Specialization Course

Efficient Use of Inputs in Protected Horticulture

February 7th to 9th, 2012

Almeria

FUNDACIÓN

cajamar

Instituto de Investigación y Formación Agraria y Pesquera
CONSEJERÍA DE AGRICULTURA Y PESCA

2012
Specialization Course

EFFICIENT USE OF INPUTS IN PROTECTED HORTICULTURE

© Coeditors: Fundación Cajamar
I.F.A.P.A.
EUPHOROS

© Text: The authors.

I.S.B.N.: 978-84-938787-1-9

Composed and digital edition:
P&V.
www.pacoveiga.com
## CONTENTS

### INTRODUCTION

- NEW DEVELOPMENTS IN PLASTICS CLADDING MATERIALS FOR GREENHOUSE.
  - Juan C. López - Esteban Baeza - Juan I. Montero
  - Page 9

### EUPHOROS DEVELOPMENTS APPLICABLE FOR ROSE CULTIVATION (THE NETHERLANDS)

- Nieves García
  - Page 37

### ENERGY AND VENTILATION

- Esteban Baeza - Juan I. Montero
  - Page 73

### FERTILIZATION WITH PURE CARBON DIOXIDE IN UNHEATED, VENTILATED GREENHOUSES

- Cecilia Stanghellini
  - Page 111

### CLOSED SYSTEMS FOR SOILLESS CULTURE

- Alberto Pardossi - Luca Incroci
  - Page 137

### LYFE CYCLE AND ECONOMIC ANALYSES OF GREENHOUSE SYSTEMS

- Assumpció Antón Vallejo - M. Torrellas Iglesias - M. Ruijs - Juan I. Montero Camacho
  - Page 169
INTRODUCTION

The Project EUPHOROS, acronym for Efficient Use of Inputs In Protected has received funding from the EU in its 7th Framework Programme and counts among its drivers with universities, research centers and prestigious companies which in Europe are active in the area of protected Horticulture R+D+i.

This project aims to develop a production system for greenhouse agriculture that is sustainable, which eliminates the need for fossil fuels and the release of water and fertilizers to the environment, minimizes the carbon footprint and allows recycling of substrates and reduces the use of plant protection chemicals, maintaining high productivity and efficient use of resources.

Course content includes the most significant developments made in the areas of work covered in the project: economic and environmental evaluation of greenhouse system, efficiency of energy use in closed cycles of water, fertilizers and substrates, reduction in the use of pesticides, integration and evaluation of the various tools developed. Classes will be taught by expert researchers responsible for each of the working groups involved in the project.

Among the objectives of the project is to transfer knowledge and technological developments made during its implementation through dissemination and training activities, such as workshops and technical seminars nationally and internationally. So Cajamar Foundation and IFAPA La Mojonera organize a course on dissemination of the project results to be held in Almeria in the facilities of both institutions.

The course is aimed for PhD and master’s specialization students in protected agriculture, research staff, technicians and professionals of the food industry.
NEW DEVELOPMENTS IN PLASTICS CLADDING MATERIALS FOR GREENHOUSE

J.C. López¹ - E. Baeza² - J.I. Montero³
¹ Estación Experimental Las Palmerillas Fundación Cajamar
² Universidad de Almería
³ IRTA Centre de Cabrils

The choice of a covering material is made as a function of its optical and mechanical properties as well as the climate and location where the greenhouse is situated (Waaijenberg and Sonneveld, 2004). Regarding their optical properties, good agricultural practices dictate that a greenhouse plastic should have maximum solar transmission so that dust does not stick to it and is washed away easily and should be opaque to long wave radiation to reduce night time heat losses.

Greenhouse films are composed of polymers and additives. Polymers are the basic component of the film while additives put in different properties to the film such as infrared absorption/reflection, of light diffusion, etc. Greenhouse cladding films range in thickness from 80 to 200 microns (μm). The film width is up to 20 m. Today either single layer or multilayer (typically three-layer) films are widely used in commercial production, but multilayer films are preferred since they combi-
ne the positive properties of their individual components (for instance, good mechanical resistance and good light transmission). The life-span of greenhouse films has increased from nine months during the fifties to forty five months approximately today. Weathering is dependent on the photo-additives incorporated to the film as well as the geographic location and the exposure of the film to pesticide treatments (Cepla, 2006)

Table 1: Density of different polymers used in horticulture

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low density polyethylene (LDPE)</td>
<td>0.915 – 0.930</td>
</tr>
<tr>
<td>Copolymer ethylene vinyl acetate (EVA)</td>
<td>0.920 – 0.930</td>
</tr>
<tr>
<td>Copolymer ethylene butyl acrylate (EBA)</td>
<td>0.920 – 0.930</td>
</tr>
<tr>
<td>Polyvinyl Chloride (flexible) (PVC)</td>
<td>1.250 – 1.500</td>
</tr>
<tr>
<td>Polymethyl methacrylate (PMMA)</td>
<td>1.180</td>
</tr>
<tr>
<td>Polyester / Fiberglas</td>
<td>1.500 – 1.600</td>
</tr>
<tr>
<td>Glass</td>
<td>2.400</td>
</tr>
</tbody>
</table>

The low density and thickness of plastic materials is a great advantage in horticulture since it facilitates transportation, handling and installation over the greenhouse frame. For instance, 1 m² of LDPE film 200 m thick weighs 184 g approximately, the same film made of PVC weighs around 260 g while a glass pane 4 mm thick weighs 10 Kg. The light weight and flexibility of the covering material allows a significant reduction of the size and number of the supporting members, making the greenhouse frame lighter compared to the glasshouse frame and thus much cheaper.

Additives are an essential part of the covering materials. They are dispersed between the chains of polymer molecules without interacting chemically with them. Additives are used to facilitate the manufacturing of the film as well as for improving their performance under field conditions. Related to Good Agricultural Practices small quantities of additives change and improve relevant properties of the covering materials.
Table 2. factors affecting lifespan of films used in horticulture (Espí, E., 2011)

**Intrinsic factors**
- Base polymers (LDPE, LLDPE, EVA)
- Film type (mono o multilayer)
- Film thickness
- Stabilization
- Other additives (loads, pigments, additives anti-drip...)

**External factors before use**
- Manufacturing conditions
- Storage conditions
- Placement conditions

**External factors during use**
- Greenhouse structure (material, protection of contact surface, design, fixing of the film)
- Weather conditions (radiation, temperature, wind, rain, snow...)
- Crop
- Chemicals

The two most common additives in horticulture are UV stabilizer additives and IR absorbing additives. UV stabilizers make the film more stable to UV radiation. UV stabilizer additives absorb UV radiation or protect the polymer molecules. As a consequence the ageing of the film is delayed. The vast majority of plastic films in horticulture last more than a year and include UV stabilizer additives.

A good greenhouse film is expected to block long wave IR radiation (wavelength between 7 and 14 μm) in order to reduce heat losses by radiation. The so called thermal films are particularly effective for increasing leaf temperature in passive, unheated greenhouses during clear nights. Polyethylene films are very transparent to long wave IR radiation, therefore absorbing IR additives are commonly used to improve the thermal properties of the films.
1.2 Properties of greenhouse plastic covering materials with special relevance in Good Agricultural Practices

1.2.1 Clear films and diffusive films.

In areas with clear skies and high solar radiation, direct radiation can cause leaf burning in greenhouse crops during warm days. To avoid this problem new plastic films have been developed that increase the percentage of diffuse radiation in the greenhouse. Radiation is considered to be diffuse when it deviates more than 2.5° from the direct incident radiation. The ISO 13468-2 and ASTM D 1003 are used to measure light transmission of the films, both global or TGLV and diffuse, which is the one that deviates more than 2.5° to the incident light beam direction. A diffusive film is considered when the turbidity is equal to or above 30% for thicknesses between 70 and 150 microns and 35% for thicknesses equal to or greater than 150 microns (EN 13206). The percentage of diffuse radiation to global radiation is referred as turbidity.

The increase in turbidity increases light uniformity and produces an increase in yield in Mediterranean countries. (Castilla and Hernandez 2007, Cabrera et al, 2009). Diffusive light has also positive effects in Northern countries such as Holland. Hemming et al, (2008) compared the effect of diffusive glass against clear glass. The conclusion was that more light was intercepted by the crop in the diffuse treatment, especially by the intermediate leaf layers, thus the assimilation rate was higher and cucumber production increased approximately by 8%.

In Mediterranean climates (low cloudiness, high irradiance and low rainfall) diffusive films are recommended, because the light transmission is then not too restrictive and shadows inside the greenhouse and burns on the plants are prevented. In more humid climates films as clear as possible are preferred because in this case the limiting factor is usually the light transmission. Turbidity of the film is not required because the major component of global radiation is already diffusive due to cloudiness.
1.2.2 Anti-dust films

Most polymers are poor electricity conductors. This fact makes them particularly prone to accumulate static electricity after rubbing a surface against another, or by frictions caused by the wind, etc.

As a consequence most plastics attract dust on their surfaces. To reduce static electricity some additives that increase electrical conductivity can be incorporated into the interior or the surface of the film. Montero et al., (2001) reported that dirt accumulation reduced light transmission by approximately 6% of a new PE plastic film after one year of exposure to the weather in Coastal Spain. EVA films are reported to lose more light transmission due to dust accumulation.
Today materials for greenhouse cladding are being introduced in the market with self-cleaning properties by means of modifying the contact angle that water forms on the surface, presenting what is known as “lotus effect” or “self-cleaning.” The development of self-cleaning synthetic surfaces is based on the particular structure of the surface of the leaves of the lotus plant (Nelumbo nucifera), which is a rough combination of two structures, one on the microscale and the other on the nanoscale. The first surface is formed by cells that form ridges, while the second consists of nanocrystals of waxes that coat the surface of these cells. This structure imparts superhydrophobic surface features, making the contact angle of water droplets being greater than 150 ° allowing water droplets to runoff on the leaves dragging any dirt particles.

1.2.3 Anti-drip films.
Water vapour condenses on the cold inner cover surface forming small droplets of liquid water. This has negative consequences on light transmission; some condensation studies have reported PAR transmission losses close to 20% for incident radiation angles bigger than 15 °. This
loss in light transmission varies with the drop size: bigger drops reduce less the transmission than smaller drops, due to the different contact angle of the drop with the plastic (Castilla, 2005).

Moreover, condensation can fall over the crop fostering the development of fungal diseases. Anti-drip additives modify the surface tension of water, eliminate droplets and form instead a continuous thin layer of water (Figure 9 and 10).

Figure 9. Anti-dripping film on the right side of the photo.

Figure 10: Effect of condensation on light transmission: left, drop wise condensation; right, film condensation.
There are a number of methods to produce a continuous layer of condensed water, such as the treatment of the film surface, oxidation of the polymer surface) but the most efficient method for agricultural films is the incorporation of additives during the manufacturing process. A problem to be resolved is that such additives migrate towards the plastic surface and are washed away by rain or condensation. Usually anti-drip properties are lost before the end of the lifespan of the plastic. Recently multi-layer plastics use one of their central layers as a reservoir of anti-drip additives, so that they continuously supply replacement to the additives lost by washing.

1.2.4 Blocking-NIR plastic materials

Only about half of the energy that enters a greenhouse as sun radiation is in the wavelength range that is useful for photosynthesis (PAR, Photosynthetically Active Radiation). Nearly all the remaining energy fraction is in the Near InfraRed range (NIR) and warms the greenhouse and crop and does contribute to transpiration, none of which is necessarily always desirable. (Figure 11)

Some new plastic film prototypes contain NIR-reflecting pigments with several concentrations. By doing so, a significant reduction of the sun radiation energy content in the NIR range is possible without much reduction in the PAR range. The effectiveness of NIR films on the reduction of greenhouse air and crop temperatures and their effects on crop yield and quality depends on a number of factors, such as the amount of NIR filtered by the film, the ventilation capacity of the greenhouse, the crop density and the canopy transpiration. The desk study of Hemming et al. (2006) showed that under Dutch conditions, mean air temperature in a Venlo-type greenhouse can be reduced by about 1°C during the summer months, but the NIR film increased energy consumption for heating in the winter months. Field tests conducted in Southern Spain produced more optimistic results. Temperature reductions up to 4°C during summer months have been reported. This NIR film increased yield and quality of a pepper crop (Garcia-Alonso et al., 2006).
UA cover with high NIR reflectivity would reduce thermal load by 50% without reducing assimilation. The NIR-selective filters that are commercially available can be applied in three fashions: as permanent additives or coatings of the cover; as seasonal “whitewash” and as movable screens. It seems reasonable that it is the combination of external climate conditions and type of greenhouse that determines the most appropriate form of application in a given place. Some of these factors have been taken into account in the study of Kempkes et al., (2008) quantifying the expected benefits, in terms of inside climate. They show that year-round filtering of the NIR component of sun radiation is unlikely to increase productivity, even in mild winter climates, unless the reflected energy can be used.

1.2.5. Blocking UV radiation to limit the activity of harmful insects

The use of plastics known as anti-pest (photoselective), which block some UV radiation (Salmeron et al., 2001) and eliminate the wavelength corresponding to the color most visible to insects, can hinder the development of insect pests (Salmeron et al., 2001; Antignus
et al., 2001, Lapidot, et al., 2002), or viruses transmitted by insects that are sensitive to the decrease or absence of ultraviolet radiation (Gonzalez et al., 2003; Monci et al., 2003; Rapisarda, et al., 2006). However, it also can have a negative effect on the activity of pollinators, which are in need of the spectrum of UV radiation by limiting their vision (Hair et al., 2005, 2006, Soler et al., 2005), as ultraviolet light conditions can change the perception of pollinator bee (Apis mellifera) and bumblebees (Bombus terrestris) on the different colors of the flower, thus increasing the difficulty to locate the flowers between the crop.

However, this negative effect can be mitigated by the responsiveness of pollinators, bumblebees have an excellent ability to learn fast and they can adapt to the absence of ultraviolet light (Dyer and Chittka, 2004). The limitation of the UV light reduces, decreases, and even prevents the growth and sporulation of pathogenic fungi such as Botrytis cinerea (Jarvis, 1997, Diaz et al., 2001)

There are studies comparing cladding materials with different levels of absorption of ultraviolet radiation (1%, 10%, 23%, 55% and 65% respectively) in tomato, melon and mini-watermelon, to evaluate the influence of filters for ultraviolet radiation additivated to plastic materials on Bemisia tabaci and Frankliniella occidentalis, and on the activity of natural pollinators (Bombus terrestris and Apis mellifera). With regard to insect pests (Fig. 12), the results show that anti-pest plastics that absorb ultraviolet radiation reaching the greenhouse limit the mobility of the insects, and therefore reproduction, making it an important tool to control whitefly and thrips in greenhouses since in the conducted trials there were 65% less of both Bemisia tabaci and Frankliniella occidentalis under plastic anti-pest than the control (Perez et al., 2009).
Figure 12. Evolution of the cumulative number of Bemisia tabaci (a) and Frankliniella occidentalis (b), in chromotropic sheets, under plastic films with a transmissivity of 1% (Pest Control) and 55% of UV radiation (control).

With respect to pollinators, experimental results show a specific interaction between the anti-pest plastic films and pollinator species, so that the activity of bumblebees (Bombus terrestris) was not affected by the use of anti-pest films, not affecting crop yield, while the activity of bees (Apis mellifera) was affected (Lopez et al., 2006, Perez et al., 2007), registering a 46% reduction in the number of bees entering and leaving the hive, resulting in maximum production shortcuts up to 34% (Perez et al., 2009).
2. Euphoros project: Effects of a NIR-absorbing plastic for greenhouse covering material with tomato crop in Almería-Spain.

2.1 Objective

Evaluate the climate and the productive response of a tomato crop (long cycle) under two different covering materials: NIR absorbing film (with partial absorption of the NIR radiation) and a control film (standard covering material used in Almería greenhouses).

2.2 Background

The advantages of the Mediterranean area for greenhouse culture are related to the good availability of light during fall and winter, the mildness of temperatures and climatic stability due to sea vicinity (Castilla and Hernández, 2005). In these conditions, the plants adapt to climatic suboptimal levels, whereas in northern European greenhouses (cold areas) optimal climatic conditions are created to maximize yields.

In northern Europe, greenhouse cultivation systems, mainly under glass, are characterized by a high-tech, highly equipped and expensive, resulting in a large use of energy. By contrast, in the Mediterranean farming system, mainly with plastic cladding, is low-tech, ill-equipped, cheaper and with limited use of energy (Castilla, 2007). The climate of the area and location of emissions must be considered in the choice of the cladding material, besides its optical and mechanical properties, (Waaijenberg and Sonneveld, 2004).

In some geographical areas the reduction of the non luminous solar thermal energy transmission (NIR= near infra red radiation) into the greenhouse, which is the one ranging from 760 and 2500 nm approximately, can be advisable, at least during certain periods of the growing cycle. It is quite frequent to avoid the excessive heating of
the greenhouse using shading screens inside the greenhouse or by means of whitening of the plastic film by applying a whitening product. Also NIR-filtering whitewash has been developed (von Elsner and Xie, 2003; Blanchard and Runkle, 2010) in order to obtain temperature regulation during daytime.

One of the most promising new developments in plastic is that that incorporates additives to block NIR radiation. Only half the energy entering the greenhouse from solar radiation is in the range of radiation useful for photosynthesis of plants (PAR, Photosynthetically Active Radiation). The remaining energy is in the range of near infrared radiation (NIR) that heats the greenhouse and the crop and contributes to transpiration, which sometimes is not always desirable (Montero et al, 2008).

The present work is enshrined within the Euphoros European project. Previous to the field test, simulations have been carried by WUR with the simulation software (Kaspro), fed by meteorological data from Almeria (EEFC meteorological data) with optical data for different NIR absorbing materials provided by CIBA. The simulations showed that the NIR absorbing materials were in principle, able to exclude a part of the incident solar energy. However, their effect seemed limited, because part of the absorbed energy was transmitted to the interior of the greenhouse by convection, and in principle, reflection instead of absorption seems a more favourable option. A good NIR filtering material must exclude a high level of NIR, because the leaves of the crop are by themselves a good reflector of NIR (45%). The material must also affect as little as possible the transmission within the PAR range. Therefore, from the set of materials simulated, the best prototype was chosen (maximum NIR absorption with least possible PAR reduction) and manufactured to be tested at the EEFC facilities.
2.3 Materials and methods

During the 2010/2011 growing season, a field trial has been performed in two identical adjacent greenhouse modules of 1,200 m² area each. Each greenhouse compartment (Figure 1) has three asymmetric curved shape modules of metal structure, with a ridge height of 5.4 m and gutter height of 3.4 m. The south wall has a sidewall rolling vent and each module has a roof vent oriented south. The greenhouse compartment orientation was east-west. The vents were implemented with a 20*10 threads cm-1 anti insect screen.

The crop was grown in a perlite bags (third year of use), of 40 l capacity, of the B-12 grain size (particles of 0-5 mm of Ø), laid over expanded polystyrene channels. The orientation of the crop rows was north-south.

Each compartment has 22 crop rows, with 16 perlite bags per row with two plants per bag.
The separation between crop rows was 1.66 m and 1.5 m between the centres of the growing bags. The tomato crop was transplanted on September 6th 2010, cultivar Ventero, with a plant density of 1.6 plants m⁻². Previous to the transplant both greenhouses were whitened (10th August) to ensure the survival of the seedlings under the harsh conditions of Almería during this month, using the same dose for both greenhouses, which involved that under the NIR absorbing film an extra NIR reflection was added. Whitening was washed away during the 5th/6th of October for the NIR absorbing greenhouse and the control respectively.

![Figure 2. Truss tomato crop (cv. Ventero). Crop was pollinated with bumblebees (Bombusterrestris).](image)

In each greenhouse a demand tray and a drainage tray were used to control the irrigation. Both trays had two growing bags, with four plants each. On a daily basis, the percentage of drainage of the crop and pH and EC were monitored.
Two treatments, one per greenhouse were established:

**NIR film**: greenhouse covered with the NIR absorption film prototype.

**Control film**: greenhouse covered with the standard three layers film used in Almería.

The covering materials were both installed in the two greenhouse compartments during August 2010. The optical characteristics of both materials, measured in a laboratory in WUR (The Netherlands) for different wavelengths are shown in Figure 2.

*Figure 2. Transmission, reflection and absorption spectrum of the two tested materials: NIR_film and Control_film (laboratory data measured and provided by WUR).*

The climate (opening and closing of the vents) was managed with a climate controller, by means of sensors located inside and outside the greenhouses.
2.3.1 Determinations

En cada tratamiento se obtuvieron las siguientes medidas y determinaciones:

- **Ambient temperature and relative humidity:** each compartment has 2 ventilated psicrometers (Pt-100, mod. 1.1130, Thies Clima, Göttingen, Germany) that read the air temperature (dry and wet bulb temperatures) from which humidity was calculated.

- **Global and PAR radiation:** Global radiation was quantified in the greenhouses with pyranometers (Kipp&Zonnen, CM6B) and PAR with a quantum sensor (LI-190 Biosciencie, Lincol, NE, USA).

- **Net radiation over the greenhouse cover.** In a representative spot, over each greenhouse, and at a height of 50 cm over the cover, a net radiometer was installed (CNR1, Kipp&Zonen, Delft, The Netherlands). Net radiation was calculated as the sum of net shortwave and longwave components. All sensors were sampled at 2-s intervals, averaged every 5 min and registered by several data logging devices (mod. CR1000 and CR3000, Campbell Scientific Ltd., Leicestershire, UK).

- **Temperature of the cover** by means of thermocouples (cover temperature measurements were corrected to overcome the problem of direct radiation impinging on the sensor following the method recommends for Abdel-Ghany et al (2006).

- **The exterior climate** data were measured in a meteorological station located in the vicinity of the two experimental greenhouses (temperature, humidity, radiation and wind velocity and direction).

- **Production:** 5 repetitions per treatment and 8 plants per repetition (4 growing bags). Marketable and non-marketable yield were separately quantified.
2.4 Results

2.4.1 Climate

The average air temperature inside both greenhouses was very similar along the whole cycle (Table 1), with average values of 24 h of 17.5 °C and 17.4 °C for the NIR_film and Control_film respectively. Both during mean daytime and night periods, air temperatures were similar, like maximums and minimums (table 1).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Air temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24h</td>
</tr>
<tr>
<td>NIR film</td>
<td>17.5</td>
</tr>
<tr>
<td>Control film</td>
<td>17.4</td>
</tr>
<tr>
<td>Exterior</td>
<td>15.5</td>
</tr>
</tbody>
</table>

Table 1. Daily mean air temperature (°C) 24 h, day, night, maximum and minimum for the total cycle of crop.
Figure 3 shows the average ambient temperature (24 h) along the whole cycle, and again it shows the great similarity in the values, which obviously were consistently higher than the exterior ambient temperature. Night air temperatures in winter under the NIR film was not less than under the Control film as it should be expected due to lower input NIR during the day under the NIR film.

Both during the warm (spring) and cold (winter) seasons, temperatures were similar in both treatments. In the cold season a similarity in air temperature between the two treatments could be expected since most of the time the setpoint ventilation temperature was higher than the greenhouse temperature (ventilation system sufficient to maintain the setpoint temperature). However, in the warm season, when the ventilation setpoint temperature was lower than the greenhouse air temperature, most of the time greenhouses kept ventilators open, being this the most favorable period to show differences between different plastics, although this was not the case.

![Air temperature mean 24h](image)

Figure 3. Daily mean 24h air temperature (°C) in NIR_film, Control_film and outside.
The net radiation measured over the greenhouse cover (Figure 4) was slightly larger for the NIR_film treatment than in the Control_film. This may partially justify the absence of ambient temperature decrease expected inside the NIR_film greenhouse due to its NIR absorption effect (heat convection from the plastic into the greenhouse).

Net radiation NIR film treatment was higher (close to 10%) versus the Control_film. Longwave radiation emitted by the NIR_film greenhouse was higher compared to Control_film in the daytime period. However it was not enough to produce a lower net radiation because the global radiation component from the greenhouse (reflected and transmitted from the greenhouse), was higher in the Control_film.

![Mean Net Radiation (W m⁻²)](image)

**Figure 4.** Daily mean net radiation (Wm-2) over greenhouse for two treatments: NIR and Control.

Figure 5 shows the ambient temperature, cover temperature and radiation data along one day of the growing cycle (20/3/2011) for both treatments. The ambient temperature was similar both under the NIR_film and the Control_film greenhouse. The cover temperature was hig-
Figure 5. Air temperature, cover temperature and radiation for a day (20/03/2011) in both treatments.
Solar radiation and NIR radiation were lower under the NIR_film, as would be expected. However, the PAR radiation was also affected, being also lower under the NIR_film (15%), a non desired side effect, due to its possible harmful repercussion on the crop yield. Regarding the long wave radiation, the NIR_film greenhouse emitted more, due to the higher temperature reached by the material, previously discussed.

### 2.4.2 Production

The total and marketable yields are shown in Figures 6 and 7. The marketable yield was higher in the Control_film greenhouse than in the NIR_film greenhouse. The difference in yield was found in the first quality fruits, 14.49 kg m-2 and 12.67 kg m-2, respectively. Second quality production was significantly lower and similar for both treatments.

![Graph showing accumulated first and second quality marketable yield across treatments](image)

**Figure 6.** Accumulated first quality and second quality marketable yield along the growing cycle for each treatment.
Differences were also found in the number of harvested trusses, being 16.4 and 15.1 for the Control_film and NIR_film, respectively (Figure 7).

Figure 7. Accumulated number of trusses harvested for each treatment along the growing cycle

Besides, it was visually observed along the trial that less condensation occurred in the inner layer of the NIR_film greenhouse than in the Control-film, in the early mornings, which could have been caused by the higher temperature reached by this film. This could have modified the transmissivity measured in the greenhouse during the period with condensation, favouring the NIR film.
2.5 CONCLUSIONS

- The tested NIR film did not reduce the air temperature versus the Control film.
- The net radiation balance was slightly higher in the NIR film than in the Control film.
- The NIR film caused a reduction in PAR close to 15% leading to a reduced tomato yield, similar to the PAR reduction.
- The development of plastic materials to reduce NIR component should be addressed to use additives to reflect the NIR and not to absorb it (study case).
- In warm areas is a priority to reduce air temperature during most of the time, so it would be of interest go on further with materials not absorbing but reflecting NIR and not modifying the PAR transmissivity.
REFERENCES


with UV-blocking plastic covers in commercial plastic houses of Southern Spain. Acta Horticulturae, 633:537-542


EUPHOROS DEVELOPMENTS APPLICABLE FOR ROSE CULTIVATION (THE NETHERLANDS).

Nieves García
Wageningen U. R.

The overall objective of the four-year project EUPHOROS is the development of a European sustainable greenhouse system that minimizes the use of inputs and emissions to the environment, yet with high productivity and resource use efficiency. Researchers from several European Universities and Horticultural Research Centers and representatives of a number of industries (horticulture supply industry, waste recycling industry) work in three commodity-based work packages in the development of a diversity of innovative tools and systems to reduce energy, water, fertilisers, pesticide consumption, and waste in the horticultural industry in Europe. Another WP optimizes the growing environment, developing innovative but robust monitoring tools for performance assessment, early detection and response management. The balance between environment and economy is addressed in a
But... How does European Horticulture look like? Well, one only needs to drive across different horticultural areas in Europe or fly above them to realize that there are certainly notable regional differences, and for sure not every greenhouse is the same. The European Horticultural Industry does not obey to one unique model. Each of the European countries has its own way to protect the crops by means of greenhouses. The greenhouse structure and equipment have evolved locally according to specific circumstances. These circumstances can be environmental (climate, water availability and quality, soil structure and quality), cultural (the education level of the grower, the management structure in the greenhouse, the level of environmental friendly conscience of the grower, the traditions that led to the actual cultivation methods), economic (how much can a grower invest in greenhouse structure, equipments and tools, which market do they serve and what does the market expect from the grower...).

