Resource Use Efficiency in Protected Cultivation: Towards the Greenhouse with Zero Emissions

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Abstract

Protected cultivations are expanding all over the world, particularly in otherwise marginal agricultural land. However, protected cultivation involves the intensive use of resources such as soil, water, fertilizers, pesticides and energy. As a consequence, such intensive production systems are perceived by many as artificial and highly pollutant processes. Protected cultivation, and more particularly greenhouse production, has to be – and to be seen – more respectful of the environment. The greenhouse of the future will have nearly zero environmental impact. This goal can be achieved by developing a sustainable greenhouse system that: does not need any fossil energy and minimizes carbon footprint of equipment; with no waste of water nor emission of fertilizers and full recycling of the substrate; with minimal need of plant protective chemicals, yet with high productivity and resource use efficiency. An environmental and economic study of the current situation is a tool to identify the most critical elements of the production process, in various climatic and market conditions, so that suitable technologies may be developed to address the locally relevant bottlenecks. The greenhouse of the future can fulfil the need for safe use of resources (energy, water, pesticides) through modification of greenhouse design and management. Coatings and additives can be used to improve the performance of greenhouse covers in terms of light transmission vs. thermal insulation. More efficient greenhouse ventilation is expected to have a positive effect on the cutback of inputs as well. The greenhouse can benefit from the reduction of waste through better management of irrigation and climate. This article will discuss the current expectations and limitations on resource use efficiency in protected cultivation.

INTRODUCTION

Protected cultivations are expanding in many part of the world, particularly in otherwise marginal agricultural land. Thanks to protected cultivation we are eating high-quality and healthy vegetables and enjoying beautiful ornamentals year-round, all at an affordable price. Protected cultivation is contributing to the economic development of formerly marginal agricultural land around the shores of the Mediterranean and farther. This is explained by the high productivity and high efficiency of use of most resources (particularly water). Nevertheless, there are drawbacks to such an intensive agriculture: for instance, the high spatial intensity of application of water, fertilizers and pesticides results in emissions. N-leaching, for instance, can be some 2 g NO_3 per kg tomato, and even un-heated greenhouse production has a Global Warming Potential equivalent to 240 g CO_2 per kg tomato (Euphoros Consortium, 2010a). In addition, off-season production and production outside the natural habitat of a crop requires application of fossil fuels, with hugely increased CO_2 emissions as a consequence.

Eleven institutions from seven European countries are cooperating in a project to decrease the need for resources in protected cultivation, while improving – or at least maintaining–the financial balance sheet. Resource use efficiency can be increased in three ways:

- reduction of the *need* for resources, mainly through smart greenhouse design (such as development of new insulating and highly transparent cover materials; optimal utilisation of sun energy through efficient energy storage; reduction of the impact of pests and diseases through the spectral properties of the cover);

- reduction of *waste* through improved management of the production processes (irrigation, fertilisation and substrates; decision support for management of ventilation, heating and carbon dioxide supply; automatic detection of dysfunctions);
- increased *productivity* through early detection of stress (biotic/abiotic) and response management.

As the list above shows, there are several means to reduce resource use along each "way". Therefore three evaluation criteria were adopted: 1. *Environment*: scope for decrease of environmental impact; 2. *Appeal*: potential for reduction of costs and 3. *Efficacy*: likely reduction of inputs. The highest potential of achieving the objective of the project is with the "means" that score high on all three counts.

Joining a Life Cycle Analysis, (evaluation of Criterion 1) and an economic model (evaluation of Criterion 2) reveals the most promising means to decrease reliance on resources. However, since the use of resources; the components of the production costs and the production processes are different in the various climatic and economic regions of Europe, the evaluation was carried out for selected combinations of crops, regions and greenhouse type (1. tomato in multi-tunnel in Spain, tomato in Venlo-type greenhouse in 2. Hungary and 3. The Netherlands and 4. roses in a Venlo greenhouses in The Netherlands). The results (EUPHOROS consortium, 2010a) are also reported by Torrellas et al. (2010). A summary is given in Table 1. Besides obvious aspects that were general to all cases (increasing productivity of a given structure is also beneficial to the environment; a lighter structure could also trim down a significant cost component, as would reduction of energy use by Dutch growers) some more unexpected candidates for input reduction appeared. For instance, Hungarian growers could gain a lot by reducing use of fertilizers (some 15% of their production costs). Fertilisers are a significant cost component in Spain as well, and substrates have a significant environmental impact in all cases.

