Climate and Yield in a Closed Greenhouse

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Abstract

The so-called closed greenhouse (closed ventilation windows) is a recent innovation in Dutch greenhouse industry. The technical concept consists of a heat pump, underground (aquifer) seasonal energy storage as well as daytime storage, air treatment units with heat exchangers, and air distribution ducts. Savings of up to 30% in fossil fuel and production increases by up to 20%, mainly because of the continuously high CO_2 concentration, have been reported. Economic feasibility of this innovative greenhouse highly depends on the yield increase that can be obtained. In this simulation study the effects of greenhouse climate on tomato yield in a closed greenhouse are presented. The explanatory model INTKAM was used, which has several submodels e.g. for light interception, leaf photosynthesis and biomass partitioning. The closed greenhouse offers possibilities for combinations of light, temperature, air humidity and CO_2 concentration that are impossible in a conventional greenhouse. At high CO_2 concentration and high light intensity, leaf photosynthesis shows a more narrow optimum for temperature than at high CO_2 and moderate light intensity. However, the response of crop photosynthesis to temperature has a much broader optimum than that of leaf photosynthesis. Besides photosynthesis, temperature also influences aspects like partitioning, leaf area development and fruit development. Yield potential reduces at temperatures above 26°C, with fruit set being one of the first processes that is negatively influenced by supra-optimal temperatures. Based on actual climatic conditions in a conventional and a closed greenhouse (same crop management) measured during two years, INTKAM predicts an increase in yield by about 17%. Hence, in a closed greenhouse a higher stem density can be maintained for obtaining the same average fruit weight (size) as in a conventional greenhouse. In 2005 actual yield increase was similar to the simulated one (16%), but in 2004 only a 9% higher yield was realized, at least partly because of botrytis infection in the closed greenhouse.

INTRODUCTION

Worldwide, greenhouse production area is increasing (Costa et al., 2004). Compared to open field production, greenhouses allow for higher production levels, better product quality, out-off-season production and a higher water use efficiency (Van Kooten et al., 2008). Greenhouses vary from simple constructions covered with plastic to high-tech automated modern glasshouses. The largest glasshouse industry worldwide is found in the Netherlands, where about 6,000 companies realise on 10,500 ha a production value of more than 7 billion euro, which is 40% of the total national agricultural production. However, this 10,500 ha is only 0.5% of the total area of agricultural land, reflecting the intensity of production in modern glasshouses.

Unfortunately, greenhouses in the Netherlands use large amounts of energy, primarily for heating and humidity control. The annual consumption of natural gas is about 40 m^3 per m^2 glasshouse and a total of 4.2 billion m^3 of natural gas, which is about 10% of the total national gas consumption. Both from an economic and a political point of view this is problematic. Depending on the crop, energy costs represent 15 to 20% of the total production costs. Politically, emphasis is on reduction of CO_2 emission (Kyoto protocol) which results from burning fossil fuel. The government has fixed for 2010 a

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maximum of 6.5 million tonnes of CO_2 emission for the greenhouse industry. In 2006 this emission was 6.6 million tonnes (Van der Velden and Smit, 2007). Greenhouse industry (LTO Glaskracht) and The Centre for Agriculture and Environment Foundation (Stichting Centrum voor Landbouw en Milieu) presented in May 2007 a plan to reduce CO_2 emission by 45% in 2020 and 75% in 2030. The use of closed and semi-closed greenhouses can substantially contribute to this ambitious reduction goal.

Over the period 1980-2005 energy efficiency (production per unit of energy) in Dutch greenhouse industry has more than doubled. However, total energy use per square meter of greenhouse hardly changed (Van der Velden and Smit, 2007). Efficiency improvement resulted from a more than doubling in yield per square meter of greenhouse, caused by, among others improved greenhouse transmission, cultivars and cultivation techniques. However, for a reduction in CO_2 emission the use of fossil fuels needs to be reduced, e.g. by applying closed and/or semi-closed greenhouses. In this simulation study the effects of greenhouse climate on tomato yield in a closed greenhouse are presented. The general greenhouse crop model INTKAM is used, after being validated for a closed greenhouse.

