures. The boxcar train is essentially a population model that keeps track of advancement in development, and changes in fruit numbers due to recruitment of new fruits and abscission (i.e., death) of existing fruits. Successive boxcars represent developmental stages, and the gradual accession of fruits in the boxcar train represents development. Development proceeds on a time scale of calendar days. Seventy-four boxcars are used to represent the changes in the developmental stage distribution of reproductive structures throughout the season as – across a wide range of genotypes – approximately 74 calendar days are required for the development of a fruit from just initiated square to open boll. Thus, in SUCROS-Cotton, the developmental duration of the fruits is fixed at 74 d irrespective of environmental conditions. Boxcars 1–22 represent squares (flower buds), boxcars 23–25 flowers, boxcars 26–33 small bolls, and boxcars 34–74 large bolls. The number of boxcars used for each of these stages

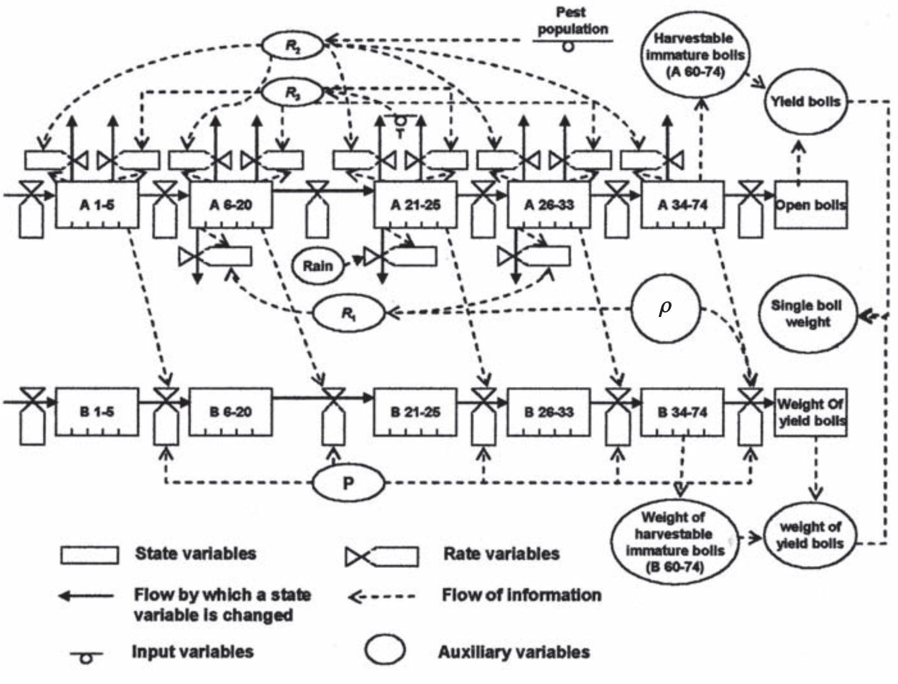

Figure 1. Relational diagram of the simulation of cotton fruit development and fruit growth in SUCROS-Cotton. A1–5 are the numbers of very small squares (flower buds), A6–20 bigger squares, A21–25 biggest squares and flowers, A26–33 small bolls, A34–74 larger bolls, A60–74 harvestable immature bolls. B*i–j* are the total biomass of the fruits in the classes *i–j* in the array B. R_1, R_2 and R_3 are the rates of fruit abscission due to assimilate stress, pest injury and extreme temperature, respectively. P is the potential growth rate of fruits from a class to the next. ρ is the ratio between assimilate supply and demand. T is air temperature.

represents their relative duration. Bolls in boxcars 60–74 have not opened yet but do mature and are eventually harvested.

Two coupled boxcar train state variables are involved in the calculation of the number and weight of fruits. The first boxcar train represents the numbers in each development class. The second boxcar train represents the total biomass of the reproductive structures within each class. Fruit age is represented by boxcar number. The terminal outflows of two coupled boxcar trains are the numbers and total biomass of the opening bolls (Figure 1).

Abscission

The main factor driving abscission is the ratio between supply and demand of assimilates (ρ), which is calculated as the ratio between the supply from daily photosynthesis plus reallocation from storage pool and the total demand for assimilates from all age classes of fruits. Reproductive structures of different age differ in their response to assimilate stress. Small fruits, i.e., squares (boxcars 1–22) and small bolls (boxcars 26–33), are shed when there is a shortage of assimilates. The rate of abscission, R_1, equals 0 when $\rho = 1$ and linearly increases to 1 when $\rho = 0$. Other factors causing abscission are pest injury and excessively high temperatures. The estimated rate of abscission from pest injury, R_2 , depends on the pest population and ranges from 0 to 0.001 d^{-1} with good bollworm control, but could potentially be higher if bollworm populations are high. The variable R_2 should then be input as a forcing function. Fruit abscission rate from extreme temperature, R_3 , is 0 below 32 °C and increases linearly to 1.0 d^{-1} at 45 °C.

Calculating fruit numbers

Equations 6–9 are used to calculate the number dynamics of fruits in each boxcar. Equation 6 defines the developmental width of each boxcar:

$$\lambda = \frac{g}{N} \tag{6}$$

where λ is the developmental width of one boxcar, g the developmental width of the whole boxcar train, set to 70 d, and N the total number of boxcars ($N = 74$), which indicates the number of days required for a fruit to develop from appearance of a square to open boll.

