Multiple-day Temperature Settings on the Basis of the Assimilate Balance: a Simulation Study

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Abstract

Temperature control on the basis of a crop's physiology offers advantages over a control that avoids strong climate fluctuations. The assimilate balance, defined as the ratio between the supply of and demand for assimilates, enables a radiation-dependent temperature regulation. The INTKAM crop growth model and KASPRO greenhouse model were coupled, and were combined with an optimization module to evaluate the potential of this regulation. The simulation study resulted for cucumber in all growing seasons in production increase or reduced energy consumption. Annual figures were 5.25 m^3 m^{-2} gas reduction or 4.4 kg m^{-2} production increase. The underlying mechanisms include a more stable and greater dry matter partitioning to the fruits, and more stable fruit size, length and age.

INTRODUCTION

It has been attempted since a number of decades to balance the temperature and radiation regimes such that production and product quality are enhanced, while reducing energy consumption (Seemann, 1956; van den Berg et al., 2001). The underlying concept of temperature integration is to increase and reduce temperature at moments of high and low radiation, respectively. In its most simple form, day and night temperatures are increased and decreased, respectively, while the daily average remains unchanged. With lengthening time horizons, this approach can be extended over a number of days (de Koning, 1990). If the greenhouse is heated at moments when energy loss is low, this approach saves energy. Temperature integration does not specifically take into account plant processes. Its prime focus is energy saving, while maintaining the temperature sum. An approach on the basis of crop physiology aims to reduce temporal variation in plant processes and characters, which, however, may lead to wider variations in climate factors. Our hypothesis is that stabilization of plant processes leads to more stable and greater dry matter partitioning towards the fruits, a more stable fruit load, and more stable fruit characters over the season (Marcelis, 1994). These are all changes welcome to growers.

Production and consumption of assimilates are important physiological plant processes. They are combined in the assimilate balance, which is defined as the ratio between supply of and demand for assimilates. Assimilate supply of an adult crop is determined by the net rate of CO_2 assimilation, which is at usual levels of temperature in modern greenhouses predominantly determined by the amount of incoming radiation, and to a lesser extent by air CO_2 concentration (not considering high photorespiration if the CO_2 concentration is very low) and relative air humidity. The radiation effect is modified by a smaller temperature effect via the maintenance respiration rate (Penning de Vries, 1975). Assimilate demand, or potential growth rate, is determined by the amount of fruits on the plant, and by the effect of ambient temperature on the demand per fruit, and on the demand of the vegetative organs. Assimilate supply is usually smaller than assimilate demand, causing an assimilate balance smaller than one. Only at the beginning of the season, when the number of fruits per plant is low, the assimilate balance may be greater than one.

If the assimilate balance is to be stabilized, then temperature must be increased and decreased at bright and dull days, respectively. This concept has been introduced earlier as the Ratio of Radiant to Thermal Energy (RRT; Liu and Heins, 1997), and is now extended with a dependency on the plant's assimilate balance. Excesses and shortages of daily amounts of energy can be balanced over several days, introducing opportunities for energy saving. We call this method multiple-day temperature setting (MTS) on the basis of the plant's assimilate balance.

We here report on a simulation study, based upon a commercial situation, that tests the hypothesis that stabilization of the assimilate balance of a plant results in a more stable and greater dry matter partitioning towards the fruits, a more stable fruit load, and more stable fruit characters, as well as in a lower energy consumption.

MATERIALS AND METHODS

Cucumber, the example crop, knows three growing cycles in The Netherlands, and is planted in weeks 50, 18 and 31. Key data on climate settings, minimum pipe, etc., and productions in 2004 were made available by a commercial grower. The KASPRO greenhouse model (de Zwart, 1996; Luo et al., 2005) generated climate and energy consumption data. The INTKAM crop growth model is a photosynthesis-based model that distributes dry matter on the basis of organ sink strengths, and accounts for the effects of radiation, temperature, CO_2 and relative air humidity on crop growth and development. It was validated previously (Marcelis et al., 1998), and calibrated to the 2004 climate and production data, which included adjustment of the number of stem fruits to match the onset of production, and the maximum fruit weight at harvest. Simulations were made once per treatment, and no within-treatment variation was generated. Therefore, no means and standard errors were computed. Coefficients of variation were computed over treatments.

