Effects of Anti-Transpirants on Transpiration and Energy Use in Greenhouse Cultivation

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Abstract

Greenhouse production in North-West Europe consumes a lot of energy. The energy is needed for heating the greenhouse and controlling air humidity. Transpiration of a crop increases the energy use. The aim of this study was to explore the possibilities for the application of anti-transpirants to save energy by reducing crop transpiration without reducing crop yield. Literature and model calculations were used to explore the effects of increased leaf resistances on transpiration, energy use and production in tomato, cucumber and sweet pepper.

In literature a large number of compounds are described that act as anti-transpirant. A two to five fold increase in stomatal resistance can be expected from treatment with anti-transpirants. Model calculations for tomato showed that increasing the stomatal resistance (from 2 to 5 times) throughout the whole year leads to substantial yield reduction: crop growth was reduced by 6-19%, while transpiration by 15-42% and consequently energy use by 9-16%. However, in the winter period (beginning of October/end of March) the growth reduction was only 0.3-1.3%, as in this period light levels are low and CO_2 concentrations in the greenhouse are relatively high. Raising the (maximum) set-point for CO_2 concentration from 1000 ppm to 3000 ppm, increased the actual concentration during day-time from 892 to 1567 ppm (flue gases were the only source of CO_2). When the application of anti-transpirants was combined with raising the set-point for CO_2 concentration, the model showed no growth reduction due to the application of anti-transpirants, while the annual energy use was reduced by 5.5-10.4% in tomato. Similar results were obtained for sweet pepper (5-9% energy saving) and cucumber (2-5% energy saving). These model calculations show that increasing stomatal resistance by anti-transpirants during the winter period may potentially save a substantial amount of energy (2-10%), without affecting yield of vegetables such as tomato, cucumber and sweet pepper. It is concluded that increasing the stomatal resistance by anti-transpirants in wintertime may lead to substantial energy saving due to the reduced transpiration and need for humidity management, without yield reduction. Such model calculations are useful to analyse beforehand the chances of a good combination of energy saving and yield loss of a possible application. Experiments will be needed to verify the results.

INTRODUCTION

Greenhouse production in North-West Europe consumes a lot of energy. The energy is needed for heating the greenhouse and controlling air humidity. Transpiration of a crop increases the energy use. Besides the energy for transpiration (latent heat), the vapour that is generated has to be “ventilated away”, which usually carries sensible heat. Stanghellini et al. (2003) estimated that, in Dutch conditions, transpiration of 15 liters of water results on average in an energy use of about 1 m^3 natural gas. There is a potential for energy saving by reducing transpiration, provided the yield is not significantly reduced.

There have been hundreds of studies on the use of anti-transpirants to reduce transpiration of crops in the open field under (semi-) arid conditions. Common purpose was saving the limited amount of available water, reduction of drought stress and consequently improved crop production. Three groups of anti-transpirants can be discerned:

- reflecting: substances that reflect the light when applied on leaves. Example: Kaolin. Reflecting substances seems not interesting for greenhouse production as they lead to a loss of light on the leaves and consequently will lead to reduction in photosynthesis.
- film forming: substances that form a film on the leaf (on the stomata) and therefore reduce gas diffusion. Examples: Vapour Gard, film forming polymers.
- closing: substances that lead to a (partial) closure of stomata. Examples: abscisic acid (ABA), acetylsalycic acid.

Anti-transpirants may increase stomatal resistance to 150% (Schon, 1993), 200% (Pospisilova et al., 1998), 300% Bittelli et al. (2001), 500% (Gu et al., 1998) compared to untreated plants. Various levels of reduction of transpiration (or water uptake) have been reported, e.g. 12% (Del Amor et al., 2006) 15% (Martinez et al., 2001), 25% (Darlington et al., 1996) and 30% (Ceulemans and Impens, 1983).