THE CLOSED GREENHOUSE CONCEPT

On an annual basis, inside a Dutch greenhouse about 2800 MJ m^{-2} is received from the sun, which is almost 3 times more than the annual heating requirement. However, most of this solar energy is provided in summer, whereas heating requirement mainly exists in winter and spring, so a problem of timing exists. In the closed greenhouse concept aquifers are used to store excess heat in summer to heat the greenhouse in winter. This technique is already applied in hundreds of office buildings, hospitals and apartment blocks, but is rather new to greenhouses. Aquifers, 20 to 40 m thick layers of porous sand holding water in between 2 clay layers can be found almost everywhere in the Netherlands except for the most southern part. Besides aquifers for seasonal energy storage, the technical concept consists of a heat pump, daytime storage, heat exchangers, air treatment units and air distribution ducts (Fig. 1). In summer, greenhouse temperature is controlled by active cooling instead of opening of ventilation windows. Thus water from the cold side of the aquifer (5-8°C) is heated and stored at the warm side (16-18°C). In winter, water from the warm side is pumped up to heat the greenhouse using heat pumps, and the cooled water is stored at the cold side of the aquifer. Much more heat is stored than can be used in the closed greenhouse. Therefore, to be temperature neutral, which is demanded by the Dutch government, 1 ha closed greenhouse needs to be combined with about 3 ha conventional greenhouse, or the extra heat needs to be “used” in another way (e.g. heating apartments or destruction of heat in a cooling tower). Instead of installing a cooling capacity which can cope with the most extreme conditions (high solar radiation) in the year, the economic optimum lies at a much lower cooling capacity. In conditions were the active cooling capacity is insufficient to keep the temperature below the maximum, ventilation windows have to be opened (CO_2 concentration decreases) and hence such greenhouses are called semi-closed.

For a closed greenhouse, in combination with a conventional greenhouse, savings up to 30% in fossil fuel have been reported, whereas in an “island situation” (i.e. not combined with a conventional greenhouse) this was 20% (Opdam et al., 2005). Because ventilation windows stay closed also in summer, year-round a high CO_2 concentration in the greenhouse air can be realised. Mainly because of this high CO_2 concentration production increases of about 20% have been observed (Opdam et al., 2005). Investments for a closed greenhouse are very high, and no reliable data on profitability are available. Economic feasibility of this innovative greenhouse concept highly depends on the yield increase that can be obtained: in general 10% yield increase represents much more money than 10% reduction in fossil fuel use.

THE SIMULATION MODEL

The model is described by Marcelis et al. (2000) and is based on INTKAM

(Gijzen, 1994) and TOMSIM (Heuvelink, 1999). Global radiation outside the greenhouse, inside temperature and CO_2 concentration are model inputs. The model consists of modules for greenhouse radiation transmission, radiation interception by the crop, leaf and canopy photosynthesis, dry matter production, dry matter partitioning among plant organs (roots, stem, leaves and trusses of fruits), fruit harvest and leaf picking.

Greenhouse radiation transmission, radiation interception and photosynthesis are calculated with time intervals of half an hour. The time step of the modules for dry matter production, dry matter partitioning, fruit harvest and leaf picking is one day.

Assimilate partitioning between vegetative parts and individual fruit trusses is simulated on the basis of sink strengths, as described by Heuvelink (1996).

Computation of leaf area increase follows the approach given by Gary et al. (1995). Leaf area increase is potential if the average specific leaf area (SLA) of the whole canopy is smaller than the parameter SLA_{max}. Potential leaf area increase is computed as the product of the potential weight of new leaf material and the parameter SLA_{min}. If SLA is greater than SLA_{max} (if the leaf is thinner than permitted), leaf area increase is equal to the product of the weight of new leaf material and SLA_{max}. SLA_{max} is a constant, and SLA_{min} was made dependent on the day of the year in accordance with the sinusoid function described by Heuvelink (1999). Computations are conducted daily for each vegetative section (section consists of 3 leaves and 3 internodes). Appearance rate of new sections and trusses depends on temperature alone (De Koning, 1994).

Dry matter production of the organs is calculated as the amount of assimilates partitioned into each organ divided by the assimilate requirements for dry matter production. Fresh tomato yield is obtained by dividing the dry weight of the organs by the dry matter content. In the standard setting leaves from a section are removed when the corresponding truss above this section has reached developmental stage 0.9, which means at $20^{o}C$ about 6 days before the truss is harvest ripe.

