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Characterisation of a *new greenhouse model*: With and without insect-proof screen

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Abstract

A *natural ventilation greenhouse* is a patented new greenhouse model that maximises natural ventilation and allows stable installation of an anti-insect proof screen. The effects of the presence or absence of an anti-insect proof screen are compared with various parameters of the soil [moisture, pH, electrical conductivity (EC), nitrates], of the greenhouse environment [irradiance, Hargreaves-Samani reference crop evapotranspiration (ETo)] and of the plants [fresh matter, dry matter, leaf area index (LAI)]. The presence of the insect-proof screen reduces the water requirements of tomato. Indeed, soil moisture, delivered water and ETo are significantly lower compared to the greenhouse without an insect-proof screen. An insect-proof screen also reduces the EC and nitrates in the soil, improves LAI, doubles the amount of fresh matter of plant parts and triples the fresh matter of the productive part with respect to a greenhouse without an anti-insect-proof screen.

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Key words: Natural ventilation greenhouse; combined roof and side openings; insect-proof screen; nitrates; reference crop evapotranspiration.

Acknowledgements: this work was carried out within the project Advanced Materials for Research and the Agricultural Sector (M.A.R.eA) - Topic: Coordination of the various technical aspects of the execution of laboratory tests in the growth chamber, in greenhouse and open field, relating to the assessment of preparations suitably mixed with biopolymers, in defence of tomato, peppers and lettuce from pests and nematodes.

Contributions: the authors contributed equally.

Received for publication: 31 January 2017.
Revision received: 6 April 2017.
Accepted for publication: 14 April 2017.

Italian Journal of Agronomy 2018; 13:932
doi:10.4081/ija.2017.932

Introduction

In 2002, the area under protected cultivation in the Mediterranean region was about 400,000 ha (Tognoni, 2004). In Italy (ISTAT, 2010) 31,045 ha were used for protected cultivation, of which 8102 ha in the North (26%), 7046 ha in the Centre (23%), 12,863 ha in the South (41%) and 3032 ha in the Islands (10%). Campania region with its 10,730 ha represents about 35% of the national area, Salerno having 22% of the national are and 64% of Campania's share. Italian and Mediterranean sericulture adopted simple structures, such as tensile structures (Parral and Canary greenhouses) and tunnels covered with one layer of polyethylene. Structures characterised by having poor natural ventilation capacity make it difficult to permanently install anti-insect-proof screens. The only economic forms of air conditioning in order to reduce air temperature appear to be: the summer refurbishment of roofing, to reduce the transmittance of the solar radiation and therefore the internal air temperature; the hydrotunnel technique in winter, to limit the minimum temperature; natural ventilation through side openings (Vox *et al*., 2010; Giacomelli *et al*., 2012). The greenhouse industry has failed to meet the real needs of protected horticulture in the Mediterranean climate because it was unable to offer low costs for the construction and maintenance of greenhouses, and it was not particularly successful in improving ventilation capacity.

Dutch greenhouse manufacturers are world leaders in terms of technology, environmental control, innovation and productivity. By contrast, the initial investment is considerable and energy consumption is very high. Dutch greenhouses are used in Italy exclusively in the flower industry with very high costs and level of specialisation, and are prevalent in Campania, Tuscan and Ligurian floricultural areas. Only a limited number of greenhouses with mechanised roof openings and frontal/side openings equipped with anti-insect-proof screens have been installed, even if they are able to ensure adequate ventilation during summer. This is due to the excessively high initial costs for investment, to the high costs for maintenance of large agricultural areas due to the attention that must be paid to controlling the variable climatic conditions inside the greenhouses (wind direction and adverse weather conditions) and to the difficulties involved in installing the anti-insect proof screens (Mistriotis and Castellano, 2012; Abdel-Ghany *et al*., 2016; Castellano *et al*., 2016).

