Chapter 10
Protected Crops

Nazim Gruda and Josef Tanny

Abstract The increasing demand by world markets for high quality products has lead more and more agricultural/horticultural crop production systems to protected environments. Covering the crop allows regulation of macro and micro-environments, which facilitates optimal plant performance, extension of the production duration, induction of earliness, and obtaining higher and better quality yields. A spectrum of covered structures is used by growers, depending on the crop, the climatic region and the anticipated benefit. These structures can be generally classified as either screen construction or greenhouse. This chapter comprehensively discusses the effects of the most common types of structures on the major environmental variables: radiation, temperature, humidity, air velocity, ventilation, and carbon dioxide concentration, as well as the effects of these climate modifications on the various crop attributes such as plant growth and development, water and fertilizer supply, and some cultural practices. Moreover, the chapter outlines the objective, measurable aspects that relate to external and internal product quality that are under the influence of intrinsic and extrinsic factors. Finally, some recommendations concerning optimization management in protected cultivations are highlighted, in order to achieve high yields and high quality horticultural products, on time delivery, and energy saving at minimal expense.

Keywords Evapotranspiration · Greenhouse · Climate conditions · Cultural practices · Photosynthesis · Product quality · Soilless culture · Screenhouse · Transpiration

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Introduction

The increasing demand by world markets for high quality yield has lead more and more horticultural crop production systems into protected environments. Covering the crop does not only protect it from external natural hazards, but also allows for artificial manipulation of the crop micro environment to facilitate optimal plant performance, extend production duration, induce earliness of flowering, and improved production, and/or better quality product. According to Kacira (2011) the top 5 worldwide countries by protected cultivation area are China with more than 2,760,000 ha, Korea with 57,444 ha, Spain with 52,170 ha, Japan with 49,049 ha and Turkey with 33,515 ha.

A spectrum of covered structures is used by growers, depending on the crop, the climatic region and the anticipated benefit. These structures can be generally classified into two categories: screen constructions and greenhouses. The former are covered by permeable porous screens while the latter by impermeable transparent plastic films or glass. The two groups can also be classified according to the nature of the internal climate control, passive for the screen constructions and active for the greenhouses, although sometimes a combination of both structures and/or climate control approaches is used. Passive climate control means that once the house is constructed, no actions are undertaken by the grower to artificially modify the microclimate. There is strong interaction between inside and outside conditions and exchange processes between the crop and the outside atmosphere are governed by system attributes. On the other hand, active climate control means that besides the structure and cover, systems are installed that enable manipulating of the inside microclimate. In greenhouse structures the inside is more isolated from the outside, than in screen-constructions.

The simplest type of the first category is a porous screen cover made of plastic threads, horizontally deployed above the crop which protect crops from the sun and physical damage by reducing the incoming radiation and wind speed. A more advanced type of cover is the screenhouse (also called net-house) which, in addition to the horizontally deployed screen, includes screened sidewalls. Such structures, if made of sufficiently dense screens are insect-proof, thus avoiding insect invasion into the crop and allow for a significant reduction of pesticide application. In the analogy with screens, perforated transparent foils are used to cover the plants, in order to improve their earliness of maturity.

A more advanced structure type is the naturally ventilated tunnel or greenhouse. This structure is covered by an impermeable transparent plastic film which may include roof and/or side vents that allow the natural ventilation of the interior by wind or buoyancy forces. Opening and closing these vents can be operated either manually or automatically by a control system. These structures provide better climate control than screen constructions. In northern European countries such structures are covered by glass for higher radiation transmittance.

The most sophisticated structure is the so called Hi-Tech greenhouse. Generally, these structures can be equipped with any climate control system, thus allowing a wide range of growth manipulations. Some examples are shading, cooling by wet pad or fogging, heating and dehumidifying, and providing artificial illumination.

Most of the commercial plastic films and porous screens are made of low density polyethylene with some additives. The latter are used for purposes like, avoiding plastic film degradation due to UV radiation, preventing nighttime radiation cooling by blocking infrared radiation (IR) transmittance to the sky, avoiding dripping of condensed water vapor on the inner side of the film and decreasing dust accumulation on the outside of the cover. Such additives may modify the crop radiation and energy balances and hence greenhouse microclimate.

Microclimate of protected crops is a major factor in determining the internal atmospheric water demand and hence potential crop water use. Shade and reduced wind speed usually decrease the water demand in comparison to the open in tropical, subtropical, semi-arid or desert regions and hence may lead to increased *w*ater *u*se *e*fficiency (WUE) (see box 1). In tropical regions greenhouses, or the so called rainshelters, are used to protect the crops from rain storms. Nearly 90 % of the energy costs in greenhouses in the northern European countries are for heating. Since the first energy crisis at the end of the 1970's, the efforts for reducing the heating costs in these countries have increased enormously. Not only do the growers benefit from increased profitability due to higher yields and quality of produce grown in greenhouses, but this fits very well with our current environmental concerns and the objective to reduce carbon dioxide (CO_2) emissions within protected cultivation.

Since each type of structure and cover induces a different microclimatic modification, it is outside the scope of this chapter to review in detail all these effects. Rather, the chapter outlines the effects of most common types of structures on the major environmental variables: radiation, temperature, humidity, air velocity, ventilation, CO_2 concentration; and, in turn, how these modifications influence various crop attributes like plant growth, productivity and product quality. For didactic and practical reasons, the main approach of this chapter is to present the reactions of protected crops to singular environmental variables. In order to view the entirety of the concept, the reaction of crops to actual conditions within protected cultivations is illustrated through the use of some examples.

Most crops in protected cultivation are vegetables, followed by cut flowers and potted ornamentals and fruits. The reaction curves of plant growth and development are optimum functions marked by a minimum, an optimum, saturation, and/or a maximum of environmental conditions. However, the optimum points in curve courses are not the same for different attributes or crops. In the past, enormous investigation have been conducted concerning plant growth and productivity of protected crops, and different models have been developed; however the focus in this chapter will be on product quality that in recent years, has become more and more important due to consumer concerns.

Plant growth and productivity are very well defined; the first as a difference for any given parameter in the course of time and the second as a source of production for a given ground area of plant material. Product quality, on the other hand, is a complex issue not only depending on different factors, but also on different perspectives. The different actors involved in the value chain, from breeders through growers, traders, processors to the consumer, have their own expectations on the quality of horticultural products. Furthermore, the aspect of multidimensionality adds to the complexity and specificity of product quality. For instance, the quality parameters could be either intrinsic or extrinsic, the quality either external or internal and the criteria for its evaluation either objective or subjective (Gruda 2005). The chapter outlines the objective, well measurable aspects of quality related to the reaction of plants under the influence of intrinsic factors expressed in both external and internal qualities. Thus, it records a quality evaluation based on market, utilization, sensory, nutritional and health value of horticultural crop protected products. The influence of extrinsic factors and the use of subjective criteria are excluded here.