MODEL VALIDATION

The model INTKAM has been validated for a wide range of conditions in conventional greenhouses (e.g. Marcelis et al., 2006), however, it is not on forehand clear that it can also handle the situation of a closed greenhouse. In a closed greenhouse high light levels can be combined with high CO_2 concentrations, whereas at the same time temperature remains close to the optimum and air humidity is controlled independently.

In 2002 the first experiment was conducted in a 1400 m^2 closed greenhouse (Opdam et al., 2005). The company Themato (www.themato.nl) realized in 2004 the first closed greenhouse on a commercial scale. In 2004 and 2005 tomatoes were grown in this greenhouse and in a conventional greenhouse at the same site. Data from these cultivations were used to validate the model INTKAM. Greenhouse transmission was not measured, but estimated at 73% for diffuse radiation, based on the construction year of the greenhouse. In both years CO_2 concentration in summer in the closed greenhouse could be maintained at the setpoint value of 1000 ppm, whereas in the conventional greenhouse, where also CO_2 enrichment was applied, values dropped to about 450 ppm CO_2 (Fig. 2A,B). LAI pattern over time was simulated well for both years (Fig. 2C,D), although for 2005 only 3 measurements were available so no strong conclusion can be made. The sawtooth pattern in the simulation of LAI results from removal of old leaves (roughly one section of 3 leaves once per week). Fruit dry matter content was not determined, but estimated to be 6%. Simulated yield slightly overestimated yield in the closed greenhouse in 2004, whereas simulated and measured yields in the conventional greenhouse showed good agreement. For 2005 in both greenhouses a good agreement existed between measured and simulated yield. In all situations, early yield was overestimated. For both years INTKAM predicted a 17% higher yield for the closed greenhouse compared to conventional greenhouse. In 2005 measured yield increase was similar (16%), but in 2004 only a 9% higher yield was realized in the closed greenhouse compared to the conventional greenhouse. One reason for this low actual yield increase could be that in the closed greenhouse about 10% of the plants was affected by botrytis.

The low LAI at the end of the cultivation in the closed greenhouse (Fig. 2) also influenced yield negatively. However, this can not explain the discrepancy between measured and predicted yield increase, as this reduced LAI was also simulated (Fig. 2C).

INTERACTION BETWEEN TEMPERATURE AND CO_2

Sometimes (e.g. Van Leeuwen, 2006) high yield increases of up to 75%, are suggested for a closed greenhouse where 1000 ppm CO_2 can be maintained at optimum temperature. However, these expectations are based on leaf photosynthesis curves, which is several steps away from yield. In agreement with Van Leeuwen (2006), INTKAM shows a larger effect of CO_2 on leaf photosynthesis rate at higher temperatures (Fig. 3). However, the relative effect remains almost the same: 1000 ppm CO_2 increased leaf photosynthetic rate by 71 to 73% both at 20°C and at 30°C (Fig. 3 at 1380 µmol m^{-2} s^{-1} PAR). At increasing CO_2 concentration optimal temperature for leaf photosynthesis increases (Fig. 3).

The temperature response of leaf photosynthesis depends strongly on light intensity. At low light intensity optimum temperature is much lower than at high light intensity, and temperature response is much weaker. Despite the strong temperature response of leaf photosynthesis at high light intensity (Fig. 4A), this response does not exist at the crop level. Crop photosynthesis, which integrates leaf photosynthesis of leaf layers with different light intensities, showed only a weak temperature response (Fig. 4B). This has also been reported by Challa (1990). Therefore, optimizing greenhouse climate based on leaf photosynthetic response (e.g. Aaslyng et al., 2003) may lead to suboptimal conditions. A broad temperature optimum between 16°C and 24°C for crop photosynthesis at high CO_2 (Fig. 4B) does not necessarily mean that under these conditions yield (kg m^{-2}) is hardly influenced by temperature.