The efficiency of a greenhouse depends above all on good natural ventilation, due to the combined effect of the gradient of temperature between the inside and the outside (chimney effect) and to the flows of air lapping/investing the greenhouse (wind effect). The conditions that maximise effectiveness are: side and roof openings (the best type of roof opening is one that follows the profile of the structure); the maximised ratio between the total area of the openings and the floor area; the maximised height of the greenhouse. A *Natural ventilation greenhouse* is a new greenhouse model that is able to maximise natural ventilation and allows stable installation of an anti-insect-proof screen. It consists in a tunnel, with an opening following the profile of the structure at the roof, permanently open, that, due to its particular shape, is always closed, even under particularly adverse meteorological events. It is open because at the ridge there is an open area without PE but with an insect-proof screen that allows hot air to exit; it is closed because there is an impluvium with PE that does not allow rain to enter. It is always open thanks to the chimney effect, and then it is static so it does not need any open/close automatism. A *Natural ventilation greenhouse* is always protected by any event caused by the wind and it is always tightly closed thanks to the anti-insect-proof screen. The influence of insect-proof screens on the microclimate of the *Natural ventilation greenhouse* was evaluated, comparing a greenhouse *without an anti-insect proof screen* to another *with an insect-proof screen* (Figure 1). Several parameters of the micro climatic environment were analysed.

Materials and methods

The *Natural ventilation model*, installed at the CREA-OF of Pontecagnano, consists of two greenhouses of 144 m^2 connected by a corridor. They were covered with plastic film and the orientation of the greenhouses was 120° to southeast and 300 degrees to northwest. One greenhouse, also called the *closed greenhouse,* was closed with an anti-aphid-proof screen (with 46% porosity) while the other, also called the *open greenhouse,* was closed with a bumblebee- anti-dispersion-proof screen (with 100% porosity). In 2015, Asgrow tomato Genio F1 was cultivated in both greenhouses. The transplant took place on 23/06/2015 in double rows with an investment of 3 plants m^{-2} of the soil mulched with black plastic film and irrigated with drop system. The tomato was bred according to the ordinary method of the area. The climatic parameters recorded were external air temperature, external relative humidity, wind velocity, wind direction and solar radiation. They were recorded by a climate control unit of the agro meteorological national service placed *in situ* and managed by technicians of CREA-CMA-Rome. Three tensiometers were installed in each greenhouse, at a depth of 0.2 m, to monitor the soil moisture in order to adjust the start and end of irrigation.

During the experimental test, the following parameters were monitored: i) for the soil: moisture, pH, electrical conductivity (EC) and nitrates; ii) for the greenhouse environment: irradiance and evapotranspiration (ETo); iii) for the plants: fresh matter, dry matter and leaf area index (LAI).

The moisture monitoring, pH, EC and soil nitrate were measured twice a week. At each sampling, eight samples of soil were taken, four per greenhouse, two for each two-row furrow: the four samples of soil were taken with a random distribution on bines.

