

# Toward an Optimal Control Strategy for Sweet Pepper Cultivation – 1. A Dynamic Crop Model

F. Buwalda<sup>1,2\*</sup>, E.J. van Henten<sup>3,4</sup>, A. de Gelder<sup>1</sup>, J. Bontsema<sup>3</sup> and J. Hemming<sup>3</sup>

<sup>1</sup>PPO/Glasshouse Horticulture Division, Wageningen-UR, P.O. Box 8,  
2670 AA Naaldwijk, The Netherlands

<sup>2</sup>Horticultural Production Chains Group, Wageningen-UR, Marijkeweg 22,  
6709 PG Wageningen, The Netherlands

<sup>3</sup>Plant Research International Ltd., Wageningen-UR, P.O. Box 16,  
6700 AA Wageningen, The Netherlands

<sup>4</sup>Farm Technology Group, Wageningen-UR, P.O. Box 17,  
6700 AA Wageningen, The Netherlands

\* Corresponding author

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## Abstract

Sweet pepper production is characterized by large fluctuations in fruit yield per week. Synchronization of yield patterns between nurseries in response to weather conditions leads to variations in market supply and affects price formation. In order to improve supply chain efficiency, auctions and wholesalers require nurseries to supply production forecasts several weeks in advance. At the nursery level, yield prediction is helpful for efficient labour planning. Because the dynamics of sweet pepper production are complex, growers find it difficult to understand and effectively control the production process. A model can be useful to assist growers in making efficient decisions with regard to crop and climate management. It is hypothesized that a phase-shift in the feedback-regulation of fruit set by growing fruits could be the cause of the periodic yield pattern observed in practice. This paper describes a dynamic model of sweet pepper production based on this principle. Model output was compared with measurements of sweet pepper production obtained from a commercial nursery. The calibrated model was able to simulate the measured data fairly well, in particular the yield fluctuations. These results are consistent with the hypothesis and serve as a promising starting point for further research aiming at a better understanding of the underlying processes and, consequently, model improvement.

## INTRODUCTION

The production process in sweet pepper shows large fluctuations in the number of ripe fruits per week (Kato and Tanaka, 1971; Hall, 1977; Marcelis and Baan Hofman-Eijer, 1995; Heuvelink et al., 2003). Yield may vary between 5-10 fruits m<sup>-2</sup> wk<sup>-1</sup> during production peaks and less than 2 fruits m<sup>-2</sup> wk<sup>-1</sup> in intermediate periods. The production peaks typically occur once every 4-5 weeks, although the regular pattern of fruit production can be disturbed by sudden changes in weather conditions (Kato and Tanaka, 1971; Aloni et al., 1991; Jafaar et al., 1994).

Yield fluctuations can, to a large extent, be explained by the equally large variations in the rate of formation of new fruits. Since sweet pepper plants tend to produce ample amounts of new flower buds, the dominant factor determining the amount of new fruits formed is the abortion of buds, flowers and young fruits (Bakker, 1989; Wien et al., 1989). Abortion in sweet pepper is influenced by light and temperature (Wien et al., 1989; Marcelis et al., 2004) in a way which is consistent with instantaneous regulatory effects of the supply (source) and demand (sink) of assimilates, often observed in other glasshouse fruit species (Kinet, 1977; Ho, 1988; Marcelis, 1994). Experimental evidence in support of the influence of source and sink on fruit set was published by Heuvelink et al. (2003) and Marcelis et al. (2004), who studied the effects of variations in

light and temperature level, planting density and pruning of leaves and fruits. These authors showed that fruit set is strongly correlated with the source/sink ratio, but also found additional effects that indicate that position may also play a role. A more complex regulation mechanism is also suggested by the observation that in a sweet pepper crop with parthenocarpic fruits, a significantly more constant fraction of fruits aborted, and yield fluctuations did not occur (Heuvelink and Körner, 2001; Heuvelink et al., 2003). This suggests that the seeds play a key role in the expression of source/sink influences on fruit set and abortion.