Finally, the optimization of management in protected cultivations will be highlighted, in order to yield high quality products, on time, applying energy savings methods and at minimal expense.

The Radiation Balance of Protected Environments

General

Radiation is essential for crop photosynthesis and hence plant production (Hemming 2011). In comparison with open field plant production, light is especially important for greenhouse crops because the amount of daylight that they receive is reduced e.g. by 30 % or more by the glasshouse structure or plastic cover (Wilson et al. 1992).

In regions short in radiation protected cultivation is always a compromise between the required protection and the need to maintain maximum penetration of radiation. Despite new developments such as using new cover materials, changing the size and the height of greenhouses, using reflective covers on the ground, adapting the canopy structure and cultivation technologies to promote growth, the light loss in greenhouses will remain an important issue for the near future. On the other hand, in climates with supra-optimal radiation, the attenuation induced by the cover may sometimes be advantageous in avoiding excess heat and sun damage. Nevertheless, in all cases, the radiative properties of the cover are a significant design feature in protected cultivation.

Covers have three major effects on the radiation balance of crops: (i) attenuating the amount of light or other electromagnetic radiation (Teitel et al. 2012); (ii) increasing the fraction of diffuse radiation that reaches more shaded regions of the canopy (Hemming et al. 2008) and (iii) modifying the light spectrum (see e.g. Shahak 2008, for colored screen materials). These three effects depend on several attributes of the system. The first is the radiative properties of the cover material, including its reflectance, transmittance and absorbance at different wavelengths and solar elevation angles (Möller et al. 2010). Another property is the structure

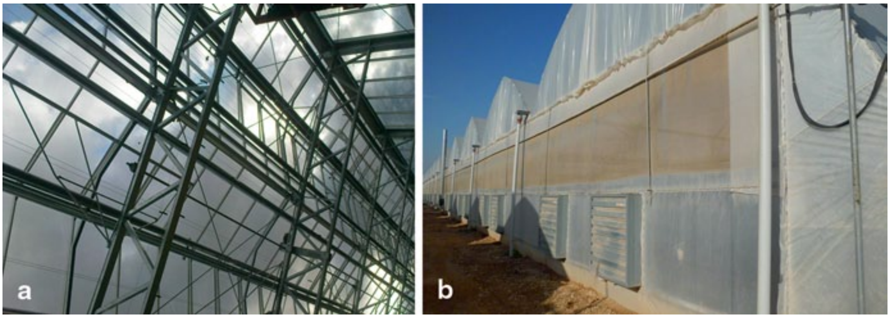

Fig. 10.1 Most materials used for greenhouse covers are either: **a** glass or **b** plastic. (Source: Gruda 2009, 2012; private collection)

of the roof and the deployment characteristics of the cover (Teitel et al. 2012). The geometrical properties of the crop (height, planting distances, and leaf area index) would also affect the radiation reaching the canopy at different vertical levels (Hemming et al. 2008).

Greenhouses consist of an impermeable material, either glass (Fig. 10.1a) or plastic film (Fig. 10.1b), which transmits part of the radiation, and may convert direct into diffuse radiation. Glass greenhouses are mainly used in northern countries like The Netherlands and surrounding countries, where radiation is limited and transmittance through the cover is crucial. These greenhouses are rather expensive both due to the glass itself and the structure which has to be strong enough to support the glass cover. On the other hand, glass is highly durable, which is an advantage for long-term production. In more southern countries, like the Mediterranean basin, where radiation levels are higher, plastic greenhouses are mostly used both due to their lower cost and the less stringent requirement for light transmittance.

In screenhouses or net-houses the crop is covered by a porous screen. The screen allows transmittance of both light and mass (air and gases) so screens should be characterized by both their radiative and aerodynamic properties. A large variety of screens is available in the market, with different porosities, texture and color. Properties of screens are not always adequately documented in the literature (Teitel 2007) which causes some confusion regarding the properties of screens in each reported study. In addition growers that purchase a certain screen are not always aware of the exact radiative and aerodynamic properties which may result in non-optimal use for a certain crop in a given climatic region. In recent years work has been carried out to characterize radiative (Cohen and Fuchs 1999; Möller et al. 2010) and aerodynamic (Tanny and Cohen 2003; Tanny et al. 2009a) properties of screens.

Transmittance of the Covering Materials and the Whole Structure

The wavelength most relevant for plant activity is the PAR, namely, Photosynthetic Active Radiation, in the range 400–700 nm. Measurements show that transmission of PAR by sheets of cladding material, subject to normal incidence of a parallel beam, was 88–90 % for 3–4 mm thick horticultural glass, 85 % for twin walled acrylic and about 90 % for 180 µm horticultural polyethylene (Critten and Bailey 2002). However, these values may decay with time due to dust accumulation (Möller et al. 2010) and water droplet condensation. Pollet and Pieters (2000) investigated PAR transmission through dry and wet glass. For glass covered structures with condensed water droplets, the transmission loss reached up to 13–15 %, at 50–65° incidence angles. Pollet et al. (2000) also showed that on glass, water droplets increased scattering significantly, from 4 to 81 %, whereas on polyethylene the increase was much lower, from 71 to 82 %.

The parameter of most interest for the grower is the overall transmittance of the structure, which determines the amount of light that would reach the plant and its uniformity in time and space. The overall transmittance may be significantly different from that of the cover material itself, mainly due to structural infrastructure. Transmittance of global radiation for single-cover Mediterranean greenhouses is usually between 55 and 70 % (von Zabeltitz 2011) and for double-cover greenhouses the range is between 50 and 60 %. Measurements (Teitel et al. 2012) and numerical modeling (Critten 1983) have been employed to estimate the spatial and temporal distribution of radiation intensity in multi-span greenhouses. Results in naturally ventilated greenhouses with roof openings showed a significant effect of the openings on radiation distribution. The mean daily PAR level directly below the cover of the greenhouses was 58–66 % of the external PAR; above the crop, the daily mean PAR level along a 10-m transect was 39–51 % of the outside level (Teitel et al. 2012). This reduction in light transmission was mainly caused by structural elements, gutters and roof openings. Teitel et al. (2012) further showed that the largest drop in radiation (15–28 %) was measured at midday, and in the region below the roof openings, it was dependant on the greenhouse type, and was larger than the drop measured at the centerline of the greenhouse span.