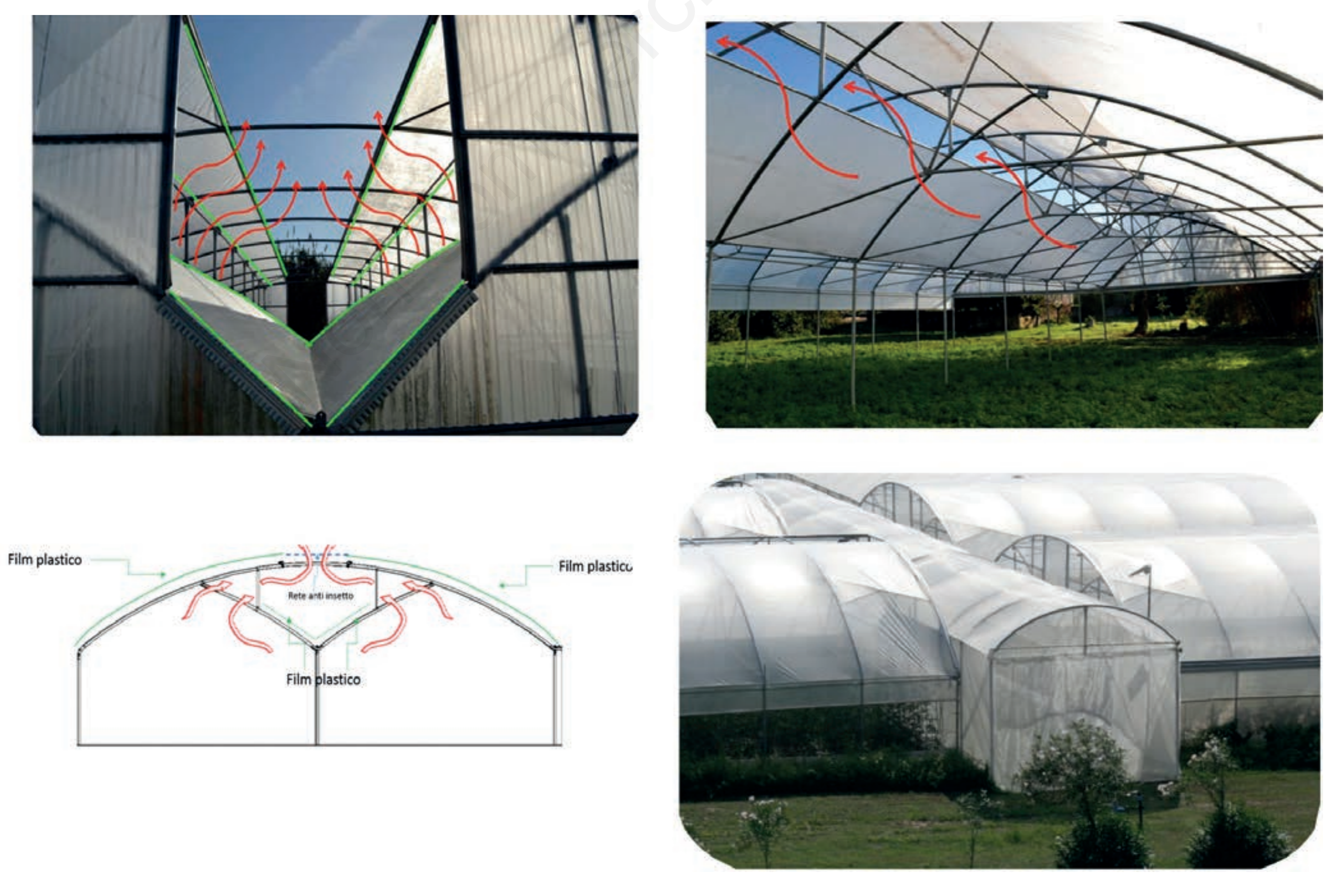

Figure 1. New greenhouse model with natural ventilation.

The moisture level achieved in the soil was monitored gravimetrically at 378.15 K and expressed in % of weight; thirty samples were taken on a weekly basis, starting on 23rd June 2015 till 12th October 2015. A dilution of 1:5 (soil: water) was used for pH determinations and EC. The pH and the electrical conductivity were measured with a portable meter (HI 9811-5 Hanna Instruments). The conductivity measured in μS cm^{-1} was transformed into dS m^{-1} related to 1 gram of dry soil (Ayers and Westcot, 1985; Sequi, 2007; Barbieri, 2014; De Pascale, 2014). Nitrates were monitored with a ultraviolet wave (UV)-Vis spectrophotometer (DU 64 Beckman Coulter S.r.l.) in the wavelength of the UV; nitrates were expressed as ppm (Edwards *et al*., 2001; Merafina, 2003; Nemade *et al*., 2014). The air temperature and relative humidity were recorded by three pairs of sensors in each greenhouse, placed at heights of 0.05 m, 2 m and 3.5 m corresponding, respectively to the ground, the plant and the impluvium level; these measurements were recorded every 30 min and were stored in a data logger (Wi-Fi model NEWSTEO P.F.P.N).

A pyranometer was installed at a height of 2.5 m to measure the solar radiation in Wm^{-2} (Hukseflux Thermal Sensors LP02-20). The measurements were recorded every 15 min and were stored in a control unit (Campbell Scientific). Evaporimetric requirements of the two greenhouses (ETo in mm per day^{-1}; Allen *et al.*, 2006) were estimated by Hargreaves-Samani formula (1985) (Bianchi, 2003, 2009; Megale, 2009), using the radiation and temperature values measured in the greenhouses.

