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Crop physiology in (semi-)closed greenhouses

Final report of the TransForum scientific project “SynErgy: Monitoring and control system for conditioning of plants and greenhouse” (WP-066)

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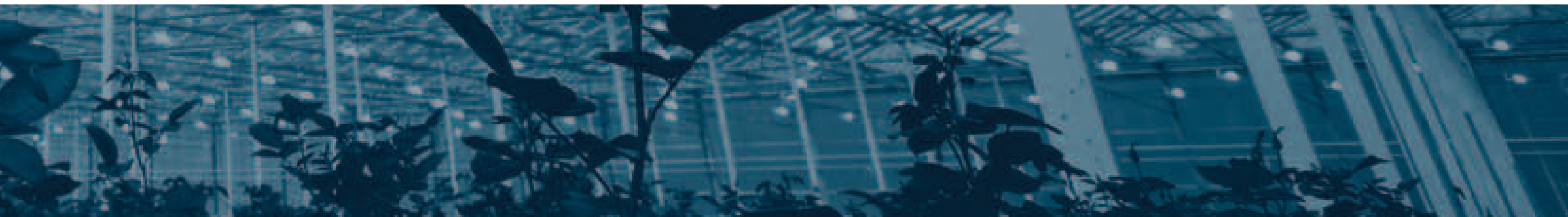

Wageningen UR Greenhouse Horticulture

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Preface

In The Netherlands, since 2002, a number of (semi-)closed greenhouses was constructed. Climate conditions in these greenhouses were found to differ considerably from those in conventional greenhouses. Knowledge of the effects of these climate conditions on the crop was scarce. Therefore, in the research project “Crop management in conditioned greenhouses”, funded by the Dutch Commodity Board and the Ministry of Agriculture, Nature and Food safety, the effects of the new climate conditions on the crop were investigated. In the accompanying scientific project “SynErgy: monitoring and control system, for conditioning of plants and greenhouses” (WP-066; May 2007 – May 2012), funded by TransForum, this knowledge is used to develop new concepts of climate control for optimal crop growth. In this report, the results and impact of this scientific project are described.

We would like to thank Prof. Dr. Evert Jacobsen, scientific director of TransForum and professor in Plant Breeding at Wageningen University for his supervision of this project. As a true representative of TransForum, he always strived to link this project to developments in society and to other TransForum project, for which we acknowledge him.

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1 Introduction

1.1 Energy conservation in greenhouse horticulture

Currently, the greenhouse industry contributes to about 10% of the total natural gas consumption in the Netherlands. However, the horticultural sector has set the ambitious goal to reduce the CO_2 emission by about 50% in 2020 compared to the reference year 1990. To achieve this goal, energy consumption in existing greenhouses will have to be reduced considerably.

In energy efficient greenhouse concepts, durable energy sources such as solar energy, wind energy or geothermal energy should be included. A number of recently developed concepts are the solar greenhouse (Bot *et al.*, 2005); closed greenhouse (Opdam *et al.*, 2005), energy producing greenhouse (Bakker *et al.*, 2006), Sunergy greenhouse (De Zwart, 2009) and the electricity producing greenhouse (Sonneveld *et al.*, 2006). In closed greenhouses, the excess of solar energy in summer is collected and stored in aquifers to be reused in winter to heat the greenhouse. This concepts results in a reduction in primary energy use of 33%, based on 1/3 of the area with closed greenhouse and 2/3 with traditional greenhouse with ventilation windows (Opdam *et al.*, 2005). Besides aquifers for seasonal energy storage, the technical concept consists of a heat pump, daytime storage, heat exchangers and air treatment units which either bring the cold air directly into the (top of the) greenhouse or do so via air distribution ducts below the gutters (De Zwart *et al.*, 2009). In this concept, ventilation windows are closed. Thereby, CO_2 levels, temperature and humidity can be controlled to the needs of the crop (De Gelder *et al.*, 2005). To reduce investment costs, in practice growers tend to choose for a semi closed system. Cooling capacity of this system is lower than that of a closed greenhouse. Therefore, when the active cooling capacity is insufficient to keep the temperature below the maximum permitted temperature, ventilation windows will be opened (Heuvelink *et al.*, 2007). CO_2 emission in (semi)closed greenhouses is considerable lower than in open greenhouses. In a recent experiment, in which tomatoes were grown with a CO_2 supply capacity of 230 kg ha^{-1} h^{-1} up to a maximum concentration of 1000 ppm, in the open greenhouse 54.7 kg CO_2 m^{-2} was supplied whereas in the closed greenhouse this was 14.4 kg CO_2 m^{-2} (Qian *et al.*, 2009).