Giacomelli et al. (1988) studied the availability of global solar radiation (GSR) and PAR inside a greenhouse by placing sensors at fixed positions: above the crop, at truss level, and outside the greenhouse which showed that the transmittance through a polyethylene film was equal for both GSR and PAR, and its value was about 67 %. In recent years many growers use porous screens to protect their crops. Cohen and Fuchs (1999) measured radiometric properties of screens composed of highly reflective aluminized materials. For short and long wave lengths, screen transmittance varied between 0.18 and 0.5, based on their measurements and data from other sources, which demonstrated that screen radiation properties, can be determined with standard meteorological equipment, i.e. pyranometers, pyrgeometers and net radiometers. Möller et al. (2010) extended the study to show that transmission of direct radiation declined with solar elevation angle and became zero below a cutoff angle depending on screen texture. In a banana screenhouse, Möller et al. (2010) showed that transmission decreased linearly with time by about 0.1 % day^{-1}, during the rainless summer due to dust accumulation on the screen but recovered after rain (Fig. 10.2).

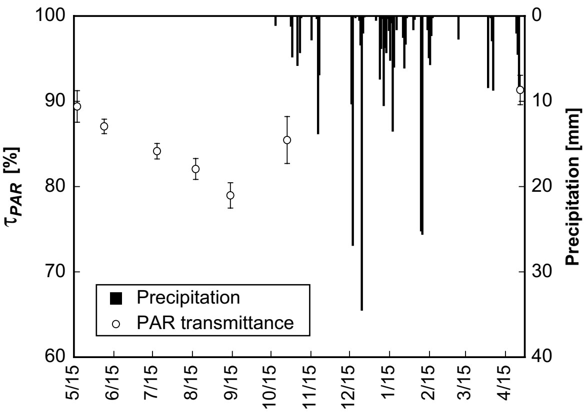

Fig. 10.2 Midday PAR-transmittance of the CCS, measured at Zemach, Israel, over 7 days from May 2005 to April 2006. Average data from 6 PAR sensors (model LI-190, Licor, Lincoln, NE, USA). *Vertical bars* represent two standard errors of the mean. Daily rainfall measured at the nearby station is indicated on the secondary Y-axis. (Source: Möller et al. 2010)

The Use of Additives to Plastic Covers

Different additives are used in order to improve the performance of plastic covers.

Ultra-Violet (UV) Ultra-Violet stabilizers, which are incorporated into the polymer matrix of greenhouse covers, stabilize the harmful UV radiation from entering into the greenhouse and allow for maximum light transmission. When used along with anti-oxidants they protect the film from photo as well as thermal degradation and help in proper and maximum light transmission, by increasing the durability of plastic materials (NN 2012a). UV additives block the invasion of insects into the greenhouse and protect the crop from infestation by insects and the spread of viruses (Antignus et al. 1998).

Infra-red (IR) During nighttime, outside temperatures are lower than inside, so the heat that accumulates inside the greenhouse during the day is lost to the outside by irradiation (NN 2012a). During the night the temperature outside the greenhouse falls below the temperature within the greenhouse. As a result there is loss of heat from the greenhouse by radiation towards the outside and the greenhouse temperature drops. This transfer mechanism takes place by the infra-red radiation. To prevent this radiation loss, mineral based additive or special polymers are incorporated within greenhouse films that help to maintain the temperature within the greenhouse and insulate the plants from the cold injury and temperature variation, save energy for nighttime heating and prevent the accumulation of heat during the day in warm climates (Hemming et al. 2006).

Anti-Fog/Anti-Drip Effect/Anti-Condensation Condensation of water vapor, results in formation of droplets on the inside surface of the greenhouse film. This has a negative effect on the crop because there is a reduction in morning light transmission, when most condensation may take place (Fähnrich et al. 1989), droplets falling on the foliage which can make plants more prone to diseases; and the burning of petals and leaves, as the intensity of rays passing through the droplet is increased as they act like a lens. To avoid such condensation the addition of additives alters the surface tension of the film (NN 2012a).

Anti-Dust Dust particles tend to adhere to polyethylene films. Over a long period of exposure considerable accumulation of dust may lead to significant reductions in light transmission (Möller et al. 2010). This can influence radiation levels and has a negative effect on plants resulting in lower yield and slower growth. Special additives, which migrate to the surface of the film, can prevent dust accumulation (NN 2012a).

The Influence of Light Intensity and Duration on Plant Growth and Product Quality of Horticultural Plants

The primary energy source for protected crops is through natural solar radiation. This source is used throughout the photosynthetic processes that converts the light energy into chemical energy and accumulates as useful biomass. In addition, light plays an important role in controlling the different biological processes, such as germination and flowering and determines plant morphogenesis.

From the total light reaching the plants in the protected cultivation area, only a very small part is used for the photosynthetic process, the remainder is reflected or absorbed and converted into heat. Generally, there is a very strong correlation between the crop yield and the total amount of PAR intercepted by the plants. Apart from the light intensity, the light duration and the spectral quality are of crucial importance with these variables essential in plant growth, the production processes, and ultimately product quality. In the following an overview of the effects of these variables under the specifics of protected cultivation is given.

Low Light Intensity

It is commonly accepted that yield is roughly linearly proportional to radiation (up to the saturation level). Marcelis et al. (2006) demonstrated that for many greenhouse crops, a 1 % light increment can result in a 0.5–1 % increase in harvested product, and the effect was larger in winter than in summer. On short and cloudy days, and during the winter period in northern latitudes, low light intensity becomes the most limiting climatic factor in greenhouses. The same holds true even for cool season plants such as lettuce grown in winter in the higher northern European latitudes.

Low yields are often associated with reduced product quality. Light intensity can influence the plant architecture, apart from genotype, other climate factors, and cultivation practices. For instance, at low light intensities plants are generally elongated and have less and longer internodes (etiolation) than plants cultivated under higher light intensities but otherwise similar conditions. This is important for ornamental potted plants which, in order to meet a particular market, have to be compact.

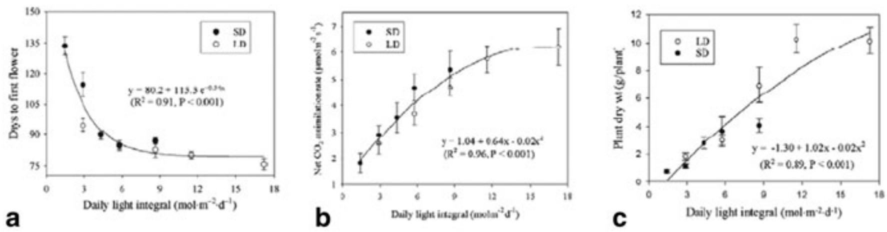

Fig. 10.3 The effect of photosynthetic daily light integral on (**a**) time to first flower, (**b**) in situ net CO_2 assimilation rate, and (**c**) plant dry weight of *Cyclamen persicum* 'Metis Scarlet Red'. Plants were grown under an 8-h short day (*SD*) or 16-h long day (*LD*). Error *bars* indicate SE. (Source: Oh et al. 2009)

In the literature, sometimes the term "daily light integral" (DLI) is used in order to address the amount of photosynthetic light received each day per unit area.

