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Simulation of dry matter accumulation, partitioning and yield prediction in processing tomato (*Lycopersicon esculentum* Mill.)

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Abstract

Simulation of dry matter accumulation and the distribution of crop growth is an important means of predicting yield. In this study, a variety of cultivars of the processing tomato (*Lycopersicon esculentum* Mill.), sowing dates and densities were tested. By analyzing the quantitative relationships between growth and physiological development time (*PDT*) based on a knowledge model, dry matter partitioning index and harvest index (*HI*), mathematical models were developed to estimate total dry matter accumulation, shoot dry matter partitioning and yield for processing tomatoes. A sowing date factor (*SDF*) was introduced to regulate partitioning intensity and the genetic features of the cultivars tested were considered. Validation of the results using trial data gained from studies with different cultivars and from sowing experiments showed that total dry matter weight was predicted correctly (*RMSE* < 1313 kg ha^{-1}, *RE* < 27.70%). Above ground biomass was predicted with an *RMSE* < 416 kg ha^{-1} for stems, < 517 kg ha^{-1} for leaves and < 545 kg ha^{-1} for the fruit. Yield, defined as ripe fruit dry matter accumulation, was also accurately predicted (*RMSE* and *RE* were 7737 kg ha^{-1} and 15.51%, respectively). This model can be used to predict different production levels and yield objectives for processing tomatoes planted in arid areas of China. Further improvements to the model are discussed.

Keywords: Dry matter accumulation; Dry matter partitioning; Partitioning index; Processing tomato; Simulation model; Yield formation.

Abbreviations: HB-Hongba; *HI*-harvest index; HY-Hongyun; HZ-35-Hongza-35; *IDF*-intrinsic development factor; LY-8-Liyuan-8; *PDT*- physiological development time; *RE*- relative estimation error; *RMSE*-root mean squared error; *SDF*-sowing date factor; SH-14-Shihong 14; WPTC-World Processing Tomato Council; XF-4-Xinfan-4; XF-8-Xinfan-8.