Specific characteristics of climate in (semi)closed greenhouses with cooling ducts under the gutters are: high CO_2 concentrations, vertical temperature gradients, high humidities, combined conditions of high light intensity and high CO_2 concentration, and increased rates of air movement (Qian *et al.*, 2011). Elings *et al.* (2007) investigated whether increased air flow rates cause photosynthetic adaptation in full grown tomato plants. Air circulation did not change the photosynthesis light-response curves. Yield increase was therefore attributable only to the instantaneous effects of elevated CO_2 concentrations (Elings *et al.*, 2007; Heuvelink *et al.*, 2007). Körner *et al.* (2009) showed that at high irradiance, the optimum temperature for crop photosynthesis increased with CO_2 concentration. This shift in optimum temperature was with 1.9 °C much lower than that reported for leaves (Cannell and Thornley, 1998), due to the fact that the leaves deeper in the canopy do not assimilate at saturating light levels (Körner *et al.*, 2009).

Higher humidities cause a reduction in transpiration rate, and thereby increased temperatures of the top of the canopy. In systems where cooling ducts are below the gutters, temperature differences of 5 ºC between roots and top of the plant can occur (Qian *et al.*, 2011). This affected the time necessary for fruits to mature. At lower temperatures, fruits need more time to ripen (Verkerk, 1955). Tomato fruits were found to be more sensitive to temperature in their later stages of maturation (De Koning, 1994; Adams *et al.*, 2001) at which they are at lower temperatures in (semi)closed greenhouses.

Development of new greenhouse concepts is ongoing. Current examples are greenhouse systems which convert natural energy sources such as solar energy into high-value energy such as electricity. Sonneveld *et al.* (2006, 2007) designed a system with a parabolic NIR reflecting greenhouse cover. This cover reflects and focuses the NIR radiation on a specific PV (photo voltaic) cell to generate electricity (Electricity producing greenhouse).

1.2 SynErgy: Monitoring and control system for conditioning of plants and greenhouse

In Dutch greenhouse horticulture, growers are organised in groups of approximately 10 growers which generally grow the same crop in the same area. They meet weekly, visit each others' greenhouses and discuss matters related to production. This has greatly improved knowledge transfer within greenhouse horticulture. In The Netherlands, since 2002, a number of (semi-)closed greenhouses was constructed. However, in these greenhouses climate conditions differ considerably from those in conventional greenhouses. On the topic of closed greenhouses, a community of practice was developed, in which the growers shared experiences with and posed questions to researchers (Hoes *et al.*, 2008). This community was funded by TransForum via the innovative practice project SynErgie. Cooperation and active exchange of knowledge proved to be necessary to help all participants of the platform to increase understanding, apply the information and realise their goals. In this community, the first topic focussed on the technical aspects of the closed and semi-closed greenhouses. However, thereafter growers realised that although they could realise the climate they wanted in the new greenhouse systems, their knowledge on the physiology of the crop under these new conditions was insufficient. Therefore, in the research project "Crop management in conditioned greenhouses", funded by the Dutch Commodity Board and the Ministry of Agriculture, Nature and Food safety, the effects of the new climate conditions on the crop are investigated. In the accompanying scientific project "SynErgy: monitoring and control system, for conditioning of plants and greenhouses", funded by TransForum, this knowledge is used to develop new concepts of climate control for optimal crop growth.

1.3 Approach

In the project "SynErgy: Monitoring and control system for conditioning of plants and greenhouse", PhD student Tian Qian at Wageningen University has set up the research according to the following steps:

1. Confirmation of production increase in conditioned greenhouses compared to that in open greenhouses.
2. Quantification of climate effects, such as temperature, air humidity and CO_2 concentration, on crop physiological processes and morphological characteristics.
3. Explanation of climate effects on crop growth and development by the quantified relations and by using crop growth model.
4. Adaptation of existing model by integration of the quantified relations, to make the model suitable to conditioned greenhouses.
5. Application of the adapted model to determine an optimal climate for crop growth and production in conditioned greenhouses.

At Wageningen UR Greenhouse Horticulture in Bleiswijk, in 2008, 2009 and 2010, in 5 greenhouse compartments, tomato crops were grown under different climates in closed, semi-closed or open greenhouses. In these experiments, climate characteristics, plant growth and development, photosynthesis in relation to light, temperature, CO_2 and humidity, adaptation to long term high CO_2 concentration and assimilate distribution were determined. The information obtained was used to calibrate the model. With this model, scenario studies will be performed to determine the optimal climate for crop growth and production in conditioned greenhouses.