Equation 7 defines C_i, the number of fruits per unit of development within each boxcar:

$$C_i = \frac{A_i}{\lambda} \tag{7}$$

where A_i is the number of fruits in boxcar i.

Transfer of fruiting structures from one boxcar to the next, or out of the boxcar train is proportional to development rate, υ , 1.0 d^{-1}:

$$Q_{i+1} = \nu\, C_i \text{ and } Q_{out} = \nu\, C_N \tag{8}$$

The number dynamics per boxcar is then given by:

$$\frac{\mathrm{d}A_i}{\mathrm{d}t} = \frac{\nu}{\lambda}\,(A_{i-1}-A_i) - (R_1 + R_2 + R_3)\,A_i \tag{9}$$

Calculation of boll weight

The growth rate of fruit biomass in each boxcar is based on gains and losses due to fruits entering and leaving a boxcar as well as to new biomass growth of fruits in a boxcar, and is calculated as:

$$\frac{\mathrm{d}B_i}{\mathrm{d}t} = \frac{\nu}{\lambda}\,(B_{i-1}-B_i) - (R_1 + R_2 + R_3)\,B_i + \nu\rho P_i A_i \tag{10}$$

where B is the biomass (g m^{-2}; dry weight) of all fruits within a certain boxcar, ρ the supply/demand ratio of assimilates, and P_i the potential increase in weight of individual fruits from one boxcar to the next (g per fruit) in boxcar number i.

The first term in Equation 10, $\frac{\nu}{\lambda}\,(B_{i-1}-B_i)$, ascertains that developing bolls in the boxcar train take their weight along. The second term allows for fruit mortality. The third term is the increase in biomass of all fruits in boxcar i under the influence of assimilate supply and demand, and the potential dry matter uptake for growth calculated for the specific developmental class i. The actual growth rate is computed as the product of fruit number, potential growth rate per fruit, and the supply/demand ratio. Up to boxcar number 33, assimilate shortage causes shedding of fruits, but not reduction of their growth rates, therefore values of ρ for these boxcars are set to 1, irrespective of the availability of assimilates. Larger bolls (boxcar 34 and higher), will not be shed when assimilates are limited, but their growth rate is decreased proportionally by ρ.

The cumulative weight of a fruit growing without any stresses is derived from a logistic growth equation (Zhang *et al.*, 2004):

$$W = \frac{W_{max}}{1+k \bullet \mathrm{e}^{-r_{\mathrm{fruit}} \bullet \mathrm{a}}} \tag{11}$$

where W_{max} is the maximum weight of a single fruit, as a genetic input parameter, varying from 7 to 8 g per single boll (Anon., 1982), r_{fruit} the relative rate of fruit growth, and a the age of the fruit (equivalent to boxcar number) in calendar days. The parameter k is 250, and the relative growth rate of the fruits, r_{fruit}, which is genotype independent, amounts to 0.114 d^{-1} ($R^2 = 0.95$, $n = 16$), which was determined by field experiments conducted in 2001 and 2002 for two varieties (CRI35 and CRI41) at Anyang (Zhang *et al.*, 2004).

The dry matter requirement of fruits in boxcar i for developing to the next boxcar, is then calculated as:

$$P_i = (W_{i+1} - W_i) \tag{12}$$

In the mature cotton boll, around 25% of the dry matter is allocated to the shell, which does not contribute to the yield, around 45% to the seeds and around 30% to the fibres. The absolute shell weight does not significantly vary among genotypes, but it does vary with fruit age and temperature. Parts of the dry matter in the shell will be reallocated to the seed during boll maturation if the temperature is higher than 15 °C (Zhang *et al.*, 2003). The dynamics of shell weight during the first 30 calendar days (boxcars 26–55) can be described by a logistic growth curve until it reaches a maximum; thereafter (boxcars 56–74) shell weight decreases exponentially at a relative rate of 0.0038 d^{-1} (Zhang et al., 2004).

Cotton relay-intercropped with wheat

During the intercropping period, especially on sunny days, the air temperature experienced by the cotton seedlings is lower in intercropped than in monocropped cotton due to shading by the wheat (Zhang *et al.*, 2008a). In growth simulations of intercropped cotton, the air temperature from the weather station is therefore replaced by the air temperature measured in a canopy of cotton shaded by wheat (L. Zhang, unpublished data). Once the wheat is harvested, the air temperature used for intercropped cotton is the same as in monocropped cotton (Zhang *et al.*, 2008a).

Light interception during the intercropping phase is computed by a model for a homogeneous canopy, because a sensitivity analysis (Zhang *et al.*, 2008b) showed that a homogeneous canopy model for intercropped cotton gave almost the same results as a row structured model, except in the 6:2 system (6 wheat rows alternating with 2 cotton rows). In this system, characterized by wide strips for both wheat and cotton, light interception in a strip-structured canopy was lower than in a canopy whose leaf area was theoretically ‘homogenized’ over the whole cropping area (Zhang *et al.*, 2008b).