Introduction

The processing tomato (*Lycopersicon esculentum* Mill.), is characterized as a self-capped dwarf variety cultivated in the field without squaring up and pruning. It also has smaller fruits with thicker skins, which makes them more amenable for storage, transport and processing. The processing tomato plays an important role in tomato production and consumption. According to statistics issued by the World Processing Tomato Council (WPTC, 2010), the total world production of tomatoes in 2009 was 4.2317 million tons, with the main production areas being the central valley of California (Hanson and May, 2006), the Mediterranean coast and the Chinese regions of Xinjiang and Inner Mongolia (Ma, 2005). In 2009, China's output of tomato products was approximately 1.1 million tons and export volume was 0.74 million tons, accounting for 17.49% and 26.00% of world tomato production and exports, respectively (National Bureau of Statistics, 2010). Moreover, in 2009, China became the world's second largest producer and exporter of tomato products with Xinjiang as one of the world's three major processing tomato production centres. Located in the central part of the Eurasian continent, the area has high light intensities and a warm climate and there is a large temperature difference between day and night, characteristics that are suitable for growing processing tomatoes. Furthermore, the tomatoes produced there are of superior quality to those produced in the United States, Italy and other major producing countries (Ma, 2005). At present, processing tomato production is the dominant industry in Xinjiang, the most arid area of China, and has a high prominence in the overall agricultural development strategy (Wu and Li, 2010). Recently, in Xinjiang, the processing tomato became the second largest economic crop, with a planted area of 70–72 000 ha annually, and tomato ketchup exports from the area constitute almost one-fifth of total world trade (WPTC, 2010). Development of a decision support system for the processing tomato in arid areas is key to increasing the productivity of the processing tomato industry, while dynamic simulation of the growth and yield of the processing tomato is the basis for building models. Dry matter accumulation and distribution directly influence yield whereas economic benefit is an important component of studies on growth simulation of the processing tomato. Currently, studies on dry matter accumulation of crop groups focus mainly on the numerical modelling of photosynthesis (Marcelis et al., 1998; Ni et al., 2005; Tang et al., 2007b), in which, a simple and identical method of calculating dry matter accumulation and radiation use efficiency (*RUE*) are applied to the simulation of canopy radiation absorption and total photosynthesis. However, the model's credibility and predictability are poor because of differences in calculation methods and the large effect of environmental factors on *RUE*. Three methods have been applied to the partitioning of crop dry matter (Marcelis, 1993): (i) modelling based on 'source–sink' adjustment theory (Minchin et al., 1993); (ii) function equilibrium theory (Levin et al., 1989; Hunt et al., 1998) and (iii) partitioning coefficient or index theory (Singels and Bezuidenhout, 2002; Tang et al., 2007a; Ni et al., 2006; Yuan et al., 2006). The 'source–sink' model has seen little use because sink ability in the absorption of assimilated products is determined by sink intensity (Marcelis, 1996), and the sink intensity of plant components are quantified by potential growth speed which is difficult to obtain in practice, especially for vegetative organs. Function equilibrium models succeed in simulating dry matter partitioning to shoots and roots by building relationships between shoot (photosynthesis rate) and root vigour (absorption of water and nutrients) but fail to simulate partitioning of the shoot's dry matter to other above-ground organs. On the hypothesis that the ratio of growth rate or relative growth rate among different organs is constant or is a function of time, accumulated temperature or plant size at a particular growth stage of the crop, a model based on a partitioning coefficient or index is not as good as the 'source–sink' model in terms of its methodology but is more practical because its parameters are easily measured. Several studies have reported simulation models for dry matter accumulation and yield accumulation in field (Jaradat, 2009; Cao et al., 2002) and horticultural crops (Marcelis, 1994; Gary et al., 1995), but there have been few studies that have investigated the processing tomato. Ni et al. (2006) developed a mathematical model for tomato dry matter accumulation and partitioning and yield prediction using relationships between *TEP* (the product of thermal effectiveness and *PAR*), leaf area and partitioning index in the stable growth environment of a glasshouse. Since the model did not take into account the type of field cultivation used, it was not suitable for predicting yield and dry matter partitioning for processing tomatoes grown in fields because of the difficulty in obtaining the effective photosynthesis radiation parameter, which is required by the model. This study combined mathematical and knowledge models by analysing the relationship between dry matter accumulation, partitioning index, harvest index and physiological development time (*PDT*) using data produced over a number of years and obtained from cultivar and sowing date testing. Using this information, a dynamic model to simulate dry matter accumulation and partitioning was then created to predict yield, in order to establish a basis for developing a comprehensive growth simulation system for the processing tomato.

Results

Simulation result of total dry matter weight

Dry matter accumulation was simulated and compared with measured values for a number of cultivars (experiment iii) and different sowing date treatments (data for 2006 in experiment iv). The results are shown in Fig 3. For the same sowing date, the *RMSE* and *RE* for observed and simulated values of population total dry matter accumulation for all the cultivars were 837.39 –1313 kg ha^{-1} and 8.95% – 27.70%, respectively. For different sowing dates, *RMSE* and *RE* for observed and simulated values of the same cultivar were 559.88 – 1120.5 kg ha^{-1} and 14.39% –20.76%, respectively. These results indicate that this model shows good predictability (Fig 3).

Simulation results for shoot and root dry weights

According to the models outlined above, shoot and root dry weights at different growth stages were calculated and compared with observed values in experiment ii. The results are shown in Fig 4 and the equation for the regression line was calculated as $y = 1.0235x$ ($R^2 = 0.9963$), where y is the simulated value and x is the observed value, which mostly overlaps with the diagonal line ($y = x$). The R^2 value between the simulation results and the 1:1 line is 0.9990 and *RMSE* and *RE* are 231.95 kg ha^{-1} and 7.36%, respectively. This indicates that the model shows good predictability (Fig 4).

Simulation results for above ground organs

Stem, leaf and fruit dry weights at different growth stages were calculated and compared with observed values from experiment ii. The results are shown in Fig 5. The values of *RMSE* and average *RE* between the simulated and observed values for stems were 49 – 416 kg ha^{-1} and 16.58%, respectively. The R^2 value between the linear equation for simulated and observed values for stems and the 1:1 line was 0.9858 ($p < 0.01$). *RMSE* and average *RE* for leaves were 31 – 517 kg ha^{-1} and 19.39%, respectively, and the R^2 value for leaves between the calculated result and the 1:1 line was 0.9783 ($p < 0.01$); *RMSE* and average *RE* for fruit were 266–545 kg ha^{-1} and 11.86%, respectively, and the R^2 value for fruit between the calculated result and the 1:1 line was 0.9424 ($p < 0.01$). Thus, the model showed a high fit between simulated and observed values for above ground organs (Fig 5).