Increasing DLI, generally, increases biomass accumulation, accelerates the developmental processes reduces the plant development phases, and improves final plant quality of many protected crops. For instance, the days to flower of petunia (*Petunia*) and cyclamen (*Cyclamen persicum* cv 'Metis Scarlet Red') decrease as DLI increases when grown at 20 °C (Kaczperski et al. 1991) (Fig. 10.3a). In addition, increasing the DLI increases growth rate by promoting photosynthesis (Fig. 10.3b) which improves the quality of this plant by increasing the number of leaves and flowers, and dry weight (Fig. 10.3c) (Oh et al. 2009).

The external and internal quality of vegetable products is also influenced by light. Grierson and Kader (1986) reported that low radiation and temperature reduced tomato fruit dry matter content, due to insufficient sugar content and in the pepper resulted in flower abscission (Aloni et al. 1996). Furthermore, Canadian researchers Dorais et al. (2001) reported that misshapen tomato fruits, as well as the formation of swollen and hollow fruits, due to low light intensity and inappropriate temperature regimes, were observed during the growing season in spring. In addition, light could be the limiting factor influencing the nitrate concentrations in green leafy vegetables, such as lettuce and spinach, under poor light conditions in greenhouses during winter (Blom-Zandra and Lampe 1985; Steingröver et al. 1986).

In general, as the light intensity declines there is a reduction in the content of ascorbic acid in plant tissues (Gruda 2005). This close relationship between the light conditions and ascorbic acid content have been reported in vegetables, such as spinach, tomato, lettuce, sweet pepper and strawberry. Gautier et al. (2009) stated that for tomatoes leaf irradiance has an impact on photosynthesis and sugar transport to the fruits, whereas fruit irradiance had an impact on ascorbic acid metabolism.

The effect of light and light intensity on carotenoid content in vegetable products is at present being controversially discussed in the literature. McCollum (1954) has shown that tomato fruits exposed to direct sunlight during their development had higher carotene levels than shaded fruits while the rates of lycopene and carotene synthesis can be increased by illuminating tomato plants during the ripening of the fruit at favorable temperatures (22–25 °C). Keyhaninejad et al. (2012) work was contrary to this where foliar carotenoid increased approximately twofold with increased light, whereas carotenoid content in fruit decreased two to threefold under the same conditions. Similarly, Brandt et al. (2006) reported that the production of lycopene was inhibited by excessive sunlight. Helyes et al. (2006) also found that the lycopene content of greenhouse grown tomatoes was 40 % higher than tomatoes grown in the open field and the more direct sunshine the fruit were exposed to, the higher the surface temperature, leading to a lower fruit lycopene content.

Comparing light intensities between field and greenhouse structures is not easy and as a consequence comparisons are difficult to make. Dumas et al. (2003) generally stated that the level of intercepted light may have affected the carotenoid content, but interactions may also have occurred with high temperatures occurring under protected growth conditions. Keyhaninejad et al. (2012) concluded that although there were many differences between the field and greenhouse settings in the above-mentioned study, which could explain the differences in fruit carotenoid accumulation, there were very few differences between the shaded and unshaded greenhouse settings, besides the reduced light.

Light intensity can also affect shelf life of greenhouse grown vegetables. The postharvest shelf life of the long cucumber (*Cucumis sativus*) is generally related to fruit greenness upon harvest. Indeed, the lower the light intensity incident on a cucumber, the shorter its shelf life (Lin and Jolliffe 1996; Heuvelink et al. 2006; Hovi-Pekkanen and Tahvonen 2008).

Artificial Lighting

Artificial lighting mitigates the adverse influence of low and short radiation levels and creates optimal growing conditions for protected crops. Differences in seasonal light levels can sometimes be very high where in mid-Europe the average day length in the end of June is about 16 h, whereas in December, day length drops to less than 8 h, while the light intensity is approximately 5 times lower.

According to Mitchell et al. (2012) artificial crop lighting is an energy-intensive necessity of the greenhouse industry, particularly with increasing latitude north or south of the equator, and can result in significant changes in seasonal photoperiod. Greenhouse lighting requirements typically fall into these general categories: photosynthetic and photomorphogenic lighting for propagation and transplant production; photoperiodic lighting to induce early or out-of-season flowering, and supplemental lighting to enhance photosynthesis for crop production, especially when grown during light-limited periods of the year (Mitchell et al. 2012) and where replacement lighting that is usually used in growth rooms or chambers. However, only supplemental assimilation lighting (SAL), which is considered the most cost-effective form of lighting when a naturally low ambient photosynthetic daily light source is required, or when crops are grown at a high density, will be discussed in this section.

The main reasons for using SAL are certainly the enhanced plant growth and crop production. Marcelis et al. (2002) reported yearly production increase of 55 %

in greenhouse tomato production. However, recently the reasons are to be seen more and more in ensuring a year-round production and improved quality, which meets market demands and a more regular labor requirement (Marcelis et al. 2002; Paradiso et al. 2011). At present approximately 90 % of rose growers in The Netherlands use SAL, while the use of this form of lighting for other cut flowers, ornamental and vegetable crops is increasing at about 1 % each year (Heuvelink et al. 2006; Marcelis et al. 2002).

Several studies reported better external and internal quality of horticultural crops. For example, increasing photosynthetic photon flux (PPF) increased plant quantity of *Petunia* × *hybrida* flower mass grown in climate chambers (Frantz and Ling 2011), and increased the number of flowering shoots and inflorescence size of Kalanchoe (Carvalho et al. 2006). Dorais and Gosselin (2002) reported a higher sugar content and ascorbic acid concentration in tomato, and Gaudreau et al. (1994) documented increased head firmness of lettuce as a result of supplemental light.

Applications of SAL from 18 October until 20 March in a glasshouse in The Netherlands, improved the yield at a light intensity of 188 μmol m^{-2} s^{-1} in comparison to a 125 μmol m^{-2} s^{-1}, by increased fruit set and average fruit weight for two cultivars of sweet pepper, when light was used between sun rise and sun set (Heuvelink et al. 2006). These authors concluded however that the use of SAL is not economically feasible for sweet pepper, tomato, and eggplant due to high energy and production costs. The position of lamps is important as well. Usually SAL is applied on the top of the canopy. Under such lighting systems, light is not uniformly distributed along the leaf layers of some crops such as e.g. tomatoes, cucumbers, and peppers that are usually vertically cultivated, or roses as well as other plants that are usually grown under high plant densities. Particularly, it has been calculated that, considering a crop with a leaf area index (LAI) of 3, even when the light intensity at the top of the plant is 400 μmol m^{-2} s^{-1}, approximately 33 % of the leaves in the lower and inner zone of the canopy receive less than 100 μmol m^{-2} s^{-1} because of self-shading (Paradiso et al. 2011).