Therefore, the testing in practice and implementation of the tools developed within the development working packages of EUPHOROS, has been addressed from a local point of view. A special Working Package dealt with implementation of the developed tools in combinations relevant to three local situations. The local situations were: Almería (Spain), Morahalom (Hugary), and Bleiswijk (The Netherlands): one situation typical for Northern, Southern and Eastern Europe. Each situation one climate, one culture, one market. All very different from each other.
Rose cultivation:
a relevant horticultural activity in The Netherlands

Unlike the other two implementation locations for Euphoros developments and tools, where the crop chosen for implementation tests was tomato, in the location in The Netherlands it was decided, despite the undisputed importance of tomatoes as horticultural crop (1,400 hectares in 2005 and increasing in the years that followed to 1,700 in 2011), to dedicate all efforts to a different relevant horticulture product. Roses was a logical choice, as cut flower cultivation, with roses as the number one cut flower, are definitely relevant in surface, economic importance, but also, as we will see later, in environmental impact. Table 1 shows the area dedicated to the cultivation of several horticultural products in The Netherlands. From a total surface cultivated under greenhouses of 10,250 hectares, almost half of it is dedicated to the cultivation of ornamental flowers and plants. Holland has the highest consumption per capita of flowers and plants in the world. The Dutch love indeed to buy, give and receive flowers and plants at any occasion. They decorate their houses, offices, shopping centers, hotels and restaurants with them. They buy them on the market or supermarket together with other essential groceries. They bring them along if they are invited to eat with friends, if they visit somebody at the hospital, when somebody graduates, moves to a different house, change jobs, Ornamental products, plants and flowers, are also a very important export product in the Dutch economy. It is also a very innovative and mechanized subsector. A project dealing with horticulture in the Netherlands could not ignore this reality.

Within the area dedicated to the ornamental plants, a little bit more than half of it (2,430 Ha) is dedicated to the production of cut flowers. Within the great diversity of cut flowers cultivated, Rose was for many years the number one, including the moment when EUPHOROS was being planned. The surface of roses cultivated in The Netherlands in 2011 (460 ha) is half of what it was at the beginning of this century, when the decline started, as more than 950 hectares of roses were
cultivated in 2001. In 2011 the rose accounts “only” for 19% of the total cut flower cultivation surface. Still, it occupies after the Crysanthemum, the second place in terms of surface. In terms of value, it still occupies the first place among the cut flowers, and it represents 23% of the total value of the cut flowers sold by the Dutch Auctions and produced in The Netherlands (table 2).

Table 1. The Netherlands. Cultivated surface per horticultural product.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(year)</td>
<td>Hectares</td>
<td>Hectares</td>
<td>Hectares</td>
</tr>
<tr>
<td>(2005)</td>
<td>10.374</td>
<td>10.250</td>
<td></td>
</tr>
<tr>
<td>(2007)</td>
<td>4.571</td>
<td>4.990</td>
<td></td>
</tr>
<tr>
<td>(2011)</td>
<td>1.396</td>
<td>1.545</td>
<td>1.700</td>
</tr>
<tr>
<td>Greenhouse horticulture</td>
<td>631</td>
<td>616</td>
<td>660</td>
</tr>
<tr>
<td>Greenhouse vegetables</td>
<td>4.445</td>
<td>4.571</td>
<td>4.990</td>
</tr>
<tr>
<td>Tomato</td>
<td>1.396</td>
<td>1.545</td>
<td>1.700</td>
</tr>
<tr>
<td>Pepper</td>
<td>1.236</td>
<td>1.187</td>
<td>1.360</td>
</tr>
<tr>
<td>Cucumber</td>
<td>631</td>
<td>616</td>
<td>660</td>
</tr>
<tr>
<td>Ornamentals (flowers &amp; plants)</td>
<td>5.616</td>
<td>5.327</td>
<td>4.700</td>
</tr>
<tr>
<td>Potted plants</td>
<td>1.377</td>
<td>1.397</td>
<td>1.360</td>
</tr>
<tr>
<td>Cut flowers</td>
<td>3.244</td>
<td>3.003</td>
<td>2.430</td>
</tr>
<tr>
<td>Crysanthemum</td>
<td>598</td>
<td>566</td>
<td>510</td>
</tr>
<tr>
<td>Roses</td>
<td>780</td>
<td>652</td>
<td>460</td>
</tr>
</tbody>
</table>

Source: www.statline.cbs.nl
### Table 2. The Netherlands: Turn over roses with respect to cut flowers Dutch Auctions

<table>
<thead>
<tr>
<th></th>
<th>Auction turn over (2009) (in millions of €)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut Flowers, total¹</td>
<td>2.200</td>
</tr>
<tr>
<td>Cut Flowers, Dutch production</td>
<td>1.600</td>
</tr>
<tr>
<td>Roses total¹</td>
<td>696</td>
</tr>
<tr>
<td>Roses, Dutch production</td>
<td>362</td>
</tr>
</tbody>
</table>

¹) includes import

Source: VBN, 2010

### Energy and labour, the most important inputs in rose cultivation.

A thorough economic and environmental analysis of the tomato cultivation systems in Hungary and Spain as well as of the rose cultivation in The Netherlands (a reference situation calculated with data from the years 2007 and 2008) was performed at the beginning of EUPHOROS project by a multidisciplinary team of researchers from different European countries. This work, part of which will be presented in chapter 6 of this publication, was a very useful development for the people having the task to integrate the different developments within EUPHOROS, as it helped to decide on which developments to focus (always in close consultation with local stakeholders). Moreover, the analysis forecasted the potential economic impact (both: cost reducing and resulting investment capacity, see table 3) when reducing a certain input by 10% and by 50%.

The economic analysis showed that within the cost components of a rose farm in the Netherlands (figure 1), the total costs are mainly determined, just as in the tomato production by three main components: energy, tangible assets and labour. These three cost compo-
nents together have a share of 80% of the total costs. The costs for energy accounts in roses for 36% of the total costs (and have only increased from then as we will see in the course of this chapter). This places the input “energy” as the most important input in which to focus in a project aiming economically viable input reduction. The costs of paid labour shares the second place with all tangible assets, (such as machinery and instruments), each accounting for 22% of the total costs. Therefore, any development able to achieve a reduction in the costs for labour, will contribute to an economically interesting improvement of the production system.

![Cost components of rose farm in Venlo greenhouse](the Netherlands). Source: Euphoros Deliverable 5.
Electricity accounts for more than 90% of the energy input in rose production.

Within the EUPHOROS project a working package was dedicated to explore different ways to store the free energy by the sun in order to use it during colder periods. These methods (see chapter 3) offer several options for serious energy savings for the purpose of heating the greenhouse.

Unfortunately, a further analysis of the energy requirements of a rose crop in The Netherlands (table 4) show that more than 90% of the natural gas used in rose cultivation is used for the generation of electricity for the lamps that supply photosynthetic light. Without lamps, it would not be possible to cultivate roses the whole year round in the Netherlands, as in the winter weeks too little light enters the greenhouse (figure 2). The lamps provide in the darkest weeks of the year up to 80% of the total light in the greenhouse.

The generation of electricity from natural gas is done by means of the so called Warmth-Power-Boiler; the combustion of gas delivers electricity as main product, and high temperature water and CO2 as residual products. Both residual products are stored and used in the greenhouse: the warm water for heating; the CO2 to enrich the greenhouse air (carbon dioxide fertilization enhances photosynthesis by the plants and therefore growth). Because the lamps themselves (1000 Watt lamps) produce a lot of heat, in rose cultivation there is rather an excess than a shortage of warmth to maintain optimal growing temperatures. This is illustrated by the fact that only an additional 8,8 m3/m2/year of natural gas is used for heating and/or CO2 production in moments when the lamps are switched off.

With the above explanation, it would not be realistic to expect on the short term a serious reduction of the input of energy from fossil origin in the cultivation of roses with any of the current developments. A reduction of 10% of electricity would already have an important econo-
mic impact, as it would reduce the costs with 4 €/m2 year, representing an investment capacity of 23 € (table 3).

Figure 2. The weekly global radiation (outside, above) and the light sum inside a greenhouse in The Netherlands along the year, with and without the contribution by the lamps. The contribution of the artificial light can represent up to 80% of the total light sum in the darkest weeks of the year.

Environmental impact of rose cultivation is by >95% due to energy

The results of the environmental analysis (see chapter 6) showed also that climate control system was the main contributor to all the impact categories selected (Impact categories: AD, abiotic depletion; AA, air acidification; EU, eutrophication; GW, global warming; PO, photochemical oxidation; CED, cumulative energy demand) with percentages of between 95.4% and 98.9% of the total.

The greenhouse structure was the second contributor to impact categories with low values of between 0.53% and 2.43%.

Fertilizers and crop protection agents: small contributors

The costs of other inputs where the EUPHOROS project is focusing on (fertilizers and crop protection agents) have very little impact in the total production cost. The cost of fertilizers, for instance,
represent just 1% of the total production costs, while the cost of crop protection agents only amount to 3% of the total costs. Recirculation of nutritive solutions in The Netherlands is due to environmental regulations already compulsory for many year and therefore common practice. Estimations indicate that only about 30% of the total water with fertilizers used in rose cultivation, practically 100% soilless cultures, is wasted. Research is being conducted at the moment of writing these lines in order to make 100% recirculation possible in the Dutch Rose cultivation (van der Maas et al., WUR Greenhouse Horticulture). However, if growers decide to waste part of their nutritive solution, this is usually the consequence of growth inhibition when full recirculation is applied for long periods, reasons totally different from the ones for which monitoring tools have been developed by The University of Pisa, UNIPI (see chapter 5). UNIPI concentrates on making 100% recirculation possible in areas with poor water quality. The water quality in The Netherlands is good; accumulation of Sodium and Boron are not likely to happen quickly. Provided the monitoring tools were ensured a 100% closure of the system, they would provide a saving of only 0,12 €/m2 year.

Crop protection and pest management in rose cultivation in The Netherlands is mainly integrated. By means of this pest control methods natural enemies of important pests are introduced in the crop. The natural enemies maintain the pest at a low infection level. If the balance is altered, and suddenly the pest pressure becomes too high, chemical corrective pesticides, often compatible (they do not kill the predators, only the pest) are used to fight hot spots. The mentioned costs of crop protection in rose (3% of the total) include both the costs of the chemicals and the natural enemies.

Calculations within the earlier mentioned economic and environmental analysis (chapter x6) forecasted that a tool that due to early detection of pest contributes to achieve a 10% reduction of pesticide use in the Dutch situation would save only 0,3 €/m2 year; translated to investment capacity, this would amount to 1,5 €/m2.
As we see, cost reduction would hardly be an incentive for rose growers to invest in developments that would have the potential to save on fertilizers or on pest control agents.

The environmental impact of these cost components are also quite small, as altogether auxiliary equipment, fertilizers, pesticides and waste management made contributions lower than 2% of the total to all of the selected impact categories.

Crop protection by means of Integrated Pest Management is however a labour intensive activity. As the grower needs to scout frequently in the canopy for the presence of pests and predators. An intimate knowledge of pest and predator species is required, as sufficient understanding of population dynamics and pest management. And given the fact that 22% of the total production costs are for paid labor, the economic impact of a tool that contributes to save precious scouting time can be calculated. If we agree that an electronic scouting device (by vision or volatile detection techniques) could achieve a reduction of 0.25 hour labour per m² per year in scouting time, this would increase the investment capacity with approximately 5 €/m².

<table>
<thead>
<tr>
<th>Cost component</th>
<th>Reduction in costs 10% reduction</th>
<th>Investment capacity 10% reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td>4.13</td>
<td>23.6</td>
</tr>
<tr>
<td>fertilizers</td>
<td>0.12</td>
<td>0.60</td>
</tr>
<tr>
<td>pesticides</td>
<td>0.30</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Table 3. Cost reduction (in €/m² year) and investment capacity (in €/m²) when reducing an input by 10% in the reference situation: Rose in Venlo greenhouse in The Netherlands.

Source: Euphoros Deliverable 5.
Table 4. The energy needs in a rose crop, assuming a installed intensity of 11.800 lux when lamps are switched on during 5751 hours, and when reducing the number of hours to save 10% electricity.

<table>
<thead>
<tr>
<th>Supplementary photosynthetic light</th>
<th>(lux)</th>
<th>11.800</th>
<th>11.800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power W/m²</td>
<td>107</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td>PAR μmol /m²/s</td>
<td>148</td>
<td>148</td>
<td></td>
</tr>
<tr>
<td>Number of hours/year with lamps on</td>
<td>hours/year</td>
<td>5751</td>
<td>4919</td>
</tr>
<tr>
<td>Gas Heat-Power Central (0,6 MWe/ha)</td>
<td>m³/m²/year</td>
<td>92,9</td>
<td>79,4</td>
</tr>
<tr>
<td>Gas Boiler</td>
<td>m³/m²/year</td>
<td>8,8</td>
<td>12</td>
</tr>
<tr>
<td>Gas total</td>
<td>m³/m²/year</td>
<td>101,7</td>
<td>91,5</td>
</tr>
<tr>
<td>Electricity required for light</td>
<td>kWh/m²/year</td>
<td>615</td>
<td>526</td>
</tr>
<tr>
<td>Electricity purchased from public grid</td>
<td>kWh/m²/year</td>
<td>270</td>
<td>231</td>
</tr>
<tr>
<td>Electricity sold</td>
<td>kWh/m²/year</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nett energy consumption excl generation</td>
<td>MJ/m²/year</td>
<td>4191</td>
<td>3724</td>
</tr>
<tr>
<td>Nett energy consumption incl generation</td>
<td>MJ/m²/year</td>
<td>5533</td>
<td>4873</td>
</tr>
<tr>
<td>Production</td>
<td>tallos/m²/ year</td>
<td>250,8</td>
<td>249,0</td>
</tr>
<tr>
<td>Energy used</td>
<td>MJ/stem</td>
<td>22,1</td>
<td>19,6</td>
</tr>
</tbody>
</table>


EUPHOROS developments tested at the greenhouse level in rose cultivation (The Netherlands).

After having analyzed the reference situation (commercial rose cultivation in The Netherlands) and the options with a serious potential to reduce inputs, and with the involvement of stakeholders, a selection was made of the developments that would be tested at a semi-commercial scale (see table 5). The most promising of them was a new cover material (diffuse glass with AR coating), as it would have the potential to increase the light transmission in the greenhouse and impro-
ve the light distribution, thus potentially increasing the production with the same energy-input, or even making possible to reduce the energy input required for electricity by 10%. Due to the importance of Energy as input, it is quite clear that this became the main trial in two greenhouse compartments of 144 m², in which the other developments with (although limited) input reducing potential were studied, each of it in a different way.

The trial set up and the results of this main trial with diffuse glass with AR coating are presented and discussed in the following pages. A summary of activities and results of the other tools and input reducing options are discussed after that.

Table 5. Developments tested at the greenhouse scale with a rose crop in Bleiswijk, The Netherlands

<table>
<thead>
<tr>
<th>Instrument / development</th>
<th>Specification</th>
<th>Potencial savings</th>
<th>Economic impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenhouse cover material</td>
<td>Diffuse Glass with AR coating (GroGlass)</td>
<td>Energy</td>
<td>10% less use of energy for supplementary light (from 5700 h to 5130 h.) saves 4,13 €/m² ⇒ 23,6 € investment capacity</td>
</tr>
<tr>
<td>Early pest / disease detection</td>
<td>Electronic nose (Warwick HRI)</td>
<td>Pesticides Labour</td>
<td>Reduction of 10% pesticide use saves 0,30 € /m² ⇒ 1,5 € investment capacity 0,25 h/m² year labour saved⇒ 5 € investment capacity</td>
</tr>
<tr>
<td>Precise irrigation</td>
<td>Sensor-model combination for monitoring transpiration (WUR PRI)</td>
<td>Water</td>
<td>Assumed is 5% watersavings by less mismanagement and early stress detection.</td>
</tr>
<tr>
<td>Rockwool plug in (small) slab</td>
<td>SPU (Grodan)</td>
<td>less substrate</td>
<td>Reduction of substrate by 20% saves 0,10 € /m² year</td>
</tr>
</tbody>
</table>
6.1% more production achieved under the diffuse glass with AR coating.

Diffuse glass (figure 3) disperses the direct light in the greenhouse making it diffuse, as it is in for instance a cloudy day. Such material contains pigments, macro- or microstructures, which are able to transform a fraction of the direct light into diffuse light; this fraction is called “the haze factor” and quantifies the diffusive effect of the material. Figure 4 shows three greenhouse compartments with respectively 0%, 30% and 70% haze. Depending on the design of the structure the incoming light scatters, the angle of incidence is changed. Efficient structures make the light diffuse without a significant reduction in light transmission. The small drawback in light transmission caused by the diffusing structure, can be efficiently overcome by an anti-reflection coating.

Figure 3. Diffuse glass disperses the light that enters the greenhouse

During the past six years Wageningen UR Greenhouse Horticulture has investigated the potential of diffuse covering materials used in Dutch greenhouses (Hemming at al., 2005A; Hemming at al., 2008B). The suitability of several greenhouse covering materials and their optical properties (PAR transmission: τ–direct and τ–diffuse, haze) was investigated in laboratories as well as in practice. Both in
cucumber and potted plant crops (Hemming at al., 2005B; Hemming at al., 2008A) diffuse covers resulted in a more effective photosynthesis and better quality. The many positive effects seen with other crops, gave good reasons to test this new materials with the most important and most energy-demanding ornamental crop in The Netherlands: roses.

The diffuse glass greenhouse cover with Anti Reflection coating on both sides of the glass was tested during a full cultivation year (see Box for experimental set up) with the variety Red Naomi!. The variety belongs to the Top-5 most cultivated varieties (see table 7) and it is known to be sensitive to high light intensities in summer. The properties of the glass used are shown in table 6. After a year of cultivation, we could conclude that indeed and as expected, the diffuse glass had a positive influence on the production of the cultivated rose cv Red Naomi!: Compared to the reference greenhouse (clear or reference glass), the diffuse glass compartment showed an increase in production of 5.2 % more flowers harvested representing 6.1% more fresh weight. (This is a good result, but the effect was lower than expected; this will be discussed further later).
average stem length, stem weight and bud length, as well as the vase life of the flowers after harvest were not affected by the glasshouse cover.

**Diffuse glass trial. Experimental set up**

<table>
<thead>
<tr>
<th>Reference Greenhouse 144 m²</th>
<th>Test Greenhouse 144 m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal glass</td>
<td>Diffuse glass</td>
</tr>
<tr>
<td>(0% haze, no AR coating, t=83%)</td>
<td>(72% haze, AR coating, t=83%)</td>
</tr>
</tbody>
</table>

Cultivar Red Naomi!
Substrate: rock wool with drip irrigation.
Heating: below the crop and supplemental light by SON-T lamps (15,000 lux, +/-170 µmol/m²s) 18 hours a day (max.). CO₂ supply (up to 800 ppm).
Integrated pest control. Climate and crop management (bending method and high harvesting) according to commercial practice. 5-minute climate data monitoring.
Harvest in commercial ripening stage once a day.

The diffuse anti reflection coated greenhouse glass cover made the light incidence inside the greenhouse less erratic, as it is to see in figure 5. Less often there were extreme high and extreme low light intensity values. In a similar tomato experiment that started just a few months later than the rose experiment, it was shown that also the horizontal distribution of the light in the greenhouse with diffuse glass was less erratic and more even, see figure 6.
Figure 5. The light as measured in both greenhouses on a nice sunny day in March 2010. The x-axis shows the time of the day; the y-axis shows the light intensity; the green line shows the outside radiation in W/m² along the day. The blue line is the Photosynthetic Active Radiation (PAR) inside the greenhouse covered with normal glass (reference) as measured by the PAR-sensor (in µmol/m²s). The red line shows the PAR-light as measured by the sensor in the diffuse greenhouse. Both greenhouses transmitted on average the same intensity of the light, but in the diffuse greenhouse there were less variations.

Growers experience with this variety is that at radiation levels at flower-bud level above 1000 µmol/m².s, the buds heat up too much (figure 7), and this causes quality damage of the crop. The damage consists of leaf tips burning and blue edges appearing on the petals (see figure 8). These quality related problems decrease the market value of the roses and therefore, in commercial greenhouses shade screens are used to reduce the radiation.

In our reference greenhouse, in consultation with the growers involved,
we adopted the commercial threshold for closing the screen of 600 W/m² outside radiation. In figure 5 it is visible that with the same outside radiation level, inside the greenhouse with diffuse light, the maximum PAR level measured is 200 µmol/m²s lower than the maximum light measured in the greenhouse with normal glass cover. The diffuse covering material reduced as a consequence, the difference between the bud temperature (measured with a hand-held IR device) and the air temperature (measured with a temperature sensor) (figure 9) on sunny days and the number of burned leaf tips. Unfortunately, this reduction was not enough to totally overcome bud overheating, so screening excess sunlight was still necessary. The good thing about the diffuse material was, that it allowed to screen less: In the glasshouse with the diffuse AR coated cover the sunscreen closed when the outside radiation reached 700 W/m², a 100 W/m² higher threshold than in the reference greenhouse. As a consequence, in the diffuse greenhouse the sunscreen was used about 150 hours less than in the reference greenhouse with clear (0% haze) glass.

Figure 6. Horizontal distribution of the light in a greenhouse with normal glass (0% haze), top graph, and in a greenhouse with diffuse glass (71% haze) with AR coating, bottom graph, on 2 sunny days.
From May onwards, as a consequence of the differences in screening regime, a difference in total light integral between both greenhouses occurred. These varied between 0 and 1.5 Mol/m² per day. Till the end of the experiment, the diffuse greenhouse received 2.7% more light than the reference greenhouse. If we consider the “light rule of thumb” by which 1% more light = 1% more production then the extra light sum would explain almost half of the total production improvement in the diffuse+ AR glazed greenhouse.

*Figure 7. A thermal image of a rose bud in the reference compartment at 14:52 in the afternoon on a sunny day. The colours in the circle indicate an average temperature of 30.9 °C, (about the same colour as the high young leaves). The green leaves transpire and maintain their temperature (spot) at 22°C*
Table 6. Transmission (perpendicular and hemispheric) and haze of the two cover materials and the overall transmission of the greenhouse compartment covered with each one

<table>
<thead>
<tr>
<th>Material</th>
<th>τ Perpendicular</th>
<th>τ Hemispheric</th>
<th>Haze</th>
<th>τ Compartment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>90</td>
<td>83</td>
<td>0</td>
<td>59</td>
</tr>
<tr>
<td>Diffuse</td>
<td>93</td>
<td>83</td>
<td>72</td>
<td>60</td>
</tr>
</tbody>
</table>

Having to control the temperature of flower bud and leap tips by means of sun screens implies a waste of natural light. An alternative method that, in combination with the diffuse glass allows a better control of the bud temperature would be a preferred solution. At a plant level, we experimented with extra air movement around the buds. With a (manual) ventilator, an air-stream of 1 m/s was created around the bud. After 4 minutes of additional ventilation, the bud temperature was
4 to 5° C lower than before the blowing.

In this experiment, there no differences found between the measured photosynthesis rate of the crop in the greenhouses with the different glass cover in none of the three measurements (November, January and May). Photosynthesis was measured both of the bent canopy, and of the horizontal stems (figure 10). In days with very high irradiation, is has been demonstrated (Dueck, Janssen and Thao, 2011) that under the diffuse glass (haze 71%), the photoinhibitive effect of high light intensities is considerably lower than under normal glass.

Figure 8. Crop damage as a consequence of (local) overheating. Left, leaf tips burning. Right: blue edges appearing on the petals. The use of screens to reduce part of the radiation helps to control the damage. Diffuse glass reduced the incidence and allowed to screen at a higher light intensity level.
Figure 9. The diffuse glass reduced during sunny weather the difference between the bud temperature (measured with a hand-held IR device) and the air temperature (measured with a temperature sensor).

**Diffuse glass with AR coating in rose cultivation: an economically feasible and impact reducing development.**

With the obtained increase in flower yield of 5.2 % more stems of equal to slightly better quality, the examined glass (tempered, by GroGlass double-sided AR coated Vetrasol 503) can be economically feasible (Ruijs et al., 2011), as it has been calculated that 1,5 % more production already can finance the extra investment costs necessary for this type of glass with a payback period of 4 year (Calculations based on price estimates by one supplier).

Despite the fact that for the production of the Diffuse glass with AR coating requires extra electricity, the environmental analysis (Torellas et al, 2011) has shown that with the obtained yield increase (it was calculated with 5%) the development had an obvious benefit reducing
environmental impacts of the production system. In terms of environmental impact this increase in yield compensated the extra energy required for the production of diffuse glass compared to standard glass. Environmental impacts were reduced around 4.6% to all considered impact categories.

Figure 10. The structure of a rose crop showing the two planes and ages of the canopy where photosynthesis was measured.

**Rockwool plugs and smaller slabs reduce substrate volume.**

The rose plants (Rosa hybrida cultivar ‘Red Naomi’) for the main Euphoros trial in Bleiswijk (The above mentioned experiment with a reference glass cover and a diffuse with AR glass cover) were propagated by cuttings using the Synchronization Method (Van Telgen et al., 2003) of Wageningen UR Glasshouse Horticulture in Rockwool plugs (Grodan). Once the plantlets were rooted they were planted in SPU (single production units) Rockwool blocks (Grodan) of 24x20x7.5 cm with 2 plants per block (Figure 11, left). The reference situation (normal commercial practice, figure 11, right) consists of +/- 4 rockwook blocks for propagation which are placed at planting on top of the substrate slab (100x12x7.5 cm) with rockwool (Grodan). The used system saves 20% substrate compared to the reference.
The reduced size of the units allow also extended propagation of the plants and transport of the productive plants (figure 12) to the experimental compartments, instead of planting small plants directly on the slab.

Figure 11  Left, plants directly after planting in Grodan SPU; right, reference situation (traditional).

Figure 12: young productive plants after extended propagation are being transferred to the trial compartments

The economic evaluation (Ruijs et al., 2011) showed that the reduction of substrate volume with SPU results in a saving of 0,10-0,16 €/m² depending on the SPU option. A sensitivity analysis of the substrate price points out that the savings (difference in yearly costs
between the option and the standard cultivation system) are not very much affected, because of the four year cultivation period.

The environmental impact analysis (Torrellas et al., 2011) confirms that lower use of substrate volume produced significant reductions in auxiliary equipment (20.6% in cumulative energy demand) but had a small effect in the total production system (4.8%). This kind of results would make difficult to convince growers to implement an alternative that gives little environmental improvements in the production system and on the other hand requires extra effort in agricultural practices. However, substrate volume reduction must be equally encouraged to move to more environmental friendly practices.

**Monitoring rose crop transpiration by means of a model-sensor combination requires further adaptation of the model.**

In the rose experiment in Bleiswijk 2 weighing gutters of 2 m length each were installed in the greenhouses in order to monitor transpiration. The transpiration data can be compared to a model and deviations of the model can help the grower to detect accidental water stress.

The transpiration in both greenhouses (diffuse glass and normal glass) was very similar throughout the time.