2 Results

Climate characteristics of conditioned greenhouses

With increasing cooling capacities of (semi-)closed greenhouse, window opening for temperature control is less. The consequence is that higher CO_2 concentrations can be maintained in the greenhouse, which is the primary reason for the production increase. When cooling is applied in the lower part of the greenhouse, vertical temperature gradients occur, which affect plant development and morphology

Plant growth and development

In (semi)closed greenhouses, tomato fruit production is higher than in open greenhouses. This production increase is due to the higher assimilation (dry matter production), i.e. higher total crop photosynthesis. Dry matter partitioning to the fruits did not differ between treatments. Analysis of climate data and data of plant growth by a crop growth model suggested that the differences in dry matter production and assimilate distribution can be fully explained by the realised differences in CO_2 concentration in the greenhouses.

Photosynthesis responses to light, CO_2, temperature and humidity

The basis for plant growth is photosynthesis, which is influenced by climate factors such as light, CO_2, temperature and humidity. In conditioned greenhouses, the climate can be controlled more accurately, and combinations of climate conditions are possible, which do not occur in open greenhouses (i.e. combination of high light and high CO_2 concentration). To determine the optimal climate in semi-closed greenhouses, effects of climate factors on photosynthesis were quantified.

Light response curves measured at four different CO_2 concentrations show a clear interaction between light and CO_2. CO_2 response curves also show an optimal pattern. At low CO_2 concentration, increasing light intensity hardly affects photosynthesis. With increasing CO_2 concentrations, the effect of light on photosynthesis increases as well.

The optimal temperature for leaf photosynthesis was found to be about 34 ºC, when light and CO_2 concentration are not limiting photosynthesis. However, under sub-optimal conditions (photosynthesis limited by light or CO_2), temperature hardly affects photosynthesis rate.

VPD response of photosynthesis was measured at a range of VPD about 0.2 – 2.5 kPa at two light intensities and two CO_2 concentrations. Photosynthesis was not affected by VPD, despite the fact that the stomatal conductance was significantly affected by VPD. Apparently, stomatal conductance in this range of humidities doe not limit CO_2 uptake.

The quantified response curves of leaf photosynthesis to environmental variables were integrated to crop photosynthesis based on light extinction through canopy. Crop photosynthesis shows the same responses to climate, but has different optima. This information will be input to the crop growth model, to determine the optimal climate for growth and production in conditioned greenhouses.

Vertical temperature gradients

Tomato crops were grown year-round in two semi-closed greenhouses with cooled and dehumidified air blown into the greenhouses from above or below the crop. Cooling from below the crop induced a vertical gradient of temperature and humidity. The temperature difference between top and bottom of the canopy was over 5 °C when solar radiation was high. Total dry matter production was not affected by the height of the inlet of cold air (4.6 kg m^{-2} and 4.8 kg m^{-2} with cooling from above and from below, respectively). Percentage of dry matter partitioning to the fruits was 74% in both treatments. However, fruit fresh weight of the harvested fruit in the semi-closed greenhouse with cooling from below was slighly higher than that in the semi-closed greenhouse with cooling from above (123.6 g $fruit^{1}$ vs. 116.1 g $fruit^{1}$).

Photosynthesis acclimation to continuous high CO_2 concentration

In conditioned greenhouses, CO_2 levels are higher than in open greenhouses. This raises the question whether plants under these conditions adapt to the prolonged high CO_2 concentrations. If photosynthesis would be down-regulated after prolonged high CO_2 concentrations, this would imply that the optimal CO_2 strategy needs to be adapted. Results of photosynthesis measurements show that there is no acclimation in the five leaf layers that were measured over time.

So far, the results were primarily described in (Dutch) reports, conference proceedings and articles in professional journals (see list of output of the project). Data analysis of the experiments is still ongoing, as the PhD contract continues until mid 2012. In 2011, a number of peer reviewed papers will be written by the PhD student of this project, Tian Qian. These papers will be part of her PhD thesis, which will be finished in 2012.