In view of the dynamic nature of the process, growers generally find it difficult to predict the behaviour of the crop and to correct disturbances as they occur. A model can be useful to understand the mechanism behind the fruit production pattern of sweet pepper, to advise the grower regarding the cultivation measures that help to maintain a regular production, and to predict the number of ripe fruits during the weeks to come. Model studies of sweet pepper production have been published by Gijzen et al. (1990), Rijdsdijk and Houter (1993), Nederhoff and Vegter (1994), but none of these models was capable of predicting yield fluctuations. Marcelis et al. (1998) referred to unpublished results, indicating that the production process of sweet pepper can be simulated using a combination of a model for dry matter production and a source/sink based partitioning function. Marcelis et al. (2006) obtained realistic simulation results, applying a fruit set function previously developed for cucumber in their sweet pepper model. However, the first publications that specifically demonstrate that periodic behaviour in sweet pepper fruit production can emerge as a dynamic model property appear to be the article by Schepers et al. (2006) and the present paper. Both models treat fruit set as depending on assimilate availability and distribution of fruits in different classes, but many details differ.

Many oscillating systems involve a counteracting response which is shifted in phase relative to the original signal. It can be envisaged that a source-sink dependent regulation of fruit set could result in such oscillating behaviour, as assimilate demand of growing fruits depends on their developmental stage (Marcelis and Baan Hofman Eijer, 1995; Opara, 2000). Potential growth rates of young fruit are relatively low. Maximum sink strength is often reached somewhere halfway the course of fruit development, to diminish again at more advanced stages of maturity. Therefore, the change in fruit assimilate demand (sink strength) as a result of new fruit formation is shifted in phase relative to the surplus in assimilate availability for fruit growth (net source strength) which originally promoted fruit set. The same principle would apply for a source-sink related hormonal regulation of fruit set as suggested by Marcelis et al. (2004), provided that the evolution of a feedback signal from the fruits is again shifted in phase relative to the original event of fruit formation.

In this paper, it is hypothesized that a dynamic crop model, constructed on the basis of these principles, should be capable of showing periodic behavior. The outlines of the dynamic model of sweet pepper production are described together with a comparison of simulations and measurements of sweet pepper production obtained in a commercial nursery in the Netherlands. Results of dynamic optimization using this production model are presented in a companion paper (van Henten et al., 2006).

## **MATERIALS AND METHODS**

### **A Dynamic Model of Sweet Pepper Production**

The model of sweet pepper production is a discrete time model, describing the evolution of the sweet pepper crop in time steps of one day. A simple dynamic photosynthesis/growth model is used to describe crop growth and biomass partitioning between fruits, vegetative plant parts and a carbon buffer as illustrated in Fig. 1. The treatment of photosynthesis, respiration, source/sink dependent assimilate partitioning and growth is similar to that in many other dynamic crop models (Marcelis et al., 1998). Since the model calculates in daily steps, carbon fluxes and other rates are expressed as discrete

quantities and the time dimension ( $d^{-1}$ ) is implicit in the units.

The model describes the crop as a collection of vegetative parts and fruits. Vegetative parts, fruits and carbon buffer compartment can be described in terms of macro-states, the carbon content of which is governed by a set of four recurrence equations. The carbon content of the common assimilate pool  $MCp$  ( $g DW m^{-2}$ ) changes from day  $k$  to day  $k+1$  according to:

$$MCp_{k+1} - MCp_k = FCa_k + FCep_k - FCmv_k - FCmf_k - FCpv_k - FCpf_k - FCpe_k \quad (1)$$

The content of the carbon storage buffer  $MCE$  ( $g DW m^{-2}$ ) evolves from the previous state as:

$$MCE_{k+1} - MCE_k = FCpe_k - FCep_k \quad (2)$$

The carbon mass of the vegetative parts  $MCv$  ( $g DW m^{-2}$ ) changes according to:

$$MCv_{k+1} - MCv_k = FCpv_k \quad (3)$$

The carbon mass of fruits  $MCf$  ( $g DW m^{-2}$ ) on day  $k+1$  is described by:

$$MCf_{k+1} - MCf_k = FCpf_k \quad (4)$$

All daily amounts of carbon transfer in equations 1-4 are expressed in  $g DW m^{-2}$ , where  $FCa$  is the flux resulting from  $CO_2$  assimilation;  $FCep$  and  $FCpe$  represent the release of carbon from, and storage in, the buffer compartment, respectively;  $FCmv$  and  $FCmf$  are carbon fluxes associated with maintenance respiration of vegetative parts and fruits, respectively; while  $FCpv$  and  $FCpf$  stand for the daily carbon gain of vegetative parts and fruits, respectively. All conversion losses and construction costs, as well as resistances and costs associated with transport, are implicitly taken into account in the calibration of the model.