Preliminary experiments by Driever, S. (2010) had shown that the tomato transpiration model of Stanghellini and the measurement of the gutters were rather different, as shown in figure 13. There was a large deviation between the calculated and the measured transpiration during most days, larger than would be expected (e.g. as previously observed for tomato)
The hypothesis to explain the observed discrepancy was that the stomatal resistance for roses behaves differently on radiation than tomato. From figure 13 it follows that the calculated transpiration is reacting much faster on increasing or decreasing radiation than the measured transpiration. So the stomatal resistance ($r_s$) for roses should have as function of the net radiation with a much less steeper slope, for example as shown in figure 14.
This alters the function for stomatal resistance to radiation and thus the resulting calculated transpiration. When this new function for the stomatal resistance was applied, the calculated resistance showed a more similar set of values when compared to the measured transpiration, as shown in figure 15. With the new function for stomatal resistance, the model-sensor combination for transpiration can now be used for both tomato and rose crops.
Figure 15. Transpiration of a rose crop in a commercial greenhouse, calculated with the model of Stanghellini with a modified relationship between net radiation and stomatal resistance (Model CS, blue line) and measured by the Pro Drain weighing gutter system (Pro Drain, red line) for the period of June 9th to June 16th 2010.

At the moment of writing this chapter, a post-doc student is working, based on the showed preliminary results by Driever, on an adapted version of the tomato model for roses. The main adaptation is the use of empiric values for stomatal conductance and leaf area index obtained during the photosynthesis measures.

Electronic pest detection in rose: promising, but not ready for implementation yet.

Several techniques for automated detection of pests and diseases in greenhouse tomato and rose crops have been considered and investigated, ranging from indirect, lab-based molecular diagnostics to direct, real-time imaging and volatile sampling. Based on initial trials and their projected cost to users, two volatile sampling techni-
ques were selected for further evaluation, the Electronic nose (figure 16) and the FAIMS (figure 17). They have been tested in the laboratory, in commercial greenhouses and also in the rose greenhouse trial in Bleiswijk. In laboratory-scale trials high accuracies were achieved, but in commercial environments the instruments have achieved at best 86% accuracy in distinguishing control plants from infected (disease) and infested (a range of pests) plants. Whilst the laboratory tests show that the technologies can deliver under closely controlled conditions, the instruments are not yet sufficiently reliable in the more variable commercial world for immediate adoption by the protected cropping industries.

Figure 16. An Electronic nose (Cyranose 320 E-nose), linked to a PC for continuous data streaming was tested in the rose crop. The nose needs 5 minute to analyse a sample and has a battery duration of only 1 hour. Although it shows a reasonable accuracy in pest detection, the speed and autonomy need to be improved for implementation.

In order to provide the industry with a pest and disease alert system based on VOC biosensors further development work in a num-
ber of key areas will be necessary. Sampling protocols need to be improved in order to allow more rapid and consistent sampling. The time per sample is currently approximately 1 minute. Further reduction in sampling time could be possible only for the FAIMS device, using a small number of targeted DF values. Such refinement and honing are normal actions taken by the manufacturers once they commit to a target industry. The horticultural sector will need to indicate sufficient desire if the company are to invest in this way. Also necessary will be further integration of the instrument with the intelligent systems software that will interpret the data. These processes must be synchronised and iterative to produce a bespoke, robust and reliable device.

Figure 17. A FAIMS Lonestar with off-line processing of data. Although the identification accuracy of pests was rather high (96%), its actual size and required analysis time (5 minutes) make it unsuitable for the purpose of electronic pest detection. They both need improvement in order to be implemented in practice.
Acknowledgements

Thanks to everyone that has contributed in one way or another to the evaluation of Euphoros developments and tools with an application in rose cultivation in The Netherlands.

Colleagues at WUR Glasshouse horticulture

- Cecilia Stanghellini
- Frank Kempkes
- Tom Dueck
- Peter van Weel
- Nico van Mourik
- Peter Lagas
- Yafei Zhao
- Mary Warmenhoven
- Vida Mohammadkhani
- Rozemarijn de Vries
- Barbara Eveleens
- Jan Willem de Vries
- Peter Schrama
- Gerard Van der Broek
- Rob Pret
- Hugo Godron
- Jan Janse
- Peter Lagas
- Vida Mohammadkhani
- Li Thao
- Johan van der Eijk
- Margreet Bruins
- Steven Driever
- Marc Ruijs
- Eric Poot
- Silke Hemming
- Juliette Pijnakker
- Ada Leman
**Financers and suppliers**

- Ministery EL&I
- Asociación holandesa de Productores hortícolas PT
- GroGlas, Glascom, HoGla, Guardian, Grodan
- Cultivadores y otras partes involucradas.
- Marc van der Drift
- André van Marrewijk
- Richard van der Lans
- Edwin van der Knaap
- Ad Schapendonk

**Growers and other stakeholders**

- Marta Torrellas
- Juan Ignacio Montero
- Assumpció Antón
- Esteban Baeza
- Juan Carlos López
- Daciana Ilescu
- Richard Napier
- Sacha White
- Ad de Koning
- Alberto Pardossi
- Luca Incrocci
- Juris Oleiniks
- Áron Balint
References and literature


García Victoria, N., Baeza, E.J., Balint, A., 2009. Feed-back from growers and experts about Euphoros tools. A combined report from experts meetings in three testing sites: Almería (Spain), Morahalom (Hungary) and Bleiswijk (The Netherlands). EUPHOROS Deliverable 4 (WP 6)


Reich, P.B., Ellsworth, D.S. and Walters, M.B., 1998. Lead structure...
(specific leaf area) modulates photosynthesis-nitrogen relations: evidence from within and across species and functional groups. Functional Ecology 12, 948-958.


GTB-1010. Wageningen UR Greenhouse Horticulture.
ENERGY AND VENTILATION

Esteban Baeza
Universidad de Almería
Juan Ignacio Montero
IRTA, Càbrils, Barcelona

PART 1.
POSSIBILITIES FOR USAGE OF THERMAL STORAGE

1.1. Introduction

During the last decades, there has been an escalation worldwide in the reliance on greenhouse products for vegetables [and for ornamentals]. This has spawned an enormous increase in production that has been achieved through intensification [productivity per unit area] in The Netherlands [Northern/Central Europe] and an increase in production area in mild environments such as the Mediterranean region. As an example, productivity of Dutch round tomatoes has increased by around 2% a year, from 42 kg/m² in 1990 (Ruijs et al., 2001) to 64 kg/m² in 2010 (Vermeulen, 2010) with a nearly constant greenhouse area of 11000 ha in The Netherlands. On the other hand, in Spain the gre-
enhouse area has grown from 28,000 ha in 1990 to more than 45,000 ha in 2007 mainly concentrated in the South of Spain. The increase in productive area rather than productivity in the Mediterranean region is caused by the limited means to control the environment in the low-cost/low-tech greenhouses typical of the region.

However, both these developments are unsustainable: the Dutch greenhouse sector relies on huge amounts of energy to warrant the perfect climate that can ensure such productions (1/3 of the production costs for a typical grower, and 7% of the gas use of The Netherlands (Euphoros consortium, 2010), whereas plastic covers more than 33% of the area of at least 4 municipalities of the province of Almería and more than 20% of the whole provincial area (Fernández Sierra & Pérez Parra, 2004). Therefore the Dutch government has required the local greenhouse sector to reduce energy use by at least 2% a year (whereas in Spain productivity will have to increase, without increasing reliance on resources. There is much scope for increasing productivity. The requirement is to find a good economic compromise between high investments in greenhouse structures and equipments and their productive performance, without notably increasing the use of inputs, especially energy, which is the main advantage most of the greenhouses in the Mediterranean area (Castilla, 2003).

In spite of the appearance, the solutions being investigated in both northern and southern greenhouse areas are based on the same principle that is a much better use of the sun energy. The greenhouse itself is by definition a sun collector (i.e. Garzoli and Shell, 1984), in which only a small fraction of the energy intercepted by the greenhouse (solar radiation) is transformed into dry matter by the plant's photosynthesis process. The greenhouse annually collects from the sun two to three times the energy needed for heating during wintertime, depending on location of the greenhouse (Heuvelink et al., 2008; Bot, 1994). The excess energy stored in the greenhouse as sensible and latent heat (water vapour transpired by the plants) is usually ventilated away (generally by means of natural ventilation) which is the
cheapest and easiest method to cool the greenhouse, both at southern and northern latitudes. Therefore all the energy evacuated through the greenhouse vents, is not stored and thus not available to heat the greenhouse when needed during the winter period.

Improving temperature management in winter in the Mediterranean greenhouses can be accomplished with different methods. Passive techniques such as improving the greenhouse soil energy storage capacity during the daytime (i.e. mulching) and the use of different types of fix or movable energy saving screens to reduce heat losses are often used in Mediterranean and Northern greenhouses and the optimum combination and management of these techniques is still a matter of research nowadays.

If the excess energy could be stored away (thermal storage), there would less/no need for natural ventilation and the recovered energy could be used when needed (closed greenhouse concept). Suggested technologies for heat storage are water tanks, underground aquifers (Heuvelink et al., 2008; Opdam et al., 2005), the ground (Mavroyanopoulos & Kyritsis, 1986), or phase-change materials (Öztürk, 2005; Kürklü, 1998). As the annual solar radiation influx by far exceeds the heating demand, a fully closed greenhouse (no ventilation at all) with seasonal storage would produce surplus heat, which could be used for other buildings (Bakker et al., 2008).

Closing the air cycle of the greenhouse (reducing ventilation) provides other benefits from an environmental point of view. Reduced ventilation allows the CO2 concentration to be increased to 1000 ppm which can increase crop yield by 22% (De Gelder et al., 2005). In addition, limiting ventilation reduces need for chemical pest control thanks to the reduced risk of contamination from outside. Van Os et al. (1994) calculated that 30-50% of the pesticides applied leave the greenhouse via ventilation. Another great advantage of limiting ventilation is the lower water use due which can be reduced by even a factor 10.

In The Netherlands, commercial greenhouses already exist
which use the confined aquifers as a heat store (a cold and a warm store) combined with the use of heat pumps, cooling tower and high efficiency air/water heat exchangers inside the greenhouse. But considering the high cooling requirement for the closed greenhouse operation in the Mediterranean summers, a completely closed greenhouse might be too costly, if sizing a full capacity cooling system is required. Therefore, the concept of a semi-closed greenhouse is introduced. The percentage of time a greenhouse requires no ventilation is an indicator of the closure rate. The difference between a closed greenhouse and a semi-closed greenhouse is that the former has a 100% closure rate, while the latter has a lower closure rate.

The challenge is therefore to develop a method that can be used to calculate and design a technically feasible system based on the use of water thermal storage for the Mediterranean area which optimizes the use of energy and that is able to maintain the greenhouse closed for as much time of the growing cycle as possible. For this, the first step has been to develop a greenhouse model in a spreadsheet capable of estimating the heating and cooling requirements and design the thermal storage system

1.2 HortiAlmeria: a greenhouse energy and climate model

The model is based on the Horticern greenhouse energy model developed by Jolliet et al. (1991) and includes the treatment of humidity and transpiration used in the Hortitrans model (Jolliet, 1994). It predicts greenhouse air temperature and humidity, estimates the heating, ventilation and mechanical cooling requirements, and the water consumed by evaporative cooling. Transpiration of a tomato crop can be estimated using either a model developed at Estación Experimental de la Fundación Cajamar or the Hortitrans model. The model includes the short term storage of energy removed by mechanical cooling for subsequent heating. The model also includes modules which estimate the energy available from the wind including heat storage, and solar (photovoltaic) energy. A photosynthesis module for tomatoes is inclu-
ded which enables the economics of CO2 enrichment to be assessed. Although the model is steady state, predictions of the heat transfer into and from the soil have been included based on measurements made at Estación Experimental de la Fundación Cajamar. The model calculates hourly values of the greenhouse conditions and control inputs in response to hourly values of external air temperature and relative humidity, solar radiation and wind speed, and a value for the black body sky temperature. The model is implemented in Excel.

**The model structure** is shown in Fig. 1. The environment model requires weather data and data to characterise the greenhouse, crop and for the environmental control settings. This model interacts with modules that determine the heating and cooling necessary to create the desired environment. Energy removed by mechanical cooling can be stored and used for heating. Together these form a complete model to predict the greenhouse inputs and the environment created. The external modules for wind energy, photovoltaic electricity and CO2 enrichment are linked to the main model only to obtain the input data each requires. Parameters required by the modules are inserted into the area of the spreadsheet where the module is located and where the outputs are displayed. The main model is contained in the Excel file **HortiAlmeria.xls** and the applications in Excel file **Applications.xls**.

![Fig. 1. Estructura del modelo de invernadero](image-url)
1.3 Semi-closed greenhouse: observations on design and estimates of performance of a water thermal storage system.

The analysis was made using the HortiAlmeria greenhouse model for the following conditions:
Almeria weather data from 1 August 2005 to 31 May 2005 (weeks 1 to 44).
Greenhouse with 6, 8 m spans 20 m long, 4 m to gutter, roof angle 30o.
Tomato crop with LAI=3, assumed to be in a steady state condition.
Time step of model 1 hour.
Perfect heat transfer between greenhouse and energy store i.e. no restrictions on heat transfer coefficients and no losses from the energy store.
Greenhouse CO2 concentration 1000 vpm during the day except when ventilation is required when the concentration is 380 vpm.
Heating temperature 12oC, ventilation temperature 27oC.
Greenhouse light transmission 75%.
Shade screen providing 30% shade (when used).
Prices: propane 0.8 €/kg, electricity 0.2 €/kWh, CO2 0.18 €/kg, tomatoes 0.6 €/kg, tomato crop production 15 kg/m2.

1.3.1 Winter use

1.3.1.1 Single energy store no heat pump

This uses a single energy store to provide cool water for cooling the greenhouse. During the day the water temperature rises and the cooling rate reduces. At night the warm water is used to heat the greenhouse which reduces the water temperature so the store can provide cooling during the following day. The cooling system in the greenhouse acts as both cooler and heater.

a) Energy store. The influence of energy store capacity on the energy provided for heating is shown in Fig. 5. The optimum size of store is 3 to 4 MJ/m2 which provides 83 to 87% of the energy required for heat-
ting a long tomato crop cycle during 2004/05

Fig 5. Influence of energy store capacity on heat demand of experimental greenhouse.

The greenhouse covers a ground area of 960 m², so the capacity of an energy store for the whole house is $3.5 \times 960 = 3360$ MJ. Using water as the heat storage medium and assuming the temperature difference between the full and empty store is 15°C, requires a store with a volume of 46 m³. For a cylindrical store the dimensions could be:

- Height 2 m
- Diameter 5.8 m

Initially only one compartment of the greenhouse will be heated and cooled. With a tank of this diameter the depth of water required for one compartment will be 0.33 m.

b) Insulation of energy store

The heat transfer from the surface of this size of tank when full would be approximately 100 W/K assuming the tank is not exposed to the sun. There would be a heat gain when the store temperature was lower than ambient air and vice versa. Simulations showed that insulating the tank reduced the heat requirement from 108.5 to 99.8 MJ/m² (reduction of 6%) but also reduced the profit from CO2 enrichment from 0.54 to 0.52 €/m² (reduction of 3%).
1.3.1.2 Heat pump with hot and cold energy stores.

This system uses a cold store to absorb energy from greenhouse cooling and a hot store to provide energy for heating. Energy is transferred from the cold to hot stores by a heat pump which operates continuously whenever the cold store is not empty and the hot store is not full.

a) Heat pump

The power \( Q_p \) used to drive a heat pump is given by:

\[
Q_p = \frac{Q_d}{COP} \quad (1)
\]

where \( Q_d \) is the energy delivered to the hot store and \( COP \) is the coefficient of performance of the heat pump.

In practice the \( COP \) can be expressed as:

\[
COP = \eta \times 0.5 \frac{Th + Tc}{Th + \Delta Th - (Tc - \Delta Tc)} \quad (3)
\]

where \( \eta \) is an efficiency factor, \( Th \) and \( Tc \) the absolute temperatures of the hot and cold stores, and \( \Delta Th \) and \( \Delta Tc \) the temperatures differences associated with the heat pump condenser and evaporator heat exchangers. The \( COP \) is highest if the denominator in this equation is made as small as possible. The operating cost of the heat pump is directly related to its power consumption \( Q_p \).

b) Heat Store Capacity

The effect of energy store capacity on greenhouse energy consumption, which includes energy to drive the heat pump and to meet shortfalls in the energy available from the heat store, is shown in Fig. 6. The two curves are for different sizes of heat pump which transfer heat at different rates between the cold and hot stores. The energy used to drive the heat pump was obtained using Eq (1) with COP values of 4 and 8. The latter is higher than is usual for heat pumps used in space heating, however, it was chosen because of the low temperature differences possible with the Heat exchange units. Equation (1) shows that the product of \( COP \times Q_p \) is the energy delivered to the hot store. For the conditions of this analysis the latter is a constant (equal to 32 W/
m2) which is defined by the conditions. Thus if the Cop is 6, the power required for these conditions will be $32/6 = 5.3 \text{ W/m}^2$.

![Graph showing the influence of energy store capacity on heat demand of experimental greenhouse.](image)

**Fig. 6. Influence of energy store capacity on heat demand of experimental greenhouse**

The cost of energy with the heat pump system is the cost of the electricity used to drive the heat pump plus the cost of gas used to provide heating which cannot be met by the hot store. Figure 7 shows the energy costs for:

- reference greenhouse – with a conventional propane fuelled heater
- greenhouse with single energy store of 3.5 MJ/m2
- greenhouse with the two different heat pumps

The air leakage rates were calculated as $0.5 + 0.25w$ air changes per hour. The energy costs do not include the operating cost of the fans and pumps required for heat collection and reuse in (ii) and (iii). These costs are likely to be similar for both options.
1.4. CO₂ enrichment

CO₂ enrichment will be thoroughly addressed by other teachers in this Course, so it is just briefly mentioned here.

When the cooling system provides sufficient cooling and ventilation is not required the greenhouse can be enriched with CO₂ to 1000 vpm. When the cooling requirement exceeds the capacity of the cooler, ventilation then provides all the cooling and the CO₂ level is equal to the external concentration of 380 vpm. The influence of the energy store capacity (single energy store option) on the total amount of net photosynthesis during the whole period is shown in Fig. 8. If it is assumed that tomato yield is proportional to total net photosynthesis this suggests the potential yield increase is approximately 8%.
CO2 enrichment is influenced very strongly by the greenhouse air leakage rate and also by its transmission of solar radiation. The air exchange rates shown result from leakage rates of respectively, zero, $0.125+0.0625w$, $0.25+0.125w$, $0.375+0.1875w$ and $0.5+0.25w$ where $w = \text{wind speed}$. For leakage rates higher than $0.25+0.125w$ air changes per hour CO2 enrichment appears not to be economic with current CO2 and tomato prices. This diagram is intended only to show the relative changes between the enrichment made possible by closing the greenhouse during the periods when energy can be collected and removed from the greenhouse thus eliminating ventilation. The reference condition is a greenhouse without heat collection for which enrichment is only possible for daylight hours when ventilation is not required. In this respect there is little difference between greenhouses with 65% (0.65) and 75% (0.75) light transmission. When heat recovery was used the biggest profit is obtained from the 65% transmission house, which is a consequence of the larger cooling requirement of the house with the higher light transmission. As the heat recovered is fixed by the greenhouse heating demand the enrichment time is reduced in the greenhouse with the higher light transmission.
1.5 Design parameters: Heat exchange cooler/heater units

1.5.1 Number of heat exchanger units required

The information obtained on the performance of the heat exchange units were the heat transfer rates (W/K) for cooling and heating at the maximum (400 W fan power) and 75% of the maximum (150 W fan power) air flow rates. In operation the fan speed and the flow rate of water from the energy stores are both varied to match the output to the greenhouse cooling and heating requirements.
Figure 10 shows the additional heating energy required by the greenhouse is influenced by the number of heat exchange units per span (160 m²) of the experimental greenhouse. Most of the potential benefit is obtained using three units. The figure also indicates that the optimum size of heat store may be higher than the value of 3.5 MJ/m² deduced from Fig. 5.

For the summer operation, energy recovered from the greenhouse during the day which is not required at night for heating must be dissipated so the energy store has capacity to accept more energy the next day. In summer no heating is required and so all the energy collected has to be removed from the energy store.

1.5.2. Cold and hot energy stores with heat pump.

The cold store provides water to cool the greenhouse and the heat pump transfers the energy to the hot store in order to maintain the
cold store temperature. The heat transferred to the hot store has to be transferred to the outside air during the night.

![Energy store capacity over day number graph](image)

**Fig. 11. Sizes of hot and cold water stores required for greenhouse cooling**

Figure 11 shows how the store capacity depends on the daily integral of the solar radiation entering the greenhouse. The hot store has a higher capacity than the cold one because it has also to accommodate the energy used to drive the heat pump. The hot store capacity was based on a heat pump with a COP for heating of 4. Figure 11 can be used to determine the required store capacity. The day with the highest solar radiation during the period when the greenhouse is to be cooled is used to identify the capacities of the hot and cold stores. The downward spikes in the curves (days with clouds) should be ignored and values taken from the maximum values which relate to radiation from clear skies.

**1.6 Experimental semi-closed greenhouse at Estación Experimental Las Palmerillas**

The results presented in this section refer to a greenhouse covering an area of 1000 m².
1.6.1 Energy store

Daily values of the energy recovered by cooling the greenhouse, consumed by the heat pump and transferred to the outside air without and with 30% shading are shown in Fig. 12 and the heat transfer rates in Fig. 13.

The energy stores have to accept energy from the greenhouse cooler which is a maximum at mid-day while the heat removal rate by the heat pump is constant over 24 hours. The energy store capacities for operation in mid summer are given in Table 5.

Fig. 12. Energy collected from the greenhouse, consumed by the heat pump (COP 4) and dissipated to the outside air from a 1000 m² greenhouse (a) with no shading and (b) with 30% shade.
Fig. 13. Average rates of energy collection from the greenhouse, consumed by the heat pump (COP 4) and dissipated to the outside air from a 1000 m² greenhouse (a) no shading and (b) 30% shade.

Table 5. Capacity of energy stores for 1000 m² greenhouse in mid summer

<table>
<thead>
<tr>
<th></th>
<th>No shade</th>
<th>30% shade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MWh</td>
<td>m³</td>
</tr>
<tr>
<td>Cold store</td>
<td>5.2</td>
<td>300</td>
</tr>
<tr>
<td>Hot store</td>
<td>6.4</td>
<td>365</td>
</tr>
</tbody>
</table>

The heat transfer rates for cooling and dissipation were obtained using the durations of the day and night; the heat pump operated continuously provided the stores permitted energy transfer.

These stores are capable of accepting all cooling energy produced during a summer day provided this energy plus the energy used to drive the heat pump can be dissipated during the following night.
1.6.2 Heat pump

In summer the heat pump has to transfer all the energy collected from greenhouse cooling from the cold to the hot stores so the heat pump capacity is determined by the total daily solar radiation received in the greenhouse. By operating the heat pump continuously its capacity is minimised. Table 3 shows the amount of energy that has to be transferred from the cold to the hot stores during a day in mid summer for a greenhouse of 1000 m² and the rate of heat delivery by the heat pump (COP = 4) to the hot store when operated continuously..

<table>
<thead>
<tr>
<th>Maximum energy to be upgraded, MWh/day</th>
<th>No shade</th>
<th>30% shade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate of heat transfer by heat pump, kW</td>
<td>110</td>
<td>75</td>
</tr>
</tbody>
</table>

From this Table the capacity of the heat pump required for a 1000 m² greenhouse is shown to be 110 kW if there is no shade or 75 kW when there is 30% shade.

1.6.3 Dissipating energy from the hot store using a cooling tower.

A cooling tower transfers energy from water to ambient air which is moved through the tower by a fan. Some cooling towers can be operated in both dry and wet modes. In the latter, water is sprayed over the cooling coils to increase the rate of heat transfer which increases the cooling rate but some water is evaporated. The tower normally operates in the dry mode and changes to the wet mode when the performance becomes low; which makes for efficient use of water. The additional cooling obtained in the wet mode is related to the wet bulb temperature of the ambient air. Figure 14 shows the dry and wet bulb temperatures of the ambient air for Almeria and indicates that using a wet cooling tower provides an additional 4 to 5° C for cooling.
Estimates were made of the energy which needs to be rejected from a greenhouse with an area of 1000 m² with no shading and with shading of 30% using Almeria weather data for 2005. The solar radiation received inside the greenhouse (light transmission 75% with no shading and shading of 30%) during the day was used to determine the total energy to be rejected (Fig. 15) and the average energy rejection rate (Fig. 16) during the night.

The COP of the heat pump was 4. The store capacities for specific time periods can be obtained from Fig. 13.
1.4.7. Conclusions

Cooling and heating the 160 m² experimental compartment in winter

It is estimated that 3 Heat exchange heat exchangers are required in the 160 m² compartment when a single energy store is used. Placing one Heat exchange unit under the ridge at one end of the greenhouse with the air directed along the greenhouse axis, with the other two units at the opposite end of the greenhouse 2 m from the side walls and angled so that the air is discharged at an angle of 5-6° from the greenhouse axis appear to be suitable locations for the Heat exchange units.

As there is limited space in the experimental compartment above the crop and between adjacent Heat exchange units it suggested that the units should be mounted so their outlets can be adjusted by 5° in the vertical and horizontal planes to enable adjustments to be made based on the air flows achieved in practice.
Cooling and heating a 1000 m² greenhouse in winter

Using a single heat store to provide both cooling and heating appears to be more economic than using two heat stores and a heat pump. The optimum capacity of the single energy store is 3500 MJ which is provided by 56 m³ of water (tank 2 m high and 6.0 m diameter). With this size of energy store, cooling the greenhouse during the heating season reduces the duration of ventilation from 1480 to 930 hours, a reduction of 550 hours.

The estimated increase in tomato crop value resulting from raising the CO₂ concentration to 1000 vpm when the greenhouse requires no ventilation is €300.

The economics of CO₂ enrichment depend strongly on the air leakage of the greenhouse. The reduction in heating cost is estimated to be €3800, but the cost of electricity used in the collection and reuse of energy has not been included.

Cooling a 1000 m² greenhouse in summer.

The capacity of the cold energy store is 5.2 MWh (300 m³ water) if the greenhouse has no shading and 4.6 MWh (265 m³ water) with 30% shade.

The capacity of the hot energy store is 6.4 MWh (365 m³ water) with no shade and 5.2 MWh (300 m³ water) with 30% shade.

The heat pump output is 110 kW with no shading and 75 kW with 30% shade.

The heat transfer rate of the cooling tower is 1100 kW with no shading and 750 kW with 30% shade.
PART 2. DECISION SUPPORT SYSTEM FOR OPTIMUM VENTILATION MANAGEMENT

The aim of this task is to develop a decision support system for minimizing the necessity of ventilation (energy and pest management), while improving crop productivity, also through CO2 fertilisation.

2.1 Development of a method to determine required natural ventilation capacity in view of the local climate conditions and the properties of the cover.

2.1.1. Introduction.

Greenhouses frequently require ventilation to prevent overheating during the day and to reduce humidity. The majority of greenhouses employ natural ventilation in which the ventilation airflow occurs through ventilators in the roof and walls. The flow of air is created by the difference between the inside and outside air temperatures and by the external wind. The important characteristics of a greenhouse natural ventilation system are, the total area of the ventilators, their position on the greenhouse i.e. only in the roof or in the roof and walls, and their location relative to the direction of the wind. This ventilation decision support system is intended to assist in making the following decisions:

- What area of ventilators is necessary in relation to the local climate and required ventilation temperatures?
- What benefit is obtained by shading in reducing the ventilation requirement?
- During which months can acceptable temperatures be achieved?

An energy balance model is used with local climate data to determine the ventilation airflow required to maintain a greenhouse at selected ventilation temperatures. Ventilation models which relate the airflow through greenhouse ventilators to the internal and external temperatures and wind speed, and to ventilator geometry are then used.
to determine the area of ventilators necessary to provide the required airflow.

The effect of applying shading to the greenhouse in summer to reduce the cooling requirement and thereby improve the effectiveness of ventilation is included.