Both light absorbance and the vertical distribution of light in the canopy are of great importance for crop photosynthesis. Heuvelink et al. (2006) reported that leaves low in the canopy, received higher light levels every day because of interlighting, performed at their maximum photosynthetic capacity, although leaf age and the time of leaf-removing, a cultural practice of lowering high-wire crops, needs to be taken into account. However Pettersen et al. (2010) found in an experiment with horizontally grown cucumbers, that the leaves showed no sign of reduction in photosynthetic capacity rate although the oldest leaves were approximately 30 days older than leaves at the moment of removal in a high-wire cultivated cucumber crop.

Many species demonstrate benefits from interlighting or inner canopy lighting. Grodzinski et al. (1999) found an increased photosynthetic activity in sweet pepper canopy when side lighting was used jointly with top lighting, whereas Hovi et al. (2004) stated a 9 % increase in annual cucumber yield in Southern Finland, when 24 % of the SAL was supplied between the plants instead of all light on top of the

Fig. 10.4 Application of LED-interlighting in tomato plants by an experimental trial at the Horticultural Center Straelen, Agricultural Chamber of North Rhine-Westphalia in Germany. (Source: Gruda 2013, private collection.)

plants. In addition, interlighting increased first class yield and decreased the unmarketable yield of cucumbers, both in weight and fruit number. Besides interlighting per se, the higher proportion of interlight tended to further improve the fruit quality as well as fruit skin chlorophyll concentration (Heuvelink et al. 2006; Hovi-Pekkanen and Tahvonen 2008).

The addition of SAL, with no adjustments in the climate set points and crop management, may result in improved vegetative growth but little or no yield improvement. The adjustments in temperature, plant density and other factors are needed, in order to optimally transfer SAL into production (Heuvelink et al. 2006).

Future applications could be the development of light-emitting diode (LED) lamps which has several unique advantages over existing horticultural lighting such as being small in size, increased longevity and low heat emission even at very high light intensity levels. In addition LED lamps have the ability to control spectral composition, given the opportunity to select the most favorable light spectrum for photosynthesis (Fig. 10.4) (Morrow 2008; Paradiso et al. 2011).

Martineau et al. (2012) compared LED and HPS lighting technologies for supplementing greenhouse lighting and found on average, that HPS and LED light treatments produced similar shoot biomass of head lettuce (*Lactuca sativa* var. *capitata*), with the LED lamps providing approximately only half the amount of supplemental light compared with the HPS lamps during a 4 week experimental treatment. In addition no significant differences were found in concentrations of β-carotene, chlorophyll a, chlorophyll b, neoxanthin, lutein, and antheraxanthin among the light treatments. According to Morrow (2008), the LED array provides three times more light output for the same Wattage of input power on an equivalent area basis and can be easily integrated into digital control systems, facilitating special lighting programs such as "daily light integral" lighting and sunrise and sunset simulations. In addition LEDs could be used at different radiation angles for different cultivation types and development stages and provided the capability of true spectral composition control, allowed wavelengths to be matched to plant photoreceptors to provide more optimal production, and influenced plant morphology and composition (Morrow 2008). With most plants reaching a major peak in the red region and a relatively lower peak in the blue region, Mitchell et al. (2012), demonstrated the use of LEDs in emitting photon colors that match the absorbance peaks of important plant pigments, such as the red and far-red-absorbing forms of phytochrome, or the red and blue peaks of leaf photosynthetic action spectra. Combining the far red and blue light rate due to LEDs not only avoids the negative effects of assimilation lighting in greenhouses related to changes in carbohydrate metabolism, but also contributes to a reduction of the supply of fertilizer and chemical control, due to an aimed shortening of the vegetation period, bud/flower induction or improvement in plant morphology.

The spectrum of assimilation lighting has recently become more important. The use of LED lamps in a green leaved rose crop increased instantaneous crop photosynthesis per incident photon by up to 12 % and for a crop with reddish leaves up to 17 %, compared to HPS lamps (Paradiso et al. 2011). Moreover, an increased red/far red ratio on rose generally reduced plant height and increased leaf chlorophyll content (McMahon and Kelly 1990) and the number of flowers (Roberts et al. 1993; Girault et al. 2008; Paradiso et al. 2011).

The addition of color to plastic films or porous nets can affect various crop processes (Shahak 2008; Stamps 2009). Due to a targeted application, e.g. by using of covering films, the induction of a range of secondary metabolite accumulation could affect the plant morphology, e.g. the plant height of transplants, as well as the internal quality. Far red light absorbing films seem to be effective in reducing stem elongation, and decreasing the incidence of tipburn of lettuce and blossom end-rot of tomatoes. Recently, Patil and Moe (2009) reported that screening daylight through light quality selective plastic film with a red/far-red ratio of 1.6 in combination with DIF (for more information concerning DIF, see the temperature-section in this chapter) reduced stem, hypocotyl and internode length in the cucumber plants by 45–50 % compared to the control film with a red/far-red ratio of 1.1, indicating an interaction between DIF and the spectral light regime.

Changing the light intensity of different colored shade nets can affect the internal quality of tomatoes. For example Ilić et al. (2012) reported higher lycopene content in greenhouse tomatoes integrated with red shade, in comparison to field-grown tomatoes. By contrast, shaded fruits have a lower content of β-carotene.

High Light Radiation Intensity

Two different aspects regarding light intensity include the “light compensation point” and the “light saturation point”. The “light compensation point” is reached when photosynthesis and respiration are in balance. The “light saturation point”, is reached when the light intensity is increased to a point where it is no longer a factor limiting the overall rate of photosynthesis. Extreme light intensity combined with excessive radiation can, adversely affect plant growth and quality leading to disorders in the development and appearance. Such is the case for sunscald (Fig. 10.5).

Fig. 10.5 Sunscald symptom on Bell Pepper, cultivated in a glasshouse in the south of Germany. A cellular death, a collapse of the tissue and papery thin skin are clearly seen in fruits that were directly exposed to solar radiation and were not shaded from leaves. (Source: Gruda 2003, private collection.)

Further disorders caused by high light intensity are uneven ripening, the occurrence of green shoulder, and blossom-end rot in tomato as well as cracking in tomato and pepper fruits.

Measures to Mitigate the Adverse Influence of High Radiation Intensity

The most common methods to reduce incoming solar radiation include the whitewashing and the use of shade screens. Natural and forced ventilation systems, as well as evaporative cooling devices, are often installed to remove excess heat due to supra-optimal radiation in protected cropping systems. Effective crop transpiration and active evaporative cooling in the form of fog and sprinkling systems, convert plant sensible heat into latent heat. The preferred system depends very strongly on outside climate conditions, greenhouse types and available facilities. In Mediterranean countries whitewashing or shade screens, as well as evaporative cooling, can be successful, whereas in hot humid areas an evaporative cooling system may not be as efficient.