In contrast to the many studies related to drought in the open field, only a few studies on anti-transpirants have been performed in greenhouses. Schon (1993) and Martinez et al. (2001) applied anti-transpirants in summer-time to reduce transpiration in order to prevent quality problems with blossom end rot in sweet pepper and tomato. However, anti-transpirants may also reduce yield (Schon, 1993), vegetative dry weight (Del Amor et al., 2006) or total biomass (Martinez et al., 2001).

Based on the literature we concluded that a large number of substances (anti-transpirants) may increase stomatal resistance. This increase can be up to 500%. The aim of the present study was to evaluate whether such substances might potentially be useful to save energy in greenhouse production. Therefore, effects of increasing stomatal resistance on transpiration, energy use and crop production were explored by model calculations.

MATERIAL AND METHODS

An increase of stomatal resistance reduces transpiration, which reduces air humidity and increases the fraction of available energy that warms up the greenhouse; the ensuing effect on the ventilation requirement of a controlled greenhouse is therefore not straightforward. Another ventilation rate, together with a reduction of heating (whose exhaust gases are used for carbon enrichment) affect the CO_2 concentration in the greenhouse. All these effects, together with the increased stomatal resistance we started with, have to be accounted for if one wants to estimate the effect of anti-transpirant application on the production of a greenhouse crop. For this, we coupled a physical model (KASPRO) simulating the greenhouse climate and energy use and a physiological model (INTKAM) simulating crop growth.

Climate Model (KASPRO)

KASPRO is a dynamic simulation model of the canopy-greenhouse system, described by De Zwart (1996). Basis of the model are the energy and mass (water vapour and CO_2) balances over the considered lumped parts of the system, resulting in a set of coupled, non-linear, first order differential equations that are solved numerically. The model describes actual air temperature, CO_2 and humidity concentration, resulting from climate set-points and a known external climate, accounting for the dynamic behavior of the greenhouse heating and ventilation systems and of the greenhouse structure and canopy. Intermediate variables that need to be calculated are: the canopy and greenhouse cover temperature, the temperature profile of the soil, water use and the artificial energy input. Variables of the external climate that need to be known are air temperature and humidity, solar radiation and wind speed.

Crop Model (INTKAM)

The INTKAM model is a mechanistic model that simulates dry and fresh weight growth of plant organs for crops such as tomato, sweet pepper and cucumber. For sweet pepper the model has been described by Marcelis et al. (2006). The crop specific modules for tomato are based on Heuvelink (1996), while modules for cucumber are based on Marcelis (1994). Input to the model are global radiation, air temperature, air humidity and CO_2 concentration in the greenhouse, as calculated by the KASPRO model. The model consists of routines 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 individual fruits) and fruit harvest.

Interception of visible and near infra red radiation, canopy gross photosynthesis and canopy transpiration are calculated for a multi-layered uniform canopy (Goudriaan and Van Laar, 1994). Leaf gross photosynthesis is calculated with the biochemical model of Farquhar et al. (1980) for the various layers in the canopy as described by Gijzen (1994).

Net assimilate production results from the difference between canopy gross photosynthesis and maintenance respiration. Assimilate partitioning between vegetative parts and individual fruits is simulated on the basis of the concept of sink strengths (Marcelis, 1994).

Using climate data which were calculated with a time step of two minutes, radiation interception, photosynthesis and transpiration are calculated with time intervals of an hour. The time step of calculation of dry matter production, partitioning and fruit harvest is one day.

Simulation of Leaf Resistance

The boundary layer resistance was estimated at 200 s m^{-1} for tomato, 300 s m^{-1} for sweet pepper and 400 s m^{-1} for cucumber based on typical data for leaf size of these crops, and a common estimate of air speed in the house of less than 10 cm s^{-1}, according to Stanghellini (1987).

Stomatal resistance was calculated as a function of radiation, air humidity, temperature and CO_2 concentration according to Jarvis (1976) with parameters from Stanghellini (1987) for tomato, Nederhoff and De Graaf (1993) for cucumber and Bakker (1991) for sweet pepper.