The macro-states of fruits, vegetative parts and carbon buffer are actually summations of micro-states. The model distinguishes the amount of vegetative growth on a single day  $j$  as a virtual vegetative unit, described by carbon content  $MCv_k^j$  and stage of development  $D_k^j$ , and implicitly including stems and leaves. At the start of a simulation, only the vegetative micro-state corresponding to day 1 has non-zero values. The number of non-zero vegetative micro-states increases by one per day, until at the end of the simulation, it equals the number of days in a growing season. Thus, carbon macro-state  $MCv_k$  ( $g DW m^{-2}$ ) can be calculated from the micro-states as:

$$MCv_k = \sum_{j=1}^{j=k} MCv_k^j \quad (5)$$

Carbon buffering is associated with the vegetative units, and is a function of carbon content and developmental stage. Thus,

$$MCE_k = \sum_{j=1}^{j=k} MCE_k^j \quad (6)$$

Similarly, the number of fruits set on day  $j$  is considered a generative unit or fruit cohort, described by number of fruits  $N_k^j$ , stage of development  $D_k^j$  and carbon mass  $MCf_k^j$ , where

$$MCf_k = \sum_{j=1}^{j=k} MCf_k^j \quad (7)$$

The total number of fruits on a plant  $N_k$  (fruits  $m^{-2}$ ) is again a macro-state, changing from the previous state depending on the daily formation of new fruits  $Rfs_k$ , as well as their removal through pruning or harvesting  $Rfh_k$  (both in fruits  $m^{-2}$ ):

$$N_{k+1} - N_k = Rfs_k - Rfh_k \quad (8)$$

where  $N_k$  is again a macro-state composed of micro-states, the fruit cohorts:

$$N_k = \sum_{j=1}^{j=k} N_k^j \quad (9)$$

The developmental stage  $D$  of unit  $j$ , where  $j$  can be a vegetative unit or a fruit cohort, is described by means of a linear thermal time difference equation:

$$D_{k+1}^j - D_k^j = \max\left(0, \frac{(T_k - c_{t,base})}{c_{t,sum}}\right) \quad (10)$$

where  $c_{t,base}$  ( $^{\circ}C$ ) is the base temperature, below which the rate of fruit development equals zero,  $c_{t,sum}$  is the heat sum ( $^{\circ}C.d$ ) of the greenhouse temperature  $T$  above the base temperature, required by a fruit to reach full maturity (Wang, 1964; Summerfield, 1994).

Fruit set  $Rfs_k$  (fruits  $m^{-2}$  per cohort) is described as an empirical function of a fruit bearing capacity signal  $BCf_k$  and a fruit load signal  $Lf_k$  as:

$$Rfs_k = N_{k+1}^{j=k+1} = \max(0, c_{fs} * (BCf_k - Lf_k)) \quad (11)$$

where fruit set implicitly includes new fruit formation and abortion. It is at this point where the phase shift between fruit bearing capacity and fruit load gives rise to the oscillatory behaviour of sweet pepper production. A positive difference between  $BCf_k$  and  $Lf_k$  indicates that the crop's production capacity is less than completely utilized, and formation of new fruits is proportional to this difference. Parameter  $c_{fs}$  determines the gain in the dynamic system.  $BCf_k$  (g DW  $m^{-2}$ ) is assumed to be identical to the source term in the source/sink ratio,

$$BCf_k = FCa_k + FCep_k - FCpe_k - FCmv_k - FCmf_k \quad (12)$$

while the fruit load signal  $Lf_k$  (g DW  $m^{-2}$ ) is calculated as a summation over all fruit cohorts of the first derivative of a Richards function normalized with respect to developmental stage, multiplied by cohort size  $N_k^j$  and developmental increment  $D_{k+1} - D_k$  (eqn. 10):

$$Lf_k = \max\left(0, \frac{(T_k - c_{t,base})}{c_{t,sum}}\right) * \sum_{j=1}^{j=k} \left( N_k^j * \frac{c_a * c_b * e^{-c_b * (D_k^j - c_c)}}{\left(1 + c_d * e^{-c_b * (D_k^j - c_c)}\right)^{(1+1/c_d)}} \right) \quad (13)$$

where  $c_a$ ,  $c_b$ ,  $c_c$  and  $c_d$  are tuning parameters of the Richards function.