Yield response to temperature, reviewed by Van der Ploeg and Heuvelink (2005), integrates temperature effects on photosynthesis, respiration and development (e.g. leaf area development, fruit initiation, ripening). Simulations with INTKAM (Fig. 5) showed that at higher temperature production starts earlier, fruits are smaller (not shown), and final yield is hardly influenced by temperature (16-24°C) at 1000 ppm CO_2. Similar results were obtained in experiments (De Koning and Buitelaar, 1990). This suggests that within this temperature range, temperature control in a closed greenhouse does not have to take into account effects on total yield, and primarily cooling capacity and cooling costs are decisive. A higher average temperature (up to 26°C) is acceptable, which reduces the needed capacity of the cooling system and hence total investment costs. Sato et al. (2006) compared tomato plants grown at 32/26°C as a moderately elevated temperature stress (METS) treatment with plants grown at 28/22°C (day/night temperatures) as a control at natural light conditions. METS did not cause a significant change in biomass, the number of flowers, or the number of pollen grains produced, but there was a significant decrease in the number of fruit set, pollen viability and the number of pollen grains released. Their research indicated that failure of tomato fruit set under METS is due to the disruption of sugar metabolism and proline translocation during the narrow window of male reproductive development. However, this effect of METS may have been partly confounded with a negative effect of low VPD on tomato fruit set.

To decide which cooling capacity is optimal for a closed greenhouse, more information is needed about crop effects of short-term peaks in temperature. Fruit set is one of the first processes that is negatively influenced by supra-optimal temperatures (Sato et al., 2006), and this is not included in INTKAM. Furthermore, in the closed greenhouse vertical temperature distribution differs from conventional greenhouses. Knowledge on effects of vertical temperature gradients on crop performance is limited.

Since, based on our simulations, closed greenhouse conditions increase biomass production by 17%, as a first approximation on average a 17% higher stem density can be maintained, if the same average fruit weight (size) as for the conventional greenhouse has to be realized. Note that this may be higher, considering that production increase is primarily in summer whereas 17% is on annual basis. However, stem density increase will be less, if greenhouse temperature is allowed to increase, which will reduce fruit size.

CONCLUDING REMARKS

Both observed and predicted annual tomato yield increase in a closed greenhouse was about 17% compared to a conventional greenhouse. This increase is almost completely caused by higher CO_2 concentrations in summer. In a closed greenhouse a higher stem density can be maintained for obtaining the same average fruit weight (size) as in a conventional greenhouse.

It is clear that under current Dutch conditions, a completely closed greenhouse does not represent the economic optimum situation. Opening the ventilators at high radiation load (semi-closed greenhouse) and hence accepting a temporal reduction in CO_2 concentration, substantially reduces investment costs in cooling capacity. Cooling (and humidity control) can also be obtained by air humidification. The economic optimum situation depends on the trait-off between cooling costs and yield loss.

Leaf photosynthesis shows a much stronger temperature response than crop photosynthesis (16-24°C) and is therefore not the best basis for greenhouse climate optimization. Increased greenhouse temperature reduces fruit size, however, average temperature effect on yield is small in this range, and therefore economic optimum temperature in a closed greenhouse depends primarily on the investment costs for cooling capacity. For a true optimization, more information is needed on crop effects of short-term peaks in temperature.

Recently we have started greenhouse experiments on studying effects of the climate conditions (different combinations of temperature, temperature profiles, air humidity and CO_2) of semi-closed greenhouses on tomato growth, development and yield.