Model parameterization

The parameters in SUCROS-Cotton are based on literature data (Anon., 1982; Baker *et al.*, 1983; Van Heemst, 1988; Pan *et al.*, 1997), field measurements, and national cotton variety tests conducted from 1998 to 2001 at the China Cotton Research Institute in Anyang, Henan Province, China, in the Yellow River region (36°07'N and 116°22'E). Observations were made in farmers’ fields in Anyang in 2000 and 2001 to obtain phenology data for varieties, e.g., CRI35, that had not been included in the national variety test trial. The varieties used included conventional varieties that had not been genetically modified for insect resistance (e.g., CRI35), Bt-varieties that were genetically modified for insect resistance using toxin genes from *Bacillus thuringiensis* (e.g., CRI38), and ‘double gene’ varieties (e.g., CRI41) with insect resistance based on two complementary genes conferring insect resistance: a Bt-gene and a gene coding for Cowpea Trypsinase Inhibitor, derived from cowpea (*Vigna unguiculata*) (Li *et al.*, 2001). In total, 21 varieties were used that differed in earliness and in the associated variety coefficient. The following three classes of varieties can be distinguished:

1. Early maturing; sown in summer, such as CRI27;
2. Mid-early maturing varieties and hybrids; sown in spring, such as WM11 and CRI38;
3. Mid maturing varieties; such as Handan333.

Variety coefficients, $h(V)$, ranged from 0.79 in the late maturing variety CRI45 to

Table 1. Phenological development and variety coefficients of 12 cotton varieties.

Maturity type	Variety	Development duration (days)[1]	$h(V)$[2]	Year and experiment
Early maturing	CRI27[3]	100	1.00	1998, NCVT[4] 2000 and 2001, FO[5]
	CRI36	104	0.98	2000, FO
	CRI37	104	0.98	2000, FO
	Han241	103	0.98	1998, NCVT
	Lu458	101	1.00	1998, NCVT
	Nankang2	122	0.85	2001, NCVT
	Yuzao472	105	0.96	1998, NCVT
	Zhong142	105	0.96	1998, NCVT
Mid-early maturing	CRI32	124	0.82	2001, FO
	CRI41	124	0.82	2001, FO and NCVT
	CRI35	123	0.82	2001, FO and NCVT
	CRI29 (hybrid)	125	0.83	2001, FO
	Jiwu538	118	0.86	2001, NCVT
	Shiyuan321	117	0.85	2001, NCVT
	WM11	124	0.82	2001, NCVT
	ZKZ5	129	0.83	2001, NCVT
Mid maturing	CRI38 (hybrid)	126	0.80	2001, NCVT
	CRI45	127	0.79	2001, NCVT
	Handan333	126	0.80	2001, NCVT
	LuH9513	126	0.80	2001, NCVT
	Jiza566	126	0.80	2001, NCVT

[1] Days from sowing to 50% open boll.

[2] $h(V)$ = variety coefficient.

[3] Reference variety.

[4] NCVT = National Cotton Variety Test at Anyang, China, conducted by National Variety Test Station of Ministry of Agriculture.

[5] FO = field observation at Anyang, China.

1.00 in the early maturing reference variety CRI27 (Table 1). For varieties whose variety coefficient is not included in Table 1, $h(V)$ was estimated based on genotypic and phenotypic similarity to tested varieties.

The other genetic parameters, such as the node on the main stem on which the first fruit branch is formed, and the maximum weight of a boll, were also measured for each variety in field observations (Table 2). Independent experiments were conducted for validation.

Table 2. Parameters for boll growth in eight cotton varieties. [1]

Maturity type	Variety	Maximum weight of single boll (g)	Node on the main stem with first fruiting branch
Early maturing	CRI27	7.1 ± 0.2	4.5 ± 0.5
	CRI36	7.4 ± 0.4	5.1 ± 0.7
	CRI37	7.2 ± 0.3	5.0 ± 0.0
Mid-early maturing	CRI32	7.4 ± 0.3	8.3 ± 0.6
	CRI41	7.2 ± 0.1	7.9 ± 0.1
	CRI35	7.8 ± 0.2	8.4 ± 0.5
Mid maturing	CRI38 (hybrid)	7.7 ± 0.2	7.8 ± 0.2
	CRI45	7.3 ± 0.4	9.0 ± 0.0

[1] Based on field observations in 2000 and 2001 in Anyang, China.

Model validation

Experimental

Validation data were obtained from six experiments conducted near Anyang in the period 1998–2004 and from one experiment conducted in 1998 and 1999 near Arkesu (40°22'N and 80°04'E) Xinjiang Province.

Experiment 1 concerned recording of developmental stages of cotton in farmers' fields near Anyang. A field with the early maturing variety CRI27 was used in 1998, and a field with the mid-early hybrid CRI29 in 2000.

Experiment 2 concerned recording of developmental stages of cotton in farmers' fields near Arkesu. The varieties were CRI32 in 1998 and CRI35 in 1999. Plastic film mulching was used and plant density was 225,000 plants per ha.