The information on the required ventilation area is presented as the number of hours (per calendar month and per year) in which the greenhouse temperature exceeds the selected ventilation temperature.

### 2.1.2 Ventilation requirement

The greenhouse energy balance model is based on the Hor-tiCern and HortiTrans models described by Jolliet et al. (1991) and Jolliet (1994) and is executed in a spreadsheet. The energy balance of a greenhouse is expressed as:

\[
Q_{\text{solar}} + Q_{\text{conduction}} + Q_{\text{soil}} + Q_{\text{ventilation}} = 0
\]

where
- \(Q_{\text{solar}}\) is the solar energy transmitted into the greenhouse,
- \(Q_{\text{conduction}}\) the heat conducted through the greenhouse cover,
- \(Q_{\text{soil}}\) heat transferred to/from the soil,
- \(Q_{\text{ventilation}}\) the energy removed by ventilation.

\(Q_{\text{solar}}\) is calculated using the external global solar radiation, a transmissivity value for solar radiation which depends on the greenhouse cover material and an allowance for solar energy absorbed by the cover.

\(Q_{\text{conduction}}\) is calculated from the energy exchanges between the cover and the sky, the cover and the external air and between the cover and the inside air.

\(Q_{\text{soil}}\) is obtained from data recorded in an uncropped greenhouse at Estacion Experimental de la Fundación Cajamar.

\(Q_{\text{ventilation}}\) is obtained from energy and water vapour balances of the ventilation air.

\[
Q_{\text{ventilation}} = Q_{\text{sensible heat}} + Q_{\text{latent heat}}
\]

where \(Q_{\text{sensible}}\) and \(Q_{\text{latent}}\) are the sensible heats trans-
ferred by the ventilation air respectively, $Q_{\text{transpiration}}$ is the energy contained in the water vapour transpired by the greenhouse plants and $Q_{\text{condensation}}$ is the energy transferred to the greenhouse cover by the condensation of water on the inner surface. Transpiration was calculated using a model developed at Estacion Experimental de la Fundación Cajamar for a tomato crop. Condensation was estimated using the method developed by Jolliet (1994) in which the cover temperature was calculated assuming the internal air was saturated and then a correction applied based on the actual internal vapour pressure. Condensation occurred when the internal vapour pressure exceeded the saturated vapour pressure at the cover. If the external temperature exceeded the ventilation temperature, the greenhouse temperature was calculated using a maximum value for the ventilation heat transfer coefficient of 100 W m$^{-2}$ K$^{-1}$ (equivalent to a ventilation rate of 0.82 m$^3$ m$^{-2}$ s$^{-1}$).

The effect of shading is included by changing the solar radiation transmission of the greenhouse cover.

The model is used with weather data sets consisting of hourly values of air temperature, solar radiation, relative humidity and wind speed to calculate hourly values of greenhouse temperature and the ventilation airflow required to maintain the greenhouse at selected ventilation temperatures. The ventilation airflow rates are expressed per m$^2$ of greenhouse ground area.

2.1.3 Ventilation models

Numerous models have been developed to predict ventilation air flow through different designs of ventilators, ventilator positions and types and sizes of greenhouse. Some include both the effect of temperature difference and wind speed in creating the ventilation air flow, others only include the wind effect. Models have been created for flap and rolling ventilators in curved roof and pitched roof greenhouses and also in the sidewalls. Three different models have been used to deve-
lop this decision support system. Between them they encompass flap ventilators in the roofs and walls, curved and pitched roof greenhouses, and the use of temperature difference combined with wind speed and wind speed on its own.

The model of Boulard and Baille (1995) was developed for a 416 m², 2 span, film covered greenhouse with continuous ventilators on one side of each curved roof. It used both temperature difference and wind speed in predicting the ventilation air flows. The primary wind direction was parallel to the longest side walls.

Kittas et al (1997) created a model for the above greenhouse but included air flow through both the roof ventilators and continuous flap ventilators in the two 32 m long sidewalls. This model also included both temperature difference and wind effects.

The model of Bailey et al. (2004) was developed using a 1/3 scale model Venlo greenhouse with discrete panel ventilators spaced along alternate sides of each ridge and then validated on 200, 5200 and 37,800 m² Venlo greenhouses. Sidewall ventilators are not included and the model uses only wind speed in estimating the air flow.

The ventilation rates predicted by each model were expressed per m² of ventilator area.

### 2.1.4 Results

The energy balance model and the ventilation models were used with weather data recorded at hourly intervals during 2007 at the Estacion Experimental de la Fundación Cajamar, in southern Spain and weather data for the Netherlands also for 2007. By dividing the required ventilation rate (m³ / m² s) given by the energy balance model by the ventilation rate given by the ventilation models for the same temperature and wind value (m³ / m² s) the ventilator area required
to provide the ventilation air flow for that hour is obtained \((\text{mv}^2 / \text{mg}^2)\).

The transmissivity of the greenhouse cover for solar radiation was taken to be 90% which applies to glass and standard greenhouse covering films. This resulted in a transmissivity for the greenhouse of 65%. When shading in the form of whitening applied to the cover, the cover transmissivity was 28% which gave the greenhouse a transmissivity value of 25%.

![Diagram]

**Fig. 17. Ventilator areas required to achieve 26°C in a greenhouse in Southern Spain in 2007**

Figure 17 shows how the total number of hours in the year when the greenhouse temperature exceeds the ventilation temperature (in this case 26°C) reduces as the total ventilation area increases. There is reasonable agreement between the results from the different ventilation models so the average of the three values is used.

The results, given in the Appendix, are presented in tabular and are grouped according to:

- location i.e. climate data
• ventilation temperature

• shade / no shade

Table 7 is an example of one of the tables. For the specified ventilation temperature, location, shade configuration and range of total ventilator area / greenhouse ground areas between 0 and 1, the number of hours when the temperature during each month exceeds the ventilation temperature is shown. The number of hours when the external temperature exceeds the ventilation temperature during each month is shown at the top of the Table. The final column gives the number of hours during the year when the greenhouse temperature exceeds the ventilation temperature for each ventilator area ratio.
Table 7. Typical output table, enabling assessment of ventilator areas.

<table>
<thead>
<tr>
<th>Ventilation temperature</th>
<th>26 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Almeria 2007 weather</td>
<td></td>
</tr>
</tbody>
</table>

No shading

<table>
<thead>
<tr>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>52</td>
<td>138</td>
<td>324</td>
<td>373</td>
<td>140</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>1036</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vent area / g'house area</th>
<th>Hours when greenhouse temperature is higher than ventilation temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000 209</td>
<td>211 287 306 378 386 403 397 321 284 228 212 3622</td>
</tr>
<tr>
<td>0.005 154</td>
<td>172 235 247 341 363 397 371 292 238 188 3138</td>
</tr>
<tr>
<td>0.010 96</td>
<td>146 197 201 306 348 391 357 274 210 149 2774</td>
</tr>
<tr>
<td>0.025 17</td>
<td>89 99 126 267 313 362 342 240 162 74 2116</td>
</tr>
<tr>
<td>0.050 0</td>
<td>45 33 64 222 301 349 334 226 133 14 2 1723</td>
</tr>
<tr>
<td>0.075 0</td>
<td>18 9 37 196 280 341 327 210 103 4 0 1525</td>
</tr>
<tr>
<td>0.100 0</td>
<td>5 4 21 175 268 337 323 199 76 0 0 1408</td>
</tr>
<tr>
<td>0.120 0</td>
<td>2 3 14 164 256 337 320 189 68 0 0 1353</td>
</tr>
<tr>
<td>0.140 0</td>
<td>0 0 2 4 148 247 335 312 187 61 0 0 1296</td>
</tr>
<tr>
<td>0.160 0</td>
<td>0 0 0 2 139 243 332 310 183 55 0 0 1264</td>
</tr>
<tr>
<td>0.180 0</td>
<td>0 0 0 2 135 239 331 307 180 54 0 0 1248</td>
</tr>
<tr>
<td>0.200 0</td>
<td>0 0 0 131 235 328 301 178 51 0 0 1224</td>
</tr>
<tr>
<td>0.225 0</td>
<td>0 0 0 129 230 327 295 169 45 0 0 1195</td>
</tr>
<tr>
<td>0.250 0</td>
<td>0 0 0 128 227 325 290 164 42 0 0 1176</td>
</tr>
<tr>
<td>0.275 0</td>
<td>0 0 0 128 220 323 284 159 41 0 0 1155</td>
</tr>
<tr>
<td>0.300 0</td>
<td>0 0 0 124 216 321 277 156 39 0 0 1133</td>
</tr>
<tr>
<td>0.333 0</td>
<td>0 0 0 123 215 316 275 153 38 0 0 1120</td>
</tr>
<tr>
<td>0.367 0</td>
<td>0 0 0 120 214 308 269 150 38 0 0 1099</td>
</tr>
<tr>
<td>0.400 0</td>
<td>0 0 0 118 214 305 264 148 38 0 0 1087</td>
</tr>
<tr>
<td>0.450 0</td>
<td>0 0 0 117 212 301 258 146 38 0 0 1072</td>
</tr>
<tr>
<td>0.500 0</td>
<td>0 0 0 115 211 298 253 145 36 0 0 1058</td>
</tr>
<tr>
<td>0.550 0</td>
<td>0 0 0 115 211 293 247 144 36 0 0 1046</td>
</tr>
<tr>
<td>0.600 0</td>
<td>0 0 0 115 209 290 241 142 36 0 0 1033</td>
</tr>
<tr>
<td>0.700 0</td>
<td>0 0 0 0 114 207 284 237 141 36 0 0 1019</td>
</tr>
<tr>
<td>0.800 0</td>
<td>0 0 0 0 114 207 281 234 141 36 0 0 1013</td>
</tr>
<tr>
<td>0.900 0</td>
<td>0 0 0 0 113 207 280 232 141 36 0 0 1009</td>
</tr>
<tr>
<td>1,000 0</td>
<td>0 0 0 0 113 207 277 232 141 36 0 0 1006</td>
</tr>
</tbody>
</table>

Similar Tables are available for greenhouses in southern Spain and the Netherlands for a range of ventilation temperatures, with and without shading in summer months. Some are shown in the Appendix below. These tables provide information to aide making decisions on:
What ventilation area is required in a new greenhouse?
What temperatures can be achieved in an existing greenhouse with existing ventilators?
During which months can the greenhouse be used to grow plants which have a known upper temperature tolerance?
2.1.5 Effect of greenhouse size and ventilator position

The foregoing deals only with determining the total area which can be opened to provide ventilation, the position of the ventilators has not been considered. In greenhouses with areas of less than a few thousand m\(^2\) it is known that having ventilators in the sidewalls and in the roof gives increased cooling. Fig 18 shows how the relative areas of roof and sidewall ventilators influence the ventilation rate [note the total vents area is constant]. It is clear that the highest ventilation occurs when both ventilators have the same areas (Kittas et al, 1997).

![Graph showing influence of sidewall and roof ventilator areas on ventilation rate. Note the total ventilation area is the same.](image)

Fig. 18. Influence of sidewall and roof ventilator areas on ventilation rate. Note the total ventilation area is the same.

Therefore, in designing a natural ventilation system for greenhouses covering small areas the aim should be to have equal areas of sidewall and roof ventilators. However, as the size of greenhouse increases this is no longer possible. The total area of roof ventilators increases and the sidewall ventilators form a decreasing proportion of the total ventilation area. Figure 19 shows the how the ratio of roof to sidewall ventilator areas influences the ventilation performance. When this ratio exceeds 10 there is little additional benefit to be gained in ha-
ving ventilators in the sidewalls.

Fig. 19. Total ventilation areas required to achieve 26°C in a greenhouse in Southern Spain in 2007 with different ratios of roof (Ar) to sidewall (As) ventilator areas

However, sidewall ventilators can have a strong influence on greenhouse ventilation when exposed to the prevailing wind as air entering the sidewall ventilator can have a controlling influence on the airflow in the greenhouse. This situation can adversely affect plants adjacent to the sidewall particularly if there are large differences in temperature or humidity between conditions inside and outside the greenhouse. Deflectors have been used to direct the entering air upwards to create a region in which the air mixes with the greenhouse air before impinging on the crop. It has been suggested that the effects of sidewall ventilation can extend 20 to 40 m into a greenhouse, however, this distance will be reduced markedly by the presence of a tall crop.

### 2.1.6 Windward and leeward ventilation

Glasshouses usually have ventilators on both sides of the roof of each span. This can provide either leeward ventilation, windward ventilation or a combination of both. However, curved roof greenhous-
ses often have continuous ventilators along the roof which all face in the same direction when open. Depending on the wind direction, these will provide either leeward or windward ventilation.

Fig. 20. Performance comparison of leeward, windward and combined windward and leeward ventilation

Figure 20 shows clearly that combining leeward with windward ventilation gives the highest performance since it requires the smallest ventilator area. Leeward ventilation is the least effective and windward ventilation is better than leeward but not effective as combined leeward and windward ventilation. It is also clear that there are large variations in the predictions of different models, for both leeward and windward ventilation. Consequently, it is only possible to conclude that for the same ventilator area using combined leeward and windward ventilation gives the highest ventilation rate, followed by windward ventilation, with leeward ventilation giving the lowest ventilation rate.

When ventilation is first required in a glasshouse it is common practice for the ventilators on the leeward side of the roof to be opened first and for those on the windward side to be opened when the leeward vents do not provide sufficient cooling. With leeward ventilation, the
pressure distribution over the greenhouse surface created by the wind causes air to enter through ventilators in the down wind part of the greenhouse and leave via the ventilators in the upwind part. The flow of air inside the greenhouse is in the opposite direction to the external wind. At low wind speeds there are no regions of high air speed in the greenhouse. As the wind speed increases the internal flow increases and in greenhouses with typically 5 or more spans, recirculation of the incoming air can occur in the most down wind span of the greenhouse. This reduces ventilation effectiveness as a region of stagnant air is created between the re-circulating flow and the flow in the remainder of the greenhouse which is in opposite direction. As the greenhouse increases in size to 12, 18 and 24 spans, this region without positive air flow moves away from the down wind part towards the centre of the greenhouse (Kacira et al 2004). The slow removal air from these stagnant areas can lead to increased temperatures.

Appendix – Tables showing the hours that greenhouse ventilation temperatures are exceeded for a range of ventilator areas The shading consists of whitening applied to the greenhouse roof and reduces the greenhouse transmissivity to 25% during the period July to September inclusive

<table>
<thead>
<tr>
<th>Table</th>
<th>Greenhouse location</th>
<th>Ventilation temperature</th>
<th>Shade / no shade</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Southern Spain</td>
<td>22 oC</td>
<td>No shade</td>
</tr>
<tr>
<td>9</td>
<td>“</td>
<td>24 oC</td>
<td>“</td>
</tr>
<tr>
<td>10</td>
<td>“</td>
<td>26 oC</td>
<td>“</td>
</tr>
<tr>
<td>11</td>
<td>“</td>
<td>22 oC</td>
<td>75% Shade</td>
</tr>
<tr>
<td>12</td>
<td>“</td>
<td>24 oC</td>
<td>“</td>
</tr>
<tr>
<td>13</td>
<td>“</td>
<td>26 oC</td>
<td>“</td>
</tr>
<tr>
<td>14</td>
<td>Netherlands</td>
<td>20 oC</td>
<td>No shade</td>
</tr>
<tr>
<td>15</td>
<td>“</td>
<td>22 oC</td>
<td>“</td>
</tr>
<tr>
<td>16</td>
<td>“</td>
<td>24 oC</td>
<td>“</td>
</tr>
<tr>
<td>17</td>
<td>“</td>
<td>26 oC</td>
<td>“</td>
</tr>
</tbody>
</table>
### Table 8

<table>
<thead>
<tr>
<th>Ventilation temperature</th>
<th>22°C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Almeria 2007 weather</strong></td>
<td></td>
</tr>
<tr>
<td><strong>No shading</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Jan</strong></td>
<td><strong>Feb</strong></td>
</tr>
<tr>
<td><strong>Hours when external temperature is higher than ventilation temperature</strong></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>vent area / g'house area</th>
<th>Hours when greenhouse temperature is higher than ventilation temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>244</td>
</tr>
<tr>
<td>0.005</td>
<td>183</td>
</tr>
<tr>
<td>0.010</td>
<td>149</td>
</tr>
<tr>
<td>0.025</td>
<td>85</td>
</tr>
<tr>
<td>0.050</td>
<td>30</td>
</tr>
<tr>
<td>0.075</td>
<td>6</td>
</tr>
<tr>
<td>0.100</td>
<td>1</td>
</tr>
<tr>
<td>0.120</td>
<td>0</td>
</tr>
<tr>
<td>0.140</td>
<td>0</td>
</tr>
<tr>
<td>0.160</td>
<td>0</td>
</tr>
<tr>
<td>0.180</td>
<td>0</td>
</tr>
<tr>
<td>0.200</td>
<td>0</td>
</tr>
<tr>
<td>0.225</td>
<td>0</td>
</tr>
<tr>
<td>0.250</td>
<td>0</td>
</tr>
<tr>
<td>0.275</td>
<td>0</td>
</tr>
<tr>
<td>0.300</td>
<td>0</td>
</tr>
<tr>
<td>0.333</td>
<td>0</td>
</tr>
<tr>
<td>0.367</td>
<td>0</td>
</tr>
<tr>
<td>0.400</td>
<td>0</td>
</tr>
<tr>
<td>0.450</td>
<td>0</td>
</tr>
<tr>
<td>0.500</td>
<td>0</td>
</tr>
<tr>
<td>0.550</td>
<td>0</td>
</tr>
<tr>
<td>0.600</td>
<td>0</td>
</tr>
<tr>
<td>0.700</td>
<td>0</td>
</tr>
<tr>
<td>0.800</td>
<td>0</td>
</tr>
<tr>
<td>0.900</td>
<td>0</td>
</tr>
<tr>
<td>1.000</td>
<td>0</td>
</tr>
</tbody>
</table>

**NOTE:** the readers may also be interested in visiting the information on Paragraph 2.3: Identification of periods of zero greenhouse ventilation, Deliverable 14 of the Euphoros project, [http://www.euphoros.wur.nl/UK/Deliverables/]
2.2 A Decision Support System for the calculation of ventilation rate in obstructed and unobstructed greenhouses.

As a final part of this chapter a DSS based on an Excel Spreadsheet for the practical calculation of ventilation is presented.

2.2.1. Ventilation in obstructed greenhouses

Greenhouse ventilation can be strongly affected by the existence of a windward obstruction, which can produce a significant change on the air pattern and pressure field around the greenhouse. This situation is typical from dense growing areas where greenhouses are located very close to each other.

One of the tasks of the Euphoros project is the “Development of distance indicators for optimal ventilation in presence of neighbouring greenhouses. To undertake this task a number of actions have been taken:

- Use a simplified model for the calculation of ventilation rate of unobstructed greenhouses.
- Run CFD simulations to determine a set of “adjustment functions” that relates the ventilation rate of the obstructed and unobstructed greenhouse with the distance between them.
- Apply the “adjustment functions” to the ventilation rate obtained by the simplified model. This allows knowing the ventilation of the obstructed greenhouse.
- Develop a user friendly spreadsheet with the simplified ventilation model and the adjustment functions.
2.2.2 Ventilation mode

The flow of air is created by the difference between the inside and outside temperatures and by the external wind. In most occasions wind driven ventilation overrides thermally induced ventilation and therefore most simplified models only consider wind driven ventilation. A general equation to calculate ventilation rate was given by de Jong, (1990) among others (Eqn 1) in which it is assumed that half of the ventilators are inlet air and the other half outlet air.

\[
\Phi = \frac{S}{2} C_d C_w^{1/2} u \quad \text{Eqn. 1}
\]

Where \( \Phi \) is the total inlet or outlet greenhouse air flow (m\(^3\)/s), \( S \) is the total greenhouse ventilator area (m\(^2\)), \( C_d \) is the discharge coefficient of ventilators (dimensionless), \( C_w \) is the global wind pressure coefficient (dimensionless) and \( u \) is the outside air wind speed (m/s). Suitable values for discharge coefficients of ventilators as a function of their aspect ratio (length divided by height) can be found in literature (Perez-Parra et al, 2004).

In many occasions greenhouses in warm areas use insect-proof screens to protect crops from insect invasion. Insect-proof screens create a drop in pressure which leads to a significant ventilation reduction with associated high temperature risks. A simplified equation that accounts for ventilation reduction as a function of screen porosity was given by Perez-Parra el al (2004).

\[
\frac{\Phi_{sc}}{\Phi} = e^{(2-e)} \quad \text{Eqn. 2}
\]

Eqns 1 and 2 were used for the calculation of ventilation rate of unobstructed greenhouses.
2.2.3. Adjustment functions.

This task was undertaken by running CFD analysis on two groups of multi span greenhouses. The distance between both greenhouses was increased from $D=2\text{m}$ to $D=60\text{ m}$ (Figure 21). In this report we will call greenhouse A to the one on the windward side (unobstructed greenhouse) and B to the one on the leeward side (obstructed greenhouse).

![Figure 21. Scheme of greenhouses A and B separated a distance D.](image)

2.2.4. User friendly spreadsheet

After a short introduction the Excel file includes three sheets. The first sheet requires entering the following data:

- Greenhouse geometry: number of spans, span width and length, gutter and ridge height.
- Opening characteristics: number of roof vents, number of side vents, dimensions of roof and side vents, insect-proof screen porosity.
- Wind speed and direction (windward and leeward direction. Other cases are not considered)
- Distance between greenhouses.

Firstly the ventilation of the unobstructed greenhouse is calculated. Secondly the ventilation of the obstructed greenhouse is considered by applying a correction factor which depends on the distance.
between the obstructed and the unobstructed greenhouses.

By changing the ventilator size and ventilation parameters the user can find a suitable combination of ventilators to compensate the effect of the windward obstruction. The main final output is the number of air exchanges per hour. Following good engineering practises it is desirable to keep ventilation rate above 30 Volumes per hour under sunny conditions. When ventilation rate is below 30 Vols/hr a warning message is issued, so that the spreadsheet can help to detect potential situations of excessive heat.

The calculation tool can be freely downloaded from the Euphros project web page
http://www.euphoros.wur.nl/UK/Deliverables/

Please search for Deliverable 14, DSS for Optimum Ventilation, thermal storage and available sustainable energy sources.

Currently the spreadsheet is available in English and Italian. Though it is expected to be offered soon in Spanish.
Summary

In a greenhouse without carbon fertilization, the CO2 absorbed in the process of photosynthesis must ultimately come from the external ambient through the ventilation openings. The ventilation of the greenhouse implies a trade-off between ensuring inflow of carbon dioxide and maintaining an adequate temperature within the house, particularly during sunny but chilly days. Crop production is known to increase both with carbon dioxide concentration and with [average] temperature. Therefore, the management of ventilation in such conditions is looking for “the lesser of two evils”.

First we show that ventilating as little as possible coupled to carbon fertilization up to at least external concentration is the surest and cheapest way to increase productivity during relatively cold but
sunny days. Then we deal with the question of optimal fertilisation in presence of natural ventilation. Allowing for a higher than external concentration obviously reduces the efficiency of the supply, but it does not necessarily reduce profit. By applying some economics to a simple assimilation model, we show that in many conditions—particularly with relatively high radiation—maintaining higher than external concentrations does make economic sense, certainly up to ventilation rates of 10 per hour.

Finally we develop an algorithm for optimal management of CO2 supply, in order to ensure the maximum net return from cost of carbon dioxide supplied and increase in harvest. The optimal concentration depends on many factors: the expected increase of yield thanks to carbon dioxide supply under given climate conditions; the actual ventilation rate; the value of yield and the cost of carbon dioxide. We combined a calculation of the “value” of carbon dioxide supply with an algorithm to calculate the ventilation rate, into a calculation on-line of the optimal supply rate. The algorithm was implemented and tested into a commercial climate control computer.

**Introduction: carbon dioxide concentration within a greenhouse**

The process of photosynthesis is at the basis of plant growth and crop production. During photosynthesis the energy contained in light is used to form carbohydrates from carbon dioxide (CO2) taken from the air, and the water present in the leaf tissue. The speed with which carbohydrates are formed (the rate of the process) is then primarily dependent on the amount of light and CO2 concentration. Temperature and water content of the leaf tissue (turgor) play a secondary role that will not be considered in this context.

The response of photosynthesis to both light and aerial concentration of CO2 is of the saturating type, that is to say that photosynthesis increases by an ever smaller rate with each of the two factors until a level is reached beyond which increasing further the factor has no effect any more (the law of diminishing returns). Through extensive measure-
ments in commercial greenhouse tomato crops in the Dutch Westland, Nederhoff (1994) determined a 5-parameters model of net assimilation of a full-grown tomato crop vs CO2 concentration and light. For the purpose of this work we have selected a simpler model that does reproduce the trend and the level of the original one:

\[
A_{net} = 2.2 \frac{1}{1 + \frac{230}{CO_2}} [1 - \exp(-0.0015 I)] \text{ mg m}^{-2} \text{ s}^{-1} \] (1)

where CO₂ is the ambient carbon dioxide concentration, here in in vpm and Isun is the photon flux density of Photosynthetically Active Radiation (PAR), μmol m⁻² s⁻¹. For sun radiation, Isun can be estimated as twice the value of sun radiation in W m⁻², whereas Avogadro’s law ( a particular case of the gas law) gives the conversion from volume to mass: in the case of CO₂, 1 vpm ~ 2 mg m⁻³. 2.2 mg m⁻² s⁻¹ is the “maximal” assimilation rate of a tomato crop, according to Nederhooff’s extensive measurements in commercial farms, which may be reduced by suboptimal values of radiation and/or carbon dioxide. Both factors of eq(1) are always less than unity. The trend of eq(1), shown in Fig. 1, is asymptotic with respect to both radiation and CO₂ but the level of the asymptote depends on the other variable, that is: each of the two factors may be limiting assimilation, whatever the value assumed by the other one.
Figure 1. Response of net assimilation of a full-grown tomato crop to radiation and carbon dioxide concentration, as described by eq(1), a simplification of the model proposed by Nederhoff (1994).

In the semi-closed environment of a greenhouse without CO2 injection, the CO2 that is absorbed by the crop must be replaced by CO2 that comes from outside through the ventilation openings. The mass-flow continuity equation can be written as:

\[ A_{net} = g_V \left( C_{CO_2}^{out} - C_{CO_2}^{in} \right) \]  

\[ \text{mg m}^{-2} \text{s}^{-1} \]  (2)

where \( g_V \) is the volume exchange by ventilation, per unit surface area of the greenhouse, m3m–2 s–1, that is: m s–1, and \( C \) is the CO2 concentration, mg m–3, outside and inside respectively. Obviously, without additional sources of carbon dioxide, when there is assimilation, the concentration in the greenhouse must be lower than outside. This is
shown by re-arranging eq(2):

$$C_{CO_2}^{in} = C_{CO_2}^{out} - A_{net} / g_V$$  \(\text{mg m}^{-3}\) (3)

If one prefers writing eq(3) in units more commonly used in greenhouse management, the conversion from volume to mass has been given above. In addition, since \(n\) volume changes per hour means replacing in one hour as many cubic meters as the mean height, \(h\), of the greenhouse \(n = 3600 \text{ gV} / \text{h}\). Thus:

$$CO_2^{in} = CO_2^{out} - \frac{1800 \ A_{net}}{h \ n}$$  \(\text{vpm}\) (4)

where the symbol \(CO_2\) is used for carbon dioxide concentration in vpm. For instance the \(CO_2\) concentration in a greenhouse of mean height 4 m, ventilated at a rate of 4.5 h–1, with a crop assimilating 1 mg m–2 s–1 is some 100 vpm lower than the concentration outside. With an external concentration of 370 vpm, this would mean some 20% of lost production, according to the “rule of thumb” that Nederhoff derived from her measurements. That rule reads as follows: the percentage increase of production caused by a 100 vpm increase in concentration from a given mean \(CO_2\) level (270 vpm, in this example) is:

$$\text{production gain} = 1.5 \ (1000/CO_2)^2$$  \(\%\) (5)

The \(CO_2\) fertilization strategy implemented in modern Dutch greenhouse climate computers is based on determining thus benefits of increasing the concentration, against the cost of \(CO_2\), either from gas fumes or bottled/piped from industrial plants.
Carbon dioxide depletion: how much lost production?