The assimilate balance was computed on a daily basis (Fig. 1). The daily values show wide variation associated with variation in global radiation (short-term variation). For each season, a 2^{nd}-degree polynomial description of the daily assimilate balance was given, which was defined as the target balance, and which describes the long-term variation of the assimilate balance. To stabilize the assimilate balance, its daily value should be equal or close to the value of the target balance. As there is no guarantee that the best statistical fit leads to the best physiological results, also other target balances were evaluated, viz. lines that are positioned e.g. 10% or 20% below or above the best statistical fit. The lines are referred to as the 80%, 90%, 100%, 110%, 120% lines.

On a daily basis, the average daily temperature was chosen between 15 and 25°C, such that the assimilate balance was equal to, or as close as possible, to the target balance. Four sets of computations were performed:

1. Simulation of the reference cultivation with the INTKAM crop growth model.
2. MTS–Crop: Multiple-day temperature settings on the basis of the plant's assimilate balance, without taking into account limitations related to the greenhouse's temperature control. Simulations were performed with the INTKAM crop growth model, and indicate the crop's potential.
3. MTS–ES: Multiple-day temperature settings, taking into account limitations related to the greenhouse's temperature control. For instance, in the winter the heating capacity may not be sufficient to achieve a daily temperature of 25°C, while in summer it may not be possible to cool down to a daily temperature of 15°C. Energy saving (ES) was not a goal. Simulations were performed with the combined INTKAM crop model and the KASPRO greenhouse model.
4. MTS+ES: Multiple-day temperature settings, taking into account limitations related to the greenhouse's temperature control. Energy saving was an optimisation goal. All temperature settings that on a particular day realized an assimilate balance equal or close to the target balance, were selected. The energetic consequences for three days were quantified, and the temperature setting within lowest energy use over three days was selected. Simulations were performed with the combined INTKAM crop model and the KASPRO greenhouse model, and optimisation was done on a daily basis.

RESULTS

All generated data are simulated values. Not all simulated data are presented.

The average temperature (T_{av}) under reference conditions during the winter, summer and autumn season is 19.3, 21.3 en 20.6°C, respectively. Pursuing a lower target balance (increasing the demand for assimilates) requires a higher temperature. MTS+ES leads to lower temperatures than MTS–ES, which is a direct consequence of the optimisation towards energy saving. T_{av} for MTS+ES in summer and autumn that is equal to the reference T_{av} is reached by pursuing the 90% or 95% target balance. T_{av} is in winter for all target balances lower than the reference T_{av}.

The pursued assimilate balance is realized at most days for MTS–Crop, as the daily temperature can be varied fully between 15 en 25°C. As daily temperatures can be varied less freely in case of MTS–ES and MTS+ES, the pursued assimilate balance is less well realized.

There is a seasonal difference in gas consumption for MTS–ES and MTS+ES that pursues the same target balance, of approximately 4 m^3 m^{-2} in winter and autumn and 2 m^3 m^{-2} in summer. Optimisation towards energy saving has therefore a substantial effect. Gas consumption for MTS+ES that is lower than the reference gas consumption, is achieved in winter for all pursued target balances, while in summer and autumn a target balance of 90% or higher must be pursued. However, the optimal target balance must be selected on the basis of both gas consumption and production (see below). T_{av} and gas consumption are linearly related (Fig. 2). The relation is in winter and summer not influenced by optimisation towards energy saving, implying that energy can only be saved by pursuing a lower T_{av}. This is precisely what MTS+ES is doing: a temperature reduction without consequences for production (see below). In autumn, however, energy saving slightly reduces the intercept of the relation between T_{av} and gas consumption. The seasonal difference is 0.64 m^3 m^{-2} at 20°C, or 0.3°C at 10 m^3 m^{-2}. Gas is saved through a reduced T_{av}, and by the slightly lower energy requirement to reach a certain T_{av}.