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Figures

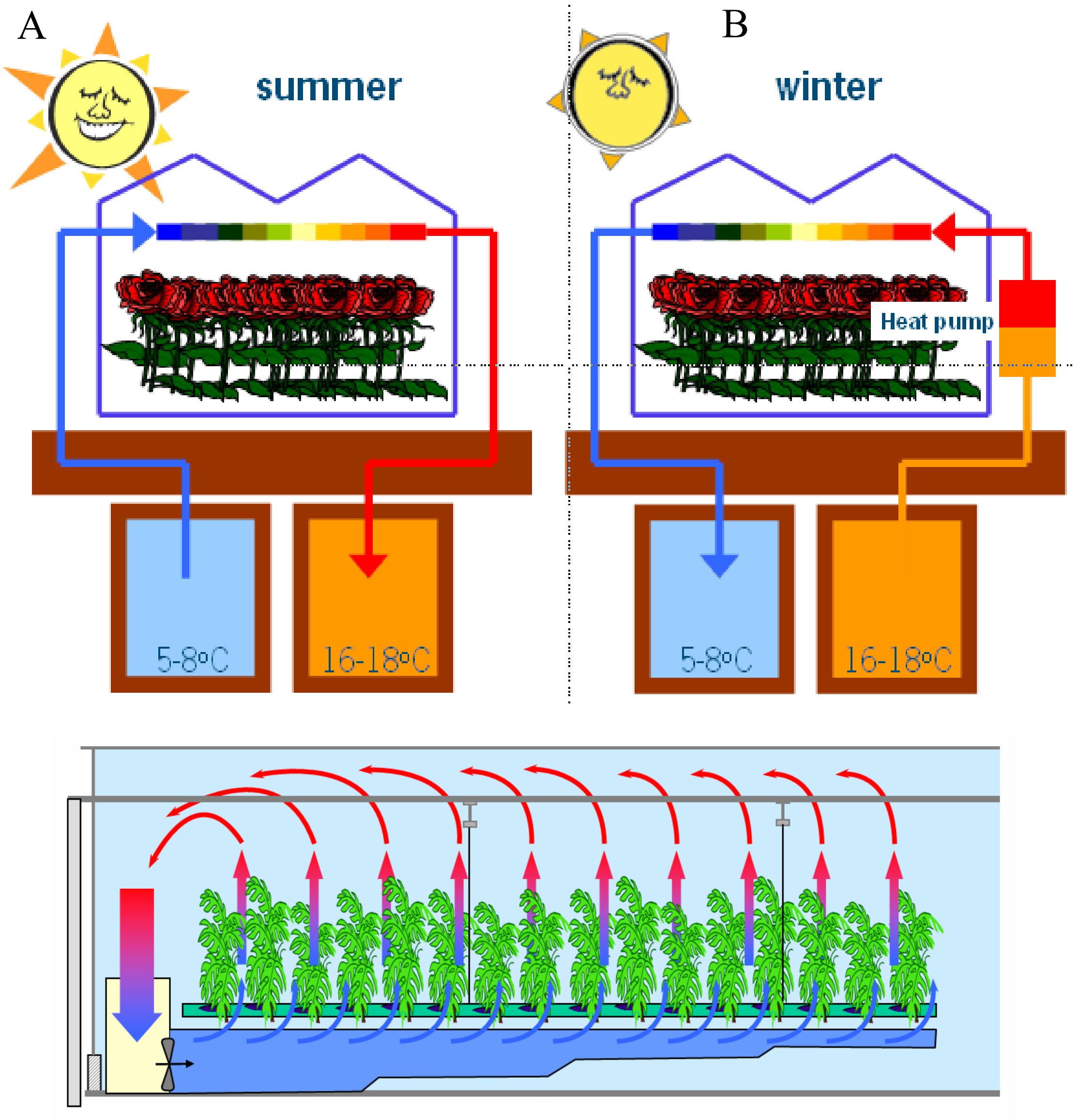

Fig. 1. (A) The closed greenhouse concept: cooling the greenhouse air, and storage of heat in an aquifer in summer and use of stored heat in winter (Körner, WUR Greenhouse Horticulture), and (B) air circulation in a closed greenhouse (De Zwart, WUR Greenhouse Horticulture).