Simulation result for yield

Processing tomato yield was calculated and compared with the observed values from experiment ii (Fig 6). The *RMSE* and average *RE* between simulated and observed values were 7737 kg ha^{-1}and 15.51%, respectively. The R^2 value between simulation results and the 1:1 line was 0.98 ($p < 0.01$), indicating that this model shows a high fit between simulated and observed values for fresh fruit yield (Fig 6).

Discussion

This research, after considering other crop models (Tang et al., 2007a; Ni et al., 2006; Cao and Moss, 1997), has developed a model for dry matter accumulation and partitioning and yield accumulation by analysing dry matter partitioning in processing tomatoes using data obtained from different growth years and cultivars. Tests with different data sets involving different cultivars and sowing dates showed that the model gave reliable predictions and was practicable. The dry matter accumulation models that are available mostly rely on the measurement of photosynthesis and are based on physiological processes (Ni et al., 2005; Tang et al., 2007b). These are relatively difficult to use in practice because they require a number environmental reference factors to be measured (Heuvelink, 1999). This study developed a total dry matter accumulation model for the processing tomato based on the *PDT* of a number of cultivars by combining a mathematical model with a knowledge model. Although the model was not as efficient as others in terms of mechanism, it was still good with respect to regularity and stability. In most existing crop growth models, the distribution coefficients obtained by calculating the ratio of each organ

Table 1. Location, climatic characteristics and soil types of the trial sites.

Item	Shihezi	Hejing county	Zhangye
Location	44° 18′ 69″ N, 86° 03′ 30″ E	42° 18′ 20″ N, 86° 28′ 69″ E	38°56′52″N,100°26′33″E
Altitude (m)	463	1101	1483
Average multiannual effective accumulated temperature (°C)	3570	3495	3160
Frost-free period (day)	166	195	158
Average solar radiation (April–September)(h)	1750	1942	1707
Average multiannual temperature（°C）	7.1	8.5	7.3
Annual precipitation (mm)	152	56.5	109
Evaporation (mm)	1540	2280	1978
Soil type and	Sandy loamy, gray-brown desert soil	Clay loamy, chestnut soil	Fine loamy, brown desert soil

Table 2. Field experimental design at each site.

Experiment	Site	Year	Sowing date	Variety	Planting density (plants ha^{-1})	Plot setting
i	Shihezi University Experiment Station	2006	April 12, April 22, May 6 and May 20	Liger 87-5 HY	54000 48500	Plots of 18 m^2 were replicated three times, each plot having two plastic films and four rows
ii	Shihezi University Experiment Station	2007	April 5, April 25, May 6 and May 20	Liger 87-5 XF-8 HB	55500 48000 42000	Plots of 18 m^2 were replicated three times, each plot having two plastic films and four rows
iii	Shihezi University Experiment Station and Zhangye Institute of Agricultural Science	2007	April 25	Q020, uc-82, HZ-35, LY-8, XF-4 and HB	52700	Each cultivar was planted in two rows with one 7-m plastic film
iv	Agricultural technology extension station of No. 223 Farm of the Second Agriculture Division, Hejing county, Xinjiang	2005	April 14	Liger 87-5, LY-8 and AS9081	48000	Plot sizes were 3 × 10 m^2, each with three plastic films and six rows
		2006	April 5, April 25 and May 8	SH-14		

weight to biomass are used to predict the growth of various organs (Goudriaan and Van, 1994; Habekotté, 1997). However, it is difficult to estimate the distribution coefficient itself because of the long duration of simultaneous vegetative and reproductive development and the interaction between sources and sinks. In addition, most existing tomato growth models have low accuracy and adaptability as they do not consider the effects of the sowing date and genotype on the partitioning of matter to different organs. This research, developed a dynamic model of dry matter partitioning between shoots, leaves, stems and fruits that predicted yield based on partitioning indices and a harvest index that varies with *PDT*. It also considers the influence of factors such as sowing date and genotype on *PDT* as a continuous growth time scale, with a logistic curve representing a law of increase quantified with an economy coefficient and the yield level. Compared with traditional horticultural crop models based on ‘source – sink’ regulation, this model was accurate, practical and convenient, overcoming the shortcomings of other models, which have more parameters that are difficult to obtain. Dry matter partitioning to vegetative organs and fruit and yield formation are affected not only by temperature, light and planting density, but also by the supply of water and fertilizer and by human activity. This model is suitable only for dry matter partitioning and yield prediction and does not consider the amount of water and fertilizer supplied, so its general practicability would be improved by conducting fertilizer experiments. But the modeling concepts could provide references for the simulation of dry matter partitioning in the processing tomato under different production and management conditions, and also establishes the basis for the application of simulation models.