Experiment 3 was conducted in 2001 near Anyang and comprised four cotton varieties: the mid-early hybrid CRI29, the double-gene GM mid-early variety CRI41, the early maturing conventional variety CRI37 and the mid-early maturing conventional variety CRI32. The experiment had three replications, plot size was 6.3 m × 14.5 m, row spacing 0.7 m, and plant density 60,000 plants per ha.

Experiment 4 was also conducted in 2001 near Anyang, and comprised two management practices: (1) removing vegetative branches, performing 'cut-out', and no plastic film mulching, and (2) removing vegetative branches, performing 'cut-out', and plastic film mulching, Hybrid CRI29 was used. Plant density was 60,000 plants per ha.

Experiment 5 was conducted in 2002 in Anyang and comprised 4 sowing dates – 15 April, 5 May, 25 May, and 14 June – factorially combined with three varieties: the mid-early conventional CRI35, the early conventional CRI36 and the double gene GM-variety CRI41. There were three replications, plot size was 9.6 m × 14.5 m and plant density 60,000 plants per ha.

Experiment 6 was conducted near Anyang in the period 2002–2004. Its main focus was to compare productivity of monocropped cotton with that of four wheat–cotton relay-intercropping systems: 3:1, 3:2, 4:2 and 6:2 according to the number of wheat rows that alternated with cotton rows (Zhang *et al.*, 2007). Row distance in sole cotton was 80 cm. Width of the wheat strips, as measured between the outer wheat rows, was 100 cm in the 6:2 system, 60 cm in the 4:2 system, and 40 cm in the 3:2 and 3:1 systems. The distance between outer rows of adjacent wheat strips (destined for sowing cotton) was 100 cm in the 6:2 system, 90 cm in the 4:2 system, 80 cm in the 3:2 system, and 60 cm in the 3:1 system. Total width of one adjacent wheat and cotton strip was 200 cm in the 6:2 system, 150 cm in the 4:2 system, 120 cm in the 3:2 system and 100 cm in the 3:1 system. Experiment 6 was of a randomized block design laid out in four replications. Plot size was 180 m^2. Mid-early maturing Bt cotton Shiyuan321 ($h(V) = 0.85$) was used in 2002 and CRI45 ($h(V) = 0.80$) in 2003 and 2004.

Water and nutrient management of all experiments was such that it met the requirements for potential crop growth. The treatment 'cut-out' was applied on 30 July at Anyang, and 15 July at Xinjiang Province. By using the results from the above six experiments, the model was validated with major differences in ecological environment, genotype, management, and cropping system.

Weather data for Anyang were obtained from the weather stations of the Cotton Research Institute. Weather data for Arkesu were obtained from Arkesu Meteorological Bureau (40°22'N and 80°04'E).

The root mean square error (RMSE) was used for measuring the difference between observed and simulated results:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} \times \sum_{i=1}^{n} (O_i - S_i)^2} \tag{13}$$

where O_i and S_i are observed and simulated results, respectively, and n is the number of observations. The results from the replications were averaged before calculating the residuals.

Validation of the simulation of development

Monocropped cotton

The validation of the cotton crop's development in the sole cotton system is presented in Figure 2. The RMSE was 1.1 d for sowing to emergence (7.3% of the observed), 1.5 d for emergence to flowering (2.5% of the observed), 3.7 d for flowering to 50% open boll (6.7% of the observed), and 4.2 d for the period from sowing to 50% open boll (3.3% of the observed). Considering the large differences between ecological zones and years, these results are considered satisfactory.

Relay-intercropped cotton–wheat systems

Compared with sole cotton, the delay in development of intercropped cotton as calculated by the model was 4.7 physiological days (Zhang *et al.*, 2008a). Observations and simulations of the duration from sowing to flowering and from flowering to open boll in intercropped and monocropped cotton showed good agreement in all three years

(Figure 3). The RMSE of the time from sowing to flowering and from flowering to open boll ranged from 2.1 to 2.9 d (3.0% to 3.4% of the observed). The results show that the model simulates phenology satisfactorily for both the monocropped and the intercropped cotton.

Effect of plastic film mulch

Figure 4 presents the phenological development of cotton with and cotton without film mulch in the Yellow River region and in Xinjiang Province. The results show that cotton with film mulch emerged 4 to 5 days earlier, flowered 6 to 10 days earlier, and took around 7 days less to reach the 50% open boll stage. There was close agreement between simulations and observations (Figure 4).