For finding out the extent of CO2 depletion in regions where CO2 fertilization is not common and discussing the options available to a mild-winter grower, we have used two existing data sets of November 2006, one from a 3-span multi-tunnel in the experimental station Las Palmerillas (El Ejido, Almeria, Spain, 36°48’N; 2°43’W; 151 m.a.s.l.) and the other from a 14-span multi-tunnel of Azienda Fratelli Dezio, a commercial grower (loc. Gaspanella, Ragusa, Italy, 36°57’N; 14°26’E; 104 m.a.s.l). The Spanish greenhouse are three spans, each 7.5 by 28 m (total surface 630 m2) oriented E-W, gutter height 3 m and 4.5 m on top, with side openings on the South and North facing sides, and a zenith opening in each module (Fig. 2, left). The commercial greenhouse in Italy is 14 modules 8 by 120 m each (total surface 1.34 ha), oriented SE-NW, gutter height 4 m and 5.6 on top. There are no side openings and one longitudinal on each tunnel (Fig. 2, right). In both cases the openings were fitted with insect nets type 20/10 and were controlled by the climate computer. In none of the two cases the heating system was switched on in the month of November.

The crop in Spain was a round Tomato, cv Colby, planted on August 4th, 2006 with a density of 2 m–2 whereas in Sicily it was a cherry, cv Shiren, planted on September.

Figure 2. The greenhouses where the data used here were collected: left the Spanish greenhouse, right the one in Sicily, Italy
Table 1. Average day- and night-time climate values measured out- and in-side the two greenhouses, in the month of November 2006, and estimated actual and potential assimilation (see text).

<table>
<thead>
<tr>
<th></th>
<th>Daytime</th>
<th>Night-time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Almeria</td>
<td>Ragusa</td>
</tr>
<tr>
<td>Temperature out °C</td>
<td>19.4</td>
<td>18.2</td>
</tr>
<tr>
<td>Total radiation MJ m–2</td>
<td>255.80</td>
<td>250.96</td>
</tr>
<tr>
<td>Wind velocity m s–1</td>
<td>1.6</td>
<td>2.0</td>
</tr>
<tr>
<td>Temperature in °C</td>
<td>22.0</td>
<td>18.8</td>
</tr>
<tr>
<td>CO2 in vpm</td>
<td>320.6</td>
<td>372.9</td>
</tr>
<tr>
<td>Estimated assimilation g m–2 month–1</td>
<td>471.1</td>
<td>499.6</td>
</tr>
<tr>
<td>Potential assimilation g m–2 month–1</td>
<td>513.3</td>
<td>508.7</td>
</tr>
</tbody>
</table>

As the mean measured CO2 concentration in a month that the Italian greenhouse was empty was 378 vpm, we have taken this value as the prevailing concentration outside, in both cases. Actual assimilation rate was estimated through eq(2), whereas a “potential” (that is, non limited by CO2 depletion) assimilation rate was estimated by using a constant value of 378 vpm for CO2 concentration, for both locations. In order to “fill the gaps” in the Almeria record we preserved the ratio observed in the Ragusa record between totals for the days that were missing in Almeria and the month total. Obviously this whole procedure can give only a very rough estimate of the total assimilation (Table 1). It is a comforting thought that applying a dry matter allocation of 2/3 to the fruits and a dry matter content of 6%, the estimated tomato production in Almeria would be 5.06 kg m–2, which is comparable to the 4.95 kg m–2 that were harvested between Nov 3rd and Dec 5th. The first harvest in the Sicilian farm was Dec 18th and there are no records of vegetative growth.

The worth of 1 kg assimilated CO2 can be calculated as follows (Stanghellini and Heuvelink, 2007): the conversion efficiency of CO2
fixation into dry matter is about 70% and the ratio of molecular weights of CH2O and CO2 is 68%, which means that each kg assimilated CO2 yields about 500 g dry matter. With a harvest index of 65% and a dry matter content of the produce of 6% (for instance tomato), this is a fresh weight of tomatoes of about 5 kg. To assign it a value, for instance, the producers’ price of tomato, Ptom in Almeria in the month of November of the years 2003 through 2006 has been between 0.55 and 1.15 €/kg (Fundación Cajamar, 2006 and 2007). Altogether the value of 1 kg assimilated CO2 would have then been between 2.75 and 5.90 €.

The differences in CO2 concentration and estimated assimilation, observed in Tab. 1 between the two places, are explained in Fig. 3, where a sunny day is shown as an example.

Aside from the nights in this particular example—which were colder in Almeria—the weather in the two places was quite similar. Yet, whereas the temperature in the Italian greenhouse strictly shadowed outside temperature, the temperature in the Spanish house exceeded midday outside temperature by some 5ºC. This can only mean that the Ita-
lian house was much more ventilated than the Spanish one, which is consistent with the much higher daytime CO2 concentration. Indeed, mean daytime values shown in Table 2 for the whole month, show that whereas the Italian greenhouse was only 0.6°C warmer than outside, temperature in the Spanish one exceeded ambient temperature by 2.6°C. The backside of the coin is that average daytime CO2 concentration in the Spanish house was 50 vpm lower that in the other.

<table>
<thead>
<tr>
<th></th>
<th>Almeria</th>
<th>Ragusa</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{CO}_2$ (vpm)</td>
<td>321</td>
<td>373</td>
</tr>
<tr>
<td>$I_{\text{sun}}$ (MJ/m$^2$.d)</td>
<td>8.5</td>
<td>8.4</td>
</tr>
<tr>
<td>$\Delta T$ (in – out)</td>
<td>2.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 2. Mean daytime values of carbon dioxide concentration; daily total of sun radiation and temperature difference between inside and outside, in the two greenhouses, November 2006.

Which is the lesser of two evils?

In such conditions a grower is faced with a trade-off between ventilating in order to ensure sufficient inflow of carbon dioxide, and limiting ventilation to maintain a relatively high temperature. The two growers clearly adopted different strategies, which ensured very different climate conditions within the greenhouses, in spite of the similarity of the weather. According to the estimated assimilation at the bottom of Table 1 a high ventilation rate was the better choice. Of course this is only half of the story, since our model, Eq.(1), does not reward higher temperatures.
Indeed it is known that photosynthesis of tomato is only slightly affected by temperatures in the range between 17 and 24°C (e.g. Heuvelink and Dorais, 2005), but all other growth-related processes are. To begin with, re-distribution of assimilates is slowed by low temperatures.

The ensuing accumulation in leaves limits their expansion, in young commercial tomato varieties (Heuvelink, 1989) as well as their wild relatives (Venema et al., 1999). Particularly in young plant this limits light interception, thus photosynthesis and thus crop growth. In addition, vegetative development (the differentiation of new leaves and trusses) is known to respond linearly to average temperature in a wide range. A much used “rule of thumb” for Dutch tomato growers is shown in Fig. 4. According to that, the grower in Almeria could harvest 3.8 trusses in the month November, whereas the one in Ragusa not even 3.4. Obviously this is quite speculative, since the two growers did not even have the same variety. De Koning (1994), however, observed that, although the slope could change across varieties, the response of truss formation to temperature remained linear. Altogether, the 8%
production loss (Tab. 1) caused by CO2 depletion in Almeria, was comparable to the production loss due to the lower temperature caused by ventilation in the Ragusa farm. Obviously, the fact that the monthly mean outside temperature was about 1.5°C lower in Ragusa would have required an even lower ventilation rate (and larger depletions) to achieve the mean temperature that was measured in Almeria. On the face of it, both growers may have selected the best course in their conditions. Unless we consider the option to compensate for depletion through carbon dioxide fertilization, particularly during the relatively cold months when ventilation would result in an undesired cooling of the greenhouse and the product prices are high.

**Carbon dioxide supply**

Indeed, carbon fertilization–made possible by the direct application of heating fumes–is one of the factors leading to the high productivity of Dutch glasshouse horticulture. Energy saving and application renewable energies ensure that there are less fumes around, a slump gradually made up by piped or bottled CO2. Bottled CO2 is increasingly sold at competitive prices also in the unheated greenhouses of the Mediterranean region. Thanks to the ongoing implementation of the Kyoto protocol into a system for trading emission rights, current world prices of bottled or piped CO2, PCO2, are between 0.1 and 0.2 €/kg of carbon dioxide, which is comparable to the cost of producing carbon dioxide by burning gas (as used to be done in the greenhouses of Northern Europe even in the absence of heating requirement, for instance). Therefore, in view of the strong relationship between temperature and production, the most profitable choice for a grower seems to be ventilating as little as possible (under the constraints of humidity and temperature control) and to supply bottled CO2 up to at least the external concentration. Since in this case there is no outflow of CO2, this level ensures that all CO2 that is supplied is assimilated. A method for CO2 control aimed at maintaining within the greenhouse the same concentration as outside has been described by Kläring et al. (2007).
Maintaining a concentration higher than external would obviously result in a lower efficiency of carbon fertilization, since some CO2 would flow through the ventilators, but it may still make economic sense. The supply (S) of CO2 must then balance net assimilation (A) and the loss through ventilation (V).

\[ \text{MAXCO} \times \text{CO}_{2} \times \text{PP} \times \text{SP} \times \text{A} \times \text{P} \times \text{S} \times \text{V} = 2, 2, 2, 2, 2, 2, 5, 5 \text{ mg m}^{-2} \text{s}^{-1} \] (6)

where gV is the volume exchange by ventilation, per unit surface area of the greenhouse, m3m–2 s–1, that is, m s–1, and CO2 is the CO2 concentration, mg m–3, inside and outside, respectively. An approximate function for the net assimilation, is given by eq(1).

The net profit of supplying carbon dioxide with a fixed capacity is shown in Fig.5, for a number of combinations of sun radiation at the top of the crop, and ventilation requirement of the greenhouse. Ob-
viously not all combinations are possible in a naturally ventilated greenhouse, since usually a high sun radiation implies a high ventilation requirement. Therefore, the naturally occurring combinations will tend to crowd along the lower-left to upper right diagonal. Nevertheless, Fig. 5 makes clear that there is scope for an intelligent management of carbon fertilization.

**Economic management of carbon dioxide fertilisation**

An economic management must account for cost and benefits, that is the cost of the supply (the price of 1 kg CO2) and the value of 1 kg assimilated CO2. We have seen above that 1 kg of assimilated CO2 results in 0.5 kg dry matter. The value of each kg dry matter depends obviously on the crop, its value and harvest index (the fraction of dry matter that goes into the organs that are sold). It will be indicated in the following as Pd.m. and its units are €/kg of dry matter.

The optimal concentration of carbon dioxide is then the one that maximizes profit, that is the value of assimilated CO2 minus the cost of the supply. Indeed, maximising the profit implies that supply should be modulated in order to maintaining the internal carbon dioxide concentration that ensures that the value of A minus the cost of S is maximal at any time:

\[
0.5P_{d.m.}A - P_{CO2}S = (0.5P_{d.m.}-P_{CO2})f(I_{sun},CO_{2,in})-P_{CO2}g_{V}(CO_{2,in}-CO_{2,out}) \Rightarrow MAX \quad € m^{-2} \tag{7}
\]

Where obviously if A and S are in mg m\(^{-2}\) s\(^{-1}\), the prices must be €/mg and CO2 must be in mg m\(^{-3}\). Looking for a maximum implies that the derivative of the left hand side of eq(7) with respect to the CO2 concentration must be equal to zero (Fig. 6). By taking into account that 230 vpm = about 460 mg m\(^{-3}\) and defining:
Figure 6. Schematic example of the calculation of the optimal carbon dioxide concentration, that is the concentration that ensures that the difference between yield value and the cost of supplying CO2 is maximal. The trend of yield value with CO2 concentration is the same as that of assimilation. The cost of CO2 supply consists of capital costs (the installation) which are not dependent on supply, and then the price of each kg CO2 that is given. The figure shows that the point where the difference between value of yield and cost of supply is maximal, is the point where the tangent of the yield line has the same slope as the cost line. The derivative of a function gives the slope at each point.

\[ F_I = 2.2 \left[ 1 - \exp\left( -0.0015 I_{\text{sun}} \right) \right] Y \quad 0.5 P_{d.m.} - P_{CO_2} = R P_{CO_2} \]

The derivative then can be calculated as:

\[ \frac{\partial}{\partial CO_{2,\text{in}}} P_{CO_2} \left[ R \frac{F_I}{460} - \frac{g_V}{1 + \frac{CO_{2,\text{in}}}{CO_{2,\text{in}}}} \left( CO_{2,\text{in}} - CO_{2,\text{out}} \right) \right] = 0 \]
Divide by 2 to transform in vpm. Eq(8) shows that the optimal CO2 concentration increases with both sun radiation (accounted by FI) and with the ratio R between the value and the cost of CO2, and it decreases with ventilation. Eq(8) is calculated for various conditions in Fig. 7, which makes clear that there are quite a number of conditions in which it does make sense maintaining a higher than external concentration in the house, in spite of its ventilation. “Optimal” management of carbon fertilizations should therefore aim at maintaining relatively high concentrations in the absence of ventilation, and gradually falling back to the “minimal” management—that is matching inside the carbon dioxide concentration outside—only at relatively large ventilation rates or expensive CO2. Fig. 7 shows that both the level to be maintained in the absence of ventilation and the steepness of the trend at intermediate ventilation rates depend on the intensity of radiation and on the economics, that is the value of yield vs the cost of CO2.

The optimal supply (that is, the injection rate that warrants the maximum profit) can be calculated as well:

\[
S_{OPT} = A_{CO2, \text{in,OPT}} + V_{CO2, \text{in,OPT}} = F_l \frac{CO_{2, \text{in,OPT}}}{CO_{2, \text{in,OPT}} + 460} + g_v \left( CO_{2, \text{in,OPT}} - CO_{2, \text{out}} \right) \Rightarrow
\]

\[
S_{OPT} = F_l - g_v \left( 460 + CO_{2, \text{out}} \right) + 21.5 \left( F_l g_v \right)^{\frac{1}{2}} \left( R^\frac{1}{2} - R_0 ^\frac{1}{2} \right) \quad \text{mg m}^{-2} \text{ s}^{-1} (9)
\]

with outside CO2 concentration in mg m\(^{-3}\), \( g_v \) in m s\(^{-1}\) and the prices in € mg\(^{-1}\). Multiply by 36 to get kgCO2 ha\(^{-1}\) h\(^{-1}\). Eq(9) shows that the optimal CO2 supply rate only depends on the ratio R between value
and price of CO2 and not on the two singularly. Figure 8, where eq(9) is calculated for a number of cases, shows that—under given conditions (of radiation and R = value/price ratio)—the optimal supply rate rapidly increases with ventilation rate and then decreases to the level that replaces crop assimilation.

Fig. 7. Carbon dioxide concentration that warrants the highest profit, eq(8), depending on sun radiation at the top of the crop, and the air exchange rate in a greenhouse of 4 m mean height. The four panels are calculated under various combinations of prices. Clockwise from upper left: bottled CO2 0.10 €/kg and tomato 0.40 €/kg; bottled CO2 0.20 €/kg and tomato 0.40 €/kg; bottled CO2 0.20 €/kg and tomato 0.80 €/kg; bottled CO2 0.20 €/kg and tomato 1.20 €/kg.
Figure 8. Optimal carbon dioxide supply (kg Ha⁻¹ h⁻¹) as function of the ventilation rate (h⁻¹) of a greenhouse 4.5 m high. The two groups of lines are calculated respectively for a sun radiation at the top of the crop of 600 W m⁻² (drawn lines) and 300 W m⁻² (dashed lines). Within each group, the darker the line, the highest the ratio between the value of assimilated CO2 and its price. The horizontal value is the value that maintains concentration inside equal to outside, in both cases.

What this means in terms of required injection capacity and potential profit can be seen in Fig. 9 which demonstrates that, in the measure that the expected value of produce increases, it is worthwhile supplying significant amounts of CO2 even at relatively high venti-
In the context of high-value crops, where sunlight is abundant, injection capacities exceeding 180 kg/Ha·h = 5 mg m−2 s−1 can be advantageous, surpassing the typical capacity of Dutch glasshouses. Obviously, the largest profits are obtained under conditions of high sunshine and low ventilation rates, which support the Dutch approach of the “semi-closed greenhouse,” prioritizing methods of temperature management before ventilation (Heuvelink et al., 2008). It is clear that effective management of carbon fertilization requires high capacity (dependent on the value of the product and the cost of CO2) and the ability to control supply according to light intensity and ventilation rate, even though this increases the installation cost compared to simpler systems with constant flow.
Fig. 9. Optimal carbon injection rate (mg m⁻² s⁻¹, left) and expected profit (€ h⁻¹ ha⁻¹, right—only variable cost of CO₂ supply are considered), for various combinations of sun radiation and ventilation rates. Price of bottled carbon dioxide is assumed to be 0.20 €/kg throughout, and value of produce is 0.5, 1.0 and 1.5 €/kg of tomato, respectively, from top to bottom.
The ventilation rate: can it be determined?

The wisest form of management of CO2 supply is to account for the ventilation rate. Unfortunately this is seldom known and the opening fraction of the ventilators is used as a proxy. However, the real ventilation rate at any time, will depend from many more factors than just the opening of the ventilators, such as: ventilators geometry, wind speed and direction.

An alternative way, suitable for implementation in climate control computers, is to determine the ventilation rate through measured climate variables inside and outside the greenhouse (Bontsema et al., 2007). This is done by determining $g_v$ as the solution of the combined steady-state enthalpy and vapour balance equations of the greenhouse. Although in principle the ventilation rate could be determined by the sensible heat balance alone, the solution becomes very unstable with small temperature differences between inside and outside. Therefore we have applied the following procedure that is more robust. In particular, the enthalpy balance is written as:

$$I_{rad}\tau \cdot c_{pipe}(T_{pipe} - T_{in}) + c_{rad}(T_{air} - T_{in}) - c_{cover} \cdot A_{cover}(T_{in} - T_{out}) - g_v \rho c_p(T_{in} - T_{out}) - L(E - C) = 0 \quad \text{W m}^{-2} \quad (10)$$

Where $I_{rad}$ indicates sun radiation (W m$^{-2}$); $\tau$ the transmissivity of the greenhouse cover; $c$ the heat transfer coefficient, respectively of the heating pipes, the soil and the cover (W m$^{-2}$ K$^{-1}$); $T$ the temperature, respectively of the heating pipes, the soil and the air inside and outside ($^\circ$C); $A$ is the surface of the cover and the soil of the greenhouse (m$^2$); $\rho c_p$ is the volumetric heat capacity of air (J m$^{-3}$ K$^{-1}$); $L$ is the latent heat of evaporation (J g$^{-1}$); $E$ and $C$ are the evapotranspiration and condensation flux densities (g m$^{-2}$ s$^{-1}$).

And the vapour balance is:

$$E - C - g_v(\chi_{in} - \chi_{out}) = 0 \quad \text{g m}^{-2} \text{ s}^{-1} \quad (11)$$
with \( \chi \) indicating the vapour concentration (g m\(^{-3}\)). The two equations can be combined in matrix form:

\[
\begin{bmatrix}
L \left( \rho c_p (T_{in} - T_{out}) \right) \\
1 - (\chi_{in} - \chi_{out})
\end{bmatrix} \times \begin{bmatrix} E - C \end{bmatrix} = \begin{bmatrix}
I_{rad} + \frac{c_{pipe}}{A_{soil}} (T_{pipe} - T_{in}) + c_{soil} (T_{soil} - T_{in}) - \frac{A_{cover}}{A_{soil}} (T_{in} - T_{out}) \\
0
\end{bmatrix} \]

and inversion yields the two unknowns: \( g_v \) (the ventilation rate) and the difference between evapotranspiration and condensation, although the second is not used here:

![Graph showing sun radiation and ventilation rates over hours of day.](image)
As both assimilation and ventilation requirement vary with the conditions, the optimal supply Eq. (9) has to be calculated on-line by the climate control computer, the ventilation rate $g_v$ being determined through Eq. (12). We implemented this algorithm as a DLL into the commercial climate control system (HortiMaX Optima) of one of the greenhouses of the Experimental Station of the Fundación Cajamar, Almeria, Spain. Figure 10 shows the results for one sunny spring day in two compartments: one very well ventilated and one allowed to become warmer. The crop was tomato, expected to be valued at 1 €/kg (value of 1 kg assimilated CO2 ≈ 5.5 €) and the price of bottled CO2 was 0.2 €/kg, both of which the grower had to enter beforehand. As it could
be guessed also by Fig. 8, the optimal supply strategy, under these financial conditions, drops very soon to maintaining inside the external concentration, that is to supply exactly the amount absorbed by the canopy. It is therefore worthwhile ventilating as little as possible, allowing higher temperatures in the greenhouse which can be helpful in taking advantage of a high CO2 concentration (Dieleman et al., 2005).

We have not considered capital costs in this analysis, since fixed costs obviously do not affect the optimal strategy, but only the net profit to be attained. Incrocci et al. (2008) have analyzed the overall profitability of carbon fertilization in market conditions where installations are relatively expensive because of the dearth of demand, such as in Italy. They observed that, even then, capital costs are a significant fraction of the overall costs only for dedicated installations in greenhouses smaller than 1 Ha.

**Conclusión**

Whenever carbon dioxide is not available simply as the rest product of heating, it must be supplied in the most economical fashion. This ensures the best possible return for the grower and prevents unnecessary emissions. It is quite likely that most growers could expect a good return on the investment of an installation for CO2 fertilization, certainly with farms exceeding about 1 Ha. The system should have a maximal injection capacity not less than the 180 kg/Ha·h typical of Dutch installations, and the ability to regulate the flow accounting for current sun radiation and ventilators’ opening.

If such an installation were available, a good management strategy would be to ventilate as little as possible (that is, as little as the control of humidity and temperature would allow) and control the CO2 concentration gradually within the house, from a high level (higher than 1000 vpm) in the absence of ventilation, down to the level outside, at ventilation rates well exceeding 10 per hour.

A more accurate management would be to determine on line the optimal CO2 supply rate, in view of the actual ventilation rate and
of the potential assimilation, which vary continuously with the weather conditions. We have shown that a simple assimilation model and a routine to determine ventilation on-line can be combined into an optimisation algorithm that can be implemented in a climate computer, to calculate in real time the economically optimal CO$_2$ concentration and the corresponding CO$_2$ injection rate.

References:


CLOSED SYSTEMS FOR SOILLESS CULTURE

Alberto Pardossi and Luca Incrocci
Dipartimento di Biologia delle Piante Agrarie, University of Pisa

INTRODUCTION

Greenhouse crops cover a small fraction of total cultivated land in the world, but they may play an important role for regional or national economy (EFSA, 2010). Greenhouse operations crops are generally concentrated in relatively small areas (often nearby cities) with potential consequences on the environment due to the discharge of waste materials (e.g. plastics and artificial growing media) and the large use of water and agrochemicals. Awareness of the pollution associated with greenhouse cropping systems forces growers to adopt more eco-friendly cultivation methods, such as closed soilless culture and biological control of pests and diseases.

Closed growing systems, in which drainage water is captured and recirculated, reduce water consumption and nutrient leaching.
However, commercial application of these systems is scarce because their management is more difficult compared with open (free drainage) systems (Savvas and Passam, 2002; Pardossi et al., 2006).

In this chapter, some guidelines are provided for efficient management of closed soilless culture with the aim to reduce the consumption of water and fertilisers (and then production costs) and the emission of nutrients with drainage water.

**HYDROPONIC TECHNOLOGY**

Soilless culture (or hydroponics) is a broad term that includes all the techniques used to grown plants in solid media other than soil (substrate culture) or in aerated nutrient solution (water culture). The categorization of soilless techniques considers the type of substrate and container, how the nutrient solution is delivered to the plant (drip irrigation; subirrigation; flowing, stagnant or mist water culture) and the fate of the drainage nutrient solution (NS; free drain or recirculating NS system).

Table 1 summarizes the main characteristics of different hydroponic techniques and a few examples of soilless culture are shown in Figure 1.

The most widely used soilless techniques is container (substrate) cultivation, while water culture systems such Nutrient Film Technique (NFT), floating culture and aeroponics are less common on commercial scale. Substrate culture is generally used for row crops (e.g. fruit vegetables such as solanacea and cucurbits; strawberry; cut flowers such rose, gerbera, anthurium etc.) while water culture is used mainly for crops with short growing cycles (e.g. leafy vegetables). For instance, floating culture is increasingly used for fresh-cut leafy vegetables and herbs and to force bulbs (e.g. tulips). Closed-loop subirrigation is increasingly adopted for pot ornamentals; the pots are cultivated in gullies with an intermittent flow of nutrient solution or in ebb-and-flow benches or floors.

Different containers (banquette, pots, bags, slabs) are used fi-
filled with inorganic or organic substrate, or a combination of two or three different materials, such as the peat-perlite or peat-pumice mixture. The volume of growing media ranges from approximately 10 (e.g. rockwool slabs) to 40 (e.g. perlite bag) L m-2 (100 to 400 m3 ha-1).

The disposal of spent substrate is a potential threat to the environment as they may contain pesticides and affect the landscape visual amenity, in particular when they are discarded illegally. Several types of substrates, such as mineral wools, are disposed to landfill at the end of one or more growing cycles. However, landfill costs are increasingly expensive and unavailable in many countries.

<table>
<thead>
<tr>
<th>Substrate and drip irrigation</th>
<th>Substrate and subirrigation</th>
<th>NFT</th>
<th>Floating system</th>
<th>Aeroponics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial application</td>
<td>Large</td>
<td>Large</td>
<td>Scarce</td>
<td>Increasing</td>
</tr>
<tr>
<td>Crop type</td>
<td>Fruit vegetables</td>
<td>Pot plants</td>
<td>Leafy vegetables</td>
<td>Leafy vegetables Bulb flowers</td>
</tr>
<tr>
<td>Strawberry</td>
<td>Cut flowers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substrate</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Recirculating nutrient solution</td>
<td>Yes/no</td>
<td>Yes</td>
<td>Yes</td>
<td>Stagnant or fairly static</td>
</tr>
<tr>
<td>Investment costs</td>
<td>Moderate/high</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Running costs</td>
<td>Moderate/high</td>
<td>Moderate/high</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>System's buffer</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Growing risks</td>
<td>Moderate</td>
<td>Moderate</td>
<td>High</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
Open versus closed system

Both open and closed system may be installed for drip-irrigated substrate culture. In closed systems, the drainage water is captured and reused following the adjustment of pH and nutrient concentration (namely, the electrical conductivity - EC) and, eventually, disinfection to minimize the risks of root-borne diseases.

In substrate culture, an excess of fresh (newly prepared) nutrient solution is generally supplied to overcome the difficulties associated to the unequal transpiration of individual plants and to prevent salt accumulation and ion imbalance in the NS. Typically, a drainage fraction (i.e. the percent ratio between the volume of drainage water and the volume of irrigation water) of at least 20-30% is used in substrate cultivation to prevent root zone salinization. Therefore, in open systems there is a massive waste of water and nutrients, which results in higher running costs and in contamination of water bodies. Malorgio et al. (2001) reported that the annual drainage loss of water and nitrogen from open substrate culture of rose was, respectively, 2123 m3 ha-1 and 340 kg ha-1. Therefore, the application of closed systems is essential for sustainable protected horticulture. Unfortunately, the application of these systems is scarce on a commercial scale and, apart from The Netherlands where they are compulsory (Stanghellini et al., 2007), open systems are commonly used for greenhouse crops, as their management is much simpler
Figure 1. A few examples of soilless culture: top, row crops on substrate (tomato, left; gerbera, right); middle, pot plants in ebb-and-flow benches (right) or floor (left); bottom, basil seedlings (left) or tulips (right) in stagnant water culture.