3 Deliverables

The deliverables of this project and their status at the end of 2010 are:

1. Concepts to remove barriers for the development of energy-poor and energy-producing greenhouses.
    - Results of the experiments performed in 2008, 2009 and 2010 show that growing crops in (semi-)closed greenhouses, which are net energy producers, results in a good crop with an increased production. In the scientific papers that will be written in 2011, the concepts will be described.
2. Quantification of effects on plants of new climate conditions such as high air humidity under summer conditions.
    - These effects are described in a number of reports and articles in professional journals (in Dutch; see list of output in chapter 5). The quantification by means of the crop growth model is partly described in these reports as well, and will furthermore be described in the scientific papers that will be part of the PhD thesis of Tian Qian.
3. New ways to control crop performance by manipulating the temperature of the different plant organs
    - In the experiment in 2009, vertical temperature gradients of greenhouse air were applied. The effects on growth and development of different plant organs were determined. Data will be analysed with a crop growth model in 2011. In the scientific paper, the possibilities of affecting crop growth by affecting organ temperatures will be discussed.
4. An integral crop growth model that includes plant water status and its effects on physiological processes as well as using temperature of the different organs instead of a general air temperature.
    - Data of the experiments with (semi-)closed greenhouses will be used to improve and add modules to the existing crop growth model, which will enable the model to determine the effects of organ temperatures on crop growth and development.
    - The acquisition of detailed climate data over canopy depth enables more precise model estimation of photosynthesis and transpiration rates at various places in the crop. In combination with the obtained fundamental research results on photosynthesis, crop behaviour can be simulated more accurately. It has elsewhere been demonstrated that data acquisition and self-learning capabilities of the model, in combination with on-going crop simulation can greatly assist growers and researchers in understanding the current crop status and possible future management regimes. This also applies to (semi-)closed greenhouses.

4 Impact

4.1 Relation with other TransForum projects

This scientific project “SynErgy: Monitoring and control system for conditioning of plants and greenhouses” is closely linked to the innovative practice project “SynErgie” and the scientific project “Robustness of production systems”. In the “SynErgie” practice project, information on energy-efficient horticulture is shared between innovative growers and researchers with the aim to develop new knowledge and transmit this knowledge to the early adopters. The SynErgie scientific project has supported this project, aimed at increasing knowledge of the physiological aspects of cropping systems in closed greenhouses. In the 2-monthly meetings of the community of growers, the progress of this project is discussed. Furthermore, in the supervision group of the project “SynErgy: Monitoring and control system for conditioning of plants and greenhouses”, three of the companies of the innovative growers of the SynErgie network are represented, which indicates the fact that the growers consider this project to be very valuable. The TransForum scientific project “Robustness of production systems” aims to clarify the conceptual and social implementation of robustness. It does so via the interaction between various agricultural production systems and scientific research. One of the cases in this project is the production of vegetables and energy in an energy-generating greenhouse.

4.2 Meaning for TransForum

Currently, greenhouses industry contributes to about 10% of the total gas consumption in The Netherlands. Recently, new greenhouse concepts are being developed, which reduce the amount of energy per m^2 considerably, or which even transform greenhouses into net energy producers. Climate in these new types of greenhouses is completely different from the climate in conventional greenhouses. A major bottleneck in introducing the new concepts into practice is the lack of knowledge on the crop response to these new climate conditions. This project aims at obtaining knowledge on crop growth and development and underlying physiological processes, such that this bottleneck can be solved. This will facilitate the introduction of energy friendly or energy producing greenhouses.

4.3 Implications for Metropolitan Agriculture

To make the energy producing greenhouse sustainable, the surplus of energy it collects, has to be used for other purposes. Heating houses could be one of the applications for the surplus of heat. Therefore the energy producing greenhouses are suited to be part of a Metropolitan Agricultural community. Furthermore, the fresh produce of the greenhouses can be directly distributed to the inhabitants of the city, thereby reducing energy costs of transport and the time between harvest and consumption or use.

4.4 Implications for Connecting Values and Agro-Innovations System

The combination of plant production and production of energy instead of using energy is new. This scientific project contributes to enable the development of an energy producing greenhouse in combination with a high and controllable production. This ensures the competitiveness of the greenhouse horticultural sector for the future. In this project, new plant physiological knowledge will be developed, which can be used for this and future new greenhouse concepts to reduce energy consumption and further increase production and quality, thereby improving the profit of the horticultural sector.

5 Output of the project

Arkesteijn, M., 2008.

Geconditioneerd telen geeft een meerproductie van 5 kg/m^2. 'Met de gegevens uit de proef begrijpen we beter wat er met het gewas gebeurt'. Onder Glas 10: 26-27

Arkesteijn, M., 2009.