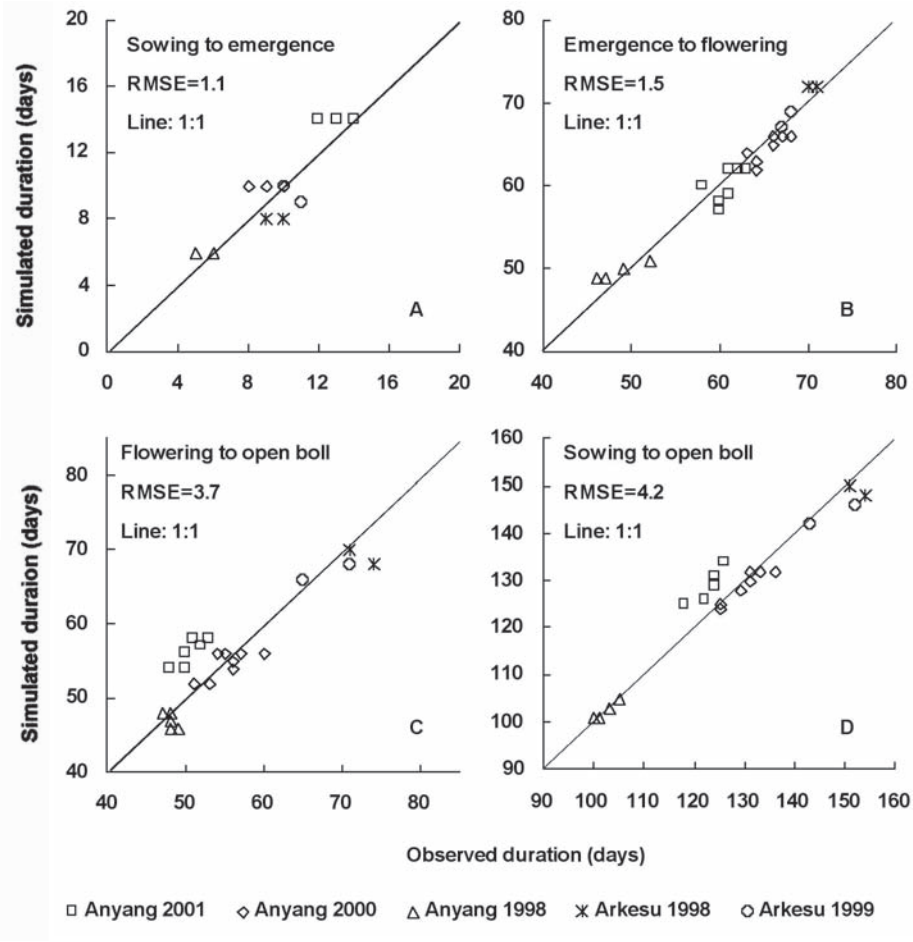

Figure 2. Observed and simulated duration of phenological stages (d, days) in Anyang in 1998 and 2000 (Experiment 1), in 2001 (Experiment 3) and in Arkesu, Xinjiang, in 1998 and 1999 (Experiment 2).

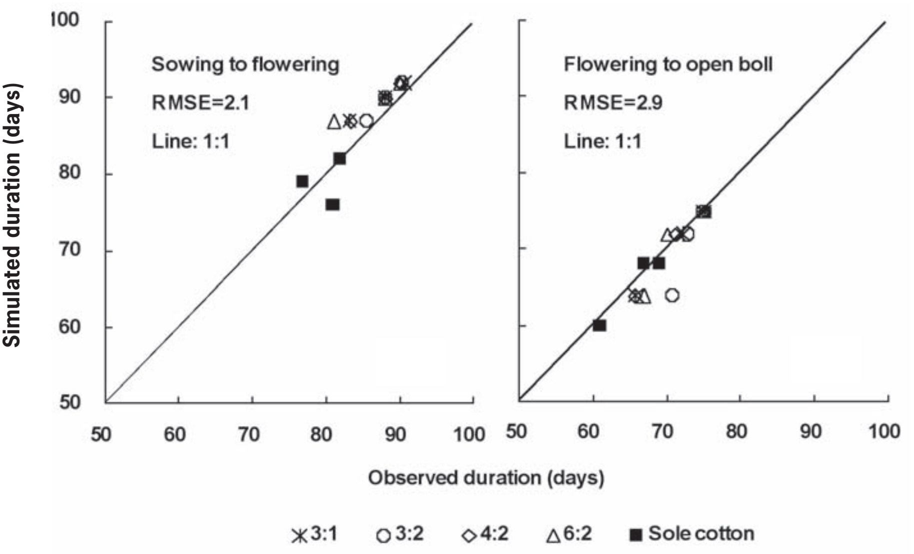

Figure 3. Observed and simulated durations of phenological stages of cotton in monoculture and in four different relay-intercropping systems with wheat, Anyang, 2002–2004 (Experiment 6).