To observe the physiological state of the plants, two of them were sampled at three different stages: flowering of the first branches, on 7th July; enlargement of the tomato fruits at I, II, III and IV branches, on 6th August; flowering of the fifth branches, on 29th September. The fresh and dry weights were determined on different fractions and expressed in kilograms; LAI per plant was measured in cm^2 and expressed in m^2m^{-2}. The statistical analysis was carried out with R version 3.2.2 (2015-0814) Copyright 2015 The Foundation for Statistical Computing (R, 2015); the Student t test for normal variables and the Wilcoxon test for non-parametric variables were used, to a level of significance of 5%.

Results

Soil moisture was consistently lower in the *open greenhouse* with a media of 29.55%, compared to the mean value of soil humidity recorded in the *closed greenhouse* that was 32.93% (Figure 2), although the water supplied in the open greenhouse was consistently higher (Figure 3) throughout the cultivation period (23rd June - 12th October).

The total amount of water supplied was 112.75 and 105 m^3, respectively in the open and closed greenhouses.

The pH values were sub-alkaline and lower in the *open greenhouse*, 7.66 on average, compared to those recorded in the closed greenhouse, 7.75 on average (Figure 4), with a significant P value, 0.001191, by t test.

The average electrical conductivity value was 3.06 dS m^{-1} in the greenhouse *without insect-proof screen* with maximum values of 8.46 and 7.81 dS m^{-1}, while in the greenhouse *with insect-proof screen* electrical conductivity was 1.96 dS m^{-1} with maximum values of 3.46-3.25 dS m^{-1} (Figure 5). The statistical comparisons were not significant, when assessed with the Wilcoxon test.

The higher number of fertirrigations, due to the greater water demands, increased the concentration of nitrates in the open greenhouse, reaching peaks of 1742-1715 ppm, while in the

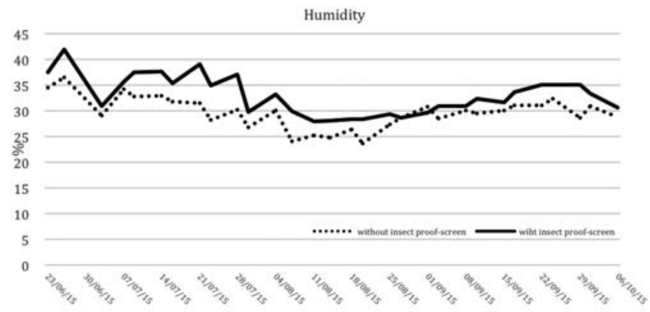

Figure 2. Measurement of moisture trends recorded in two cases.

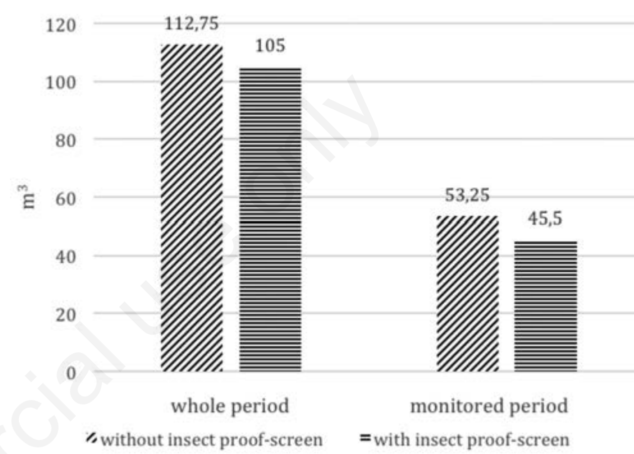

Figure 3. Different volumes supplied during two periods (from 29/6 to 12/10 and 11/8 to 12/10) in both greenhouses.