In the following we will give a short review of our knowledge so far with respect to smart greenhouse design and improved management of the production process.

LESS NEED FOR RESOURCES: SMART DESIGN

Innovative Greenhouse Covers

Innovative (spectral selective) cover materials have the potential of reducing pest pressure (plastics), energy saving (glass) and improving summer growing conditions (plastic and glass), although unfortunately very often the requirements of a high PAR (Photosynthetically Active Radiation) transmittance, spectral selectivity and high thermal insulation are conflicting.

The environmental and economic potential of combinations of NIR-blocking (NearInfraRed) plastic additives and of glass coatings was evaluated through a dynamic greenhouse climate and production simulator (Kempkes et al., 2012). The results are disappointing about the potential for NIR-filters in the greenhouse cover material. A filter can work two ways: reflecting or absorbing. Evolution has already endowed leaves with a high (~50%) NIR-reflectance, so that NIR-reflection will lead to multiple reflection between crop and cover and a fraction of crop reflection will not escape the greenhouse. Therefore only NIR-filters with very high reflectance will have some consequence. On the other hand, NIR-absorption will warm up the cover, so that a fraction of the withheld energy will end up in the greenhouse at longer wavelengths and through convection. In addition, as the contribution of NIR to heating the greenhouse may be welcome often enough, a permanent NIR filter may backfire, in terms of either a worse winter climate or higher energy requirement in un-heated and heated greenhouses, respectively.

For the latter, high light transmissivity coupled to high insulation are the conflicting requirements. Modern anti-reflection (AR) coatings allow for panes of double glass to have the total transmittance of a single standard pane. The obvious potential for energy saving can even be increased by a low-emission coating.

Light diffusion has been proven to increase photosynthetic efficiency of crops. Dueck et al. (2009) have shown that the productivity of cucumber in The Netherlands could be increased by 9.2% by a highly diffusive cover (haze 70%), in spite of an overall reduction in transmission of 3%. Recent developments (such as AR coatings on diffusing panes) are able to reduce the [inevitable] light loss caused by diffusion to almost nothing. In regions where the fraction of direct radiation in a year is larger than the 30% typical of the Netherlands, the potential for increasing productivity through diffusing cover materials must be even larger.

Ventilation Design (Ventilation Capacity)

The ventilation capacity must be enough to allow for control of greenhouse temperature in the worst possible conditions. Research up to now has focused on natural ventilation rate (mainly as affected by wind speed) of various types of greenhouse and type/position of openings. Recent studies about the effect of ventilator configuration on the climate of greenhouses have been reviewed by Bournet and Boulard (2010). They pointed out the importance of combining side and roof ventilation, in spite of the fact that the ventilation rate strongly decreases as the number of spans increases. Other studies have shown that by reducing the greenhouse width the ventilation rate and climate homogeneity are increased, particularly under low wind conditions (Baeza et al., 2009).

CFD simulations have strongly helped to design more efficient ventilation systems. They have proved that increasing the ventilator size and the roof slope has a positive effect on the ventilation rate (Baeza, 2007). In some ventilation systems there is the risk that the incoming air may exit the greenhouse through the next roof ventilators without mixing with the air in the crop area. To avoid this problem, the use of screens or deflectors to re-direct the air stream has been recommended (Montero et al, 2001; Nielsen, 2002). The results of ventilation studies have substantially helped to improve ventilation efficiency. Some of this knowledge has been put into practise through the design and evaluation of new greenhouse structures that, compared to less ventilated greenhouses, have been able to reach much higher yields with minimum input increase. (Baeza et al., 2010).

Greenhouses, however, seldom are isolated, so that the real ventilation rate of a greenhouse within a cluster is usually [much] lower that what could be estimated on the basis of the findings listed above. Indeed, the air flow pattern in and around single greenhouses is different to that of a greenhouse group. For this case the external wind flows over the greenhouse on the windward side; the air flow accelerates over the first two spans and separates from the greenhouse roof. The second and successive greenhouses are “shadowed” by the first one since they are under an area of low external wind speed. CFD simulations show that there is a clear effect of the windward greenhouse on the ventilation rate and temperature of the successive greenhouses.