Shading is necessary to limit the temperature rise in the greenhouse. The actual shading percentage of products such as traditional whitewash can be influenced by different climate conditions, the type of the greenhouse construction, plant cultivations and the applied settings and can decrease during the year.

Villegas et al. (2006) reported a positive effect of shading when cyclamen (*Cyclamen* spp.) plants, were cultivated in the Mediterranean area under double shade cloths with an accumulative 50 % of shading. These plants had better quality and were more compact whereas plants under grey shade cloths at the same shading rate had a higher number of flowers. The authors recommend treating the results with caution when growing plants under cool and cloudy environments. For instance, Marcelis (1993) reported that shading can affect cucumber weight by reducing the distribution of photosynthate to the fruits, resulting in a strong decrease in fresh and dry fruit weight. Young fruits are usually relatively more sensitive to a reduction in assimilate supply (irradiance) than older fruits on the same plant. Cockshull et al. (1992), stated that 23 % shade was sufficient to reduce the yield of tomatoes by 20 % in England. Consequently no general recommendations can be made here.

According to Peet (1999), the reduction of light intensity is more likely to be a limiting factor than otherwise; hence a movable shade applied for only a couple of hours during sunny periods, is a possible solution. Lorenzo et al. (2004), for instance, reported a 10 % increase in marketable yield of tomatoes, when mobile shade was applied during a couple of hours of intense sunlight in Spain. In addition, the combination of different measures for different genotypes, and at different plant growth and development phases has to be emphasized here.

Air Temperature, Air Humidity and Energy Considerations

In protected cultivation, global solar radiation, which is composed mainly of short wavelength, and is transmitted through the cover, is absorbed by the greenhouse structural elements and mostly converted into heat. Heated air cannot be freely exchanged into the free atmosphere, and any reflected energy is of a long wavelength nature, as both atmosphere and greenhouse covers are partially opaque to these wavelengths, such energy is trapped within the greenhouse, causing the so called "greenhouse effect."

Greenhouses

One of the advantages of cultivation in greenhouses is the possibility of controlling the air temperature through heating or cooling. In cases of high global radiation, in hot seasons and arid regions, the plant temperature can exceed air temperature by 5–10 °C. For many plants, ventilation does not provide sufficient cooling. In arid regions, internal humidity should also be increased for crop growth (von Zabeltitz 2011). The combined effect of cooling and humidifying the inside air can be achieved by evaporative cooling, mostly implemented by one of two systems: (i) fan and pad; and (ii) fogging.

In the fan and pad cooling system, air is sucked by fans installed on one sidewall of the greenhouse (Fig. 10.6a). The air entering the greenhouse, which replaced the sucked air, passes through a wet pad, installed on the opposite sidewall and which is fed with water by sprinklers (Fig. 10.6b). The inflow of external, relatively dry air, through the wet pad, cools down the air and increases its water vapor content. This is the so-called "negative pressure" system. In the "positive pressure" system, fans and wet pad are positioned on the same sidewall and push air into the greenhouse which then leaves through openings on the opposite sidewall.

The main drawback of the fan and pad system is the generation of thermal gradients along the direction of air flow through the greenhouse. This is due to the air being heated during its flow along the greenhouse section. To minimize this effect growers tend to shade the downwind half of the greenhouse where the air is al-

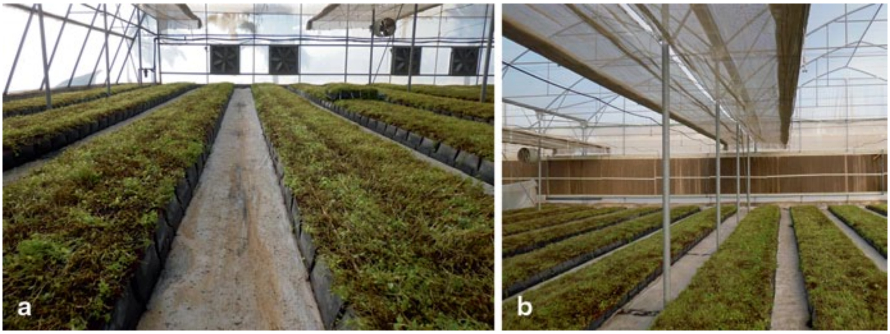

Fig. 10.6 A negative fan and pad cooling system: **a** fans installed on one sidewall of the greenhouse, and **b** wet pad, installed on the opposite sidewall in a greenhouse at The Jordan Rift Valley. (Source: Gruda 2012, private collection)

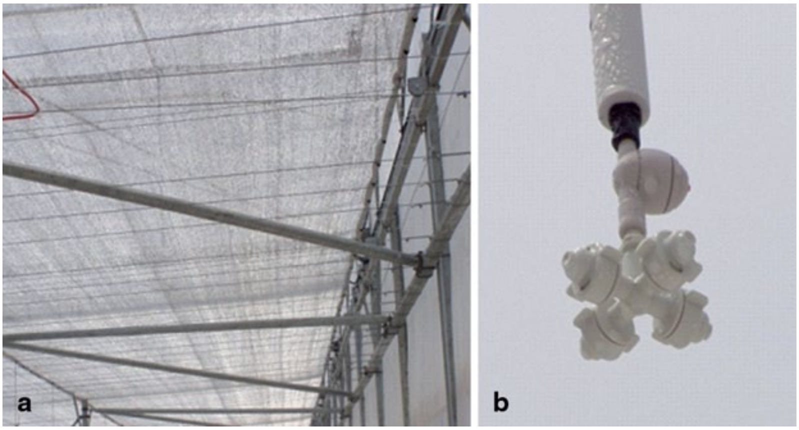

Fig. 10.7 **a** The aluminized shade system (Aluminet 60-I, 60–64 % shade, Polysack Plastic Ind., Nir-Yitzak-Sufa, Israel) installed at a height of 4.5 m. **b** The mist system designed using high-pressure foggers (Micronet 4-Way Fogger, 30.6 L. h^{-1} with a mean droplet size of 90 microns at 60 psi) from Netafim USA, Fresno, Calif. installed above the plant canopy at a height of 3.9 m from the floor, both in passively ventilated greenhouses located at the Plant Science Research and Education Center in Citra, Florida. (Source: Gruda 2004, private collection.)

ready warm (Fig. 10.7a). Kittas et al. (2003) derived a climate model that predicted the temperature gradient along the greenhouse, incorporating the effects of the fan and pad system, partial roof shading and plant transpiration. In experiments for model calibration, they measured temperature differences of up to 8 °C, along the 60 m greenhouse length from pad to fans. The model showed that high ventilation rates and shading contributed to reduce the thermal gradients. Fuchs et al. (2006b) investigated for a greenhouse rose crop the combined effect of fan and pad cooling and crop transpiration on the greenhouse microclimate. The evaporative pad cooled the air considerably; but the lowering of transpiring leaf temperature was only minor. They have also showed that evaporation from the pad decreased when external humidity increased. When the wet pad operated crop transpiration rate was nearly independent of external humidity and ventilation rate.