Materials and methods

Study site and cultivars

The study was conducted from 2005–2007 at three sites that have a typical desert oasis climate and represent the varied environments and soil types that can be found in northwest China (Table 1).The varieties selected in this study included early-maturing conventional varieties: Liger 87-5 and Q020, the late-maturing conventional variety uc-82, the early-maturing hybrids: Hongza-35 (HZ-35) and Liyuan-8 (LY-8), the medium maturing hybrids: Xinfan-8 (XF-8) and Shihong 14 (SH-14), and the late-maturing hybrids: Hongyun (HY) , Xinfan-4 (XF-4), AS9081 and Hongba (HB). These varieties were all supplied by the Vegetable Institute of Shihezi.

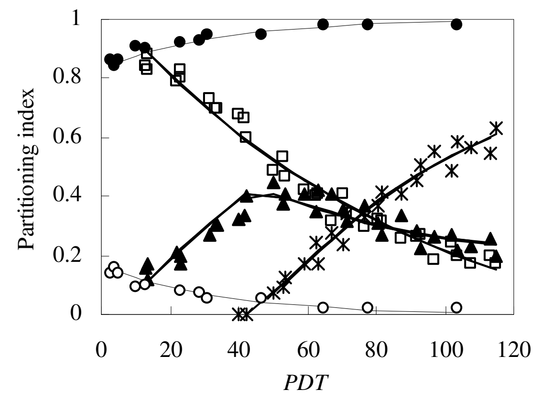

Fig 1. Partitioning index dynamics for shoot (●), root (○), and different organs, i.e. stem (▲), leaf(□) , fruit (*) with *PDT*, which was obtained by using test data from different cultivars and sowing days (experiment i). — indicates simulated values of partitioning index.

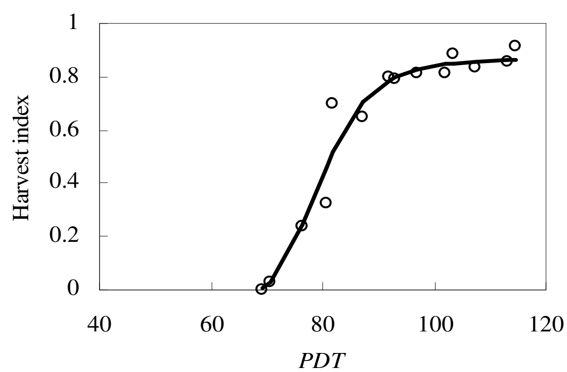

Fig 2. Relationship between harvest index and *PDT*,— indicates using simulated values for the partitioning index.

Field experiments

Separate experiments for different sowing dates, varieties and planting density were carried out at a number of sites, which included sowing date experiments conducted at Shihezi in 2006 (experiment i), variety and sowing date experiments conducted at Shihezi in 2007(experiment ii), variety testing conducted at Shihezi and Zhangye in 2007(experiment iii) and varieties and sowing dates experiments conducted in 2005 and 2006 respectively at Hejing county (experiment □) (Table 2). In these experiments, where under-film drip irrigation was used, the tomatoes were directly planted using spacings of 40 cm between narrow rows and 60 cm between wide rows. Thinning out of the seedlings was undertaken at the 4- to 5-leaf stage. Three inter-row cultivations were conducted at 10 day intervals during the seedling stage and the plants irrigated a total of 12 times during the growing period. The first watering consisted of drip irrigation at 190 $m^3\ ha^{-1}$ after the final thinning out of the seedlings; subsequently, the plants were irrigated once every 10 – 15 days, using 225–300 $m^3\ ha^{-1}$ on each occasion. For the 3rd to the 8th drip irrigations, drip feed fertilization was carried out using a total of 120 kg ha^{-1} urea and 60 kg ha^{-1} KH_2PO_4. The experimental field was kept free of weeds, and no visible disease and insect pests were observed during the growing season. Observations included growth, development and plant morphology indicators. Every 7 – 8 days, representative plants from the guard rows of each plot were sampled during the growing season. Two plants (five plants before flowering) were sampled destructively on each sampling date. The plants were excavated to a soil depth of 80 cm using a spade and all soil was washed from the roots; the sampled plants were cut at ground level in order to measure of plant height and count the number of main-stem nodes, branches, leaves and flower clusters. After obtaining plant height data, the fresh weight of roots, leaves (leaf blades plus petioles), stems and fruits were measured, the root, stem, leaf, fruit, and ripe fruit samples were over dried at 65°C to a constant weight and their dry weight determined. Meteorological data were provided by the China meteorological data sharing service system (http://cdc.cma.gov.cn) and the Bureau of Meteorology, Shihezi.