Fruits are considered harvestable when their stage of development  $D_k^j$  exceeds target value  $c_{Dt}$ . At full maturity,  $c_{Dt}$  of the fruits equals 1.0. However in summer, growers tend to harvest the fruits slightly prematurely ( $c_{Dt} \approx 0.9$ ). Fruit cohorts become harvestable

when their developmental stage  $D_k^j$  exceeds  $c_{Dt}$

$$D_k^r = D_k^j \geq c_{Dt} \quad (14)$$

where  $r$  is the cohort number of the fruits matured on day  $k$ . As all fruits in a cohort have the same developmental stage, they are harvested at the same time. Their micro-state then becomes zero. The daily amount of fruits harvested (fruits  $m^{-2}$ ) is:

$$Rfh_k = N_k^{j=r} \quad (15)$$

### Measurements Obtained at a Commercial Nursery

Data of weekly averages of the outdoor radiation sum and measured indoor temperature as well as counts of the number of fruits set, the number of developing fruits and production in kg of sweet pepper (*Capsicum annuum* L. ‘Ferrari’) were obtained from a commercial nursery. The data set includes a complete production season (November 2003 – November 2004) of an entire greenhouse section of 10,000  $m^2$ . Counts of fruit set and number of developing fruits were obtained in two special registration plots of 6  $m^2$  each in the greenhouse section.

### Simulations and Parameter Estimation

The model was implemented in Matlab 7.0 R14SP3 (The Mathworks, Natick, MA, USA). Using the recorded data of the weekly average radiation sum and indoor temperature, sweet pepper production was simulated and results were compared with the measurements obtained from the commercial nursery. Model parameters were adapted so as to fit the model output to the measured data.

## RESULTS AND DISCUSSION

Results of the simulations are shown in Fig. 2, together with the measurements. The results demonstrate that the parameterized model was able to simulate the measured data of fruit set (Fig. 2a), number of fruits on the plants (Fig. 2b) and the cumulative fresh weight of fruits harvested in time (Fig. 2c) quite well. Finally, Fig. 2d shows the daily change in fruit load plotted against the difference between fruit bearing capacity  $BCf_k$  and fruit load  $Lf_k$  (both expressed in g DW  $m^{-2}$ ), which is the basis for the oscillating behavior of sweet pepper production. Even though fruit set (eqn. 11) is restricted to positive values of  $BCf_k - Lf_k$ , Fig. 2d shows that the system is capable of attaining negative values as well. These arise when  $Lf_k$  exceeds  $BCf_k$ , a condition likely to occur when many large fruit cohorts attain developmental stages near the maximum of the Richards curve (Eqn. 13).

Clearly, the model has not yet reached a stage of full maturity and still needs to be validated against independent data. However, current results serve as a promising starting point for further research aiming at a better understanding of the underlying processes and, consequently, improvement of this model. Simultaneously, the model is used to search for alternative crop production strategies aiming for instance at reduced energy input and reduction of harvest fluctuations. Results are reported in a companion paper of van Henten et al. (2006).

## CONCLUSIONS

In this paper it was demonstrated that periodic behaviour of sweet pepper production is an emergent property of a dynamic model based on application of the physiological principle of a phase-shift in the feedback regulation of fruit set by growing fruits. We therefore conclude that our original hypothesis is confirmed. By incorporating a simple dynamic growth model, the system could be parameterized to yield realistic simulation results, as evident from a comparison with production data obtained from a commercial nursery.