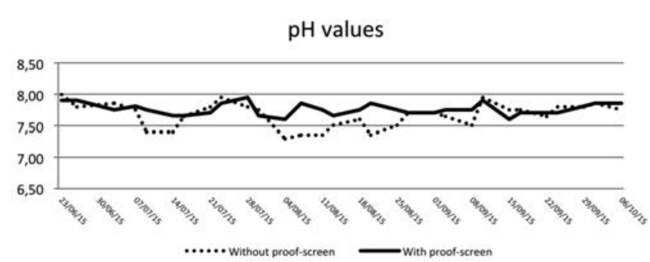

Figure 4. Measurement of pH trends.

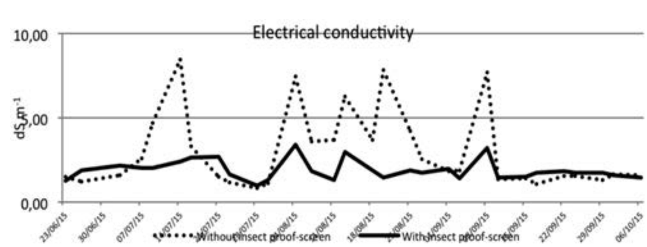

Figure 5. Measurement of electrical conductivity trends.

greenhouse with the insect-proof screen the values did not exceed 564.79-449.26 ppm (Figure 6).

The ordinary method of irrigation in this area of Italy always consists of fertilisation, so the plants are unable to absorb this huge amount of nitrates administered that is accumulated in the soil with a consequent increase of the conductivity recorded. The high conductivity in turn creates an inhospitable environment for the root systems and for the absorption of nutrients. A negative fact to consider is that being in an environment protected from rain makes it difficult to naturally dispose of the accumulation of nitrates over time. The average nitrate concentrations were 612.06 and 206.81 ppm, respectively, in the open greenhouse and the closed one. The statistical comparisons with the Wilcoxon test were significant (P=0.013).

In terms of total wet weight, the entire plant produced 1240 kg and 2152 kg, in the greenhouse without insect-proof screen and in the greenhouse with insect-proof screen, respectively, and this difference was also recorded in their fractions of leaves (300.44 *vs* 359.46 $\times 10^{-3}$ kg), stems (395 *vs* 409.75 $\times 10^{-3}$ kg), fruits (461 *vs* 1284.50 $\times 10^{-3}$ kg) and roots (84.25 *vs* 98.50 $\times 10^{-3}$ kg) because higher values were recorded in the greenhouse with the insect-proof screen (Figure 7). Fresh matter has an average of 275.58 $\times 10^{-3}$ kg than the 403.12 $\times 10^{-3}$ kg.

In the greenhouse *with insect-proof screen,* the amount of dry substance showed lower values for all components of the plant, with an average of 15.89% (compared to 16.70%); only the root showed greater dry weight of 3, 34 $\times 10^{-3}$ kg, compared to the plants grown in the greenhouse without screen. The comparison with the Wilcoxon test does not, however, show significance (Figure 8). LAI reached values of 1.33 and 2.29 m^2m^{-2}, respectively, in the greenhouse without and in the one with insect-proof screen, at the time of ripening of the fifth branches, which corresponds to the third sampling in the graph (Figure 9). The comparison with the t test is statistically significant (P=0.0051). The Harvest Indexes recorded were 0.37 in the open greenhouse and 0.60, nearly double, in the closed greenhouse (Figure 10). All the observed differences are confirmed by the fact that the evaporative demand calculated (ETo) with the Hargreaves-Samani formula is higher in the open greenhouse in all the three months considered. In any case, the ETo values decreased from August to October, as clearly shown by the histogram of the mean daily values (Figure 11). Having a low porosity, the closed greenhouse tends to keep the environment and consequently also the soil more humid; the increased moisture tends to reduce the evaporimetric requirement of the environment, thus saving irrigation water and in the routine method also saving fertilisers. Figure 12 shows the different ETo in August at ground, plant and impluvium levels in the greenhouses. The differences between the greenhouse *without* and the greenhouse *with insect-proof screen* amounted to a mean of 24.57 (112.59-88.02) mm per m^2 in the period monitored. Figure 13 clearly shows the three groups of ETo curves according to the Hargreaves-Samani formula: the uppermost one is that of the external environment, meaning that of the open greenhouse, and the smallest one that of the closed greenhouse. The evapotranspiration of the greenhouse without insect-proof screen was 112.59, and 88.02 mm in the greenhouse with the insect-proof screen during the monitored period. These estimated values expressed in the same units of measurement (m^3) in the same period correspond to 25% of amounts actually administered following the indications of the lysimeters. This discrepancy is probably due to the coefficient of the formula, Hargreaves-Samani, unsuitable for the environment present inside the greenhouse. The estimate of daily evaporation with this formula is very simple because just a few climatic parameters can determine