Model development

Data gained from experiments i and iii were used to develop the models for dry matter accumulation, partitioning and yield and data gained from experiment ii and ⅳ were used to test the model. Physiological development time (*PDT*) was defined in the model as the number of development days where optimal light and temperature conditions prevailed, which was determined by the interaction of physiological thermal effectiveness, effective day length and genetic or varietal parameters (Cao and Moss, 1997; Cao and Luo, 2003). The *PDT* at specific growth stages of each variety was kept stable by introducing an intrinsic development factor (*IDF*) to regulate genetic differences. The *PDT* values of the main stages of processing tomato development were as follows: 42 for the beginning of fruit set, 74 for fruit ripening (half of the plants having more than one mature fruit) and 110 for the end date (when 85% of the fruits were red or orange) (Wang et al., 2008).

Model test

Root mean squared error (*RMSE*) and relative estimation error (*RE*) (Delden et al., 2001) were used to assess the degree of conformity between simulated and observed values. The smaller the *RMSE* and *RE* values, the smaller is the deviation between simulated and observed values; that is, the more accurate are the simulation results of the model. The linear equation $y = kx$ was derived by comparison of the simulated value y and the observed value x. The simulation was considered accurate if the coefficient k was equal to 1. The significance of the correlation between the linear equation and the coefficient of determination (R^2) of the 1:1 line was evaluated using Student's *t*-test.

$$RMSE = \sqrt{\sum_{i=1}^{n}(OBSi - SIMi)^2 \Big/ n} \tag{1}$$

and

$$RE = (RMSE \big/ \overline{OBSi}) \times 100\% \tag{2}$$

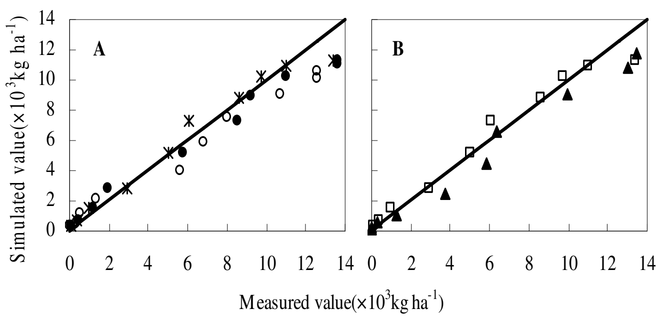

Fig 3. Comparison between simulated and measured total dry weight of the processing tomato using independent data where Fig 3A is compares different cultivars on one sowing date (A: Sowing date of April 5 , ○ is HB with a yield = 108053 kg ha^{-1},● is XF-8 with a yield = 86527 kg ha^{-1}, ☆ is Liger 87-5 with a yield = 76875 kg ha^{-1}) and Fig 3B compares one cultivar over two sowing dates (B: Liger 87-5 cultivar, □ represents an April 5 sowing date with a yield = 100989 kg ha^{-1}, ▲ represents an April 25 sowing date with a yield = 88987 kg ha^{-1}). Lines represent 1:1 relationship.