Along with the risks consequent to the possible diffusion of root pathogens, the salinity of irrigation water represents the main difficulty for the management of closed growing systems. When the use of saline water is imposed, there is a more or less rapid accumulation of ballast ions (e.g. Na and Cl), which are dissolved in the water at concentration higher than crop uptake concentration (i.e. the ratio between the ions and the water taken up by the plants). Under these conditions, the NS is normally recirculated till EC and/or the concentration of some potential toxic ion reach a maximum acceptable value, afterwards it is
replaced, at least partially (‘semi closed’ systems).

According to Stanghellini et al. (2005), when saline water is available to the grower, closed systems are not financially viable under strict environmental rules and the most valuable strategy is likely the improvement of water quality, for instance by desalinization or conjunctive use of groundwater and rainwater. Nevertheless, in species with moderate salt tolerance (e.g., tomato and melon) the application of specific fertigation control procedures can prolong the recirculation of the same NS and minimize the content of polluting agents (e.g. nitrate) in the NS, when this is ultimately discharged (Massa et al., 2010). Some fertigation strategies are illustrated in the following paragraph.

FERTIGATION MANAGEMENT
Irrigation scheduling

In greenhouse crops, annual use of irrigation water ranges from 150-200 mm (L m-2) in short-cycle, soil-grown crops, such as leafy vegetables, to 1,000-1,500 mm in soilless-grown fruit vegetable.

Greenhouse crops are often over-irrigated and this results in water loss and pollution due to fertilisers leaching (Thompson et al., 2007). Over-irrigation often is the result of inappropriate irrigation scheduling, which consists in the determination of optimal irrigation dose and frequency. Accurate irrigation scheduling is crucial in open substrate as it determines the seasonal irrigation volume and the pollution resulting from fertilisers leaching. On the other hand, over-irrigation or deficit irrigation may affect crop yield also in closed system, for instance by increasing the incidence of physiological disorders (e.g. blossom-end rot in tomato and pepper; Savvas et al. 2009) or the susceptibility to root diseases (Saha et al., 2008).

The determination of optimal watering irrigation dose requires the computation of two quantities: net and gross (actual) irrigation volume as expressed as L m-2 (or mm). The first quantity corresponds to the maximum oscillation in substrate water content that is tolerated by
the crop. Actual irrigation dose is generally higher than net dose as generally an excess of water is necessary due to: the unequal transpiration of individual plants; the differences in water discharge of individual trickle nozzles and the consequent uneven water distribution; the need to prevent salt accumulation in the root environment.

Hence, actual dose is calculated as net dose multiplied by a safety coefficient, which depends on crop and irrigation uniformity and the risk of substrate salinization. It ranges from 1.15 (uniform crop and water distribution; use of irrigation water with relatively low salinity; high crop tolerance to salinity) to 2.0 (large inter-plant variability in crop evapotranspiration - ET; poor irrigation uniformity; use of saline water; salt-sensitive crop). These values result in a drainage fraction between 13% and 50%. The determination of safety coefficient is less relevant in closed systems, although drainage fraction influences the costs for water pumping and NS disinfection.

Irrigation frequency is computed as ET divided by the net irrigation dose; if ET is expressed on a daily basis, the result is the irrigation events in a day.

In substrate culture, generally the crop is irrigated many times during the daytime, starting early in the morning. More than 90% of daily crop ET occurs during the light period; however, in heated greenhouse or dry seasons and/or regions, irrigation may be also necessary in the night. Irrigation of soilless culture is generally under the automatic control provided by:

- timer, which is set up on the basis of grower’s experience;
- weather station or simple light sensor, which allow the estimation of ET with more or less complicated equations (modelling approach);
- weighing gutter (Figure 2), which measures gravimetrically ET of a few test-plants over a short time (minutes to hours).
- root zone sensor, which measures directly substrate volumetric water content or moisture tension (Pardossi et al., 2009).
ET modelling

Models of different complexity have been developed to predict ET in greenhouse crops. Baille et al. (1994) proposed a simplified equation to predict ET as a function of LAI, intercepted radiation ($R_{int}$, MJ m$^{-2}$ h$^{-1}$) and vapour pressure deficit VPD (kPa):

$$ET = A \cdot \frac{R_{int}}{\lambda} + B \cdot LAI \cdot VPD$$  \hspace{1cm} \text{Eq. 1}

where A (dimensionless) and B (kg m$^{-2}$ h$^{-1}$ kPa$^{-1}$) are empirical coefficients, and $R_{int}$ is estimated from LAI and a crop-specific light interception coefficient ($k$; it ranges between 0.6 to 0.8), as follow:

$$R_{int} = \left(1 - \exp^{-k \cdot LAI}\right) \cdot R$$  \hspace{1cm} \text{Eq. 2}
After appropriate calibration, the equation reported previously predicted accurately ET in a variety of greenhouse crops. Table 2 reports the values of coefficients A and B for some greenhouse crops.

Table 2. Values for the coefficient A (dimensionless) and B (kg m\(^{-2}\) h\(^{-1}\) kPa\(^{-1}\)) of Eq. 1 for some greenhouse crops.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Growing conditions</th>
<th>LAI</th>
<th>A</th>
<th>B</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Begonia</td>
<td></td>
<td>2.7</td>
<td>0.20</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>Cyclamen</td>
<td>France; heated glasshouse; autumn and spring; pot plants</td>
<td>2.9</td>
<td>0.32</td>
<td>0.019</td>
<td></td>
</tr>
<tr>
<td>Hibiscus</td>
<td></td>
<td>2.4</td>
<td>0.37</td>
<td>0.037</td>
<td></td>
</tr>
<tr>
<td>Impatiens</td>
<td></td>
<td>5.1</td>
<td>0.67</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>Geranium</td>
<td></td>
<td>5.7</td>
<td>0.61</td>
<td>0.017</td>
<td></td>
</tr>
<tr>
<td>Poinsettia</td>
<td></td>
<td>2.0</td>
<td>0.12</td>
<td>0.017</td>
<td></td>
</tr>
<tr>
<td>Schefflera</td>
<td></td>
<td>4.4</td>
<td>0.60</td>
<td>0.014</td>
<td></td>
</tr>
<tr>
<td>Gardenia</td>
<td></td>
<td>4.5</td>
<td>0.46</td>
<td>0.019</td>
<td></td>
</tr>
<tr>
<td>Gardenia</td>
<td></td>
<td>6.6</td>
<td>0.53</td>
<td>0.013</td>
<td></td>
</tr>
<tr>
<td>Cucumber</td>
<td>Almeria, Spain; autumn and spring; perlite pot substrate</td>
<td>0.5 - 2.6</td>
<td>0.26</td>
<td>0.034</td>
<td>Baille et al., 1994.</td>
</tr>
<tr>
<td>Geranio</td>
<td>Spain</td>
<td>2.5</td>
<td>0.56</td>
<td>0.018</td>
<td>Montero et al., 2001.</td>
</tr>
<tr>
<td>Zucchini</td>
<td>Italy; autumn and spring; pumice culture</td>
<td>0.5-5.5</td>
<td>0.63</td>
<td>0.009</td>
<td>Rouphael and Colla, 2004.</td>
</tr>
<tr>
<td>Gerbera</td>
<td>Almeria, Spain; autumn and spring; semi-closed rockwool culture.</td>
<td>1.0 – 2.2</td>
<td>0.55</td>
<td>0.019</td>
<td>Carmassi et al., unpublished</td>
</tr>
<tr>
<td>Rose</td>
<td>Greece; perlite pot culture</td>
<td>2.5-3.5</td>
<td>0.24</td>
<td>0.026</td>
<td>Kittas et al. 1999</td>
</tr>
<tr>
<td>Tomato</td>
<td>Spain; autumn and spring; perlite culture</td>
<td>2.5</td>
<td>0.58</td>
<td>0.025</td>
<td>Medrano, personal communication</td>
</tr>
</tbody>
</table>

**Root zone sensors**

Soil moisture sensors could be used to regulate the frequency of irrigation and, possibly, the water dose by continuously monitoring the volumetric water content (\(\theta\)) or the matric potential (\(\psi_m\); also called...
tension or suction) in the substrate (Pardossi et al., 2009). In soil and soilless growing media, the relationship between \( \theta \) and \( \psi_m \) is described by the water retention curve, which is determined in the laboratory following standard methods (e.g. De Boodt and Verdonck, 1972; EN 1301 method).

Expensive and complicated SMSs, such as neutron probe and TDR (time-domain reflectometry) instrument, are available for soil and plant scientists, while low-cost and practical devices are needed for irrigation control of commercial crops. Interesting possibilities have been opened up by new types of SMS that measure soil dielectric properties (Pardossi et al., 2009). New dielectric SMSs are cheaper and need much less maintenance and user's expertise compared to traditional water-filled tensiometers. The utilization of SMS technology for irrigation management in both soil and soilless culture has been documented by many papers and currently a variety of simple irrigation controllers are available on the market that are interfaced to one or more SMSs.

Threshold values for volumetric water content or tension depend on crop species and growing media. Typical range for \( \psi_m \) is from -4 kPa to -10 kPa in substrate growing systems (Pardossi et al., 2009). These value can be converted to \( \theta \) on the basis of the water retention curve; for instance, in perlite a \( \psi_m \) of -5 kPa corresponds to a \( \theta \) of 34%.

Sensors, such as 5TE (Decagon Devices) or WET (Delta-T Device), have been also developed for simultaneous measurements of temperature, volumetric water content and pore water EC in soil and soilless media (Pardossi et al., 2009). These sensors provide the possibility of controlled fertigation. An automated fertigation device was designed and tested successfully to modulate both irrigation frequency and EC of fertigation water based on the simultaneous measurement of \( \theta \) and pore water EC of the growing medium by means of the WET sensor (Incrocci et al., 2010). Specific algorithms were implemented in the control software in order to activate irrigation when a pre-set \( \theta \) threshold was reached and to modulate irrigation dose and/or NS EC (also by mixing different sources of irrigation water) with the aim of avoiding salt accumulation in the substrate and minimizing water drainage.
**Nutrient solution**

High crop yield in soilless cultivation results from the optimal conditions provided by artificial substrate, if any, and the supply of a well-balanced and highly-concentrated NS. The use of high nutrient concentration aims to:

- guarantee adequate nutrient supply without the difficulties of maintaining a fairly constant ion concentration in the root zone;

- prepare automatically the NS by fertigation mixer systems that normally dilute 100- to 200-fold concentrated stock solutions with raw water on the basis of EC measurement (due to the salt dissolved in raw water as well as the accuracy of current mixers, it would be not possible to use low-concentration NS in commercial greenhouses);

- at least in some crops, to improve fruit quality (osmotic effect). In these cultivations, an EC of 2.5-3.0 mS cm\(^{-1}\) is necessary for high quality standards.

NS contains all macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium and sulfur) and micronutrients (iron, boron, copper, manganese, zinc and molybdenum) at concentration of the order of milli- and micro-moles per liter, respectively (Table 2). Depending on crop physiology (e.g. tolerance to salinity) and stage, climatic conditions and hydroponic system, total molar concentration ranges between 20 and 40 mM (1 and 2 g l\(^{-1}\)). On a molar basis, the dominant ion is nitrate. Generally, horticultural crops do not tolerate ammonium form of nitrogen, which then is not used or used only used at very low concentration. Optimal values of pH are between 5.5 and 6.5.

Normally, the concentration is expressed as EC (dS m\(^{-1}\)). For most balanced NSs in the range of 1.0 to 4.0 dS m\(^{-1}\), a simple linear relationship can be used to convert equivalent concentration of cations (C\(^{+}\), meq L\(^{-1}\)) in EC, assuming that the concentration of cations is
equal to the one of anions (Sonneveld et al., 1999):

$$EC = 0.19 + 0.095 \, C^+$$  \hspace{1cm} \text{Ec. 3}

Chemical characteristics of the NS can be measured using portable instruments, quick test kits and laboratory analysis. Commonly, pH and EC are checked very frequently, also automatically, especially in closed systems.

The quality of raw water must be known in order to check whether it specific treatments and to calculate the amount of fertilizers required to prepare nutrient stocks. Some computer programs are available, also in the Internet, to calculate the exact amount of salts required to prepare nutrient stocks. An Excel spreadsheet (SOLNUTRI) was developed by L. Incrocci at University of Pisa (available at: http://www.euphoros.wur.nl/UK/Deliverables/).
Table 2. Concentration of macro- and micro-nutrients in the nutrient solutions used for commercial vegetable and ornamental crops in hydroponic culture.

<table>
<thead>
<tr>
<th>Crop</th>
<th>N-NO$_3$</th>
<th>N-NH$_4$</th>
<th>P</th>
<th>S</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomato</td>
<td>11-15</td>
<td>1-1.5</td>
<td>1.5-2</td>
<td>3.5-4.5</td>
<td>5-9</td>
<td>3.5-5</td>
<td>2-2.5</td>
</tr>
<tr>
<td>Pepper</td>
<td>14-17</td>
<td>1-1.25</td>
<td>1.5-2.5</td>
<td>1.75-2</td>
<td>4-7</td>
<td>4-5</td>
<td>1.5-2</td>
</tr>
<tr>
<td>Eggplant</td>
<td>13-17</td>
<td>1.5-2</td>
<td>1.5-2</td>
<td>1.25-2</td>
<td>4-6</td>
<td>3.5-3</td>
<td>2-2.5</td>
</tr>
<tr>
<td>Cucumber</td>
<td>16-18</td>
<td>1-1.25</td>
<td>1.25-2</td>
<td>1.25-2</td>
<td>5-8</td>
<td>3.5-4</td>
<td>1.5-2</td>
</tr>
<tr>
<td>Zucchini</td>
<td>15-18</td>
<td>1-1.5</td>
<td>1.5-2</td>
<td>1.75-2</td>
<td>5-8</td>
<td>3.5-4.5</td>
<td>2-2.5</td>
</tr>
<tr>
<td>Strawberry</td>
<td>11-13</td>
<td>1-1.25</td>
<td>1-1.75</td>
<td>1-1.5</td>
<td>4-6</td>
<td>3-3.5</td>
<td>1.5-1</td>
</tr>
<tr>
<td>Melon</td>
<td>16-19</td>
<td>0.5-1</td>
<td>1-1.75</td>
<td>1.25-2</td>
<td>5-8</td>
<td>4-5</td>
<td>1.5-2</td>
</tr>
<tr>
<td>Carnation</td>
<td>13-16</td>
<td>1.5-2.5</td>
<td>2-2.5</td>
<td>3-3.5</td>
<td>7-9</td>
<td>3-5.4</td>
<td>2-2.5</td>
</tr>
<tr>
<td>Gerbera</td>
<td>11-13</td>
<td>0.5-1.5</td>
<td>1.75-2</td>
<td>3-3.5</td>
<td>4-5-6</td>
<td>3-5.4</td>
<td>1.5-2</td>
</tr>
<tr>
<td>Rose</td>
<td>12-15</td>
<td>1-1.5</td>
<td>1.5-2</td>
<td>2.75-3</td>
<td>4-5-6</td>
<td>3-5.4-5</td>
<td>2-2.5</td>
</tr>
<tr>
<td>Anthurium</td>
<td>7.5-9</td>
<td>0.5-1</td>
<td>1-1.25</td>
<td>1-1.5</td>
<td>4-5.5</td>
<td>1-1.75</td>
<td>1-1.25</td>
</tr>
</tbody>
</table>

| Micronutrients (mmol m$^{-3}$) |
|-----------------|--------|--------|--------|--------|--------|--------|--------|
| Crop            | Fe$^3$ | B$^3$  | Cu     | Zn     | Mn     | Mo     |
| Tomato          | 20-25 | 30     | 1      | 5      | 10     | 0.5    |
| Pepper          | 20-25 | 30     | 1      | 7      | 10     | 0.5    |
| Eggplant        | 15-20 | 30     | 1      | 5      | 10     | 0.5    |
| Cucumber        | 15-20 | 25     | 1      | 5      | 10     | 0.5    |
| Zucchini        | 10-15 | 30     | 1      | 5      | 10     | 0.5    |
| Strawberry      | 20-25 | 15     | 1      | 7      | 10     | 0.5    |
| Melon           | 10-15 | 25     | 1      | 5      | 10     | 0.5    |
| Carnation       | 30-35 | 30     | 1      | 5      | 5      | 0.5    |
| Gerbera         | 35-45 | 35     | 2      | 5      | 5      | 0.5    |
| Rose            | 35-45 | 30     | 1      | 5      | 10     | 0.5    |
| Lisianthus      | 25-35 | 30     | 1      | 5      | 10     | 0.5    |
| Anthurium       | 15-20 | 20     | 0.5    | 3      | 5      | 0.5    |
Fertigation systems

The main components of a fertigation system (Figure 3) are the following:

• pressured and filtered water from single or multiple sources (e.g. groundwater and rainwater) and, in closed system, recirculating NS (disinfected or not); due to the risk of pathogen contamination, the disinfection of recirculating NS is advisable in closed system;
• irrigation pipelines, drippers, electrovalves and tanks;
• probes for monitoring EC and pH of supply, recirculating and drainage NS;
• dosing machine (many devices are available on the market), which injects two to more stock solutions into raw water and adjust pH and EC of supply NS;
• water meters to control the injection of nutrient stocks and irrigation water flows in the system;
• weather station, which is used to estimate crop ET;
• control system (computer program) to schedule irrigation and NS adjustment.

A few of these components (e.g. computer and disinfection unit) are installed only in sophisticated systems.

Figure 3. Typical layout of substrate soilless growing system.
Fertigation strategies for closed systems

In closed systems, water requirements correspond to genuine water uptake, which approximates ET as generally evaporation from the substrate and uncontrolled seepage are negligible. If saline water is used, there is a more or less rapid accumulation of ballast ions. Under these conditions, NS is recirculated till its EC and/or the concentration of some ions (e.g., Na, Cl or trace elements such as B) reach maximum acceptable thresholds value (ECMAX or CMAX) for the crop under consideration; afterwards, NS is replaced, at least partially (flushing).

Three different procedures differing for the criterion used for nutrient replenishment could be adopted in commercial closed systems: A) Reservoir tank is replenished by refill NS, which is prepared by mixing raw water and drainage NS at a ratio generally equal to the drain fraction and adding nutrient stocks to reach a target EC (Figure 4).

![Fertigation scheme following Strategy A](image)

This procedure maintains the EC of recirculating NS constant but it results in progressive nutrient depletion, if ballast ions are dissolved in raw water. In this system, EC does not provide information on
the concentrations of individual ions, as shown by the example reported in Figure 5.

Therefore, recirculating NS should be regularly (every 1-2 weeks) analyzed by quick tests (on farm) or by external laboratory in order to adjust the composition of refill NS and make a decision about the need for flushing. NS is discharged when the concentration of a given ion reaches Cmax. In The Netherlands, growers have the permission to leach their systems whenever a crop specific ceiling of Na concentration is reached (Vermeulen et al., 2005): for example, 8 mol m-3 for tomato. Alternatively, NS is discharged when the concentration of some polluting agents (e.g. nitrate) is lower than a limit imposed by legislation to wastewater (Massa et al., 2011).

B) Water uptake is compensated by refilling the mixing tank with NS at full strength (Figure 6) and the recirculating NS is flushed out whenever its EC and/or concentration of a given ion surpasses ECmax or Cmax. Such procedure results in a relatively constant concentration of nutritive ions but leads to a progressive EC increase due to the accumulation of ballast ions. The main disadvantage of this strategy is that EC oscillated in the NS and this is not suitable for salt-sensitive
crops. For instance, salinity oscillation may result in blossom-end rot or cracking of tomato fruits (Savvas, 2009).

C) This procedure is similar to Strategy A, but when ECmax or Cmax is reached, crop water uptake is compensated only with pH-controlled raw water for a few days, in order to minimize the concentration of polluting ions in the NS before flushing.

Figure 7 illustrates time-course of EC of drainage (open system) or recirculating (semi-closed systems) and how nutritive and ballast ions contribute to EC.

Massa et al. (2010) explored the influence of three fertigation strategies (A-C, as described previously) on water and nitrogen use efficiency of semi-closed rockwool culture of greenhouse tomato conducted using saline water (NaCl concentration of 9.5 mol m-3). In both years, there were no important differences in fruit yield and quality among the
strategies under investigation. Strategy C produced the best results in terms of water use and drainage, while strategy B was the most efficient procedure with regard to nitrogen use. In contrast to strategies A, the application of strategies B and C minimized nitrogen emissions and also resulted in nitrate concentrations in the effluents that were invariably lower than the limit (1.42 mol m⁻³) imposed to the nitrate concentration of wastewater discharged into surface water by the current Italian legislation associated to European Nitrate Directive.

A composite model was developed by Massa et al. (2011) for water and mineral relations of greenhouse tomato cultivated in semi-closed systems.
or open soilless (rockwool) culture. The model simulated on a daily basis: i) the evolution of crop leaf area index and water uptake using empirical equations; ii) the variations of ion concentrations and electrical conductivity (EC) in the recirculating or drainage nutrient solution using a mass balance equation based on the concept of ion uptake concentration.

The model was calibrated using measured data collected in previous works and validated in two independent experiments in which different fertigation strategies were tested using NSs prepared with saline (9.5 mol m-3 NaCl) water. The model predicted acceptably the time course of EC and ion concentration in recirculating (semi closed systems) or drainage (open system) nutrient solution; in general, there was a good agreement between simulated and measured values of total water and nutrient use.

Main advantages of this model are that it is easy to use, requires few variables and parameters, and can be easily recalibrated based on regular measurement of water uptake and chemical analysis of the recirculating NS. The composite model could be implemented in a decision support system (DSS) for fertigation management in soilless culture. In addition, the model could enable local assessment of water withdrawal and fertiliser leaching in greenhouse crops or scenario analysis of different cropping practices. In The Netherlands, the current legislation imposes limits to the amount of irrigation water that may be applied to greenhouse crops (for instance, 1140 L m-2 in tomato culture; Stanghellini et al., 2007). Simulation models of seasonal water use may be useful tools for both growers (for efficient water management at the farm gate) and policy makers (for instance, to establish limits to water application). The model could be also used to estimate emission of plant protection products applied to the crop through recirculating nutrient solution, which depend on dissipation kinetics and root uptake of the substance under consideration, and the frequency of flushing (Vermeulen et al., 2010).

The model is currently implemented in an Excel spreadsheet (SIMULHYDRO), which is freely available to interested readers at www.euphoros.wur.nl/UK).
Monitoring nutrient solution

Quick test kits (QTK) are valid alternative to time-consuming and expensive laboratory analysis of substrate extracts and nutrient solution. A large variety of QTK is commercially available. Many manufacturers offer QTK for a variety of analytes.

QTK generally consist of ready-to-use reagents, vessels and a portable measuring device. Their average prices range from a few euros (colorimetric assays with reactive strips) to a few hundred euros for ion selective electrodes (ISE). The commercially available QTK are basically of the following types:

- Titrimetric QTK: they are based on the reaction between the analyte and a reagent of known concentration; the reaction occurs generally in the presence of a substance undergoing a colour change when the reaction is complete.
- Colorimetric QTK: they entail a colour-forming reactions. The simplest colorimetric tests are the reactive strips. The colour intensity of the final compound, which is proportional to analyte concentration, is measured quantitatively by means of a photometer or a reflectometer (Figure 8), or semi-quantitatively by comparing sample colour with standard scale

![Figure 8. Quick determination of nitrate content in hydroponic nutrient solution by means of a portable reflectometer](image)
In a study conducted at the University of Pisa, it was found that titrimetric and reflectometric determinations were suitable for analysing the following ions, in certain ranges of concentrations, in irrigation water, substrate extracts and recirculating NSs (Maggini et al., 2010):

- Ammonium (reflectometry; 0.2 – 0.7 mg L-1)
- Boron (titrimetric assay; >0.2 mg L-1)
- Chloride (reflectometry; 2 – 50 or 50 – 1000 mg L-1)
- Nitrate (reflectometry; 2 - 90 or 5 - 225 mg L-1)
- Phosphate (reflectometry; 0.1 – 5 or 5 - 120 mg L-1)

A relatively expensive (a few thousands of euros) portable multi ion-meter is now available on the market (Clean Grow, Cork, Ireland; www.cleangrow.com). It has a single probe that allows for the rapid measurement of calcium, chloride, potassium, sodium, ammonium, nitrate ions and temperature. To our knowledge, no independent evaluation of this device for horticultural application has been performed.

**Leaching requirement in semi-closed system**

Simulation models can contribute to improved fertigation control in semi-closed system by considering variations in the ionic composition of recirculating NS and supporting grower’s decision on NS replenishment and leaching requirements.

Several models were designed for automated fertigation in closed systems (e.g. Heinen, 2001; Silberbush et al., 2005; Mathieu et al., 2006). However, commercial applications of these models are difficult, as they require many variables and parameters. Instead, Carmassi et al. (2007) proposed a simple mass balance equation to predict W of semi-closed soilless culture based on few variables and parameters, including CU of nutritive and ballast ions.

From the equation proposed by Carmassi et al. (2007), a simple equation can be derived with these assumptions: i) uptake concen-
tration is negligible compared to the concentration of considered ion in the refill NS (that is, in raw water - Cl); ii) at flushing, the entire volume of recirculating NS is discharged. The equation is the following:

$$LR = \frac{C_i}{C_{\text{MAX}} - C_i}$$

Eq. 4

with Cmax as defined previously.

This equation can be used to estimate the maximum Cl (Cl,max) that will make it possible to grow crop with known ET and tolerance to the ion under consideration (namely, Cmax) and with the constraints of limited water availability (maximum available volume or irrigation water - Wmax), which in turn determines LR:

$$C_i = \frac{C_{\text{max}} \cdot LR}{(1 + LR)}$$

Eq. 5

where

$$C_i = \frac{C_{\text{max}} \cdot LR}{(1 + LR)}$$

Eq. 6

Figure 9 shows the value of Cl,max as a function of Cmax and LR.
Figure 9. Maximum concentration of a given ballast ion in the raw water as determined by crop tolerance to this ion (as expressed by ceiling concentration in the recirculating nutrient solution) and target leaching requirement (LR).

MANAGEMENT OF ROOT DISEASES

Plant pathogenic microorganisms may accumulate in soilless systems, especially in the recirculating NS. The control of plant pathogens in recirculating water in greenhouses and nurseries can be achieved by several techniques of disinfection (Ehret et al., 2001; Stewart-Wade, 2011; see Table 3 for short description). However, the most effective strategy in preventing the occurrence of root diseases in closed soilless culture is one or more disinfection techniques associated with the adoption of prophylactic measures:

- clean and disinfect greenhouse floor and structures (e.g. benches, irrigation lines, etc.) before planting;
- prevent entry of pests and pathogens from outside with clothes
and shoes and with irrigation water (it may be contaminated before and/or during storage;

- keep crop healthy by adequate management of both climate and fertigation and integrated pest and disease control (including regular scouting and removal of all infected materials);
- monitor regularly the presence of pathogen propagules in the growing system (substrate and/or recirculating NS);
- disinfect the recirculating NS;
- disinfect the substrate before a new cultivation in case of low or moderate incidence of root diseases and/or pests. In contrast, when a crop is severely affected by root diseases or nematodes, re-using growing media is quite risky, notwithstanding disinfection.