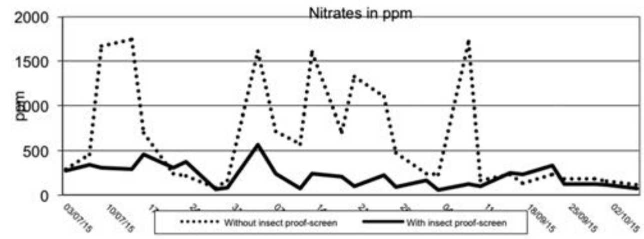

Figure 6. Measurement of nitrate trends.

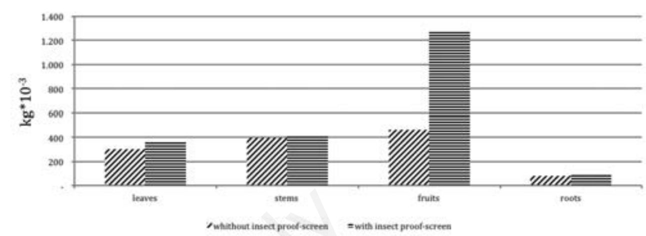

Figure 7. The mean values of the fresh weight of the different parts of the plant.

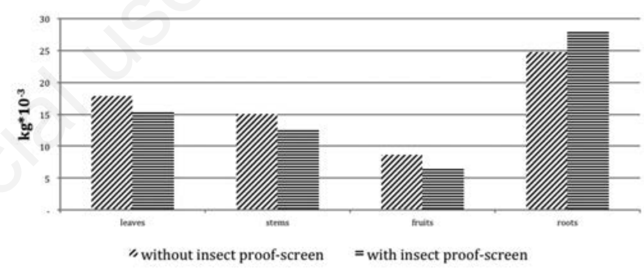

Figure 8. The mean values of the dry weight of the different parts of the plants.

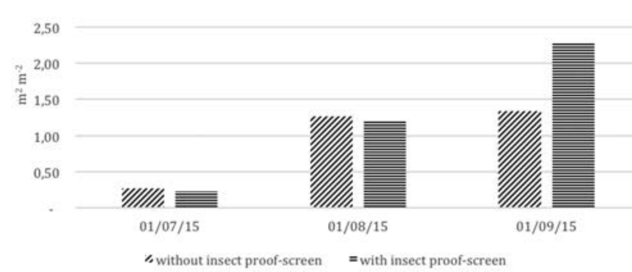

Figure 9. The mean values of leaf area index in different plant phenological stages.

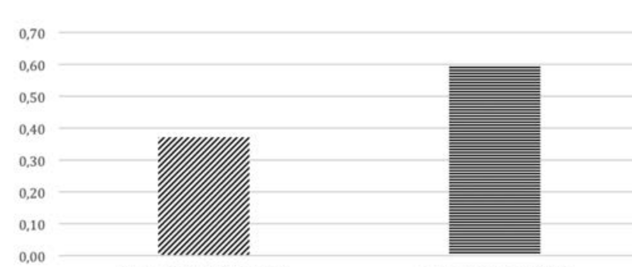

Figure 10. Harvest index in two greenhouses.

it. Unfortunately, however, this formula has a weak point, which is the calibration of the constant C in an open environment with respect to a protected environment. It was therefore necessary to typify this coefficient for each zone, thus providing the simple tools that directly measured the evaporation in order to precisely estimate the constant C in our microclimate.