The fog cooling system consists of spraying very small water droplets from nozzles positioned above the crop area. The drops should be small enough to evaporate fast, and before reaching the foliage (Fig. 10.7b). Several techniques were proposed for droplet generation (Arbel et al. 1999; Li and Willits 2008) that ranged from twin-fluid nozzles combining compressed air and water; low pressure systems; and high pressure systems (von Zabeltitz 2011).

The advantage of fog cooling systems, as compared to fan and pad, is the possibility to operate in both forced and natural ventilation greenhouses, and the more uniform temperature and humidity distributions in the greenhouse. For example, Arbel et al. (2003) studied a greenhouse equipped with a forced ventilation system combined with fogging. The results revealed that inside the greenhouse an air temperature and relative humidity of 28 °C and 80 %, respectively, were maintained at noon during the summer. Furthermore, the high uniformity of the climatic conditions (the same magnitude of temperature measurements error $\pm 0 \cdot 5$ °C), within the greenhouse, in the lengthwise (north–south) and vertical directions were reported. Uniform microclimatic conditions are preferable since they induce uniform crop growth, yield and quality.

Temperature, humidity ratio and CO_2 concentration gradients can also develop in fan-ventilated greenhouses without evaporative cooling. Teitel et al. (2010) measured and modeled horizontal gradients in a greenhouse in which pepper was grown. The model results showed that the largest gradients are to be expected at around midday (11:00–12:00), when the intensity of solar radiation is greatest.

Vertical gradients in greenhouses were also investigated by Zhao et al. (2001) who measured vertical gradients of temperature and humidity in a pepper greenhouse grown under different ventilation conditions. Their experiments were conducted in a full-scale, commercial greenhouse, under closed and naturally ventilated conditions. A comparison was made between ventilation by continuous roof openings only and ventilation by opening both roof and side windows. Two cases were considered for each of the ventilation modes: (i) the plants in the greenhouse were mature and big, and (ii) the plants were young and small. With mature plants, the gradients of temperature and humidity ratio before opening the ventilation windows were considerable and they remained so after the windows were opened (either roof only or both roof and side windows). Smaller gradients were observed with only roof ventilation, than with ventilation via roof and side openings. With young, small plants the gradients were much smaller than with mature plants and they could be assumed negligible for either ventilation mode. Both Teitel et al. (2010) and Zhao et al. (2001) results illustrate the interactive effects between plants and greenhouse microclimate.

Greenhouse heating is a common approach in northern countries or in regions susceptible to frost. It is also used in subtropical regions to keep nighttime and even daytime temperature at the biological optimum. Under certain climatic conditions greenhouse heating is necessary, however, it is an economic problem due to the high energy costs. In addition to the direct biological effects of rapid growth and earliness, heating is important in reducing the relative humidity, thus lowering the risk of several common plant diseases, which may also lead to a reduced pesticide application (Baille 2001).

In the literature different approaches for greenhouse heating, and their effects on air temperature, were investigated. For example, Bartzanas et al. (2005) have demonstrated that in a tunnel where tomato was grown, combining heating pipes with air heaters increased the temperature difference between inside and outside from 10 to 15 °C during night. It was also shown that with the air heater, although the mass transfer conductance to the cover was higher, the condensation flux was smaller which resulted in less condensation at the inner surface of the cover.

In 2000 Kempkes and co-workers (Kempkes et al. 2000) developed a simulation model to predict the effects of the heating system on the vertical distribution of crop temperature and transpiration. The simulation model predicted crop temperature distribution as a function of the position and temperature, of the heating pipes, as well as the vertical distribution of crop evaporation. In addition Teitel and Tanny (1998) investigated the effects of pipe positioning and pipe surface temperature on radiative heating of the crop and found that the best pipe position was near the crop at its mid-height and that at low pipe surface temperatures, the radiative heating efficiency increased sharply with the surface temperature.

Screenhouses and Screen Covers

In screenhouses, due to the strong interaction between the inside and outside, heating or cooling is non-practical. It is commonly accepted that climate control in screenhouses is passive, namely, it is governed by factors such as screen type, screen deployment, and structural and canopy properties that cannot be actively manipulated by the grower (Tanny 2013).

Tanny et al. (2009b) demonstrated the effect of shade in reducing the air temperature in an apple orchard in northern Israel. Results showed that during daytime, air temperature under the screened plots and near the foliage were lower by about 1.4 °C than at the exposed plots (Fig. 10.8). During night-time, air temperature under the screened treatments was larger by about 0.3 °C than under the exposed ones due to the reduced long wave radiative cooling effect under the screens. The air humidity under the screens was found to be higher than that in the exposed treatments during daytime, which may lead to lower ET and hence water saving.

Kittas et al. (2012) measured both air and leaf temperature of tomato plants under different shading treatments and showed that although the air temperature under the shade was almost similar to that without shade, leaf temperature of shaded plants was nearly 5 °C lower than un-shaded plants. This temperature reduction was associated with a 50 % reduction in VPD of the shaded plants in comparison with the un-shaded ones. The equality of air temperature under the shaded and exposed treatments was attributed by Kittas et al. (2012) to the fact that the shading screens they used were deployed only on the roof and not on the sidewalls, and that the measurements were done near the coast where sea breeze is significant. Both fac-

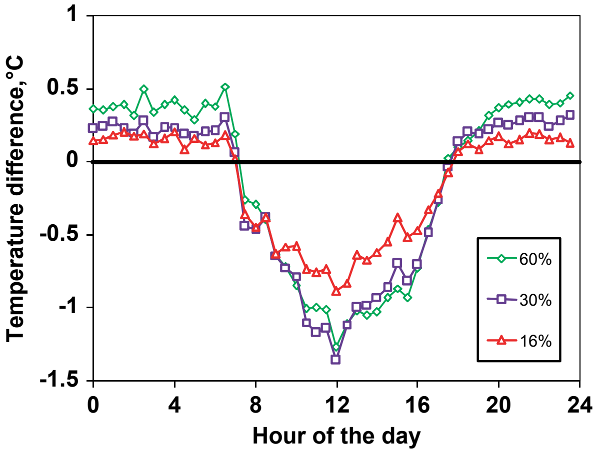

Fig. 10.8 Diurnal curves of temperature difference between shaded and unshaded treatments for the three shading screens covering apple trees. Each curve represents an average over the 12 days DOY 232–243. *Shading screens*: diamond—60 %; *square*—30 %; *triangle*—16 %. (Source: Tanny et al. 2009b)

tors allowed high ventilation of the shaded plants which eliminated air temperature differences.