Reference Situation

All calculations were performed with a standard weather data set of the Netherlands (SEL year). The method to create these data is described by Breuer and van de Braak (1989). Here we used a standard based on the climate between 1990 and 2000. The calculations were performed for a modern greenhouse without mechanic cooling or misting installation, but with energy screen, temperature integration, cogeneration of heat and power and heat storage. Humidity is controlled by a combination of ventilation and heating. Ventilators are opened whenever relative humidity exceeds 85%. The opening (as a fraction of the maximum opening angle) is proportional to the excess relative humidity (above 85%), and the proportionality factor varies linearly from 0.01 (when outside temperature $\leq 2^oC$) to 0.05 (when outside temperature $\geq 12^oC$). The ensuing heating requirement follows from the independent heating set-point. Tomato was grown from 5 Dec until 20 Nov. Sweet pepper from 11 Dec until 25 Nov, while for cucumber 3 crops a year were grown.

CO_2 set-point was 1000 ppm. CO_2 was supplied from exhaust gases produced by either the boiler or cogenerator. By using a heat storage tank (a common practice in The Netherlands), production of CO_2 is de-coupled from the actual heat demand of the greenhouse. The system was constrained so that there was no CO_2 production whenever there was no use for the [stored] heat. Altogether, the capacity of the supply system could (and did) limit the actual CO_2 concentration in the house, in spite of the set-point.

RESULTS AND DISCUSSION

Increasing stomatal resistance throughout the whole year reduced simulated crop growth substantially in tomato due to reduced photosynthesis (Fig. 1). This reduction was

6 to 19%, when stomatal resistance was increased by a factor 2 or 5, respectively. The reduction in transpiration was stronger and varied between 15 and 42% (Fig. 1). The stronger response of transpiration than of photosynthesis can be explained by the fact that stomata represent one of in total 2 resistances relevant for transpiration while they represent only one of the 3 resistances relevant for photosynthesis. For transpiration the boundary layer represents the other resistance, while for photosynthesis additionally a the mesophyll resistance determines the CO_2 diffusion. The strong reduction in transpiration also reduced the use of energy by 9 to 16% (Fig. 1).

Analysis of the time course of effects on growth and energy saving showed that the yield reduction occurred during the summertime, while most of the energy saving occurred during wintertime (Fig. 2). During wintertime CO_2 concentrations are usually high in the greenhouse (800-900 ppm) and light level is low. Therefore CO_2 diffusion, and consequently stomatal resistance, is not limiting photosynthesis or growth in winter. However, in the summer the light level is high and CO_2 concentrations are lower (500-600 ppm). Furthermore, the reduced transpiration at high stomatal resistance led to less evaporative cooling of the greenhouse. More ventilation was required to control air temperature, which reduced the attainable CO_2 concentration in summertime (a fivefold increase in stomatal reduction reduced average CO_2 concentration from 561 to 525 ppm in July).

As the effects of increased stomatal resistance were most promising in wintertime, a simulation run was performed where stomatal resistance was increased during DOY (day of year) 281 to DOY 84. This resulted in saving 5.5-10.4% of the annual energy consumption, when stomatal resistance increased by a factor 2 to 5, with a yield loss of 0.3-1.3% (Fig. 3).

As the yield reduction at high stomatal resistance is due to the limited CO_2 diffusion, we analysed whether this could be compensated by increasing the CO_2 set-point from 1000 to 3000 ppm. The limited CO_2 production capacity ensured that seldom this value was attained. In wintertime the average day-time CO_2 concentration was raised from 892 ppm in the reference situation to 1567 ppm. Such increases in CO_2 concentration fully compensated for the increased stomatal resistance. Hence increasing stomatal resistance by up to a factor five did not reduce yield when CO_2 concentration was increased simultaneously in wintertime (Fig. 4), which means that 5.5 to 10.4% could be saved on energy use, without yield reduction.