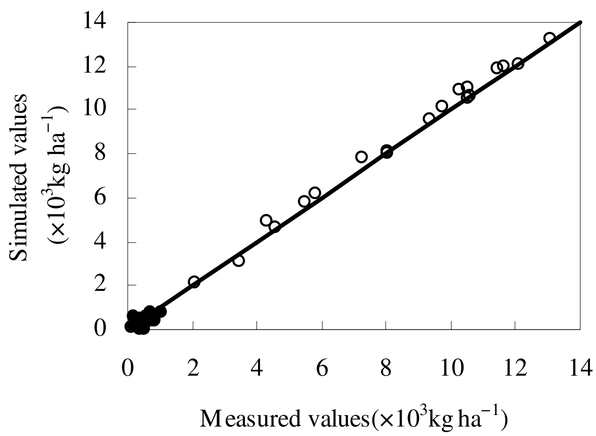

Fig 4. Comparison between simulated and observed dry weights of shoots (○) and roots (●) at different growth stages, for different cultivars and for different sowing dates (experiment ii).

where, *OBSi* is the actual measured value, *SIMi* is the corresponding simulated value, *n* is sample size and $\overline{OBSi}$ is the mean value of actual observed values.

Model Description

Dynamic model of total dry matter accumulation

Crop dry matter accumulation is the basis of yield accumulation. The accumulated mass and the partitioning proportion directly influences vegetative and reproductive growth and the population dynamics of the tomato. The results of analysing the data from experiments i and iii indicated that the dry matter accumulation of the processing tomato increased according to a logistic curve, quantified as:

$$DMA(PDT) = \frac{TDMA}{1 + CVidm \times e^{-INSTDMI \times PDT}} \tag{3}$$

where *DMA*(*PDT*) is dry matter accumulation over a certain time period (kg ha^{-1}); according to the above model, as *PDT* is infinite, *DMA*(*PDT*) = *TDMA*. Therefore, *TDMA* could be calculated approximately as total dry matter accumulation when the plant is at the end date stage. *TY* is yield (kg ha^{-1}); η is the water content of the fruit, which equalled 0.95 in a previous study (De-Koning, 1993), and *HC* is the economy coefficient (the ratio of ripe fruit dry weight to total dry weight). Usually, when yield is at a medium or low level, it increases with dry matter accumulation. When it reaches the high or super-high level, yield increases mainly by improvement in the economy coefficient. The relationship between the economy coefficient and yield can be stated as:

$$TDMA = \frac{TY \times (1-\eta)}{HC} \tag{4}$$

And

$$HC = -0.0789 + 0.6237 \times \sqrt{1 - \frac{165000 - TY}{165000}} \tag{5}$$

CVidm is a constant determined by dry matter when it starts to increase; when *PDT* is zero, *DMA(PDTv) = TDMA/ (1 + Cvidm)*. Because 90% of the nutrients in seeds are required for germination, *Cvidm* can be quantified as:

$$CVidm = \frac{TY \times (1-\eta)}{0.92 \times SR \times HC \times 100} - 1 \tag{6}$$

where *SR* is the amount sown per unit area. *INSTDML* is the transient rate of increase in dry matter, calculated as:

$$INSTDMI = -\ln\left(\frac{TDMA - DMA_{bt}}{DMA_{bt} \times CVidm}\right) / PDT_T \tag{7}$$

where PDT_T is the physiological development time when the colour-changing period is reached (PDT_T = 70, calculated using a sub-model of dynamic growth (Wang et al., 2008)). $DMAR_{at}$ is the amount of dry matter accumulated as a proportion of the total amount after the colour-changing period. The rate of accumulation of dry matter in the processing tomato is slow during the early growth stages when the plants are small and leaf area increases slowly, but after flowering, the leaf area and photosynthesis rates increase rapidly and the amount of dry matter reaches 90% of the eventual total when the first spike of fruit is borne.