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## Literature Cited

- Aloni, B., Pashkar, T. and Karni, L. 1991. Partitioning of  $^{14}\text{C}$  sucrose and acid invertase activity in reproductive organs of pepper plants in relation to their abscission under heat stress. *Ann. Bot.* 67:371-377.
- Bakker, J.C. 1989. The effects of temperature on flowering, fruit set and fruit development of glasshouse sweet pepper (*Capsicum annuum* L.). *J. Hort. Sci.* 64:313-320.
- Gijzen, H., Vegter, J.G. and Nederhoff, E.M. 1990. Simulation of greenhouse crop photosynthesis: validation with cucumber, sweet pepper and tomato. *Acta Hort.* 268:71-80.
- Gijzen, H., Heuvelink, E., Marcelis, L.F.M., Dayan, E., Cohen, S., Fuchs, M. and Challa, H. 1998. HORTISIM: a model for greenhouse crops and greenhouse climate. *Acta Hort.* 456:441-450.
- Hall, A.J. 1977. Assimilate source-sink relationships in *Capsicum annuum* L. I. the dynamics of growth in fruiting and defoliated plants. *Aust. J. Plant Physiol.* 4:623-636.
- Heuvelink, E. and Körner, O. 2001. Parthenocarpic fruit growth reduces yield fluctuation and blossom-end rot in sweet pepper. *Ann. Bot.* 88:69-74.
- Heuvelink, E., Marcelis, L.F.M. and Körner, O. 2004. How to reduce yield fluctuations in sweet pepper? *Acta Hort.* 633:349-355.
- Ho, L.C. 1988. Metabolism and compartmentation of imported sugars in sink organs in relation to sink strength. *Ann. Rev. Plant Physiol. Plant Mol. Biol.* 39:355-378.
- Jafaar, H., Black, C.R. and Atherton, J.G. 1994. Water relations, dry matter distribution and reproductive development of sweet pepper (*Capsicum annuum*). *Asp. Appl. Biol.* 38:299-306.
- Kato, T. and Tanaka, M. 1971. Studies on the fruit setting and development of sweet peppers. *J. Jap. Soc. Hort. Sci.* 40:359-366.
- Kinet, J.M. 1977. Effect of light conditions on the development of the inflorescence in tomato. *Sci. Hort.* 6:15-26.
- Marcelis, L.F.M. 1994. Fruit growth and dry matter partitioning in cucumber. Thesis, Wageningen University, Wageningen, The Netherlands.
- Marcelis, L.F.M. 1994. A simulation model for dry matter partitioning in cucumber. *Ann. Bot.* 74:43-52.
- Marcelis, L.F.M. and Baan Hofman-Eijer, L.R. 1995. Growth analysis of sweet pepper fruits (*Capsicum annuum* L.). *Acta Hort.* 412:470-478.
- Marcelis, L.F.M., Heuvelink, E. and Goudriaan, J. 1998. Modelling biomass production and yield of horticultural crops: a review. *Sci. Hort.* 74:83-111.
- Marcelis, L.F.M., Heuvelink, E., Baan Hofman-Eijer, L.R., Den Bakker, J. and Xue, L.B. 2004. Flower and fruit abortion in sweet pepper in relation to source and sink strength. *J. Exp. Bot.* 55:2261-2268.
- Marcelis, L.F.M., Elings, A., Bakker, M., Brajeul, E., Dieleman, A., De Visser, P.H.B. and Heuvelink, E. 2006. Modelling dry matter production and partitioning in sweet pepper. *Acta Hort.* 718:121-128.
- Nederhoff, E.M. and Vegter, J.G. 1994. Canopy photosynthesis of tomato, cucumber and sweet pepper in greenhouses: measurements compared to models. *Ann. Bot.* 73:421-427.
- Opara, L.U. 2000. Fruit growth measurement and analysis. *Hort. Reviews* 24:373-431.
- Rijsdijk, A.A. and Houter, G. 1993. Validation of a model for energy consumption,  $\text{CO}_2$  consumption and crop production (ECP-model). *Acta Hort.* 328:125-131.
- Schepers, H., Kromdijk, W. and Kooten, O. 2006. The conveyor belt model for fruit bearing vegetables: Application to sweet pepper yield oscillations. *Acta Hort.* 718:43-50.

- Summerfield, R.J., Roberts, E.H., Ellis, R.H. and Lawn, R.J. 1991. Towards the reliable prediction of time to flowering in six annual crops. I. The development of simple models for fluctuating field environments. *Exper. Agric.* 27:11-31.
- van Henten, E.J., Buwalda, F., de Zwart, F., de Gelder, A., Hemming, J. and Bontsema, J. 2006. Toward an optimal control strategy for sweet pepper cultivation – 2. Optimization of the yield pattern and energy efficiency. *Acta Hort.* 718:391-398.
- Wien, H.C., Tripp, K.E., Hernandez-Armenta, R. and Turner, A.D. 1989. Abscission of reproductive structures in pepper: causes, mechanisms and control. *Tomato and pepper production in the tropics: International symposium on integrated management practices, Tainan, Taiwan, 21-26 March 1988*, S.K. Green (ed.), AVRDC Publ 89-317, Shanhua, Taiwan. p.150-165.