The relation between temperature and gross photosynthesis is weak at common levels of temperature. Lower temperatures, however, may result in lower CO_2 availability from the heating system and a slightly lower photosynthesis. This effect is stronger for MTS+ES than for MTS–ES. Seasonal gross photosynthesis is greater for MTS+ES than for the reference situation only in autumn if a target balance below 100% is pursued.

Dry matter production results from gross photosynthesis minus maintenance respiration. These processes interact in two manners. 1) Temperature plays a dominant role if a target balance between 80% and 90% is pursued. Pursuing a higher target balance implies a lower T_{av}, a lower maintenance respiration, and a higher dry matter production. 2) If a target balance of 95% and higher is pursued, then increasingly lower CO_2-concentrations due low T_{av} cause reduced photosynthesis and dry matter production. Having mentioned this, it should be stressed that differences in photosynthesis and production are small: e.g., approximately 1% between MTS–ES and MTS+ES.

Trends of crop and fruit dry matter production in relation to the pursued target balance are similar. Small differences between the two are caused by differences in dry matter partitioning. There is a small effect of energy saving on the relation between T_{av} and fruit dry matter production. This effect is strongest in winter: the difference between MTS–ES and MTS+ES is 17 g m^{-2} at T_{av} 19°C at the advantage of MTS–ES. Apparently, the energy-optimising algorithm has a small negative effect of fruit dry matter growth.

Dry matter partitioning to the fruits, compared to the reference partitioning, improves in almost all cases when a stable assimilate balance is pursued (see also Marcelis, 1994). It improves for MTS–Crop, averaged over all target balances, from 0.643 to maximal 0.671 in winter; from 0.665 to maximal 0.678 in summer; and from 0.624 to maximal 0.645 in autumn. MTS–ES and MTS+ES know different temperatures, causing slightly lower demand for assimilates and a lower dry matter partitioning than for the reference situation. However, dry matter partitioning is still better than in case of the reference. Greatest dry matter partitioning for MTS+ES is in winter realized if the 100% target balance is pursued. In autumn, the 105% target balance must be pursued, while in summer, dry matter partitioning is hardly influenced by the target balance. Large fluctuations in dry matter partitioning to fruits and the fruit load are stabilized if the assimilate balance is stabilized. This enables growers to realize a more stable production. Small fluctuations remain, but large fluctuations do not occur.

As fruit dry matter percentage is negatively related to temperature (Marcelis, 1992), lower temperatures reduce fresh production. Fresh fruit production is the combined effect of fruit dry matter increase and fruit dry matter concentration. The latter dominates, and a fresh production that is higher than for the reference situation can for MTS+ES only be achieved in case of relatively low assimilate balances, and relatively high temperatures. For MTS-ES more options exist, and increased fresh production can be attained if the 100% target balance is pursued.

The relations between fresh production, temperature, and energy use are important (Table 1, Fig. 3):

- Winter: T_{av} is reduced by approximately 1°C without fresh production loss, resulting in a gas use that is lower by 2.25 m^3 m^{-2}. Or, at the same temperature an approximately 1.5 kg m^{-2} greater fresh production is realized. Best is to apply MTS+ES, as this is more energy-efficient that MTS–ES, and to pursue the 95-100% target balance.
- Summer: T_{av} can not be reduced without production loss, however, more importantly, gas use is reduced by 1.5 m^3 m^{-3} without production loss (MTS+ES, 90-95% target balance), or fresh production is increased by 1.9 kg m^{-2} without using additional energy (MTS+ES, 80% target balance).
- Autumn: a greater production of 1.0 kg m^{-2} is achieved at the same T_{av} and same gas use, or 1.5 m^3 m^{-2} less gas is used without production loss (MTS+ES, 90-100% target balance).