Results for sweet pepper and cucumber were comparable. By increasing the CO_2 set-point no growth reduction related to the increase in stomatal resistance was calculated for the same period. The annual energy saving was 5-9% for sweet pepper and 2-5% for cucumber. The main reason for the smaller effect of stomatal resistance in cucumber is the higher boundary layer resistance of cucumber leaves (400 s m^{-1} in cucumber versus 200 s m^{-1} in tomato).

The main conclusion of this desk-study is that there is a potential for energy saving in greenhouse production in North-West Europe to be attained by application of anti-transpirants in wintertime. According to our results, a smart management of the CO_2 supply makes it possible to do that without yield reduction. It would be advisable, however, first to test in real-life experiments such predictions. Additional aspects that may need to be detailed further are: a. the actually attainable increase in stomatal resistance; b. an application protocol (concentration, frequency and mean of application) for the most promising products and c. the existence of possible side effects. This desk study does give ground for further experimental research.

ACKNOWLEDGEMENTS

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Figures

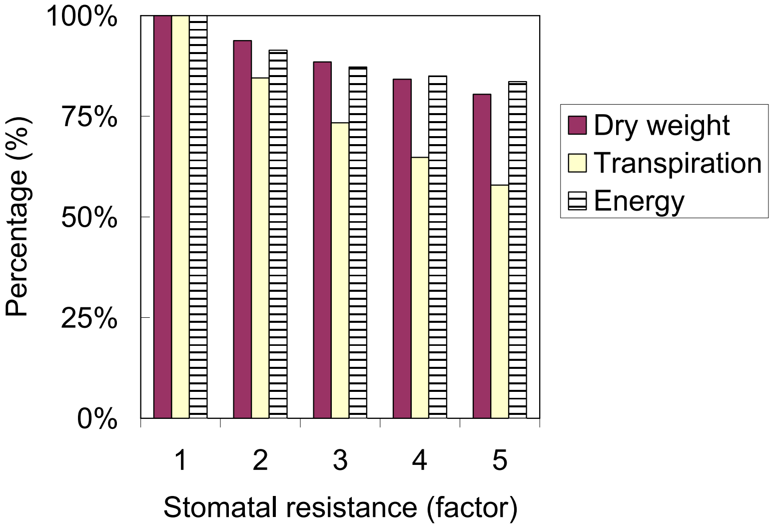

Fig. 1. Simulated effect of increasing the stomatal resistance throughout the whole year on annual total dry matter production of the plant, transpiration and energy use in tomato. Stomatal resistance was increased by a factor 1 (reference), 2, 3, 4 or 5. In the reference situation dry matter production was 5 kg m^{-2}, transpiration was 709 l m^{-2} and energy use was 44.3 m^3 natural gas m^{-2}.

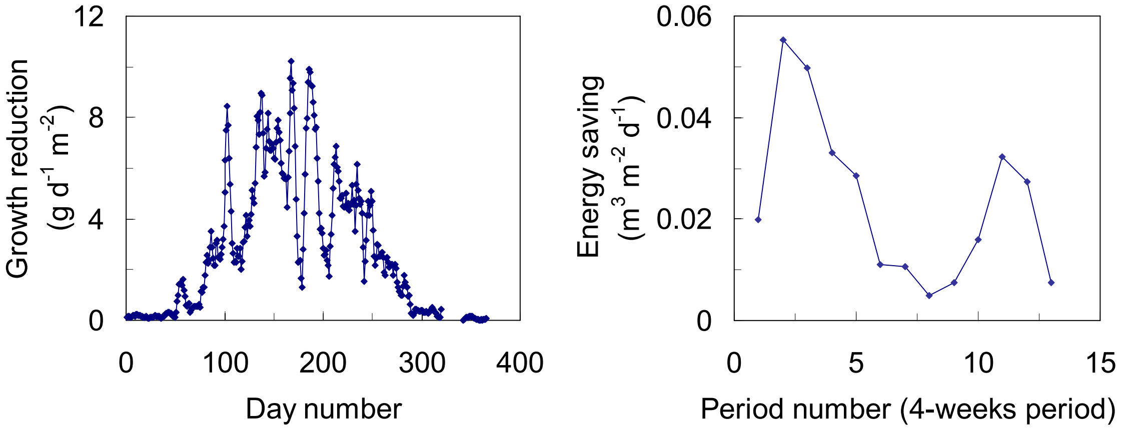

Fig. 2. Simulated time course of the growth reduction and energy saving (natural gas) by increasing the stomatal resistance by a factor 5 throughout the whole year in tomato.