Figure 14 shows the difference of radiation expressed in mm between the internal environment of the greenhouses *with* and *without* insect-proof screen and the external environment. Figure 15 shows the percentage of radiation detected inside and outside the two greenhouses. On average, these percentages are equal to 66.08% and 52.12% of those recorded in the external radiation respectively, in the open and in the closed greenhouse. The differences in the two greenhouses are positive because the comparison showed that the simple addition of the insect screen determines the saving of some factors very important for production, such as water and nitrates, and an increase in production (fruit tripled), raising costs to a limited extent compared to the benefits obtained. A polyethylene covering film reduces the transmittance of solar radiation, lowering the indoor air temperature and improving the greenhouse environment. This reduction, combined with considerable aeration at the top of the new model of greenhouse (due to *chimney effect*) and the subsequent drawing in of outside air, does not permit heat to accumulate in the upper part of the greenhouse. This condition determines a more comfortable environment for the development of the plant, above all for the temperature. The combination of the aphid-proof screen and low porosity in this greenhouse model further reduces the transmission of solar radiation, due to the coverage of the side walls, while the presence of the insect-proof screen maintains a higher level of humidity inside the greenhouse, contributing to lower the temperature and on the other hand to reduce the water demand. The screen and chimney effects on microclimate are very important in Mediterranean countries, especially because they reduce water demand and high temperatures; this last parameter always exceeds the optimal thresholds during the summer season, preventing good plant growth.

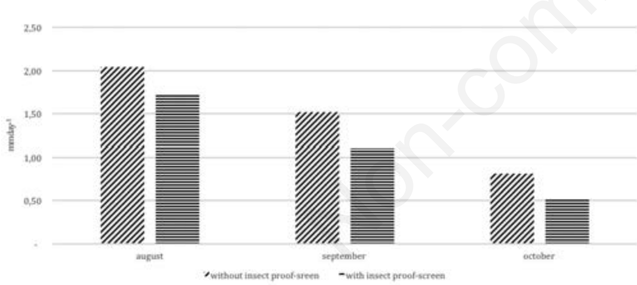

Figure 11. Mean of evapotranspiration in different months.

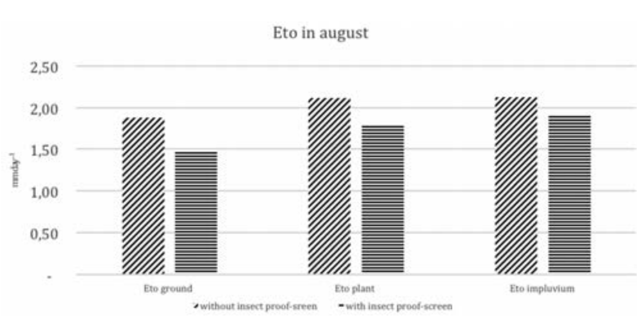

Figure 12. Mean of evapotranspiration at different heights in the greenhouses.

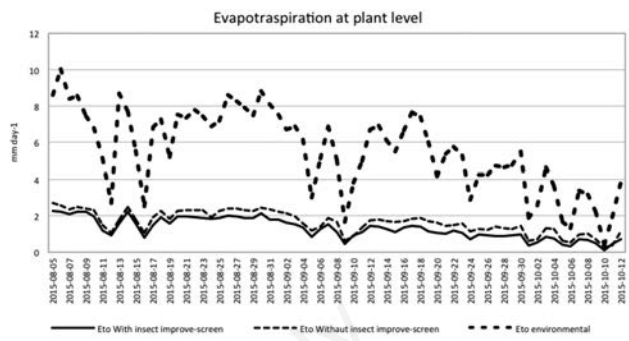

Figure 13. Evapotranspiration in greenhouses and environment.

