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The effect of reducing the heating set point on the photosynthesis, growth, yield and fruit quality in greenhouse tomato production

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ABSTRACT

Lowering the temperature set point for heating is an important method of reducing energy consumption, and hence carbon dioxide emissions, in greenhouse tomato production. Nonetheless, this measure is rarely applied in Central European and North American greenhouses due to the high value of the product, worries about a decline in yield and quality, and the prices of fossil fuels, which continue to be relatively moderate. Temperature decreases can only be introduced successfully if the constraints of ecological and economic feasibility involved are known. To this end, two experiments were conducted in which tomato plants were cultivated at day and night heating set points of 20/18, 16/14 and 11/9 °C, respectively. In all of the treatments, the set points for opening the ventilation were an air temperature of 27 °C and 80% relative air humidity. Crop photosynthesis appeared to be unaffected by the temperature set point for heating, although the concentrations of leaf soluble sugar and starch increased significantly at low temperatures compared to at high temperatures. The reduction in the temperature set points also appeared to have no impact on the total production of dry matter, the dry matter fraction allocated to the fruit and, thus, the total fruit yield. However, each one Kelvin reduction in temperature resulted in a 3.5-day increase in the time required for fruit to develop and, thus, in a considerable delay of the first harvest. This delay was balanced out by higher yields generated in later harvests. The temperature of the fruit itself rather than that of the complete plant was responsible for this delay. Surprisingly, the reduction in temperature had little effect on the quality of the fruit: the mass of single fruits increased significantly as temperature decreased. However, there was no effect on the fruit reducing sugar content, and only a slight decrease in fruit titratable acid content. From an ecological perspective, carbon dioxide emissions caused by tomato production can be cut considerably by reducing the heating set points without affecting yield and only having a slight effect on the quality of the fruit. From an economic perspective, any loss of profit due to the delay of harvests would have to be balanced out by the savings generating by turning down the heating.

1. Introduction

Lowering the temperature set point for heating is a simple method of reducing energy consumption, and hence carbon dioxide (CO_2) emissions, in greenhouse tomato production. Elings et al. (2005) estimated that a 1 K decrease in the air temperature of a greenhouse would generate heat energy savings of 8% in year-round tomato production. Nonetheless, energy-saving climate strategies are rarely applied in Central European and North American greenhouses. The value of the product on the market is high compared to the prices of (fossil) fuels, which continue to be relatively moderate, and growers are concerned about a potential decline in yield and quality. Temperature decreases can only be introduced successfully if the constraints of ecological and economic feasibility involved are known. Decreasing the capacity of the heating system also significantly reduces the investment costs involved in constructing greenhouses, and enables low-temperature heating systems to be used. The latter are very important for greenhouses that aim to consume only little primary fossil energy. Some such greenhouses capture and store thermal energy during high solar radiation for reuse as heating during dark and cold periods (Wong et al., 2011; Schmidt et al., 2011). Other greenhouses are heated using low-temperature industrial rejected heat (Von Elsner, 2008).

Many reports describe the effects of low temperatures on the growth and development of young tomato plants (see the review by Van der Ploeg and Heuvelink, 2005): Leaf and truss initiation rates decrease linearly with decreasing temperature (De Koning, 1994).

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This delays the start of the harvest considerably. Crop photosynthesis is significantly reduced until the leaf area index reaches an optimal value – around 3 $m^2 m^{-2}$ for tomato (Bertin and Heuvelink, 1993). Reduced crop photosynthesis due to delayed leaf area development results in reduced early and total yield. Since energy costs in the Central European greenhouse industry make up approximately 20% of total costs, it can be concluded that each per cent of loss of returns must be balanced out economically by 5% energy savings (Bot, 2001), which is virtually impossible. For this reason, it makes no sense to drastically reduce heating set points during the leaf area establishment stage. In greenhouses with limited heating capacity, it may even be preferable to improve greenhouse insulation using (transparent) energy-saving screens during the day at the early growth stage (Kläring et al., 2012).

In contrast to the large number of reports on temperature effects in young tomato plants, no studies have investigated the complex effects of low temperature on growth in fruit bearing crops, as well as on the yield and product quality of tomato. Individual processes are often considered in detail. For example, Adams et al. (2001) report a linear relationship between temperature and the rate of progress to ripening with a base temperature of 5.7 °C. Drews and Heißner (1982) demonstrate that low night temperatures result in a marked delay of the harvest which, however, is balanced out later by higher yields. Unfortunately, most experiments on the effect of temperature on crop yield fail to investigate the link between yield and total plant growth (Van der Ploeg and Heuvelink, 2005) and the interaction between temperature and the quality of the fruit (see the review by Dorais et al., 2001).