Table 2 shows the effect of the size and distance of a windward obstruction on the ventilation rate of a greenhouse. Percentages shown in Table 2 are referred to a similar greenhouse without a windward obstruction. For the greenhouse with no side ventilation, the obstruction strongly reduced the ventilation rate; for instance, the 120 m long obstruction reduced the greenhouse ventilation rate to only 13% of that the same greenhouse without obstruction. Side ventilators considerably helped to increase the ventilation rate. With side ventilation, if the distance between the obstruction and the greenhouse were 24 m, the negative effect of the obstruction would be eliminated. But keeping such a long distance between greenhouses is not economical; therefore some other solutions have to be found.

This is shown in Figure 1. Top is the map of temperature of a 100 m wide greenhouse with a windward obstruction: the obstruction can change the internal air flow pattern producing hot spots and lack of homogeneity. Bottom is a group of four 50 m wide greenhouses, separated 8 m each other. Compared to the previous case, better climate uniformity can be observed since the main hot spots are eliminated. The subject of natural ventilation for a greenhouse cluster is still under investigation. Nevertheless a number of actions such as increasing the vents area by reducing the span width, using side ventilation combined with roof ventilation, limiting the greenhouse width, etc. can help to have good climate conditions in the cluster.

REDUCING WASTE: PROCESS MANAGEMENT

Control of Ventilation

Once the "optimal" cover and ventilation capacity have been selected, a very fine management of the ventilation may ensure the best possible climate for the crop and the most efficient use of resources. This point is made clear in Figure 2 that quantifies the temperature range between a fully ventilated and a non-ventilated greenhouse. Fine tuning of the ventilator openings (roof flaps in this particular case), would allow for any temperature within this range to be attained at any time. Limiting the ventilation to the minimum required for control of temperature would have the advantage of "trapping" more sun energy in the greenhouse (particularly the soil) during the day, allowing for higher night-temperatures. Indeed, the large difference in temperature at night between the two unheated greenhouses can only be explained by the fact that the [larger amount of] energy released by the soil at night remained within the non-ventilated house. In spite of this, a recent survey of the technical level of greenhouses in the region of Almeria (Cuadrado Gomez, 2009) demonstrated that only 1% of the greenhouses were fitted with automated openings and, which is worse, only some 3% of the growers were planning to install them. An additional advantage of reduced ventilation is the increased possibility of efficient injection of [waste] carbon dioxide in the greenhouse, which would increase productivity of Mediterranean greenhouses.

The main limit to reducing significantly ventilation is the need for controlling humidity. Montero (2010) has proposed that a higher slope (45%) of the greenhouse roof could reduce humidity (by increasing the surface where condensation may take place). With plastic covers this would have the additional advantage that condensed water would slide down (and could be recovered) rather than dripping on the crop and create an ideal environment for moulds. Alternative means for controlling humidity by more energy-efficient ways than natural ventilation have been investigated and reviewed by Campen (2009).

Energy Storage

The greenhouse soil is in itself a store of heat energy. In unheated greenhouses the heat transfer from the soil surface to the greenhouse air is the major source of energy during the night (see the example in Fig. 2), while for heated greenhouses the heat delivery from the soil leads to a non-negligible reduction of the heat demand. The capacity of the soil to store and release energy depends on the soil properties and the type of mulching. Experimental measurements have shown that during the daytime the average temperature in the first 10 cm of the soil with sand mulching was 4°C higher than in the bare soil (Granados et al., 2012). However minor differences were found on the night time air temperature of greenhouses with sand mulching and bare soil respectively. Double walls and thermal screens are effective means to increase air temperature in unheated greenhouses (Montero et al., 2005) but both systems have shortcomings that prevent their implementation.

Ventilation could even be reduced (and efficiency of use of sun energy increased) further by application of active thermal storage, on top of the passive storage that happens naturally in the greenhouse soil. In Almeria (Southern Spain) a novel closed circuit system to collect warm water when cooling the greenhouse and vice versa is being studied (Baeza et al., 2012). The system is based on high-efficiency fine-wire heat exchangers and a water tank that stores energy, the storage efficiency being enhanced by thermal stratification. According to Figure 3, during the night the system used the heat from the storage tank and kept the greenhouse temperature at 12°C, which was about 3ºC more than the outside air. The adjacent ventilated compartment maintained a temperature almost equal to the outside temperature. During the day the cooling mode was active in the closed greenhouse and the temperature was kept below 25°C (very similar temperature to that of the ventilated compartment). After the sunset, the heating mode was active again making use of the energy accumulated during the day.