An early diagnosis is crucial to prevent the occurrence of root diseases. Regular tests are needed for determining whether a disinfection of the recirculating NS is necessary or not. Using DNA methodology may allow the detection and identification of pathogens in many types of crop samples including irrigation water, nutrient solution, plant tissues and growing media. DNA tests are quick (the results may be available in a couple of days), specific (only the target pathogen is detected), sensitive and indicate the level of infection.
Table 3. Advantages and disadvantages of most popular nutrient solution disinfection methods (source: van Os et al., 2003; Stewart-Wade, 2011; van Os 2012).

<table>
<thead>
<tr>
<th>DISINFECTION METHOD</th>
<th>DOSES</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat treatment</td>
<td>95°C for 30 s 85°C for 3 min</td>
<td>High efficacy</td>
<td>High investment and running costs (only for farm &gt; 1 Ha).</td>
</tr>
<tr>
<td>UV-C radiation (Figure 11)</td>
<td>100-250 mJ/cm² UV-C</td>
<td>Moderate efficacy and investment cost</td>
<td>Sometimes unreliable results; needs pre-filtration; iron chelate breakdown.</td>
</tr>
<tr>
<td>Membrane filtration</td>
<td>Pores size: 0.05 μm for Fusarium; 0.1 μm</td>
<td>High efficacy</td>
<td>Sometimes unreliable results; needs pre-filtration; iron chelate breakdown.</td>
</tr>
<tr>
<td></td>
<td>for Verticillum</td>
<td></td>
<td>Expensive; needs preventive filtration and acidification; iron chelate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>breakdown.</td>
</tr>
<tr>
<td>Ozone</td>
<td>10 g m⁻³ h⁻¹</td>
<td>High efficacy</td>
<td>Expensive; needs preventive filtration and acidification; iron chelate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>breakdown.</td>
</tr>
<tr>
<td>Chlorine</td>
<td>2 ppm Cl, 1 min; for P. Cinnamomi</td>
<td>High efficacy; used for sanitation of greenhouse</td>
<td>Difficulties to establish the efficacy doses; acidity and organic compound</td>
</tr>
<tr>
<td></td>
<td></td>
<td>structure and devices</td>
<td>influence the efficiency.</td>
</tr>
<tr>
<td>Hydrogen peroxide</td>
<td>100 ppm for Fusarium spp.</td>
<td>Low investment costs</td>
<td>No kill completely the nematodes; iron chelate breakdown.</td>
</tr>
<tr>
<td>Slow filtration</td>
<td>Flow rate of 100–300 L m² h⁻¹; Sand grain</td>
<td>Low investment costs; suitable for low technology,</td>
<td>Eliminates completely zoosporic fungi and only partially Fusarium, viruses</td>
</tr>
<tr>
<td></td>
<td>size: 0-2 mm</td>
<td>small-size greenhouse operations</td>
<td>and nematodes.</td>
</tr>
</tbody>
</table>

Another problem that could reduce the crop production is the accumulation of plant and microbial metabolites in the recirculating NS and/or in the growing media substrate. Some of these compounds may have beneficial consequences on plant growth, but others have an allelopathic nature and may have a phytotoxic effect. For instance, in closed substrate cultivation of greenhouse rose, in particular in the Netherlands, the recirculating NS is discharged frequently in order to avoid NaCl accumulation and the plant growth inhibition which is ascribed to unknown organic substances and is indicated by an increase in
flower production and quality in the weeks following the discharge (Van Os et al., 2012). These authors investigated the effect of advanced oxidation of recirculating nutrient solution in two rose nurseries in the Netherlands. Advanced oxidation is based on the addition of hydrogen peroxide to the nutrient solution followed by an exposure to UV-C light. It was found that such treatment reduced the growth inhibition, degraded plant protection products added to the recirculating NS and eliminated plant pathogens with no important effect on the composition of the nutrient solution (with the exception of iron, due to UV degradation of iron chelate). To investigate the presence of harmful metabolites in the drain water the Phytotoxkit™ (http://www.microbiotests.be) was used by Van Os et al. (2012). The Phytotoxkit is a quick test based on germination and early growth of a few reference plants, such as Sorghum saccharatum, Lepidium sativum and Sinapis alba.

Figure 10. Unit for UV disinfection of recirculating nutrient solution. (Photo: Spagnol Greenhouse Technologies, Vidor, Italy)
LITERATURE


EN 13041 1999. Soil improvers and growing media. Determination of physical properties, dry bulk density, air volume, water volume, shrinkage value and total pore space.


technologies for greenhouse crops, in: Ramdane Dris (Ed.), Crops: Quality, Growth and Biotechnology, WFL Publisher, Helsinki (Finland), pp. 360-378.


Identification of irrigation and N management practices that contribute to nitrate leaching loss from an intensive vegetable production system by use of a comprehensive survey. Agr. Water Mgt. 89, 261–274.


LYFE CYCLE AND ECONOMIC ANALYSES OF
GREENHOUSE SYSTEMS

A.Antón Vallejo¹, M.Torrellas Iglesias¹, M.Ruijs² and J.I. Montero Camacho¹
¹IRTA. Centre de Cabrils, 08348 Cabrils, Barcelona, Spain
²Wageningen UR Greenhouse Horticulture. PO box 644, 6700 AP Wageningen, the Netherlands

INTRODUCTION

EUphoros project objective is the development of sustainable greenhouse production systems in Europe, with reduction of inputs and waste yet with high productivity and resource use efficiency. The economic and environmental assessment of present production systems in Europe was analysed and reported in Deliverable 5 (Montero et al., 2011;). Results showed the main bottlenecks that could be improved to reduce economic and environmental impacts: energy consumption, greenhouse structure, fertilizers and substrate. Subsequently it is conducted an assessment of the implementation of new technologies developed during the project with the objective to reduce the environmental and economic impacts of the production systems. At this course it will be showed a summary of the results of two of the scenarios stu-
died: a) Tomato production in a multi-tunnel greenhouse in Spain and b) Tomato production in a Venlo greenhouse in the Netherlands. The reader interested in detailed information, please visit the web of the project (www.euphoros.wur.nl/uk).

MATERIAL AND METHODS

Economic assessment

The economic assessment is based on cost-benefit analysis. The goal is to assess the financial consequences of the implementation of alternatives for improvement in the greenhouse systems.

The system boundary is defined at farm level, such that all costs and benefits of alternative greenhouse systems are considered at farm level. The greenhouse scenario can be seen as a black box with several inputs and outputs.

The following costs and benefits are considered:

- benefits: yield (tomatoes, sales of electricity (Dutch situation))
- costs: planting material, water and fertilizers, pesticides (biological and chemical), energy, other crop assets, labour and contractors, tangible assets (depreciation and maintenance), interest payments and general costs (cost of waste, accountancy office, membership fees, etc.).

All costs and benefits of the reference greenhouse production systems are taken into account to ensure the economic soundness of the tools developed in the course of the EUphoros project. The objective is not the absolute net financial result but the economic effect of input reducing options compared to the reference situation in the different scenarios. The inventory included costs for greenhouse equipment, plant material, energy sources, electricity, fertilizers, crop protection and labour (employers and employees). A tangible asset is the
component that contains the cost of depreciation and maintenance of the farm equipment. It does not include the interest costs. To get an idea of economic opportunities for input reductions an economic analysis was carried out. The effect of applying several of the cost-reducing alternatives for energy, fertilizers or crop protection agents is calculated and expressed as the extra net financial result, the payback period and/or the investment capacity.

The cost-benefit analysis results in a net financial result. The absolute net financial results are of limited relevance, because the alternative greenhouse systems will be evaluated for the relevant cost and benefit components, the so called partial cost-benefit analysis. The partial cost-benefit analysis will show the economic effects of (combinations of) input reducing options in the four greenhouse scenarios. The partial cost-benefit analysis focuses on the improvements for each greenhouse scenario separately. A comparison of the net financial result of the reference or alternative greenhouse systems between the different countries is no part of the study.

The results of the cost-benefit analysis give insight in the reference situation for both scenarios. Which cost components contributes most strongly to the net financial result or the profitability of the greenhouse system scenarios. Based upon the cost level of the inputs in the reference situation also the investment capacity is calculated in order to give an indication of the economic possibilities of alternative greenhouse systems/options to reduce inputs.

With respect to the developing and testing tools the (partial) cost benefit analysis will give insight in the profitability of the input reducing options in the different scenarios. For the most relevant factors the effect will be determined of fluctuating amounts, levels or prices on the net financial result. The following relevant factors can be mentioned: production level, product prices, and energy prices changes in simulated or calculated reductions of the consumption of energy, pesticides and nutrients. The sensitivity analysis will be carried out for the tested tools in the different scenarios.
Environmental assessment

Environmental assessment is conducted following Life Cycle Assessment methodology, LCA. As defined in ISO 14040 (ISO-14040, 2006), LCA is a “compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle”. The complexity of LCA requires a fixed protocol for performing and LCA study. Such a protocol is established by the International Standards Organisation (ISO-14040, 2006). According to this normative, LCA studies comprise four phases that are iterative between them. The relationship between phases is illustrated in Figure 1. These phases are:

- Goal and scope definition,
- Inventory Analysis,
- Impact Assessment, and
- Interpretation

**Goal and scope definition**

Goal: To assess two representative scenarios of greenhouse crops in Europe at the present moment. The reason for carrying out the study is to use these environmental profiles as a reference situation for comparison with alternative greenhouse system designs with reduced inputs and reduced emissions. In this study we considered the current...
agricultural practice for protected European crops, established as the starting point for the alternatives analysis. Several potential alternatives are analysed for reduction of environmental impacts. The majority of improvements are oriented to the agricultural practice according to each scenario: reduction of the volume of substrate and extension of its life span; reduction of the amount of fertilizers, extension of greenhouse life span and new cultivation methods. The purpose is to present feasible objectives that can be commonly applied by growers. Environmental and economic analyses are conducted comparing results from alternatives for improvement with the reference situation.

Scope: Two representative European greenhouse production scenarios are studied:

2. Tomato in Venlo structure in the Netherlands

Functional unit: The functional unit (UF) is the main function of the system analysed. A system may have a number of possible functions and the one selected for a study depends on the goal and scope of the LCA. In this case, since the most important function in horticultural crops is the production of vegetables, the functional unit chosen is the horticultural production of 1000 kg of tomatoes. This choice gives us a reference to normalise all the system’s input and output flows (ISO-14040, 2006).

System boundary: LCA is conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system. As the goal of this project is to improve production means (greenhouse), the system boundary is defined up to farm gates without considering post stages, such as commercialization but considering materials disposal. Therefore, the following life cycle stages and unit
processes are taken into account:

- acquisition of raw materials
- inputs and outputs in the main manufacturing processes for Greenhouse infrastructure, auxiliary equipment, climate control system, fertilizers and pesticides.
- transportation of materials
- production and use of fuels, electricity and heat
- crop production and greenhouse management (including water, fertilizers and pesticides consumption).
- recovery of used products or recycling
- disposal processes of waste and products
- additional operations such as lighting and heating

**Impact categories selected:** one energy flow indicator (i.e. cumulative energy demand) and five impact categories (i.e. abiotic depletion, global warming, air acidification, eutrophication and photochemical oxidant formation), are considered. Impact categories are defined by the CML (Guinée, et al., 2002) and are selected for this study because of its relevance in agriculture and energy processes. Abiotic depletion and global warming are important indicators related to energy consumption. Emissions related to agricultural inputs, mainly fertilizers and pesticides, are important contributors to Global Warming, while ammonia and nitrate emissions from N-fertilisers are important to acidification and eutrophication. Photochemical oxidant formation is a category that may have important consequences on agriculture (i.e. ozone contamination).

**Quality and origin of the data in the inventory:** the broad system under study required a detailed data-collection process. Most of these
primary data related to greenhouse dimensions, management and crop production are obtained from representative commercial greenhouses by the involved partners, i.e. Estación Experimental Fundación Caja-mar, Spain, Mórakert Production Organization, Hungary and Applied Plant Research, the Netherlands. Therefore these data are considered as Own Experimental Data (OED). For the secondary data (reference database, RDB), database such as Ecoinvent (Frischknecht, et al., 2005) and LCAFoods (Nielsen, et al., 2003) are used to complete the life cycle inventory. Figures considered are representative values and average for each of the scenarios studied.

In order to simplify calculations and due to the fact that production is a variable with strong dependence on temporal and spatial factors, data are related to crop area as reference flow. In a second step, these data are related to functional unit (1000 kg tomatoes or 1000 rose stems).

The software tool used for the assessment is the SimaPro program version 7.2 (PRéConsultants, 2010), only performing the compulsory phases of classification and characterization. Simapro program v.7.2 includes the last Ecoinvent database v 2.2.

Inventory analysis

Life Cycle Inventory (LCI) involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. The process of conducting an inventory analysis is iterative. As data are collected and more is learned about the system, new data requirements or limitations are identified.

Stages and processes considered: Greenhouse crop production system was structured in several stages or processes to facilitate the study and interpretation of the results. Figure 2 showed the process flow diagram that outline all the unit processes to be modelled including their relationship.
**Figure 2 General flow diagram for greenhouse production**

- **Greenhouse Structure characteristics**
  
  Two types of structures are considered depending on the area of study: multi-tunnel greenhouse (Mediterranean, Spain) and Venlo greenhouse (the Netherlands). In both cases, greenhouse structure consisted of a metal frame and a covering made of plastic film for multi-tunnel greenhouse in Spain and glass in Venlo greenhouses in the Netherlands. Metals considered in all the structures are steel and aluminium. We have considered that metal production is based in recycled metal in the four scenarios. This assumption is considered for all the metal elements in the greenhouse, which are included in structure, auxiliary equipment and climate control system stages.

- **Auxiliary equipment**
  
  The watering system begins at the well, channel or tank, which provides the water from the source to the water tanks and fertilizer tanks. Pumps and injectors supply fertilizers and water to the main
pipe and this main pipe to the secondary pipes which finally distribute water to the crop. There are as many secondary pipes as plant rows. Each tomato plant is watered by a dripper system composed by a micro tube, a pickaxe and a dripper. The plant rows run from side to side of the greenhouse, and are divided by a main path that allows labours operations.

Water for irrigation is included in the stage Auxiliary equipment. Electricity consumption for extraction and distribution pumps is also counted in the tomato crop in Spain. In the case of tomato crops in the Netherlands, we assume that this electricity consumption is counted in the total amount of electricity consumption of the greenhouse and included in the climate control system stage.

- **Climate control system**

  Depending on each production system, climate control system can include heating system, cogeneration system, distribution equipment, thermal water, natural ventilation, CO2 enrichment system, roof cooling and crop lighting.

  Total electricity consumption for the greenhouse is also included in this section for Venlo scenario. In tomato production in Spain, climate control system only includes the electricity for ventilators operation. Electricity consumption for the watering system is included in auxiliary equipment stage.

  These particular characteristics are described in the climate control system section of each scenario and can be consulted for more details in the website of the project (www.euphoros.wur.nl/uk).

- **Fertilizers**

  Fertilizers use involves important environmental impacts, both by manufacturing processes and emissions produced by their application. It is also true that fertilizers emissions are a controversial subject that needs further study. There are different approaches and parameters to calculate the emissions. In this case, the reference choice was
the one proposed by Bentrup for ammonia, NH3-N and dinitrogen oxide, N2O-N (Bentrup, et al., 2000) and Ausdley for nitrogen oxides NOx-N and NO3- emissions to water (Audsley, 1997).

- Ammonia emitted to air: kg NH3-N per ha is 3% of the fertilizer N (kg/ha).

- Nitrous oxide to air: kg N2O-N per ha is 1.25% of the fertilizer N (kg/ha).

- Nitrogen oxides to air: kg NOx-N per ha is 10% of N2O-N.

It is considered that closed systems do not produce lixiviates. It is assumed that in case of flushing, this will be considered as a waste, without being thrown away to soil or aquifers. This is the situation for tomatoes in the Netherlands. In the case of Spain, the dripping watering system is not a closed one. Therefore, emissions to water are calculated.

**Phytosanitary treatments**

En esta sección se consideran las cantidades de principio activo de los pesticidas aplicados (específicamente el impacto medioambiental del proceso de fabricación) y la maquinaria para su aplicación. No se evaluó la toxicología de las emisiones. Esta es una cuestión controvertida dado que no hay consenso sobre que metodología de cálculo debería ser aplicada en estudios de ciclo de vida.

**Residuos**

In this section, the amount of active ingredient of pesticides applied (specifically the environmental impact of manufacturing process) and the machinery for its application was considered. Toxicology of the emissions was not evaluated. This is a controversial aspect without general consensus about what methodology for calculations should be used in life cycle assessment studies:

- 15 years life materials: Steel, aluminium, concrete, glass, PC and copper from structure, climate control
system and auxiliary equipment. Since most part of these materials take part of the frame, we can also name them “frame materials”.

- Plastics: PE, LDPE, PP, PVC, polyester and polystyrene. Plastic films such as the greenhouse covering or substrate bags are considered to have a life span of three years, while the others plastics (irrigation equipment, etc) are contemplated to last five years.

- Substrate: Perlite useful life is 3 years and rockwool is 1 year.

- Green biomass: Once the crop was over, it is estimated that plants are cut and let dry partially in the greenhouse. From previous experience it is assumed that 40% of the fresh weight of plants is transported to the composting plant.

Materials that are directed to a recycling process are not considered as a phase of the production system. For the management of waste from cultivation, we use the “cut-off” method—defined by Ekvall and Tillman (1997)—by which each system receives the burdens for which it is directly responsible. Under this method, there is no uncertainty in the case of the extraction of raw materials, production processes or transport, because these are all directly assigned to the system. In the case of waste disposal, such treatment is fully attributable to the system being studied; while for this waste which is recycled or reused, it is considered its burdens should be attributed to the system that will use it as a material source. Therefore, the process of recycling is included in the new material created in substitution of raw material in another system. We also make the assumption that the recycling company is going to the greenhouse to collect the materials. This is the reason why only transport and emissions for materials transported to landfill and incinerator are counted. In the case of green biomass, transport to the composting plant is considered part of the system because as far as we know it is usually done in this way.
• Transport

Transport considered delivery of materials and devices from its origin to the greenhouse. All transport was on road by lorry or van in the sites under study.

Process of transport included vehicle and road manufacture and maintenance, as well as diesel consumption.

Fertilizers transport is not incorporated in this study. Usually growers can afford fertilizers from a near distributor. On the other hand, distributors usually receive fertilizers from other distributors and manufacturers from all over Europe and consequently it would have been difficult to track these data. Since fertilizers transport is not going to be improved in this study, it was decided not to include it.

Transport to market or auction is not also considered because commercialization is a process not included in the crop production system.

Table 1 summarizes the main characteristics for both greenhouses. More detailed information about reference production systems and the methodologies used for the study for improvements are reported in Deliverable 5 (Montero et al., 2011) and Deliverable 13 (Montero et al, 2012). The reader can consult both Deliverables at the project web site www.euphoros.wur.nl/uk (EUPHOROS, 2008-2012).
Table 1. Main characteristics of the two reference scenarios

<table>
<thead>
<tr>
<th></th>
<th>Scenario a) Tomato, multi-tunnel, Spain</th>
<th>Scenario b) Tomato, Venlo, the Netherlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface (m²)</td>
<td>19,440</td>
<td>40,000</td>
</tr>
<tr>
<td>Number of spans</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>Concrete (m³·ha⁻¹)</td>
<td>63</td>
<td>45</td>
</tr>
<tr>
<td>LDPE covering (kg·ha⁻¹)</td>
<td>3,787</td>
<td></td>
</tr>
<tr>
<td>PC walls (kg·ha⁻¹)</td>
<td>1,707</td>
<td></td>
</tr>
<tr>
<td>Steel (kg·ha⁻¹)</td>
<td>76,994</td>
<td>109,829</td>
</tr>
<tr>
<td>Aluminium</td>
<td></td>
<td>28,110</td>
</tr>
<tr>
<td>Glass (kg·ha⁻¹)</td>
<td></td>
<td>118,927</td>
</tr>
<tr>
<td>Crop</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield (kg·ha⁻¹)</td>
<td>16.5 kg·m⁻²·y⁻¹</td>
<td>56.5 kg·m⁻²·y⁻¹</td>
</tr>
<tr>
<td>Crop period</td>
<td>52 weeks</td>
<td>52 weeks</td>
</tr>
<tr>
<td>Crop density (stems·m⁻²)</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Auxiliary equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substrate</td>
<td>Perlite</td>
<td>Rockwool</td>
</tr>
<tr>
<td>Substrate (kg·ha⁻¹)</td>
<td>18,877</td>
<td>4,476</td>
</tr>
<tr>
<td>Substrate per plant (l)</td>
<td>10</td>
<td>5.22</td>
</tr>
<tr>
<td>Fertirrigation system</td>
<td>Drippers, Open-loop</td>
<td>Drippers, Closed-loop</td>
</tr>
<tr>
<td>Water source</td>
<td>Well</td>
<td>Rainwater tank</td>
</tr>
<tr>
<td>Water (l·m⁻²)</td>
<td>474.8</td>
<td>794</td>
</tr>
<tr>
<td>Water use</td>
<td>28.8 l·kg⁻¹</td>
<td>14.1 l·kg⁻¹</td>
</tr>
<tr>
<td>Fertilizers (kg·ha⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>798</td>
<td>1688</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>506</td>
<td>406</td>
</tr>
<tr>
<td>K₂O</td>
<td>1,562</td>
<td>1855</td>
</tr>
<tr>
<td>Air emissions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH₃-N</td>
<td>24</td>
<td>51</td>
</tr>
<tr>
<td>N₂O-N</td>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td>NO₂-N</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>Water emissions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO₃</td>
<td>359</td>
<td></td>
</tr>
<tr>
<td>Pesticides (kg·ha⁻¹)</td>
<td>32</td>
<td>10</td>
</tr>
<tr>
<td>Climate control system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Climate system</td>
<td>Natural ventilation</td>
<td>Co-generation</td>
</tr>
<tr>
<td>Energy source</td>
<td>no</td>
<td>Natural gas</td>
</tr>
<tr>
<td>Lighting</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Energy screen</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>CO₂ enrichment</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Waste</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste disposal emissions</td>
<td>Transport Landfill</td>
<td>Transport Landfill Incineration</td>
</tr>
</tbody>
</table>
Allocation of flows and releases

One vegetable product (i.e. tomato) is obtained for each scenario; therefore there is not any problem of allocation. Nevertheless, in the Netherlands scenarios, there is a Combined Heat and Power (CHP) system that produced heat to heat the greenhouse and electricity at the same time. When the electricity produced exceeded the electricity greenhouse consumption the surplus is transferred to the public grid. In this sense, two products are obtained: tomato and electricity. In fact, the real situation is to consider both products. Therefore, and as a first approach, results presented here showed the production system considering the amount of electricity produced as an output and consequently as an avoided product of our system. Other procedure (ISO 14044) advises that inputs, in this case natural gas, should be partitioned between its different products. For this reason, calculations are also done following both methodologies.

Total consumption of natural gas is 64.7 m3·m-2 in Venlo greenhouse. Cogeneration system produced 178 kWh·m-2, total electricity consumption for the greenhouse was 10 kWh·m-2. Therefore the surplus of electricity after the electricity used by the tomato greenhouse was discharged to the public grid 168 kWh·m-2. A 40% electrical efficiency CHP engine was considered and avoided emissions due to electricity were subtracted to get the net emissions. To produce 1 kWh electricity with CHP 0.129 m3 of natural gas is needed (Blonk et al. 2009). Therefore, 23.01 m3·m-2 natural gas were needed to produce 178 kWh electricity; or 728.2 MJ·m-2 considering calorific value natural gas 31.65 MJ·m-3 with heat efficiency of 90%. To heat the greenhouse 41.74 m3 of natural gas or 1319.6 MJ·m-2 are used (table 2). As CO2 produced by the CHP is usually incorporated to greenhouse, allocation between heat and CO2 was not considered.
Table 2. Energy consumption and production in scenario b)

<table>
<thead>
<tr>
<th>Natural gas consumption at CHP</th>
<th>Scenario b</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m³·m⁻²</td>
</tr>
<tr>
<td>Total, heating+electricity</td>
<td>64.7</td>
</tr>
<tr>
<td>Energy allocation, heating</td>
<td>41.7</td>
</tr>
<tr>
<td>Energy allocation, electricity</td>
<td>23.0</td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
</tr>
<tr>
<td>Greenhouse consumption</td>
<td>10</td>
</tr>
<tr>
<td>Produced by CHP</td>
<td>178</td>
</tr>
<tr>
<td>Surplus</td>
<td>168</td>
</tr>
<tr>
<td>Bought at public grid</td>
<td>0</td>
</tr>
</tbody>
</table>

**Life Cycle Impact Assessment**

The impact assessment phase of LCA, LCIA, is aimed to evaluate the significance of potential environmental impacts using the LCI results. This process involves associating inventory data with specific environmental impacts categories and category indicators, thereby to understand these impacts. This phase also provides information for the life cycle interpretation phase.

In this phase the ISO 14040 (2006) defines the mandatory and optional elements. Mandatory elements include: 1) selection of impacts categories, category indicators and characterization models, 2) classification or assignment of LCI results to different impacts categories selected and 3) characterization or calculation of category indicator results. Optional elements were normalization, grouping and weighting. They involve calculation of results relative to the reference situation. In this way, such elements give a value of importance to the different environmental problems. The optional normalization and valorisation phases are excluded of this study because scenarios will be used as a reference themselves for the future development of the project. These phases entail a high degree of subjectivity since they
considerably depend on local characteristics and they reduce the information contributed with regard to environmental impacts (Bare, et al., 2006, Finnveden, 1997).

Figure 3 outlines the classification and characterization elements of the LCIA with an example for the global warming category. In the LCI, a list of interventions were recorded and quantified including different inputs and outputs of the processes. From that list, a selection of different interventions (e.g. CO2, CH4, N2O, etc) meaningful for the category chosen (e.g. global warming) was done. For a given impact category (e.g. global warming), a characterisation method comprises a category indicator (e.g. kg eq. CO2), a characterisation model (e.g. IPCC (IPCC, 2007)) and a characterization factor (e.g. 296 kg N2O per kg CO2) derived from the model. By means of characterization factors, also named equivalent factors, the addition of the different interven-
tions is possible to provide a total value.

The category indicator can be located at any point between the LCI results and the damage consequences for ecosphere (where the environmental effect occurs) in the cause-effect chain. Within this framework, two main schools of methods developed:

a) Midpoints categories: Classical impact assessment methods (e.g. CML (Guinée, et al., 2002) and EDIP (Hauschild, et al., 1998) which restrict quantitative modelling to relatively early stages in the cause-effect chain. The finality is to limit uncertainties and group LCI results in so-called midpoint categories, according to themes. Such themes are common mechanisms (e.g. climate change) or commonly accepted grouping (e.g. ecotoxicity).

b) Endpoints categories: Damage oriented methods such as Eco-indicator 99 (Goedkoop, et al., 2000) or EPS (Steen, 1999), which try to model the cause-effect chain up to the endpoint, or damage, sometimes with high uncertainties. Damages can be correlated directly to areas of Protection, i.e. human health, natural resources (providing options for extraction) and natural environment (with significance not related to extraction).

The objectives of this study advised to select midpoints categories in order to reduce uncertainties in the comparison of improvements coming out from next advances in the project. The main characteristics of the different categories chosen are developed below. Moreover, the main substances that contributed to each category are listed in table 3.

• Cumulative energy demand, CED MJ eq

Cumulative energy demand aims to investigate the energy use throughout the life cycle of a good or a service. This includes the direct as well as the indirect uses; or grey consumption of energy due to the use of, e.g. construction materials or raw materials. The cumu-
relative energy demand is also widely used as a screening indicator to point out the priorities of energy saving potentials in their complex relationship between design, production, use and disposal. Furthermore, CED-values can be used to compare the results of a detailed LCA study to others where only primary energy demand is reported. Characterization factors were given for the energy resources divided in: non renewable, fossil and nuclear, renewable, biomass, wind, solar, geothermal and water.