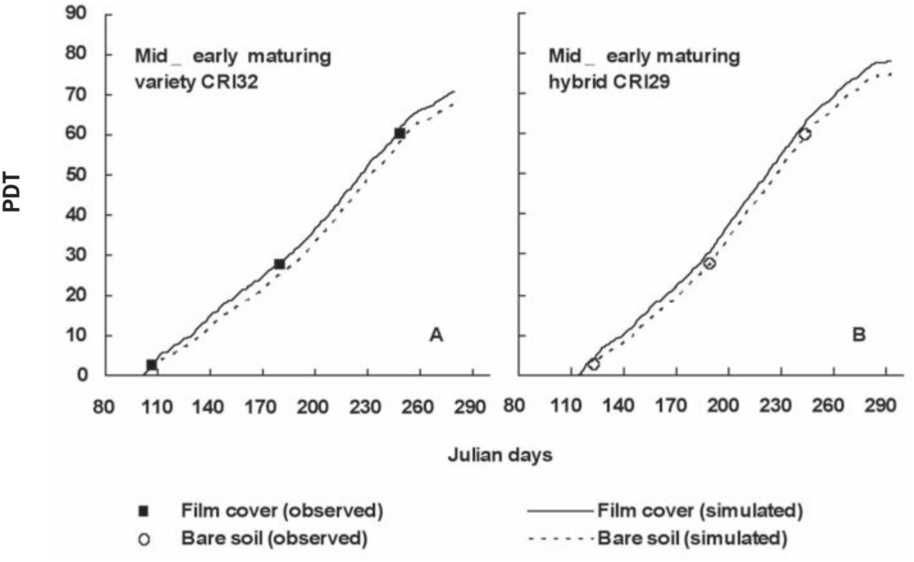

Figure 4. Observed and simulated physiological development time (PDT, τ) with and without film cover in (A) Arkesu, Xinjiang, 1998 (Experiment 2), and (B) Anyang, Yellow River region, 2001 (Experiment 4).

Validation of leaf area index

Simulations of LAI were validated in 2001 for the mid-early maturing variety CRI32, mid-early maturing hybrid CRI29 and early maturing variety CRI37 (Figure 5). The RMSE was 0.17 for CRI32, 0.25 for CRI29 and 0.31 for CRI37, i.e., 9.3%, 10.4% and 12.5% of the highest observed LAIs in the three varieties, respectively.

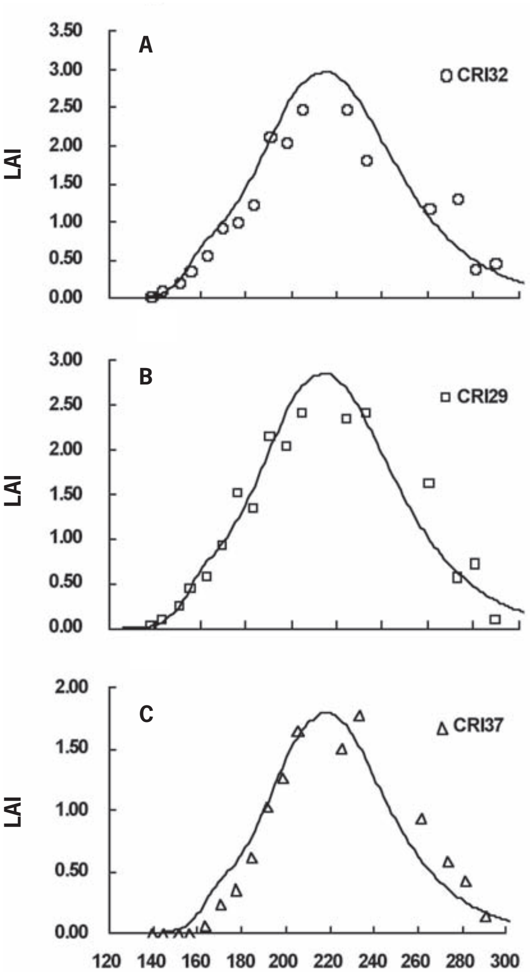

Figure 5. Observed and simulated leaf area index (LAI) for mid-early maturing variety CRI32 (A), mid-early maturing hybrid CRI29 (B) and early maturing variety CRI37 (C) in Anyang, 2001 (Experiment 3).