## Figures

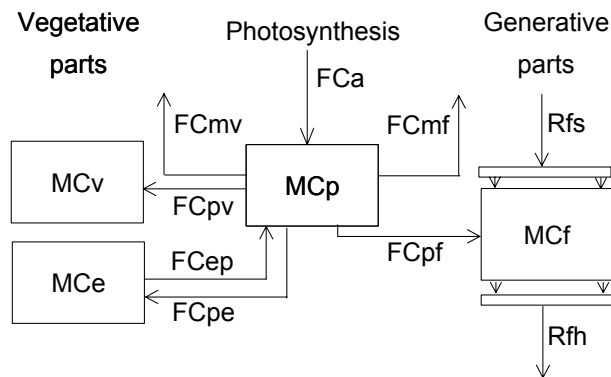


Fig. 1. A schematic diagram of the sweet pepper model in which MC represents the carbon contents ( $\text{g DW m}^{-2}$ ) of the carbon pool (p), the carbon buffer (e), vegetative plant parts (v) and fruits (f), respectively, and FC stands for the daily amount of carbon transferred ( $\text{g DW m}^{-2}$ ). FCmv and FCmf represent daily carbon requirements for maintenance respiration of vegetative parts and fruits. Daily amounts of fruit set Rfs and fruit harvest Rfh ( $\text{fruits m}^{-2}$ ) determine the size of fruit cohorts. FCa is the daily carbon gain resulting from  $\text{CO}_2$  assimilation.

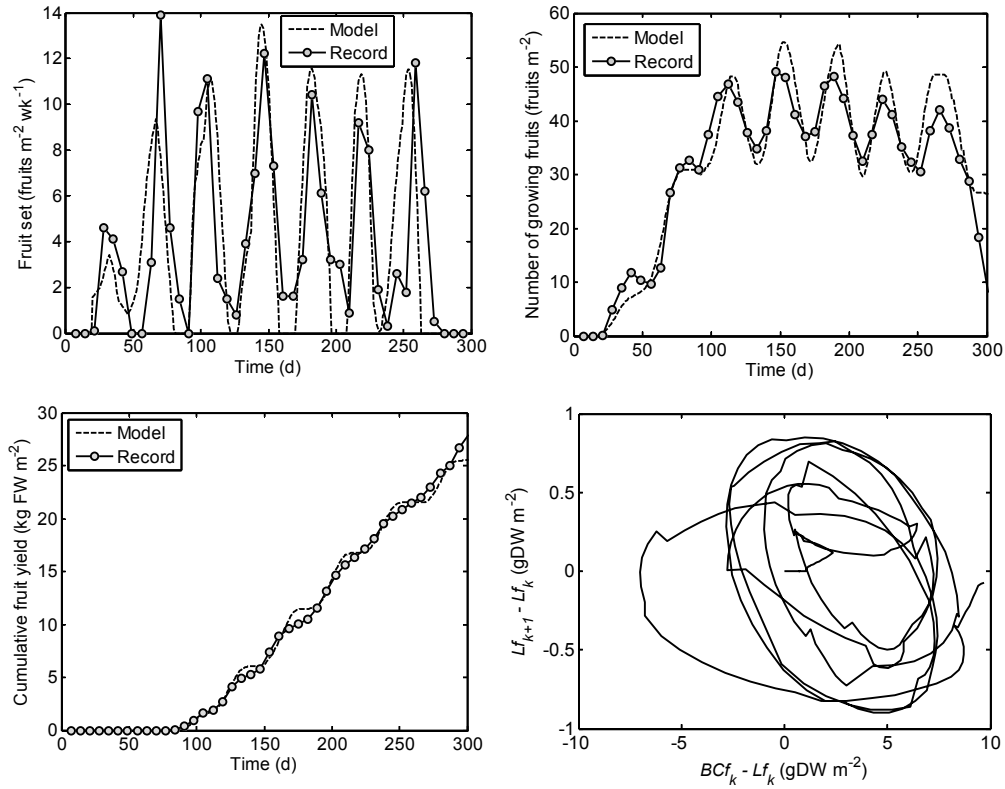


Fig. 2. (a): simulated (dashed) and recorded (-o-) fruit set (fruits  $m^{-2} wk^{-1}$ ), (b): simulated (dashed) and recorded (-o-) number of growing fruits  $N_k$  (fruits  $m^{-2}$ ), (c): simulated (dashed) and recorded (-o-) cumulative fresh weight of harvested fruits (kg FW  $m^{-2}$ ), (d): daily change in fruit load ( $Lf_{k+1} - Lf_k$ ) plotted against the difference between fruit bearing capacity and fruit load ( $BCf_k - Lf_k$ ), both in g DW  $m^{-2}$ .