• **Abiotic depletion, AD, kg Sb eq (Guinée, et al., 2002)**

  This impact category, depletion of abiotic resources, is concerned with protection of human welfare, human health and ecosystem health. This impact category indicator is related to extraction of minerals and fossil fuels due to inputs in the system. The Abiotic depletion characterization factor is determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration reserves and rate of de-accumulation.

• **Air acidification, AA, kg SO2 eq (Guinée, et al., 2002)**

  Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). The majors acidifying pollutants are SO$_2$, NOx and NH3. Acidification characterization factor for emissions to air is calculated with the adapted RAINS 10 model, describing the fate and deposition of acidifying substances (Guinée, et al., 2002). AA is expressed as kg SO$_2$ equivalents.

• **Eutrophication, EU, kg PO4--- eq (Guinée, et al., 2002)**

  Eutrophication (also known as nutrification) includes all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil. Eutrophicatin characterization factor is based on the stoichiometric procedure of Heijungs (Heijungs, et al., 1992) and expressed as kg PO$_4^{3-}$ equivalents.
• **Global warming, GW, kg CO$_2$ eq (Guinée, et al., 2002)**

Climate change can result in adverse affects upon ecosystem health, human health and material welfare. Climate change is related to emissions of greenhouse gases to air. The characterization model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterization factors (IPCC, 2007). Factors were expressed as global warming for time horizon 100 years (GW100), in kg carbon dioxide equivalents.

• **Photochemical oxidant formation, PO, kg C2H4 eq (Guinée, et al., 2002)**

Photo-oxidant formation is the formation of reactive substances (mainly ozone) which were injurious to human health and ecosystems and which also may damage crops. This problem is also indicated with “summer smog”. Winter smog is outside the scope of this category. Photochemical ozone characterization factor for emission of substances to air is calculated with the UNECE Trajectory model (including fate), and expressed in kg ethylene equivalents (Guinée, et al., 2002).

• **Water use, L**

Nowadays, although research is advancing in the development of a method for assessing the environmental impacts of freshwater consumption (Milà i Canals, et al., 2009, Pfister, et al., 2009), there is not yet an agreement among the scientific community about how to handle this category. In this study and due to the relevance of water assessment in agriculture production, Liter of water was used as a rough indicator.

As far as there were not characterization factors for water and pesticides indicators only the inventory values were delivered. These values are used as a reference for the future improvements that are being developed in the course of EUphoros project.
Table 3 Main contributing substances and units for each environmental impact category.

<table>
<thead>
<tr>
<th>Category</th>
<th>Units</th>
<th>Main contributing substances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative energy demand</td>
<td>CED</td>
<td>MJ</td>
</tr>
<tr>
<td>Abiotic depletion</td>
<td>AD</td>
<td>kg Sb eq</td>
</tr>
<tr>
<td>Acidification</td>
<td>AA</td>
<td>kg SO₄ eq</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>EU</td>
<td>kg PO₄⁻ eq</td>
</tr>
<tr>
<td>Global warming 100a</td>
<td>GW</td>
<td>kg CO₂ eq</td>
</tr>
<tr>
<td>Photochemical oxidation</td>
<td>PO</td>
<td>kg C&gt;H₂ eq</td>
</tr>
</tbody>
</table>

- **Interpretation**

  Interpretation is the phase of LCA in which the findings from the inventory analysis (LCI indicators, water and quantity of pesticides) and the impact assessment were considered. The interpretation phase delivers results that were consistent with the goal and scope definition, reaches conclusions, explains limitations and provides recommendations to decision-makers.

  The interpretation phase may involve the iterative process of reviewing and revising the scope of the LCA. This phase reflects the fact that the LCIA results were based on a relative approach, indicate potential environmental effects and were understandable, complete and consistent.

**RESULTS**

**Reference scenarios**

This section provides a first insight into the environmental and economic hot spots in the life cycle of the reference scenarios assessed, with recommendations to improve the processes which will re-
duce environmental impact. The main results and issues that could be improved are described for the reference situation relating to each scenario:

Tomato production in a multi-tunnel greenhouse in Spain. A multi-tunnel greenhouse is an unheated passive system that needs little energy and inputs other than fertilizers and water. The main environmental burdens and cost components of the production system for this scenario are presented in Figures 4a, 4b and 5.

- **Structure**: Structure is a major contributor to most impact categories (Figure 4a). The large amount of steel in the frame is reflected in the results. Its environmental impact can be reduced by extending the life span of the greenhouse and by increasing productivity, which is low in Spain. Plastics also make an important contribution to the impact categories. Plastics make the largest contribution to abiotic depletion and cumulative energy demand.

- ** Auxiliary equipment**: Auxiliary equipment had a high environmental impact because of the consumption of electricity by the irrigation system and the manufacturing of perlite. Electricity consumption includes the consumption required by pumps and injectors to water the crop. This is the main burden in the air acidification and eutrophication impact categories. Substrate processes include the manufacture of perlite and plastic bags as well as transport to the greenhouse; the manufacturing of perlite is the most significant. Substrate presented the highest contribution scores to the impact categories relating to abiotic depletion, global warming and cumulative energy demand (Figure 4b).

- **Fertilizers**: fertilizer use entailed environmental impacts as a result of both manufacturing processes and emissions. An efficient balance of fertilizers and water is recommended. Emissions due to the use of fertilizers made a very high contribution to the eutrophication impact category. With regard to the risk of eutrophication, it should be noted that the methodologies currently used to assess the amount of fertilizer reaching the aquifers are only
approximate and subject to debate.

- In the economic assessment, tangible assets and labour are responsible for almost 60% of total costs. The cost associated with the structure of the greenhouse and other equipment amounted to almost 1/3 of the total cost. The variable costs of crop protection and energy were low (3-4%). Fertilizer costs amounted to 7% of the total costs (Figure 5).

- For this scenario, a reduction in fertilizer use can potentially be used to create a high investment capacity, especially if inputs or emissions of fertilizers can be reduced by 50%. The question is whether halving fertilizer inputs will be realistic in terms of plant growth and development. Furthermore, halving the use of pesticides can offer a saving of nearly 0.9 €/m² of investment capacity.

Tomato production in a Venlo greenhouse in The Netherlands. The main burdens are:

- Climate control system: results for this scenario showed that climate control system is the major contributor to all impact categories (81% to 96%) Figure 6a. The high amount of natural gas used to heat the greenhouse is the main reason for such high environmental impacts. The use of a Combined Heat and Power (CHP) system to heat the greenhouse could significantly offset natural gas consumption and its environmental impact because of the electricity produced. The reduction in the environmental burden associated with the cogeneration process is discussed in this Deliverable.

- Auxiliary equipment: the LCIA showed the importance of substrate contribution to all impact categories. This is also one of the improvement targets of the EUPHOROS project. Process contributions are represented in Figure 6b. Substrate processes include the manufacture of rockwool and plastic bags as well as
transit to the greenhouse. Rockwool manufacture is the most significant of the three.

- The greenhouse production systems in The Netherlands are more capital intensive than those in Spain. This is mainly due to higher levels of investment in greenhouse structure, climate control systems and fertirrigation systems. Nevertheless, the difference between total outputs and total costs for both scenarios is more or less the same.

- Total costs mainly depended on natural gas consumption, tangible assets and labour. Energy accounted for 31% of total costs (Figure 7). The costs attributable to fertilizers and crop protection are relatively small (1-2%).

- Energy saving options can be very favourable in this scenario. By saving 10%-50% of energy, investment capacity will rise from 10 to 52 €/m². In scenario 3 halving the use of pesticide can also have an interesting influence on investment, as well other cost reducing options (such as improving pest control). However, reductions in energy consumption can have a negative economic effect if cogeneration is used to produce heat and power at the farm level and the excess electricity is sold to the national grid.
Figure 4. a) Stage contribution to impact categories for scenario tomato production in Spain; b) detail for auxiliary equipment; Impact categories: AD, abiotic depletion; AA, air acidification; EU, eutrophication; GW, global warming; PO, photochemical oxidation; CED, cumulative energy demand.
Figure 5. Cost components of scenario of tomato in Spain.
Figure 6. a) Stage contribution to impact categories for scenario of the Netherlands tomato production with allocation of natural gas for heating the greenhouse in CHP in The Netherlands; b) detail for auxiliary equipment; Impact categories: AD, abiotic depletion; AA, air acidification; EU, eutrophication; GW, global warming; PO, photochemical oxidation; CED, cumulative energy demand.

Figure 7. Cost components of scenario of tomato production in the Netherlands.
PROVEMENT ALTERNATIVES

The scenarios selected for the study and a brief description of alternatives for improvement for each one of them is described as follows:

- **Scenario a**, Tomato crop in a multi-tunnel greenhouse in Spain:
  - Rational use of substrates and fertirrigation system: Reduction of substrate volume, extension of substrate life span, reduction of fertilizers doses.
  - Extension of greenhouse life span
  - Increase of renewable energy in electricity production
  - Closed-loop irrigation system.
  - New type of greenhouse with improved ventilation

Scenario b, Tomato crop in a Venlo greenhouse in the Netherlands:

- Energy saving cultivation method. Contains several steps in the cultivation techniques to obtain energy saving. These steps can be implemented successively.
- New type of greenhouse with double glazing.

Scenario a, Tomato crop in a multi-tunnel greenhouse in Spain: The main burdens in the reference situation were structure, auxiliary equipment and fertilizers (Table 4).

Major environmental impact reductions could be obtained by a combination of several individual alternatives in the best case alternative and with a new type of greenhouse (Table 5). In the first case, environmental impacts can be reduced by 30.1% in the air acidification impact category; 22.7% to 28.7% in abiotic depletion, eutrophication,
global warming and photochemical oxidation impact categories; and by 17.4% in the cumulative energy demand impact category. Major reductions, 10.2% and 15.3%, could be obtained in eutrophication impact category with 20% and 30% of fertilizer dose decrease, respectively. It is noticeable that the increase to 40% of renewable energy in the electricity production mix reduced contributions to air acidification by 12.7%. A reduction of 25% of substrate volume and extension of perlite life span to four years gave similar environmental impact reductions to impact categories and similar economic effects (Table 6).

With the implementation of a closed-loop irrigation system, water consumption and fertilizer doses would be reduced. Consequently, fertilizer environmental impacts would decrease, because of the reduction of emissions due to fertilizer manufacture and their application. Contributions to eutrophication impact category highly decrease because of reduction of nitrate emissions to water. Economic results in table 7 show that an investment in a closed fertirrigation system seems to be profitable. The payback period is within three year. If disinfestations of the nutrient solution is required to prevent spreading of diseases the financial result will be negative.

In the new type of greenhouse environmental impacts would be significantly reduced (36% to 42.7%) because of a high increase of productivity. Results in table 8 point out that an investment in a new type multi-tunnel greenhouse with improved ventilation appears to be profitable. The extra investment can be earned back within 5 years under the assumptions.
Table 4. Stage contributions to selected impact categories (IC) per ton of tomato, for reference tomato production in a multi-tunnel greenhouse.

<table>
<thead>
<tr>
<th>IC</th>
<th>Unit</th>
<th>Total</th>
<th>Structure</th>
<th>Climate System</th>
<th>Auxiliary equipment</th>
<th>Fertilizers</th>
<th>Pesticides</th>
<th>Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>kg Sb eq</td>
<td>1.7E+00</td>
<td>7.8E-01</td>
<td>1.1E-03</td>
<td>6.3E-01</td>
<td>2.0E-01</td>
<td>1.7E-02</td>
<td>2.3E-02</td>
</tr>
<tr>
<td>AA</td>
<td>kg SO₂ eq</td>
<td>1.0E+00</td>
<td>3.9E-01</td>
<td>1.5E-03</td>
<td>4.2E-01</td>
<td>2.1E-01</td>
<td>1.9E-02</td>
<td>1.2E-02</td>
</tr>
<tr>
<td>EU</td>
<td>kg PO₄³⁻ eq</td>
<td>4.9E-01</td>
<td>1.5E-01</td>
<td>2.7E-04</td>
<td>8.0E-02</td>
<td>2.5E-01</td>
<td>6.5E-03</td>
<td>3.9E-03</td>
</tr>
<tr>
<td>GW</td>
<td>kg CO₂ eq</td>
<td>2.5E+02</td>
<td>8.8E+01</td>
<td>1.5E-01</td>
<td>7.7E+01</td>
<td>8.2E+01</td>
<td>2.0E+00</td>
<td>3.1E+00</td>
</tr>
<tr>
<td>PO</td>
<td>kg C₂H₄</td>
<td>5.4E-02</td>
<td>2.0E-02</td>
<td>5.4E-05</td>
<td>2.7E-02</td>
<td>4.9E-03</td>
<td>1.2E-03</td>
<td>1.0E-03</td>
</tr>
<tr>
<td>CED</td>
<td>MJ</td>
<td>4.0E+03</td>
<td>1.9E+03</td>
<td>3.1E+00</td>
<td>1.6E+03</td>
<td>3.9E+02</td>
<td>4.1E+01</td>
<td>5.7E+01</td>
</tr>
</tbody>
</table>

AD, abiotic depletion; AA, air acidification; EU, eutrophication; GW, global warming; PO, photochemical oxidation; CED, cumulative energy demand.

Table 5. Environmental impact reductions (%) versus reference situation per alternative and impact categories

<table>
<thead>
<tr>
<th></th>
<th>AD</th>
<th>AA</th>
<th>EU</th>
<th>GW</th>
<th>PO</th>
<th>CED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizers ↓ 10%</td>
<td>1.2</td>
<td>2.0</td>
<td>5.1</td>
<td>3.2</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Fertilizers ↓ 20%</td>
<td>2.4</td>
<td>4.0</td>
<td>10.2</td>
<td>6.5</td>
<td>1.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Fertilizers ↓ 30%</td>
<td>3.6</td>
<td>6.0</td>
<td>15.3</td>
<td>9.7</td>
<td>2.7</td>
<td>3.0</td>
</tr>
<tr>
<td>20 years greenhouse life span</td>
<td>5.2</td>
<td>6.3</td>
<td>6.3</td>
<td>5.6</td>
<td>6.4</td>
<td>5.2</td>
</tr>
<tr>
<td>Perlite 4 years life span</td>
<td>4.5</td>
<td>3.0</td>
<td>1.3</td>
<td>3.9</td>
<td>2.8</td>
<td>4.4</td>
</tr>
<tr>
<td>Perlite volume ↓ 5%</td>
<td>0.8</td>
<td>0.6</td>
<td>0.3</td>
<td>0.8</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Perlite volume ↓ 15%</td>
<td>2.5</td>
<td>1.7</td>
<td>0.8</td>
<td>2.3</td>
<td>1.6</td>
<td>2.5</td>
</tr>
<tr>
<td>Perlite volume ↓ 25%</td>
<td>4.2</td>
<td>2.9</td>
<td>1.3</td>
<td>3.8</td>
<td>2.7</td>
<td>4.1</td>
</tr>
<tr>
<td>Perlite volume ↓ 35%</td>
<td>5.8</td>
<td>4.0</td>
<td>1.8</td>
<td>5.3</td>
<td>3.8</td>
<td>5.7</td>
</tr>
<tr>
<td>↑10% renewable energy</td>
<td>0.4</td>
<td>0.8</td>
<td>0.3</td>
<td>0.4</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>↑20% renewable energy</td>
<td>2.4</td>
<td>4.8</td>
<td>1.8</td>
<td>2.1</td>
<td>3.4</td>
<td>0.6</td>
</tr>
<tr>
<td>↑30% renewable energy</td>
<td>4.3</td>
<td>8.8</td>
<td>3.4</td>
<td>3.8</td>
<td>6.1</td>
<td>1.1</td>
</tr>
<tr>
<td>↑40% renewable energy</td>
<td>6.3</td>
<td>12.7</td>
<td>4.9</td>
<td>5.5</td>
<td>8.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Best Case</td>
<td>22.7</td>
<td>30.1</td>
<td>28.7</td>
<td>27.6</td>
<td>22.8</td>
<td>17.4</td>
</tr>
<tr>
<td>Closed irrigation system</td>
<td>5.2</td>
<td>9.9</td>
<td>48.2</td>
<td>12.3</td>
<td>5.1</td>
<td>4.9</td>
</tr>
<tr>
<td>New type of greenhouse</td>
<td>42.6</td>
<td>38.8</td>
<td>36.0</td>
<td>39.3</td>
<td>41.8</td>
<td>42.7</td>
</tr>
</tbody>
</table>

AD, abiotic depletion; AA, air acidification; EU, eutrophication; GW, global warming;
**Table 6.** Effect of reduced substrate volume and life span on yearly costs of substrate bags (€/m²) *  

<table>
<thead>
<tr>
<th>Substrate bags (perlite)</th>
<th>Units/ha</th>
<th>Investment</th>
<th>Depreciation</th>
<th>Interest</th>
<th>Costs</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference cultivation system</td>
<td>4650</td>
<td>1.80</td>
<td>8370</td>
<td>33.3</td>
<td>7.5</td>
<td>0.34</td>
</tr>
<tr>
<td>25% volume reduction</td>
<td>4650</td>
<td>1.42</td>
<td>6591</td>
<td>33.3</td>
<td>7.5</td>
<td>0.27</td>
</tr>
<tr>
<td>4 year life span</td>
<td>4650</td>
<td>1.80</td>
<td>8370</td>
<td>25.0</td>
<td>7.5</td>
<td>0.27</td>
</tr>
</tbody>
</table>

* Option 1: Price per litre substrate is about 5% higher than the standard substrate bag

**Table 7.** Effect of closed fertirrigation system, quick test nutrient solution analysis and UV filtration on balance of benefits and costs and payback period (€/ha, year) 1) 2) 3)  

<table>
<thead>
<tr>
<th></th>
<th>Investment</th>
<th>Depreciation</th>
<th>Maintenance</th>
<th>Interest</th>
<th>Other var. costs</th>
<th>Fertilizer savings</th>
<th>Balance</th>
<th>Pay-back period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>€/ha</td>
<td>€/ha</td>
<td>€/ha</td>
<td>€/ha</td>
<td>€/ha</td>
<td>€/ha</td>
<td>€/ha</td>
<td>yr</td>
</tr>
<tr>
<td>Closed fertirrigation system</td>
<td>7500</td>
<td>750</td>
<td>565</td>
<td>1200</td>
<td>4650</td>
<td>2135</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Closed fert. system + quick test</td>
<td>8300</td>
<td>910</td>
<td>625</td>
<td>810</td>
<td>4650</td>
<td>2305</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Closed fert. system + quick test + UV filtration (desinfestation)</td>
<td>23300</td>
<td>3270</td>
<td>1750</td>
<td>1390</td>
<td>4650</td>
<td>-1760</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

1) Variable costs: chemical (12x) and phytopathological (2x) analysis  
2) Variable costs: chemical (2x) and phytopathological (2x) analysis and reagents.  
3) Fertilizers savings: nutrients and water consumption.
Table 8. Effect of new type multi-tunnel greenhouse with improved ventilation on benefits and costs in comparison with reference tomato production system (€/m²) and pay-back period of extra investment (year)

<table>
<thead>
<tr>
<th>Benefit-cost component, economic indicator</th>
<th>Difference with reference system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>9.10</td>
</tr>
<tr>
<td>Variable costs</td>
<td>4.45</td>
</tr>
<tr>
<td>Fixed costs</td>
<td>3.05</td>
</tr>
<tr>
<td>Total costs</td>
<td>7.50</td>
</tr>
<tr>
<td>Net financial result</td>
<td>1.60</td>
</tr>
<tr>
<td>Payback period of extra investment (year)</td>
<td>5</td>
</tr>
</tbody>
</table>

Scenario b) Tomato crop in a Venlo greenhouse in the Netherlands: The main burden in the reference situation was climate control system, because of the high amount of natural gas to heat the greenhouse (Table 9).

It is noticeable the high reductions of environmental impacts in the two alternatives for improvement as both had significant reductions of natural gas consumption (Table 10). A new saving cultivation method made reductions between 20% and 31% to all impact categories. In spite of the substantial energy savings, the balance of benefits and costs was negative because of the reduction of sales of electricity to the public grid (Table 11).

The new type of greenhouse with double glazed cover and new energy cultivation method had environmental impacts equal or higher than 30% to most impact categories. It is remarkable the low reduction to eutrophication impact category (6%). Eutrophication is an impact category where emissions from electricity production are a high burden. For this impact category, the effect of a 155% electricity consumption increase in the alternative scenario is much higher than the effect of reducing 55% natural gas consumption. Economic results showed that the balance of extra benefits and extra costs results in an investment capacity of 27 €/m² for the double glazed and AR cover. The investment capacity is very much dependent on the energy price (Table 12).
Table 9. LCIA results per FU, for a tomato greenhouse crop in the Netherlands, with energy allocation of natural gas in CHP

<table>
<thead>
<tr>
<th>IC</th>
<th>Unit</th>
<th>Total</th>
<th>Structure</th>
<th>Climate System</th>
<th>Auxiliary</th>
<th>Fertilizers</th>
<th>Pesticides</th>
<th>Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>kg Sb eq</td>
<td>1.5E+01</td>
<td>3.4E-01</td>
<td>1.5E+01</td>
<td>1.4E-01</td>
<td>9.9E-02</td>
<td>1.6E-03</td>
<td>3.3E-03</td>
</tr>
<tr>
<td>AA</td>
<td>kg SO\textsubscript{2}eq</td>
<td>2.9E+00</td>
<td>3.0E-01</td>
<td>2.4E+00</td>
<td>8.8E-02</td>
<td>1.1E-01</td>
<td>1.8E-03</td>
<td>2.3E-03</td>
</tr>
<tr>
<td>EU</td>
<td>kg PO\textsubscript{4}eq</td>
<td>7.2E-01</td>
<td>9.7E-02</td>
<td>5.8E-01</td>
<td>2.1E-02</td>
<td>1.6E-02</td>
<td>6.1E-04</td>
<td>9.1E-04</td>
</tr>
<tr>
<td>GW</td>
<td>kg CO\textsubscript{2}eq</td>
<td>2.0E+03</td>
<td>5.3E+01</td>
<td>1.9E+03</td>
<td>1.4E+01</td>
<td>4.8E+01</td>
<td>2.0E-01</td>
<td>2.1E+00</td>
</tr>
<tr>
<td>PO</td>
<td>kg C\textsubscript{2}H\textsubscript{4}</td>
<td>2.1E+01</td>
<td>1.4E-02</td>
<td>1.9E-01</td>
<td>6.5E-03</td>
<td>2.2E-03</td>
<td>1.1E-04</td>
<td>7.6E-05</td>
</tr>
<tr>
<td>CED</td>
<td>MJ</td>
<td>3.1E+04</td>
<td>8.2E+02</td>
<td>3.0E+04</td>
<td>3.1E+02</td>
<td>2.0E+02</td>
<td>3.9E+00</td>
<td>7.9E+00</td>
</tr>
</tbody>
</table>

AD, abiotic depletion; AA, air acidification; EU, eutrophication; GW, global warming; PO, photochemical oxidation; CED, cumulative energy demand

Table 10. Environmental impact reductions (%) versus reference situation per alternative and impact categories

<table>
<thead>
<tr>
<th></th>
<th>AD</th>
<th>AA</th>
<th>EU</th>
<th>GW</th>
<th>PO</th>
<th>CED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy saving cultivation method</td>
<td>31.1</td>
<td>25.9</td>
<td>20.4</td>
<td>30.4</td>
<td>29.1</td>
<td>30.9</td>
</tr>
<tr>
<td>New type of glasshouse</td>
<td>38.8</td>
<td>29.9</td>
<td>6.4</td>
<td>38.0</td>
<td>39.9</td>
<td>38.7</td>
</tr>
</tbody>
</table>

AD, abiotic depletion; AA, air acidification; EU, eutrophication; GW, global warming; PO, photochemical oxidation; CED, cumulative energy demand
Table 11. Effect of new energy saving cultivation method on investments, yearly costs of investments, energy costs and balance of benefits and costs in comparison with the reference tomato production system (€/m²).

<table>
<thead>
<tr>
<th>Component</th>
<th>Difference with reference system (€/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment</td>
<td>1.20</td>
</tr>
<tr>
<td>Yearly costs of investment&lt;sup&gt;1&lt;/sup&gt;</td>
<td>0.10</td>
</tr>
<tr>
<td>Energy costs&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.45</td>
</tr>
<tr>
<td>Yield</td>
<td>-</td>
</tr>
<tr>
<td>Balance of benefits and costs</td>
<td>-0.55</td>
</tr>
</tbody>
</table>

1) Yearly costs: depreciation, maintenance and average interest.
2) Energy costs: balance of energy consumption and energy sales (electricity).

Table 12. Effect of double glazed greenhouse and new cultivation method on energy costs, production, balance of benefits and costs and investment capacity in comparison with reference tomato production system (€/m²)

<table>
<thead>
<tr>
<th>Component</th>
<th>Difference with reference system (€/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy costs&lt;sup&gt;1&lt;/sup&gt;</td>
<td>-3.40</td>
</tr>
<tr>
<td>Yield</td>
<td>-</td>
</tr>
<tr>
<td>Other costs</td>
<td>0.75</td>
</tr>
<tr>
<td>Balance of benefits and costs&lt;sup&gt;2&lt;/sup&gt;</td>
<td>2.65</td>
</tr>
<tr>
<td>Investment capacity&lt;sup&gt;3&lt;/sup&gt;</td>
<td>27</td>
</tr>
</tbody>
</table>

1) Energy costs: consumption of gas (-4.55 €/m²), electricity (0.75 €/m²) and CO2 (0.40 €/m²).
2) Excepting yearly cost of extra investment
3) Yearly costs of investment: 10% (depreciation: 7%, maintenance: 0.5% and average interest: 2.5%).
CONCLUSIONS

In terms of the environmental assessment the bottlenecks associated with the different scenarios were identified and can be summarised as follows: fertilizers represent an important burden in all impact categories for scenario a in Spain. For some scenarios the quantity of fertilizer applied is visibly high. Closed-loop irrigation systems should therefore be implemented. The manufacturing of substrate has an important environmental impact. Recycling used substrate and reducing the volume of substrate applied per plant were both to be strongly encouraged. Also, the consumption of energy in greenhouse heating for tomato production is a major issue to be considered. With regard to greenhouse structure, the large amount of steel in the frame was reflected in the results. Its environmental impact could be reduced by extending the life span of the greenhouse and by increasing productivity.

In terms of the economic assessment, the total output, costs and net financial results were determined. The cost-benefit analysis reflected the following considerations: Equipment and labour were the highest cost components for both scenarios; when cogeneration is not used, energy costs were very high in the Netherlands because of gas natural consumption therefore efforts in energy savings could reduce this item; and more efficiency in doses fertilizers could reduce fertilizers costs.

From the analysis of alternatives in each scenario it can be concluded that higher environmental impact reductions can be achieved by reduction of energy consumption, increase of productivity or combination of several improvement alternatives. Economic results showed that in some cases reduction of inputs can be also interesting. More effort should be done to implement technological management improvements and further research should be oriented to analyse the feasibility of suggested alternatives.

In order to help advisors and interested growers to simulate their own greenhouse system a web-based tool for economic and environmental support has been launched in the web site of EUphoros.
The tool is based upon the techniques and measures studied in the project. Growers are able to choose a number of actions or techniques to be implemented in their greenhouse. The economic and environmental cost of such actions is calculated and compared with the original greenhouse taken as a reference in this web tool.

References


Guinée, J. B., Gorrée, M., Heijungs, R., Huppes, G., R., K., de Koning,