This gives an annual gas reduction of 5.25 m^3 m^{-2} or a production increase of 4.4 kg m^{-2}. Following one of those approaches introduces some risks. Computations are characterized by some degree of error, which may cause energy saving at the cost of production, or production increase in combination with increased energy use. A low-risk approach may be to aim for balanced combinations of production increase and energy saving (Fig. 3).

The number of harvested fruits is higher than normal if a low assimilate balance is pursued. Fruits require more days to reach physiological maturity, which is expressed in d°C, if a higher target balance is pursued and T_{av} decreases. This results on a seasonal basis in a lower number of harvested fruits. MTS+ES gives lower temperatures than MTS–ES, and therefore less harvested fruits. The harvest weight of fresh fruits increases with decreasing target balance and with increasing temperatures. The fresh fruit weight can, in comparison with the reference, be increased by pursuing the 100% target balance or lower. The effect of the target balance on fruit size is similar to that on fruit weight. Longer fruits than normal can be realized if pursuing the 95% target balance or lower.

If the limitations of the greenhouse control are not taken into account (MTS–Crop), then the coefficient of variation of fruit weight, fruit length, physiological fruit age reduce. If the limitations of the temperature control are taken into account, then this is only partially true. Then, fruit characters are best stabilized in winter; fruit length and fresh fruit weight especially if a high target balance is pursued. In summer fruit characters are not stabilized, but in autumn a moderate stabilization can be achieved.

DISCUSSION

It has been shown earlier that a light-dependent temperature regulation can save energy (Papenhagen, 1977; Gary, 1989; Buwalda et al., 2003; Ottosen et al., 2005). This study illustrates that an approach based on crop physiology enables further energy saving. As validated crop (Marcelis et al., 1998) and greenhouse simulation (de Zwart, 1996) models were used, the modelling results can be considered reliable estimates.

Most climate controls avoid strong climate fluctuations, while, when taking the crop as a starting point, stabilization of crop physiological processes could lead to wide climate fluctuations without negatively affecting crop production. The assimilate balance is such an important physiological process. It can be disturbed by long-term unbalance between temperature and radiation, as was shown in case of rose (Dieleman and Meinen, 2006). Given strong limitations to influence radiation and assimilate supply, regulation of temperature and assimilate demand offers possibilities to stabilize the assimilate balance. Without taking into account the normal limitations of a climate control system, temperature optimization between 15 and 25°C is sufficient to almost fully stabilize the assimilate balance. Taking into account the limitations of a climate control system, full stabilization of the assimilate demand is not possible; however, the remaining quenching is sufficient to improve production and reduce energy consumption.

The production of fruit vegetables such as cucumber and sweet pepper shows strong fluctuations. Stabilization of fruit load, dry matter distribution to fruits, fruit weight, fruit length and fruit age is important for optimum harvest planning by growers. This study shows that stabilization of the assimilate balance contributes to this. It results in improved dry matter partitioning towards the fruits, as has been shown earlier by Marcelis (1994). As a consequence, this leads to improved fruit dry matter growth.

Stabilization of fruit characters is realized best in winter, to some degree in autumn, but not in summer. This is probably associated with the greatest flexibility that exists in winter in compensating energy shortages and excesses over time, which enables greatest stabilization of the assimilate balance and other related physiological characters.

Stabilization of the assimilate balance also enables lowered temperatures, which, however, also increases fruit dry matter concentration and therewith reduces fruit fresh weight. The consequence is that temperature, fruit dry matter growth, and fruit dry matter percentage have to optimized very carefully. Overall, it was shown that the 90-100% target balance has to be pursued. Higher target balances lead to relatively low temperatures that increase fruit dry matter concentration and reduce fresh havest weight, and lower target balances lead to relatively high temperatures that require too much gas.