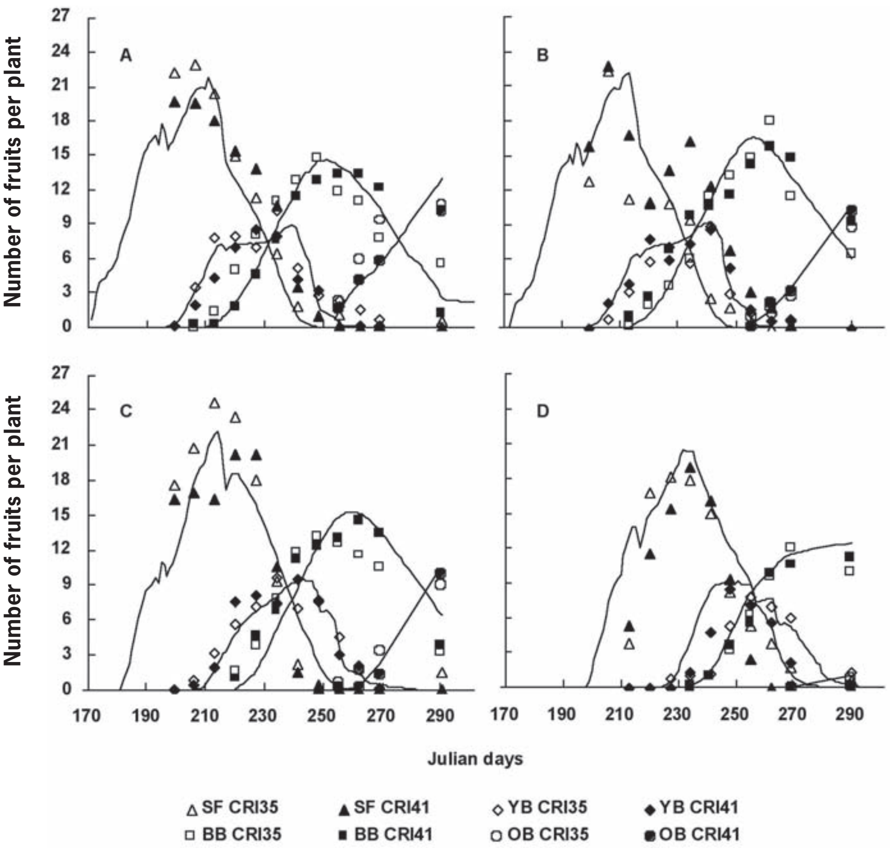

Figure 6. Dynamics of number of fruits in cotton: squares and flowers (SF), young bolls (YB), big bolls (BB) and open bolls (OB) in cotton of four sowing dates: (A) 4 April, (B) 5 May, (C) 25 May and (D) 14 June 2002 near Anyang (Experiment 5). Lines are simulated results and symbols are observations. Varieties CRI41 (open symbols, genetically modified insect resistant variety) and CRI35 (closed symbols, conventional variety) are similar in maturity type.

Validation of fruit growth and development

The simulation of fruit growth and development for different sowing dates was validated using the varieties CRI41 and CRI35 (Figure 6). Both varieties are mid-early maturing and have an $h(V)$ value of 0.82. The RMSE of the number of squares per plant was 3.36 (14.0% of the observed). The RMSE was 1.57 for the number of young bolls (15.4% of the observed), 1.57 for the number of large bolls (10.6% of the observed) and 1.04 for the number of open bolls per plant (10.0% of the observed). The dynamics presented in Figure 6 show a good agreement between simulations and observations. The results furthermore show that the dynamics of fruit development are captured satisfactorily by the algorithms in SUCROS-Cotton.

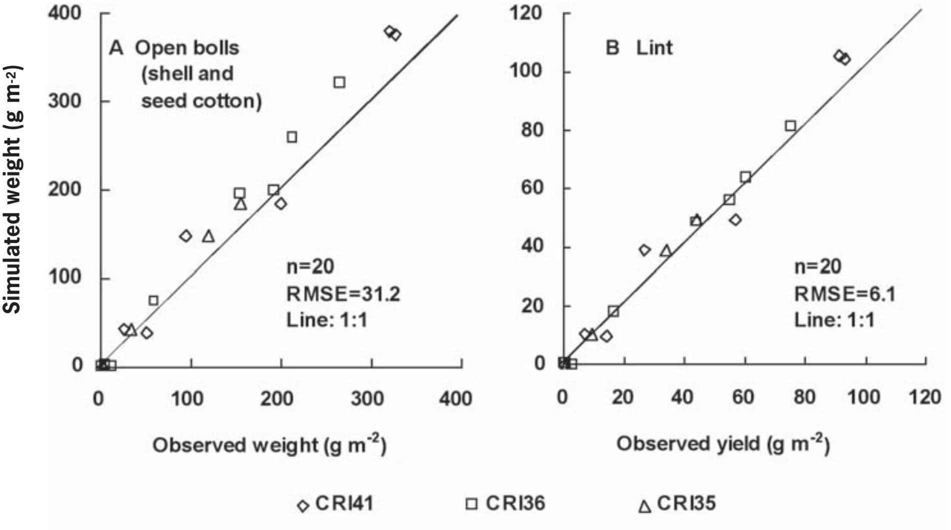

Figure 7. Comparison of simulated and observed weight of open bolls (A) and lint yield (B) in cotton sown at different dates near Anyang, 2002 (Experiment 5). n is the number of samples.

Validation of dry matter accumulation and yield

The simulation of dry matter accumulation was evaluated using results from Experiment 3 (comparison of four varieties, conducted in 2001) and Experiment 5 (comparison of four sowing dates, 2002) in Anyang. The RMSE ranged from 371 to 445 kg total dry matter per ha, 4.3 to 6.2% of the observed. The RMSE of dry matter under two different forms of management (Experiment 4), ranged from 283 to 447 kg ha^{-1}, 4.7 to 6.6 % of the observed.

The simulation of yield as affected by sowing date shows a good agreement for the three varieties, with a RMSE of 61 kg ha^{-1} for lint yield (6.6% of the observed) and a RMSE of 312 kg ha^{-1} for total open boll weight (9.8% of the observed; Figure 7). The simulations give good predictions over a wide range of yields, including yields of (almost) zero due to late sowing (Experiment 5). The slight overestimation of total boll yield (Figure 7A) indicates that simulation might be improved by taking growth limiting factors into account, particularly water.

Discussion

The results of the model validation for the years 1998–2004 at the locations in Xinjiang Province and Yellow River region show a good performance of SUCROS-Cotton. The highest relative error was 6.7% for the timing of phenological stages, 6.6% for dry matter, 6.6% for lint yield, and 10.0% for final fruit number.

Currently available crop growth simulation models have shortcomings when applied to questions related to cotton cultivation in China. First, the growing degree days (GDD) approach assesses incorrectly the effect of supra-optimal temperatures on crop growth because it assumes a linear relationship between development rate and temperature, due to the high temperatures that can occur in China and that are detrimental to the crop. In reality, development rate reaches a plateau, and it may even decrease at temperatures that are supra-optimal (Yin *et al.*, 1995).