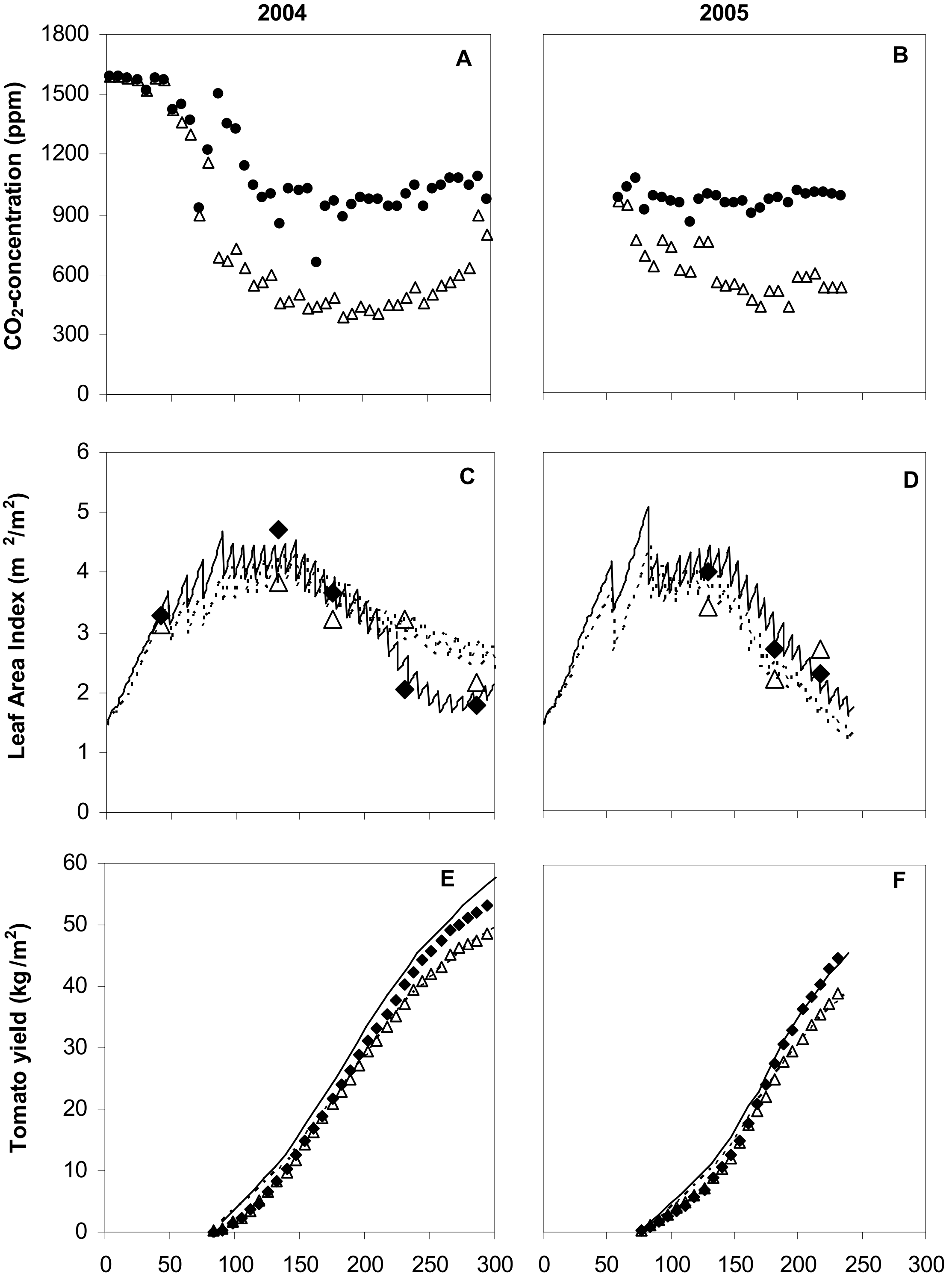

Fig. 2. CO_2-concentration (A,B), Leaf Area Index (C,D) and tomato fresh yield (E,F) for closed and conventional greenhouses in 2004 (A,C,E) and 2005 (B,D,F). Measurements (Δ conventional; ◆ closed) and simulation (- - - conventional; ——— closed).

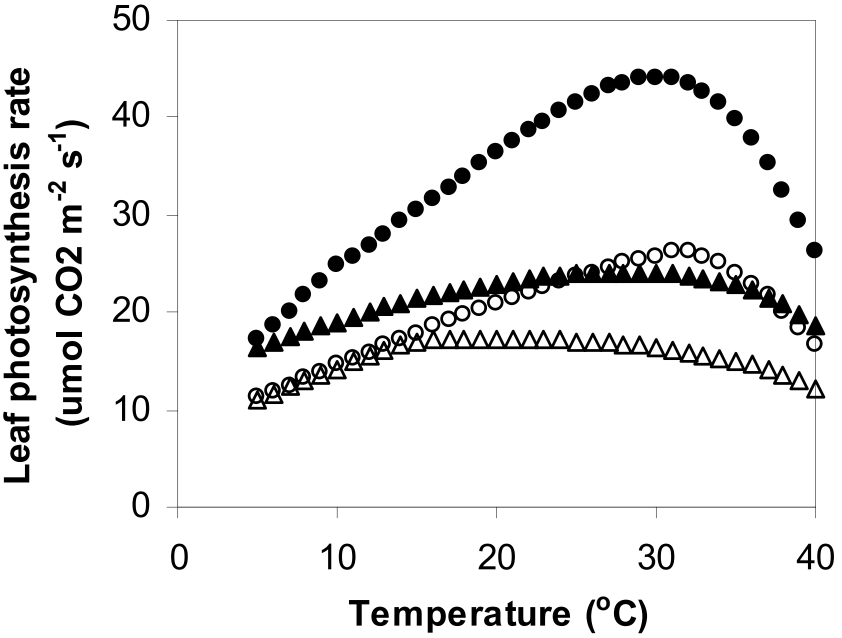

Fig. 3. Simulated temperature response of leaf gross photosynthesis at different levels of absorbed PAR (Photosynthetic Active Radiation (µmol m^{-2} s^{-1}: Δ,▲ 460; ❍,⬣ 1380) and at different CO_2-levels (ppm: Δ,❍ 350; ▲,⬣ 1000).