In the (semi-)closed greenhouse setting, research focuses on the effect of high temperature levels on plant growth and yield (Körner et al., 2009); the aim of increasing photosynthesis by keeping the CO_2 concentration high at high radiation intensities (De Gelder et al., 2012); and the goal to extract and store the greatest amount of heat energy possible for later use (Schmidt et al., 2011). In contrast, many experiments investigate the use of very low temperature ranges below 10 °C, in which plants suffer from physiological disorders (see the review by Venema et al., 2005). However, a decline in temperature to this range must be avoided in tomato production in heated greenhouses. Hence, most of these studies do not include the temperature range of 10–17 °C, nor do they consider large fruit-bearing plants. However, this temperature range and plant development stages are of considerable interest in the search for energy-saving climate strategies in greenhouse tomato production.

To close this gap, two experiments on tomato were conducted to study the effect of heating set points ranging from 9 to 18 °C at night and 11–20 °C during the day on the photosynthesis, respiration and growth of individual plant organs, on the leaf carbohydrate status, yield and taste-related fruit characteristics. The aim of this crop physiological study was to clarify and quantify the advantages and risks involved in greenhouse tomato production at low temperatures in order to cut CO_2 emissions from heating.

2. Material and methods

2.1. Plant material and cultivation

Two tomato (*Solanum lycopersicum* L.) cultivars – the round type 'Pannovy' (Novartis International AG, Basel, Switzerland) and the cherry type 'Supersweet' (Syngenta, Basel, Switzerland) – were grown in the greenhouse at Großbeeren (52° N, 13° E) using the nutrient film technique. Seeds were germinated in gravel, pricked out to rockwool cubes and transplanted in gutters in greenhouse cabins (6.4 m × 10 m) after developing around eight true leaves. Each cabin contained eight gutters, arranged in four double rows with a length of 8 m and a 1% gradient. Each gutter contained 13 plants; the distance between plants was 0.6 m. The distance between the double rows was 1.4 m, resulting in a planting density of 2.4 m^{-2}. The gutters were closed using a black (bottom side) and white (upper side) plastic film to prevent algae growth. The nutrient solution was prepared by mixing rainwater and stock solutions, according to the recipe of De Kreij et al. (1997). The gutters were flushed with the nutrient solution for 20 s every 10 min. The drainage solution was completely reused to supply the plants. The nutrient solution taken up by the plants was replenished. The composition of the nutrient solution was measured in the laboratory at fortnightly intervals and adjusted as necessary. The plants were trained weekly as follows: all side shoots and leaves below trusses with red fruits were removed. Pollination was facilitated by vibrating flowering trusses twice a week. Ripe fruits were also harvested on a twice weekly basis.

2.2. The experiments

Two experiments were carried out. Tomato plants were planted in six greenhouse cabins on 6 January (spring experiment) and 11 August 2011 (autumn experiment) and cultivated at the day and night heating set points of 18/16 °C and the day and night ventilation set point of 27 °C. Once the plants had developed around 20 true leaves, namely on 22 February and 8 September, the day and night heating set points were changed within a period of four days to 20/18, 16/14 and 11/9 °C in two greenhouse cabins each. At this time, leaf area index of both cultivars reached on average 2.1 $m^2 m^{-2}$ in spring and 2.6 $m^2 m^{-2}$ in autumn. Detailed data on plant biomass characteristics at treatment start are given in Table S1. Pure CO_2 was supplied in order to keep the concentration of CO_2 in all cabins at the same level as outside. Ventilation was also triggered when humidity exceeded 80%. The coefficient of transmission for the photosynthetic active radiation (PAR) of the greenhouse cabins was 0.5. The experiments were terminated on 30 May and 19 December 2011, respectively.

2.3. Recording yield and plant biomass characteristics

The yield and mass of the removed leaves were recorded in the course of the experiments. In addition, one plant per cultivar and cabin was completely harvested on 22 February, 6 April and 19 May in the spring experiment, and on 8 September, 20 October and 13 December in the autumn experiment, respectively. The sampling dates corresponded to the start of the treatments; six weeks later when the plants had adapted to the treatments; and towards the end of the experiments. The plants were divided into the following compartments: leaves, stems, fruit and roots. Fresh mass from all plant components and fresh and dry mass from subsamples were measured before and after drying in a ventilated oven for two days at 80 °C (fruit at 105 °C). The dry mass from all plant components, including the harvested fruit and removed leaves, was calculated by multiplying the fresh mass by its dry matter content. The length of all of each plant's leaves was measured; the leaf area was subsequently estimated using an allometric relationship (Schwarz and Kläring, 2001).

Biomass data recorded during and following the treatments was evaluated separately for each cultivar by two-factorial analysis of variance (ANOVA) with the factors 'heating set point' and 'season'. Differences between treatments were evaluated using Fisher's F-test at a significance level of $\alpha = 0.05$. In addition, it is pointed out whenever a three-factorial ANOVA with the third factor being 'cultivar' generated a significant effect of the factor 'heating set point',