New features of SUCROS-Cotton relative to existing cotton models are: (1) physiological development time is used instead of degree days, so the thermal, daylength and genetic effects are included, (2) the effects of Chinese agronomic practices such as plastic film mulching and 'cut-out' are well simulated, (3) diffuse radiation is taken into account following the approach of SUCROS, and (4) fruit growth and development are simulated by using the boxcar methodology with advantages in model transparency and conciseness. The conceptual structure of SUCROS-Cotton allows for parameterization under a wide range of conditions with respect to temperature, radiation, genotypes and cropping systems, i.e., monocropping and intercropping systems.

SUCROS-Cotton is the first process-based cotton crop growth model that is applicable in China. It addresses variety effects and contains effects of relevant management practices such as intercropping, 'cut-out' and plastic film mulch. It provides a tool for (1) assessing production opportunities in various ecological zones in response to weather and water availability, (2) deriving optimal cotton ideotypes under different agro-ecological conditions to guide breeding efforts, and (3) analysing crop management practices, e.g., effects of plastic film mulching and sowing date, or interactions with intercrops, such as wheat. SUCROS-Cotton can also be applied to estimate yield losses caused by pest damage and the magnitude of cotton compensatory growth. Use of the model can add value to and insight into field work by enabling a process-oriented interpretation of experimental findings, and by predicting *ex ante* the outcomes of experimental treatments. The model can be extended with algorithms for the uptake and utilization of water and nitrogen (Bouman & Van Laar, 2005) to broaden its application potential to a wider range of cropping systems and conditions.

Acknowledgements

The financial support from the sandwich-PhD programme of Wageningen University, the support through project '863' (2007AA10Z228) and the Programme for Changjiang Scholars and Innovative Research Teams in Universities (IRT0412) is gratefully acknowledged. We thank Professor Jan Goudriaan for helpful discussions and advice and Mrs Gon Van Laar for preparing the list of variables. Grateful acknowledgement is made to the staff of the Cotton Research Institute of the Chinese Academy of Agricultural Sciences for their assistance with the experiments.

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Appendix 1

List of symbols

Symbol [1]	Acronym [2]	Unit	Meaning
a	AGE	d	Calendar age of a fruit.
A_i	BOLL	#	Number of fruits per plant in boxcar train i.
B_i	WBOLL	kg ha^{-1}	Total biomass of reproductive structures–fruits: squares, flowers and bolls in boxcar train i.
c	IE	–	Conversion factor from increment of soil temperature to increment of air temperature.
C_i	CBOLL	–	Number of bolls per plant per unit width in boxcar i.
C_N	CBOLL	–	Number of maturing bolls per plant per unit width in boxcar N.
D	DAYL	h	Daylength.
D_b		h	Base daylength.
D_m		h	Maximum daylength.
DM	TDWW	kg ha^{-1}	Dry matter.
$f(T)$	RET	–	Thermal effect.
g	G	d	Total developmental width of the boxcar train.
$g(D)$	RPE	–	Daylength effect.
$h(V)$	VI	–	Variety coefficient.
k		–	Intermediate variable derived from maximum and initial weight of a single boll.
L	LAI	m^2 leaf per m^2 area	Leaf area index.
N	N	#	Total number of boxcars.
n	–	–	Number of independent samples.
O_i	–	–	Observed results from field experiments.
P_i	RWBOLL	g boll^{-1}	Potential growth rate of fruits in boxcar i.
Q_i	FLOW	–	Flow of fruits from preceding boxcar to boxcar i.
Q_{out}	OUTFL	–	Flow of fruits out from boxcar train.
R_1	FALL1	d^{-1}	Fruit abscission rate caused by assimilate stress.
R_2	FALL2	d^{-1}	Fruit abscission rate caused by pest injury.
R_3	FALL3	d^{-1}	Fruit abscission rate caused by extreme temperatures.
r_{fruit}	RMBOLL	d^{-1}	Relative growth rate of a single fruit.
S_i	–	–	Simulated results from running the model.
T	TMMN, TMMX or TAV	°C	Air temperatures of minimum, maximum or daily average.
T_b		°C	Biological base temperature.
T_m		°C	Maximum temperature.
T_o		°C	Optimum temperature.
T_s	TSAV	°C	Average soil temperature at 5 cm depth without film mulch.

Symbol [1]	Acronym [2]	Unit	Meaning
T_{sf}	TSCAV	°C	Average soil temperature at 5 cm depth under film mulch.
t	TIME	d	Calendar day.
W, W_i	WBAGE	g boll^{-1}	Potential weight of a single fruit of age i, in boxcar i.
W_{max}	WBMAX	g boll^{-1}	Maximum weight of a single boll.
λ	GAMMA	d	Developmental width of one boxcar in boxcar train.
ν		d^{-1}	Development rate of fruit.
ΔT	TPLUS	°C	Increment of air temperature by increase of soil temperature under film cover.
ρ	STRBOL	kg kg^{-1}	Supply/demand ratio: DM resulting from net photosynthesis per kg DM required to satisfy the demand (potential growth) of the sinks.
τ	PDT	d	Physiological development time, measured as equivalent number of days with conditions allowing maximum rate of development.

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[1] Symbol used in text.

[2] Acronym in FST-listing.