Koelen in semi-gesloten kas geeft een meerproductie van 5 tot 6 kg : temperatuur mag twee graden oplopen zonder effect op de productie. Onder Glas 6 (12): 38 – 39

Dieleman, A., 2008.

Effecten van luchtvochtigheid op groei en ontwikkeling van tomaat. Nota 519 Wageningen UR Glastuinbouw, 28 pp.

Dieleman, A., De Gelder, A., 2009.

Hogere CO_2 concentratie basis voor meerproductie. Groenten & Fruit 16: 18-19.

Dieleman, A., Eveleens, B., 2009.

Effect verneveling op productie tomaat nihil. Groenten & Fruit 18: 18-19

Dieleman, A., De Gelder, A., Eveleens, B., Elings, A., Janse, J., Lagas, P., T. Qian, Steenhuizen, J., Meinen, E., 2009.

Tomaten telen in een geconditioneerde kas: groei, productie en onderliggende processen. Nota 633, Wageningen UR Glastuinbouw, 54 pp.

Dieleman, J.A. and S. Hemming, 2010.

Energy saving: from engineering to crop management. Acta Horticulturae (Presented at GreenSys 2009, Canada; to be published in 2011)

Dieleman, J.A., A. de Gelder, T. Qian, A. Elings, L.F.M. Marcelis, 2010.

Crop physiology in semi-closed greenhouses. Acta Horticulturae (to be presented at GreenSys 2011, Greece)

Dieleman, A., A. de Gelder, J. Janse, P. Lagas, B. Eveleens, T. Qian, A. Elings, J. Steenhuizen, C. Stanghellini, E. Nederhoff, B. Farneti, R. de Visser, 2011.

Verticale temperatuurgradiënten in geconditioneerde kassen. Effecten op groei, ontwikkeling en onderliggende processen bij tomaat. Nota Wageningen UR Glastuinbouw.

Dieleman, A., De Gelder, A., Eveleens, B., Elings, A., Janse, J., Lagas, P., T. Qian, Steenhuizen, J., Meinen, E., 2011

Temperatuurstrategieën bij tomaat. Nota, Wageningen UR Glastuinbouw.

Elings, A., Dieleman, A., 2008.

Gedrag tomaat als leidraad voor klimaat. Groenten & Fruit 31: 16-17.

Eveleens, B., De Gelder, A., Dieleman, A., Elings, A., Janse, J., Qian, T., Lagas, P., Steenhuuizen, J., 2009.

Effecten van verneveling op groei en ontwikkeling van tomaat. Teelt van eind april tot eind augustus. Nota 643, Wageningen UR Glastuinbouw, 33 pp.

Jansen, M., 2008.

Alle hens aan dek voor geconditioneerde teelt. Nieuwe Oogst 4(12): 8 (21 juni 2008).

Kierkels, T., Stanghellini, C., Dieleman, A., 2011.

Tomaat in geconditioneerd systeem verdampt aanzienlijk minder. Onder Glas (to be published).

Nederhoff, E., A. de Gelder, J.A. Dieleman, J. Janse, 2010.

Future proofing. Semi-closed greenhouses and "future-proof" growing concept. Practical Hydroponics & Greenhouses 113: 47-55

Qian, T., J.A. Dieleman, A. Elings, A. de Gelder, L.F.M. Marcelis and O. van Kooten, 2011.

Comparison of climate and production in closed, semi-closed and open greenhouses. Acta Horticulturae (Presented at GreenSys 2009, Canada; to be published in 2011).

Qian, T., J.A. Dieleman, A. Elings, A. de Gelder, O. van Kooten and L.F.M. Marcelis, 2011.

Effects of vertical temperature and VPD gradients in semi-closed greenhouses on assimilate production and distribution, and organ development. Acta Horticulturae (Presented at ISHS conference 2010, Lisbon, Portugal; to be published in 2011)

Qian, T., A. Elings, G. Gort, J.A. Dieleman and L.F.M. Marcelis, 2011.

Analysis of the effects of a wide range of environmental conditions on photosynthetic parameters of FvCB model. To be submitted.

Qian, T., J.A. Dieleman, A. Elings and L.F.M. Marcelis, 2011.
Photosynthetic acclimation in response to extended exposure to high CO_2 concentration. To be submitted.

Qian, T., A. Elings, J.A. Dieleman, A. de Gelder and L.F.M. Marcelis, 2011.
Assimilate partitioning and plant development in semi-closed greenhouses. To be submitted

Qian, T., A. Elings, J.A. Dieleman, A. de Gelder and L.F.M. Marcelis, 2011.
Optimization of greenhouse climate: an integrated approach. To be submitted.