Sweet pepper, which is very similar to cucumber with regards to fluctuations in abortion processes and fruit load, is also likely to benefit from stabilization of the assimilate balance. A fruit vegetable such as tomato knows lower fluctuations in fruit load, but will nevertheless know a variable assimilate balance. It appears therefore that stabilization of the assimilate balance may be beneficial to the energy use and production of a wide range of crops. If this is done, energy can be saved in all seasons while maintaining production, or production can be increased without increased energy consumption. If desired, a low-risk compromise can be made. The computed maximum annual energy saving of 13%, or maximum production increase of 5% are considerable. Even if the procedure proves to be less efficient in reality, for example because advised temperatures are not strictly implemented, appreciable progress can be made. Commercial implementation can probably best be achieved in close collaboration with the automation industry.

ACKNOWLEDGEMENTS

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Tables

Table 1. Maximum gas savings or maximum production gains in the winter, summer and autumn seasons for cucumber, in relation to the reference situations. A low-risk approach combines more production with lower gas consumption.

Reference / Aim	Winter	Summer	Autumn	Year
Reference situation				
- gas consumption ($m^3\ m^{-2}$)	22.50	6.51	11.29	40.30
- production (kg m^{-2})	26.87	33.52	22.84	83.23
Less gas ($m^3\ m^{-2}$)	- 2.25	- 1.5	- 1.5	- 5.25
Greater production (kg m^{-2})	+ 1.5	+ 1.9	+ 1.0	+ 4.4
Low risk:				
- less gas ($m^3\ m^{-2}$)	- 1.1	- 0.75	- 0.75	- 2.6
- greater production (kg m^{-2})	+ 0.75	+ 0.95	+ 0.5	+ 2.2

Figures

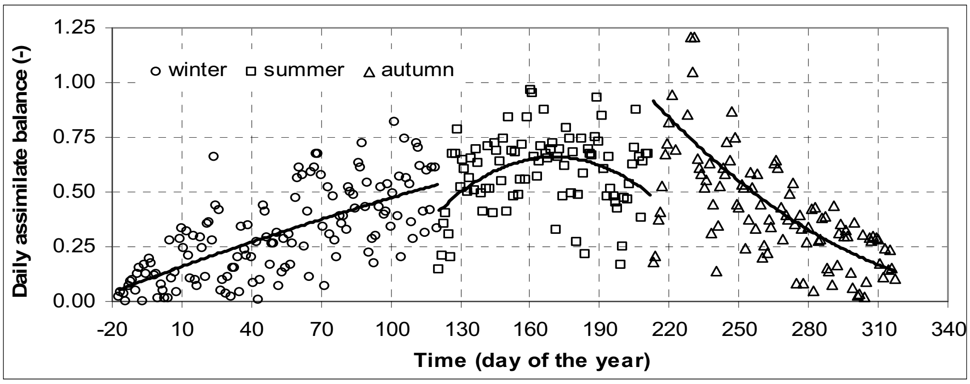

Fig. 1. Daily values of the assimilate balance (open symbols) for a reference winter, summer and autumn crop. The 2^{nd}-degree polynomial descriptions define the 100% target balances for each season.

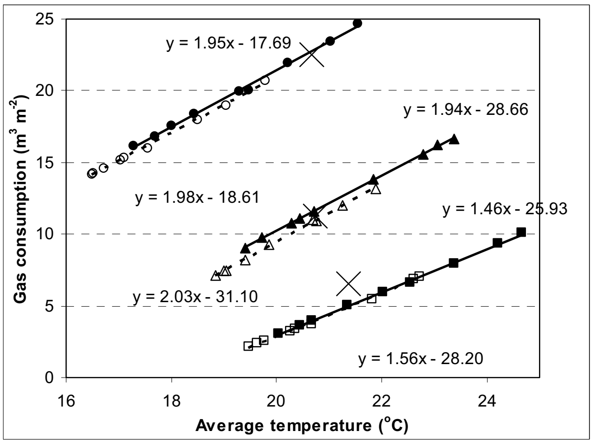

Fig. 2. The relations between average seasonal temperature and seasonal gas consumption, for winter (○,●), summer (□,■) and autumn(Δ,▲); and for MTS with (○,□,Δ) and without energy saving (●,■,▲). The reference crops are indicated by **X**.