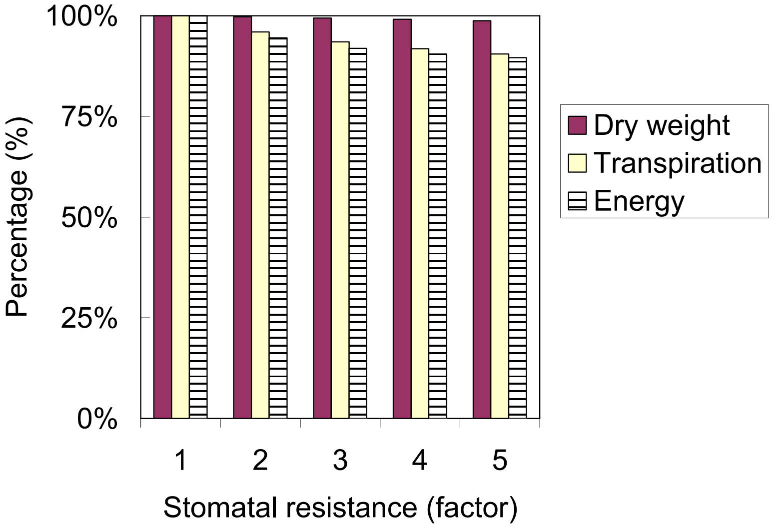

Fig. 3. Simulated effect of increasing the stomatal resistance during the winter period on annual total dry matter production of the plant, transpiration and energy use in tomato. Stomatal resistance was increased during the first three and last three 4-week periods of the year (day 1-84 and 281-365) by a factor 1 (reference), 2, 3, 4 or 5.

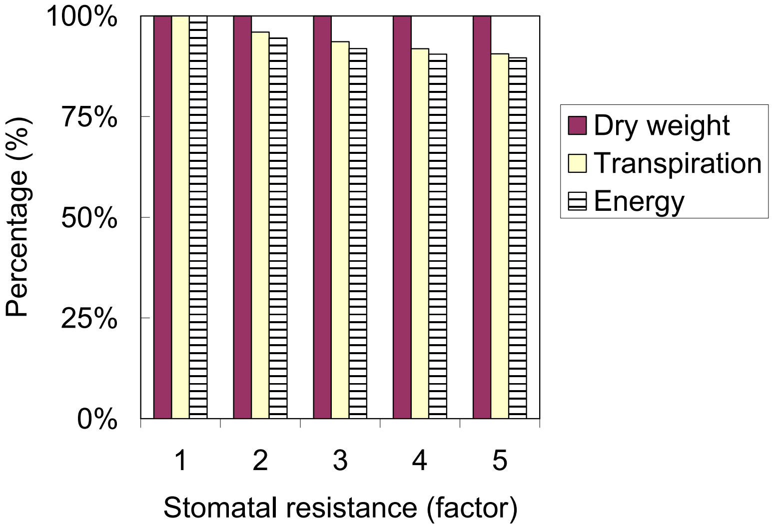

Fig. 4. Simulated effect of increasing the stomatal resistance during the winter period on annual total dry matter production of the plant, transpiration and energy use in tomato, when the set-point for CO_2 supply was increased to 3000 ppm. Stomatal resistance was increased during the first three and last three 4-week periods of the year (day 1-84 and 281-365) by a factor 1 (reference), 2, 3, 4 or 5.