The limit to this method of storage (without the application of a heat pump) is the relatively large volume of water required per unit soil surface, as soon as storage is needed to bridge a period of bad weather, as demonstrated through a desk study by Kalaitzoglu et al. (2012) for the Mediterranean region. In summary: active thermal storage would strongly contribute to reducing ventilation significantly (and economically) in the temperate zones and would increase the efficiency of use of sun radiation. However: low-temperature storage requires a [very] large volume and/or a very efficient heat transfer. High-temperature storage requires concentration of energy (heat pump) and has low efficiency. Phase change materials have to prove their worth.

Management of Irrigation and Fertilization

In terms of the environmental impact, fertilizers represent an important burden in a number of impact indicators such as Global Warming and Eutrophication. This impact is not only due to the use of fertilisers itself but to the amount of energy, materials and transport processes involved in the production of fertilisers. For some European countries studied in the EUPHOROS project, the quantity of fertiliser applied is visibly high. It is perfectly possible to reduce current doses by developing better fertilization programmes and, for soilless cultivation systems, by changing from an open-loop irrigation system to a closed-loop recirculation system

Smart irrigation is possible, both in ground (Table 3) and in substrate (Table 4) and yields significant saving of water and fertilizers (and emissions). Fertilisers costs exceed 10% of production costs in Almeria or some 15% in Hungary (Fundacion Cajamar, 2009; Euphoros consortium, 2010a). Yet growers are not exactly eager to adopt smart irrigation (Cuadrado Gomez, 2001; Incrocci et al., 2012). In some countries there is a lack of adequate technical assistance to the management of both fertigation and climate control. Growers are also concerned with the risk of failure when soilless growing systems are installed in protection structures with poor climate control. In some other cases the small size of greenhouse operations does not allow the financial investments required for updating existing structure or for building up new greenhouses. Finally some growers are still afraid of the occurrence of root-borne diseases associated to the application of closed growing technology.

In spite of these concerns the use of hydroponic technology is largely applied in Northern European countries as well as in some Mediterranean countries (mainly in Spain). It is the role of universities, research centres and particularly the extension services to promote the development of soilless culture by providing just-in-time advice to specific problems, by organising professional short-courses and by preparing sensible cultivation protocols for the dissemination of smart fertirrigation techniques and management.

CONCLUSIONS

There is a strong potential for emission reductions by improving the use of natural resources: particularly sunlight and sun energy. This is facilitated by technology: innovative structures; efficient covering materials; process control means; and smart sensors (not discussed here). Also the possible contribution to sustainability of [recycling] technologies has not been discussed here. Sustainability is based on three linked issues: environment, economics and social concerns. Eco-efficient innovations and technologies will be only implemented if they are profitable and/or if they are imposed by law in accordance with the social benefits. There is enough knowledge already for the design and management of profitable and sustainable greenhouse production systems, but they will be effective only if the growers decide to adopt them. In this sense, dissemination activities and stakeholder involvement are key factors in the way towards the zero emission greenhouse.

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Tables

Table 1. The results of analysis: Life Cycle Analysis (left) and economic (right) of the production processes and cost components in the four cases that were studied: 1. tomato in multi-tunnel in Spain, tomato in Venlo-type greenhouse in 2. Hungary and 3. The Netherlands and 4. roses in a Venlo greenhouse in The Netherlands. The coloured cells link a high environmental impact to a high cost for the grower, that is: the cases where reduction of resource use would be doubly appealing (Euphoros consortium, 2010b).

Environment: processes with the highest scope for reduction of environmental impact in each of the four cases					*Appeal: most important cost components (%) of production costs in each case*				
Case study Process	1	2	3	4	Case study Cost component	1	2	3	4
Structure/covering	√	√	√	√	Equipment	33	28	23	22
Heating		√	√	√	Labour	27	17	26	22
Auxiliary equipment	√	√			Plant material	6	9	3	3
Substrate	√	√	√	√	Energy	2	11	31	36
Fertilizers	√	√			Fertilizers	7	19	2	1
Pesticides		√			Crop protection	4	3	1	3
Lighting				√					
Increase yield	√	√	√	√					

Table 2. Relative ventilation rate of a greenhouse with a windward obstruction (Euphoros consortium, 2010b).

