Agricultural Water Management 156 (2015) 90–99

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Reducing ventilation requirements in semi-closed greenhouses increases water use efficiency

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ARTICLE INFO

Article history:
Received 1 January 2015
Accepted 8 April 2015
Available online 25 April 2015

Keywords:
Water productivity
Greenhouse cooling
Condensation
Transpiration
Omega coupling factor

ABSTRACT

We explore an under-appreciated side effect of semi-closed greenhouses: the ability to recover transpired water, thereby increasing water use efficiency. Semi-closed greenhouses are fit with cooling equipment, to limit natural ventilation requirements for temperature and humidity control. We assess the effect of cooling system capacity on ventilation needs of semi-closed greenhouses under different climate conditions and provide a general framework to evaluate potential water savings using the semi-closed greenhouse concept in different regions. We simulate greenhouse climate and crop yields for various cooling system capacities in Central Europe (The Netherlands) and Mediterranean (Greece and Algeria) by implementing a "cooling module" into an existing greenhouse model (KASPRO) and validating it using concurrent experimental data. Increasing the capacity of the cooling system has a double effect on water use efficiency (WUE): increase of fruit yield due to improved microclimate and lower water use, due to collection and reuse of vapour condensed in the heat exchanger and, to a lesser extent, lower crop transpiration. Thus WUE is strongly associated to the capacity of the cooling system. Finally, we show that there is a unique relationship between water use efficiency and the coupling of greenhouse environment to the outside air (an indicator of ventilation requirements), for all regions studied.

1. Introduction

During the last decades, engineering and technological developments in the greenhouse industry have focused on decreasing energy and water inputs and increasing yield and quality of greenhouse products. The closed or semi-closed greenhouse concept aims at covering heating, cooling and dehumidification needs of the greenhouse with minimal use of resources (De Gelder et al., 2012). In order to [partly] dispose of natural ventilation for temperature and humidity control, the semi-closed greenhouse must be fit with some cooling and/or dehumidifying system.

The rationale for reducing (at a cost) the need for ventilation has been mainly to lengthen the period when CO_2 enrichment of the greenhouse can be used to increase crop yield (Marcelis et al., 1998). Indeed, Qian et al. (2011) showed that 14 kg m^{-2} CO_2 was enough to maintain a year-round CO_2 concentration of >1000 ppm in a closed greenhouse in a moderate climate whereas, in an open greenhouse, 55 kg m^{-2} CO_2 were required to maintain an average daytime CO_2 concentration of about 600 ppm. All other factors being the same, the increased CO_2 concentration in semi-closed greenhouses resulted in higher rates of crop photosynthesis and yield increase of about 20% or even higher (Opdam et al., 2005; Dannehl et al., 2012, 2014a). In addition to yield increase, Dannehl et al. (2012, 2014a) observed higher primary and secondary plant compounds in tomatoes such as soluble solids and lycopene.

There are additional advantages of semi-closed greenhouses: better control of greenhouse environment; reduced water needs, reduced entry of insects and fungal spores in the greenhouse through the ventilation openings, and thus reduced pesticide use. This paper explores an under-appreciated side effect of semi-closed greenhouses: the ability to recover transpired water, thereby increasing water use efficiency (Dannehl et al., 2014b). This is important in arid and semi-arid regions, where limited water resources constrain the development of sustainable horticulture. This is particularly true for the Mediterranean countries, where most of the current greenhouse area development is taking place (Baeza et al., 2013), in spite of severe water shortages and uncertain future water availability. Zaragoza and Buchholz (2008) have shown the potential of a semi-closed greenhouse for at least a partial recovery of crop evapotranspiration. Stanghellini (2014) has argued that greenhouse production offers the best perspective

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http://dx.doi.org/10.1016/j.agwat.2015.04.003
0378-3774/

to achieve high water use efficiency for fresh food production. She reviewed several reasons why the protected environment of a greenhouse can have a fivefold increase in water use efficiency compared to open field production, and discussed how the ability to re-collect transpired water may yield an additional fivefold gain.

The main challenge to operate a closed/semi-closed greenhouse under subtropical climatic conditions is the large cooling requirement. Therefore there is a need to explore the relationship between the ability to limit greenhouse natural ventilation and the consequent gain in water use efficiency, and how this relationship is affected by the local climate. However, in order to do that, a non-dimensional parameter for the effects of ventilation requirements on greenhouse and crop microclimate in different regions must be defined.