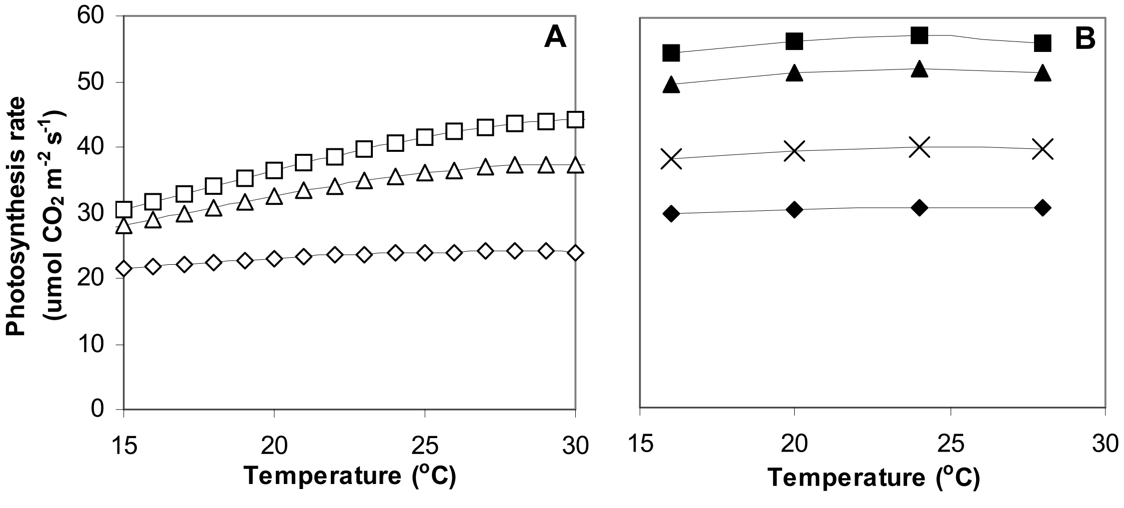

Fig. 4. Simulated influence of temperature on leaf gross photosynthesis (A) and crop gross photosynthesis (B) at 1000 ppm CO_2 and different levels of absorbed PAR (Photosynthetic Active Radiation (µmol m^{-2} s^{-1}; ◊ 460; Δ 920; □ 1380; ◆ 500; × 690; ▲ 980 ; ■ 1100).

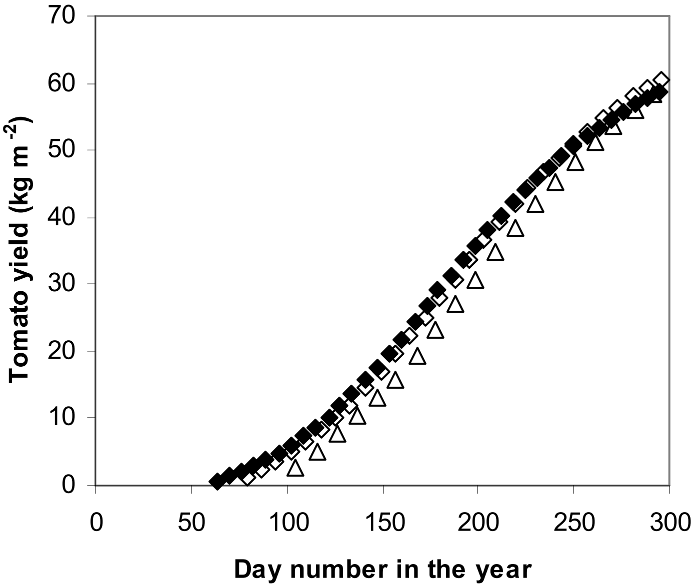

Fig. 5. Simulated effect of temperature (Δ 16ºC; ◇ 20ºC; ◆ 24ºC) on tomato fresh yield in a Dutch greenhouse at 1000 ppm CO_2. Fruit dry matter content was assumed to be 0.055.