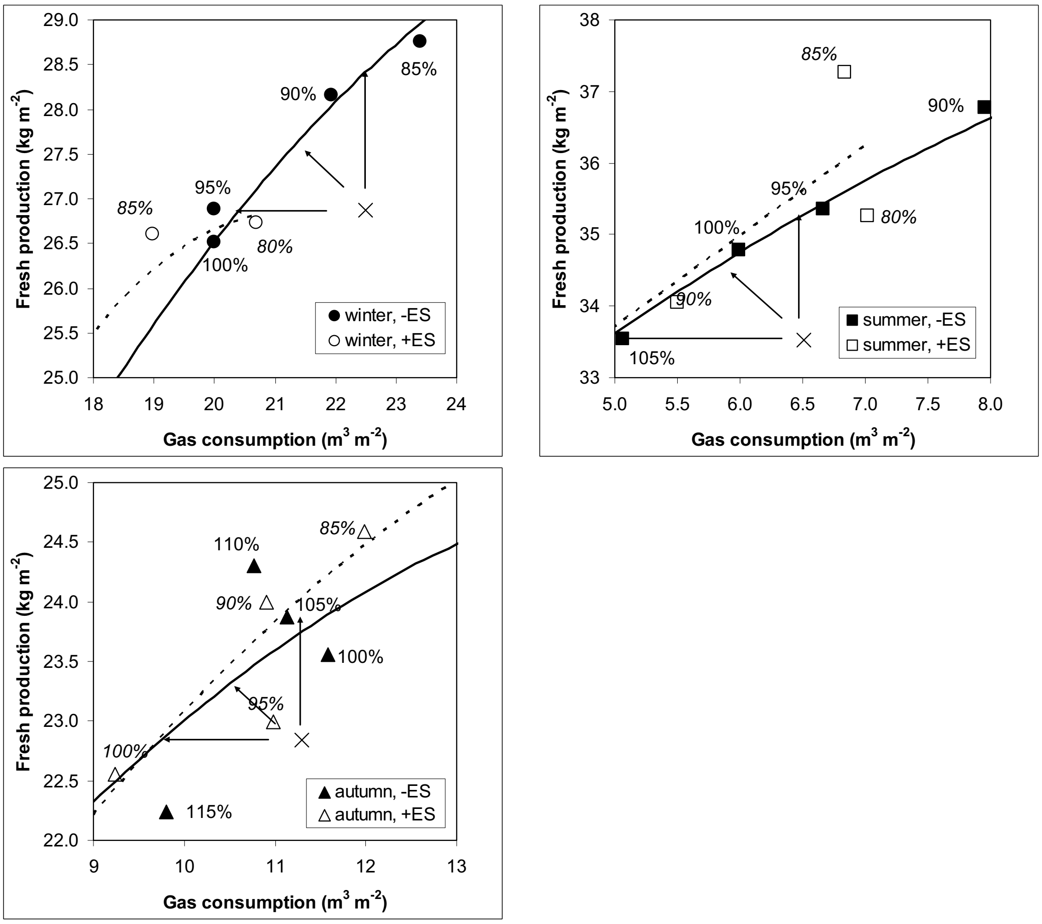

Fig. 3. The relations between gas consumption and fresh production for the three seasons, and for MTS with (+ES) and without (-ES) energy saving. Percentages indicate the target balance that was pursued. Arrows indicate options for maximum energy saving, maximum production increase, or a low-risk combination of the two.