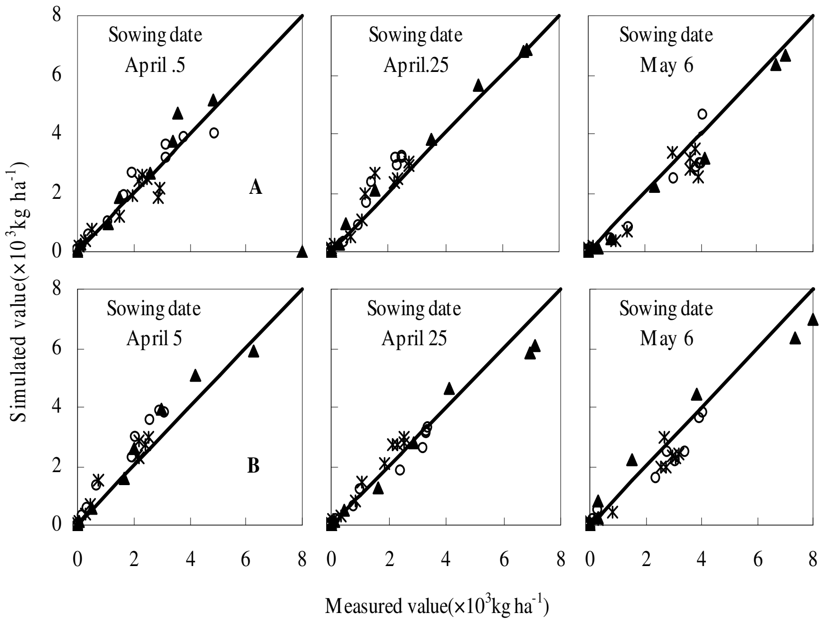

Fig 5. Comparison between the simulated and observed dry weights of different organs using independent data from different cultivars and sowing date experiments. Fig 5A (top row) shows Liger 87-5 and Fig 5B (bottom row) shows HB. The experiment took place in Shihezi in 2007 over the sowing dates shown (▲ dry weight of fruits, ○ dry weight of stems and branches, * dry weight of leaves).

Dry matter accumulation rates reach their peak in the fruit colour-changing period where the amount of dry matter accumulated reaches 47%–67% of the total. At this point dry matter is increasing along with the yield (Scholberg et al., 2000). $DMAR_{at}$ is therefore given as:

$$DMAR_{at} = \begin{cases} 0.474 & TY < 0.7 \times TY_{\max} \\ 0.025 + 0.601 \times \dfrac{TY}{TY_{\max}} & 0.7 \times TY_{\max} \le TY \le TY_{\max} \\ 0.626 & TY > TY_{\max} \end{cases} \quad (8)$$

where TY_{max} is the local maximum yield (kg ha^{-1}) obtained using the yield potential sub-model (Wang et al., 2009). DMA_{bt}, the amount of dry matter accumulated (kg ha^{-1}) before the colour-changing period, is given by:

$$DMA_{bt} = \frac{TY \times (1-\eta)}{HC} \times (1 - DMAR_{at}) \quad (9)$$

Calculation and simulation of the dry matter partitioning index of different plant organs

Partitioning indices for shoots and roots

In studies of dry matter partitioning, it is often supposed that dry matter is partitioned first to the shoots and roots, and then to the stem, leaf and fruit based on the amount partitioned to the shoot (Heuvelink, 1996). The partitioning indices for shoots and roots are the proportions of total plant dry matter weight partitioned to the shoots and roots (Scholberg et al.,2000), which are calculated as:

$$PIS = 1 - 0.31 \times e^{-\frac{PDT}{40.47}}$$
$$R^2 = 0.9773, RMSE = 0.0324, n = 12 \quad (10)$$

And

$$PIR = 1 - PIS \quad (11)$$

where *PIS* and *PIR* are the shoot and root partitioning indices, respectively(Fig 1).

Partitioning indices for shoots and organs

In agricultural production, regulating the sowing date is the main measure used to balance and solve supply and demand differences between the peak of ripeness and the processing capacity of tomato ketchup factories. In this model, the accumulation of dry matter in various organs is simulated under suitable sowing conditions. Because the sowing date influences the dynamics of dry matter accumulation, the sowing date factor (*SDF*) is introduced to simulate and regulate dry matter accumulation.

$$PIL = -0.2160 + 1.2783 \times e^{-\frac{PDT}{91.8453}}$$
$$R^2 = 0.9872, RMSE = 0.0358, n = 21 \quad (12)$$

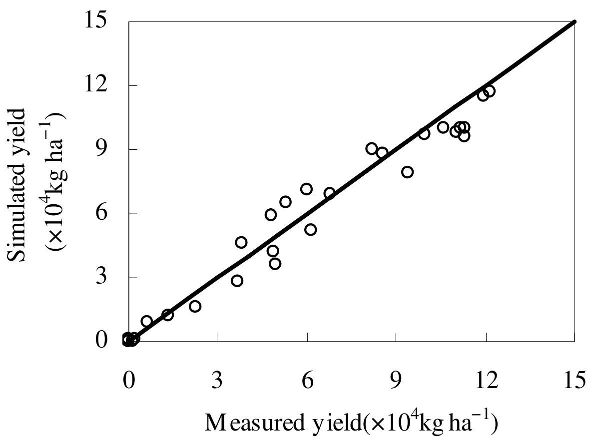

Fig 6. Comparison between the simulated and measured yields of different cultivars using data from experiments studying the effect of different sowing dates.