	Obstruction length 40 m		Obstruction length 120 m	
Distance to obstruction	*8m*	*24 m*	*8m*	*24m*
No side ventilation	22%	16%	13%	13%
With side ventilation	31%	93%	30%	105%

Table 3. Total use of water and fertilizers and yield results for soil-grown lettuce. The treatment A was irrigated as usual, the other three aimed to maintain a pre-set soil water content, under various fertilizers' supply (Balendonck et al., 2009).

Treatment	Water use (mm)	Fertilizer (kg N/ha)	Mean crop weight (g)	Class 1 (%)
A (ref)	186	100	516	98.6
B	70	100	528	98.8
C	70	83	592	97.2
D	70	58	595	98.4

Table 4. Comparison of resource use of tomato in closed and open irrigation systems. The data are from a commercial farm in Italy, and refer to one summer growing season. There were no differences in production between the two (Incrocci et al., 2012).

	Leaching	Supply		Saving
		Open	Closed	(%)
Water (m^3 ha^{-1})	1067	5334	3982	25
N (kg ha^{-1})	211.7	1041	621	40
P (kg ha^{-1})	21	196	149	24
K (kg ha^{-1})	230.7	1384	1234	11

Figures

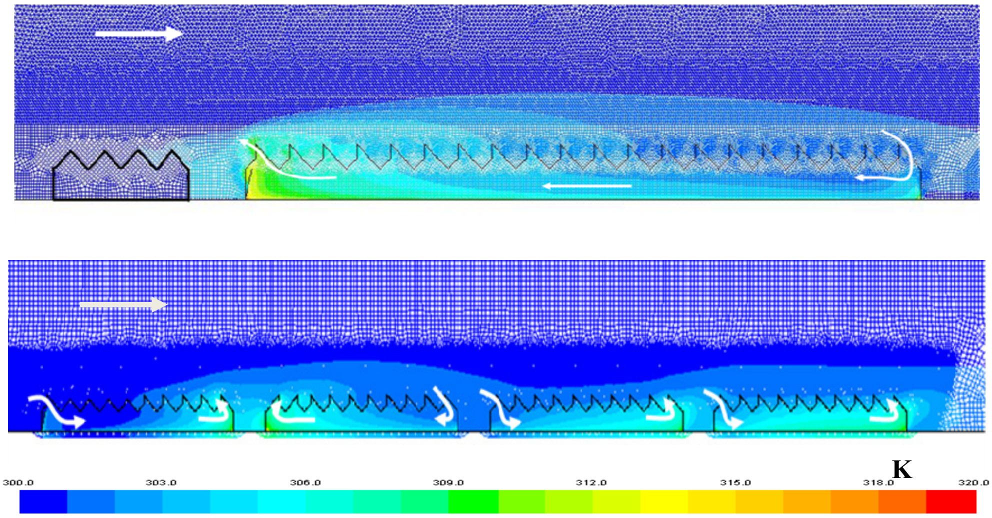

Fig. 1. Top: Map of temperature in a 100 m wide greenhouse with a windward obstruction. Bottom: Map of temperature in a group of four 50 m wide greenhouses with a distance of 8 m.