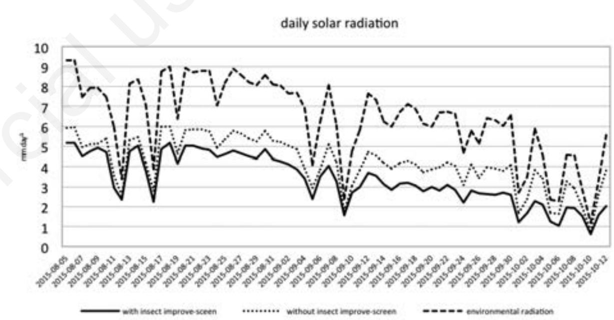

Figure 14. Difference between internal and external radiation.

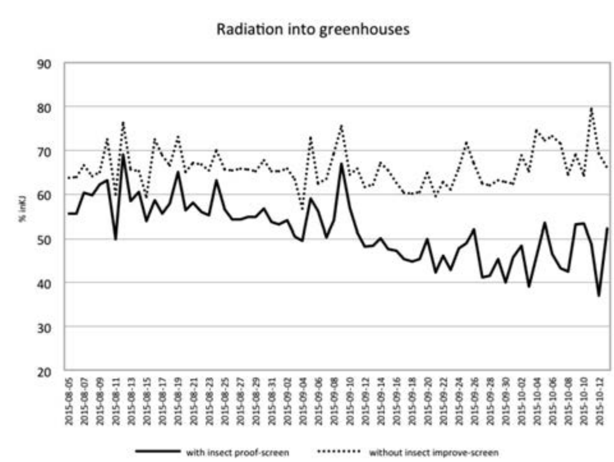

Figure 15. Difference in transmitted radiation between external and internal environment in the different greenhouses.

Discussion

The soil moisture, the water supplied and the evapotranspiration differences between the greenhouses showed that adding an insect-proof screen reduced crop water needs in our environment. There is a close relationship between soil, vegetation and environmental characteristics (Martinez-Fernandez *et al*., 1995). Some authors say that all greenhouse parameters require a detailed analysis in order to choose the correct method for application of precision farming (Bailey, 1994; Bailey *et al*., 1994; Boulard *et al*., 1994; Sato *et al*., 2000; Chaudhary *et al*., 2011). Blackmore *et al*. (1994) explained that the system could be designed to increase the quality agricultural yield by properly monitoring soil and environment.

Soil moisture was constantly higher in the greenhouse *with insect-proof screen,* thus the quantity of delivered water was lower. The reduction of water demand in the closed greenhouse had positive repercussions on the various parameters studied.

The measured values of conductivity were moderate in the greenhouse with insect-proof screen because they are contained within the threshold of 4 dS m^{-1} (De Pascale, 2014) while without the insect-proof screen these values exceeded the threshold.

In the greenhouse with screen, the concentration of nitrates was always lower, the total fresh weight per single plant was double and the fresh weight of the fruit was three times higher (Figure 6).

The amount of dry substance in the greenhouse *with screen* showed lower values for all components of the plant except for the root. This new greenhouse model thus developed a tender, more productive plant, with a more consistent and robust root, probably because it was protected from thermal and environmental humidity changes during summer. The LAI index reached almost double value in the greenhouse with a screen compared to the open greenhouse, so the greenhouse with a screen produced larger and more developed plants while the other one produced smaller and woody plants. In conclusion, the *Natural ventilation greenhouse* has the advantages of saving energy and reducing expense (Shu-zhen Liu *et al*., 2005), and the ventilation performance is most effective because vent configuration was the combination of roof and side vents (Kittas *et al*., 2005).

The introduction of the chimney effect in the new greenhouse model with the addition of insect screens with low porosity is able to modify the microclimatic parameters of the greenhouse, which in turn improved the morphological parameters of the plants in our Campanian climate representative of a Mediterranean environment.

Conclusions

The greenhouse with a screen to reduce about 66% radiation improves the plant growth conditions. It is in fact reported that the limitations due to climatic conditions in Mediterranean areas are the high temperatures associated with higher solar radiation during summer, which inhibits cellular metabolism and growth (Aldrich, 1983; De Pascale and Stanghellini, 2011), reduces net photosynthesis, and increases night respiration and stomatal conductance in tomato (Sato *et al*., 2000).

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