Qian, T., 2011.
Optimization of greenhouse climate for tomato growth and development. Thesis Wageningen UR.

Stanghellini, C., J.A. Dieleman, K.M. Lee, S. Driever, L.F.M. Marcelis, 2011.
Modeling the effect of the position of cooling elements on the vertical profile of transpiration in a greenhouse tomato crop. Acta Horticulturae (to be presented at GreenSys 2011, Greece)

Visser, P., 2008.
In gesloten kas anders naar gewas kijken. Groenten & Fruit 41: 20-21.

6 References

Adams, S.R., Cockshull, K.E. and Cave, C.R.J., 2001.
Effect of temperature on the growth and development of tomato fruits. Ann. Bot. 88: 869-877.

Bakker, J.C., De Zwart, H.F. and Campen, J.B., 2006.
Greenhouse cooling and heat recovery using fine wire heat exchangers in a closed pot plant greenhouse: design of an energy producing greenhouse. Acta Hort. 719: 263-270

Bot, G., Van de Braak, N., Challa, H., Hemming, S., Rieswijk, T., Van Straten, G., and Verlodt, J., 2005.
The solar greenhouse: state of the art in energy saving and sustainable energy supply. Acta Hort. 691: 501-508.

Cannell, M.G.R. and Thornley, J.H.M., 1998.
Temperature and CO_2 responses of leaf and canopy photosynthesis: a clarification using the non-rectangular hyperbola model of photosynthesis. Ann. Bot. 82: 883-892.

Dieleman, J.A. and Hemming, S., 2011.
Energy saving: from engineering to crop management. Acta Hort. (to be published).

Elings, A., Kempkes, F.L.K., Kaarsemaker, R.C., Ruijs, M.N.A., Van de Braak, N.J. and Dueck, T.A., 2005.
The energy balance and energy-saving measures in greenhouse tomato cultivation. Acta Hort. 691: 67-74.

Gelder, De, A., Heuvelink, E. and Opdam, J.J.G., 2005.
Tomato yield in a closed greenhouse and comparison with simulated yields in closed and conventional greenhouses. Acta Hort. 691: 549-552.

Heuvelink, E., Bakker, M., Marcelis, L.F.M. and Raaphorst, M., 2008.
Climate and yield in a closed greenhouse. Acta Hort. 801: 1083-1092.

Hoes, A.C., Regeer, B.J. and Bunders, J.F.G., 2008.
Transformers in knowledge production: building science-practice collaborations. Action Learning: Research and Practice 5: 207–220

Koning, De., A.N.M., 1994.
Development and dry matter distribution in glasshouse tomato: a quantitative approach. Thesis Wageningen Agric. Univ., 240 pp.

Körner, O., Heuvelink, E. and Niu, Q., 2009.
Quantification of temperature, CO_2, and light effects on crop photosynthesis as a basis for model-based greenhouse climate control. J. Hort. Sci. Biotech. 84: 233-239.

Opdam, J.J.G., Schoonderbeek, G.G., Heller, E.M.B. and De Gelder, A., 2005.
Closed greenhouse: a starting point for sustainable entrepreneurship in horticulture. Acta Hort. 691: 517-524.

Qian, T., Dieleman, J.A., Elings, A., De Gelder, A., Marcelis, L.F.M. and Van Kooten, O., 2009.
Comparison of climate and production in closed, semi-closed and open greenhouses. Acta Hort. (to be published)

Sonneveld, P.J., Swinkels, G.L.A.M., Kempkes, F., Campen, J.B. and Bot, G.P.A., 2006.
Greenhouse with integrated NIR filter and a solar cooling system. Acta Hort. 719: 123-130.

Sonneveld, P.J., Swinkels, G.L.A.M., Bot, G.P.A. and Flamand, G., 2007.
Conversion of NIR-radiation to electric power in a solar greenhouse. Thermovoltaic generation of electricity: TPV7: seventh world conference on thermophotovoltaic generation of electricity. AIP Conference proceedings 890: 317-326

Verkerk, K., 1955. Temperature, light and the tomato.
Meded. Landb. Hogeschool, Wageningen 55: 175-224

Zwart, de, H.F., 2009.
The sunergy greenhouse – one year of measurements in a next generation greenhouse. Acta Hort (to be published).

Projectnummer: 3242030800