$$PIF=\begin{cases}0 & PDT\le 42\\ \dfrac{PIPF}{12306\times(PDT-42)^{-1.33}+0.51} & 42<PDT\le 110\end{cases}$$
$$R^2=0.9630, RMSE=0.0251, n=21 \quad (13)$$

and

$$PIST=1-PIL-PIF, RMSE=0.2418, n=21 \quad (14)$$

where *PIL, PIST* and *PIF* are the leaf, root and fruit partitioning indices, respectively, *PFPI* is the potential fruit partitioning index, with values of 0.53 for HB and HY; 0.51 for XF-8 and AS9081; 0.56 for Liger, 87-5 for LY-8; 0.58 for Q020 and 0.54 for uc-82, HZ-35 and SH-14. The dry matter partitioning indices of leaves, stems and fruits are the weights of the above ground dry matter for each organ relative to the shoot. The relationship between the partitioning index of shoot to stem, leaf, fruit, and accumulated *PDT* is obtained by analysing the experimental data (Fig 1). Genotype and sowing date had no significant effect on the basic model for the dry matter accumulation index of above ground organs but they did affect the index values; genotype had a small effect on the leaf partitioning index, but a large effect on the fruit partitioning index. This result indicates that the potential fruit partitioning index shows little variation among years for a given cultivar, but great variation among cultivars. Thus, *PFPI* is a genetic parameter of specific cultivars; the effect of sowing date on dry matter partitioning is reflected mainly in the variation in the fruit partitioning index resulting from fruit growth as affected by temperature, which indirectly affects the redistribution of dry matter from vegetative to reproductive components of the plant.

Dynamic simulation of dry matter accumulation among organs

Shoot and root dry weights are obtained from the simulated total dry weight multiplied by shoot and root partitioning indices, respectively.

$$WSH = DMA(PDTv) \times PIS \quad (15)$$

and

$$WR = DMA(PDTv) \times PIR \quad (16)$$

where *WSH* and *WR* are shoot and root dry weights (kg ha^{-1}). Dry weights of above ground organs were calculated as:

$$WL = WSH \times PIL/SDF \quad (17)$$

$$WS = WSH \times PIST \quad (18)$$

and

$$WF = WSH \times PIF \times SDF \quad (19)$$

where *WL*, *WS* and *WF* are the dry matter accumulation of the leaf, stem and fruit. *SDF* is quantified from the relationship between growing degree-days (GDD_A) that accumulate from actual sowing to fruit-setting and growing degree-days (GDD_O) which accumulate from the earliest suitable sowing date, defined as date when the soil temperature at 5 cm depth is greater than 14 °C for 5 consecutive days (Heuvelink, 1999), to fruit -setting.

$$SDF = (GDD_A/GDD_O)^2 \quad (20)$$

Dynamic simulation of fruit yield

Fruit dry weight is calculated from the partitioning index and includes harvested ripe and unripe fruits. The actual yield was that of harvested ripe fruits. The harvest index (*HI*), the ratio of harvested fruit dry weight to total fruit dry weight, was introduced to simulate the dynamic variation in quantification of the experimental yield. *HI* was calculated using data from experiments i and iii, and was fitted to the curve shown in Fig 2. *HI* was calculated as:

$$HI=\frac{0.8618}{(1+e^{9.1200-0.1746\times PDT})^{\frac{1}{0.0111}}}$$
$$R^2=0.9778, RMSE=0.0655, n=14 \quad (21)$$

Dry weight of processing tomato yield *WMF* (kg ha^{-1}) was obtained as the product of fruit dry weight and harvest index.

$$WMF = WF \times HI \quad (22)$$

Yield of processing tomato was calculated according to fresh weight, which was obtained by:

$$TY(PDT) = WMF/(1-\eta) \quad (23)$$

where *TY* (*PDT*) is the fresh weight of processing tomato yield and η has the same meaning as above.

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