Jarvis (1985) and Jarvis and McNaughton (1986) have expressed the degree of coupling of leaves to the atmosphere in terms of a dimensionless factor, the “omega factor” (Ω), which combines the factors that affect the mobility of heat and vapour between the leaf surface and the atmosphere. These factors are: leaf size and stomatal conductance, plant height and the presence of shelters. The approach can easily be extended to protected crops, as applied by Boulard (1996), Baille et al. (2004), Möller et al. (2004), and Kitta et al. (2014). The degree of coupling has many agronomic implications but, up to now, only limited experimental data on coupling for different conditions have been reported in the literature and little attention has been devoted on the quantification and analysis of the degree of coupling between plant canopy, greenhouse internal atmosphere and the outside climate in greenhouse crops.

Accordingly, the objectives of this work are (i) to study the cooling system capacity effects on ventilation needs in semi-closed greenhouses under different climate conditions and (ii) to provide a general framework for evaluating the potential water savings attained by similar projects in other conditions.

2. Materials and methods

2.1. Modelling approach

2.1.1. KASPRO model description

The greenhouse climate simulation model (KASPRO) is constructed from modules describing the physics of mass and energy transport in the greenhouse enclosure, and a large number of modules that simulate various greenhouse climate controllers. Thus, the model takes full account of mutual dependences between greenhouse characteristics and its climate control. More details of the model can be found in De Zwart (1996) and Luo et al. (2005a,b). The cooling simulation module developed here is described in Appendix I.

2.1.2. Climate control simulation and set points

In all scenario calculations, the heating set point was 14 °C during the night and 19 °C during the day, and the capacity of the heating system was assumed to be sufficient. The cooling system was operated at daytime and its set point was 23 °C. If the cooling system capacity was not enough to cover the cooling requirements, and the greenhouse air temperature reached the ventilation set point (26 °C), the vents were opened. For the simulations without cooling, the windows were opened (disregarding temperature set points) whenever the humidity inside the greenhouse exceeded a set point (95% for night and 90% for day time, 3% opening per 1% relative humidity excess). In order to account explicitly for the ventilation needs due to humidity management alone, we simulated also a greenhouse with a cooling system used solely for dehumidification rather than for temperature control (e.g. Campen et al., 2003). Apparently, as the working principle is to remove vapour by cooling the air below the dew point, such system has a cooling effect. In some conditions this may have resulted in heating to be needed to equilibrate the air temperature reduction due to dehumidification. Obviously, in the scenarios with dual use of the cooling system (temperature and humidity management), no humidity-related ventilation took place. Table 1 summarises the scenarios simulated in the study.

Table 1
Dehumidification and cooling capacities for the scenarios simulated at selected locations.

Case study	Dehumidification	Cooling capacity (W m^{-2})
1	No	0
2	Yes	Not relevant
3	Yes	50
4	Yes	100
5	Yes	150
6	Yes	200
7	Yes	250
8	Yes	300
9	Yes	400
10	Yes	500
11	Yes	600
12	Yes	700

2.1.3. Dry matter and fruit yield

The effect of [non-optimal] climate conditions on crop yield was calculated through the tomato yield model of Vanthoor et al. (2011), which is based on the photosynthesis model of Goudriaan and van Laar (1994). In addition to the effect of temperature on photosynthesis, Vanthoor’s model accounts for the fact that temperature also affects the ability of organs to store and release assimilates, for instance the movement of assimilates out of the leaves and into growing fruit. In Vanthoor’s model the effect of non-optimal temperatures is related to their duration (the “dose”) by having different functions for tomato growth inhibition, for instantaneous and 24 h average non-optimal temperatures: the optimal range (where no inhibition occurs) is wider for instantaneous temperature values than for 24 h mean temperature values. The boundaries of the ‘optimal’ ranges are obviously species-specific. In this work we used the values reported by Vanthoor et al. (2011), which were based on an extensive literature search. In particular, the upper boundary for unhampered instantaneous growth was 28 °C and for the 24 h mean was 22 °C. In view of the purpose of this study we did not let sub-optimal temperatures occur.

2.1.4. Water use efficiency

The year round water used by the greenhouse tomato crop was calculated as the difference between the sum of crop transpiration and of the water accumulated to the biomass, minus the water collected in the dehumidifier, the cooler and the cover by condensation (after accounting for losses due to re-evaporation). The water accumulated into biomass was estimated taking into account a total plant dry matter content of 6.3% (Heuvelink, 1995). Then, the product water use (PWU, $L_{[water]}$ per $kg_{[fresh\ fruit\ yield]}$) was estimated as the ratio of the total water use (L m^{-2} $year^{-1}$) to the accumulated fresh fruit yield (FY_f, kg m^{-2} $year^{-1}$). The tomato crop transpiration and stomatal conductance were simulated by KASPRO as described in De Zwart (1996) and Luo et al. (2005a,b). Since in most greenhouses (and certainly the ones that would be equipped with a cooling system) the soil is covered with a thick plastic mulch for weed and humidity control, we neglected evaporation from the soil.