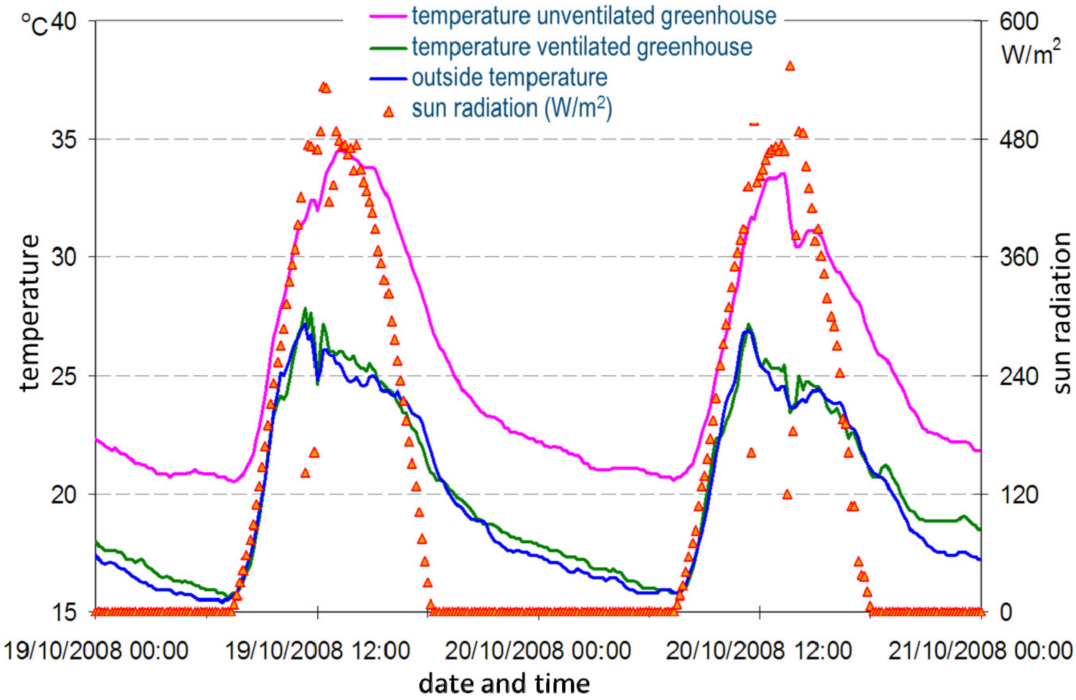

Fig. 2. Temperature in two identical multi-tunnels where a tomato crop was growing, in Sicily, Italy, for two sunny October days. A failure of the control system fully prevented ventilation in one of the two greenhouses (uppermost, pink line), whereas the roof ventilators of the other one were constantly fully open (green line approaching the outside temperature, which is the lowermost, blue). Outside sun radiation (right-hand axis) is represented by triangles. The shaded area indicates the management range of ventilation.

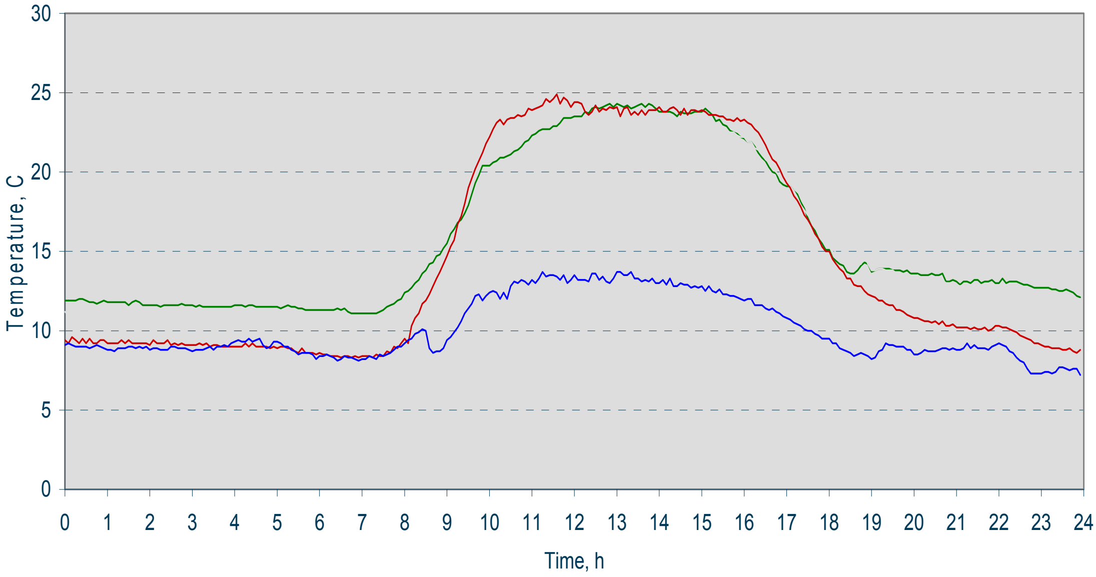

Fig. 3. Evolution of air temperature in the closed greenhouse (green line) and in an adjacent ventilated greenhouse (red line) along a 24 h clear sky period. The outside air temperature is also shown.