Insect-proof screens impose a higher resistance to air flow than shading screens and thus reduce the ventilation, which may cause higher temperature and humidity increases. Rossel and Ferguson (1979) studied a relatively small screenhouse covered with an ultraviolet-stable fine-mesh polyethylene screen which reduced light intensity by ~40 % and was insect-proof and noted that with fan ventilation, the highest inside temperature never exceeded that outside by more than 1.5 °C, but without fan the highest temperature difference between inside and outside reached up to 3.5 °C.

In an insect-proof screenhouse Tanny et al. (2003) analyzed the vertical temperature gradient in relation to the external wind speed. The diurnal variation showed the decrease in the temperature gradient as wind speed increased just before midday because the high wind speed mixed the inside air and thereby decreased the vertical temperature gradient. The temperature gradient remained positive however throughout the daylight hours, which means that it had stabilized the internal air.

In recent years large shading screenhouses for banana cultivation have become increasingly popular among Israeli growers (Fig. 10.9). Measurements showed that inside air relative humidity was higher by 8 % than that measured by a meteorological station in an open area outside the screenhouse (Tanny, unpublished data). Higher internal water vapor mixing ratio (ratio between mass of water vapor to mass of dry air) within a banana screenhouse was also obtained by Siqueira et al. (2012), in their one dimensional model of an infinite horizontal screen cover. They reported an increase of about 35 % in the water vapor mixing ratio under the screen (at 5 m height) as compared to the value at the same height above an open banana plantation. The increased internal humidity in screenhouses is presumably one of the reasons for the potential water saving.

Tanny et al. (2008) investigated the effect of roof height on inside temperature and humidity in two adjacent 60 %-shading screenhouses with different heights of

Fig. 10.9 A banana screenhouse with a hail trap, located at the Western Galilee region of northern Israel. (Source: Tanny 2007, private collection)

2 and 4 m, in a crop of ornamental ruscus (*Ruscus hypophyllum*) 0.5 m in height, grown under similar conditions (i.e., irrigation, nutrition, harvesting). Although net radiation was almost identical in the two houses, air temperature near the plants, as well as leaf temperature was higher in the lower screenhouse than in the higher one. The average daily air temperature difference between the two houses was 1.5 °C, and the maximum difference in leaf temperature was 2 °C at midday. The vertical temperature gradient within the low screenhouse was ~ 3 times larger than that within the high screenhouse, due to better air mixing and more significant movement of warm air to higher levels in the higher than in the lower house. In addition, it was shown that VPD near the plants was higher in the lower screenhouse than in the higher one due to the higher temperature in the lower screenhouse. Most of the time, the absolute humidity in the higher house was closer to the outside than to that in the lower house, presumable due to the better ventilation in the higher screenhouse.

Energy Saving Considerations in Greenhouse Climate Control

About 90 % of the total energy consumption in greenhouses among the Northern European countries is for heating (NN 2012b). The climograph of one Mediterranean and one North Europe region is shown in Fig. 10.10. This shows that at lower latitudes, e.g. Almeria-Spain, the daytime temperatures are too high for ventilation to provide sufficient cooling during the summer. The attainment of suitable temperatures then requires positive cooling. On the contrary, in temperate climates e.g. in the Netherlands, heating is indispensable and together with ventilation enables the temperature to be controlled over the whole year (Kittas et al. 2013).

A study conducted in Germany stated that sometimes, small glasshouse companies, where oil is the most frequently used energy source, lack state-of-the-art technical equipment and have higher energy costs compared to large greenhouses. In addition, many greenhouses are not optimally equipped in terms of energy con-

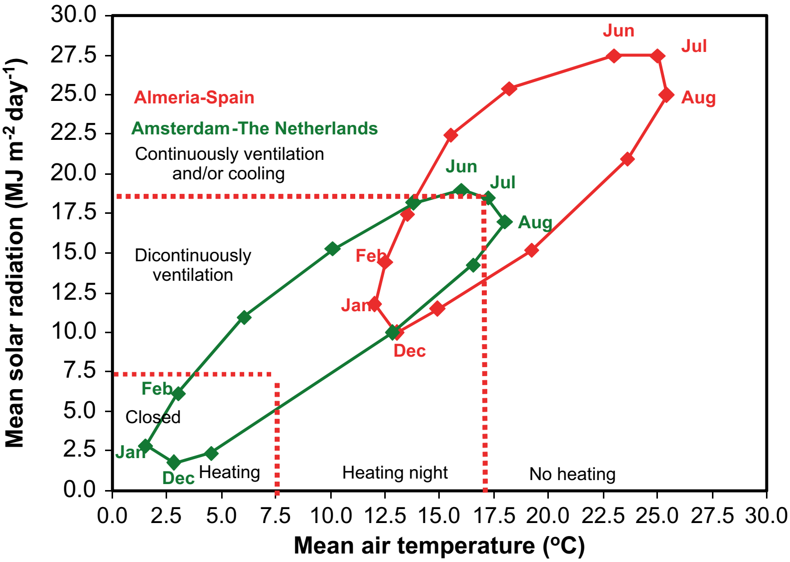

Fig. 10.10 The mean solar radiation vs. mean air temperature for Amsterdam (The Netherlands) and Almeria (Spain). The climograph: *dotted lines* indicate border lines for different control action in the greenhouse. (Source: Food and Agriculture Organization of the United Nations, Kittas et al. 2013. Reproduced with permission)

sumption (Gruda et al. 2009). The most feasible measures in cost-efficient energy conservation were due to following measures (Table 10.1):

Recently, the reduction of energy consumption using new covering materials, double and triple thermal screens, climate control strategies, energy optimized cultivation programs, and greenhouses as solar energy storage, are some of the new development projects in the Netherlands (de gesloten kas: the closed greenhouse) and Germany (ZINEG: the low-energy greenhouse). All these systematic tools together with the use of alternative and renewable energies, without using fossil fuels,

Table 10.1 Energy conservation measures in greenhouses. (Source: NN 2012b)

Nr.	Type of saving	Saving potential (%)
1	Thermal screen	20–40
2	Sealing of vents and windows	10–20
3	Heating system	10–18
4	Optimization of boiler	10–15
5	Climate control	10–20
6	Better use of cultivation area/crop planning	10
7	Special insulation and glazing	7–10
8	Sensors	5–10
9	Irrigation	5–10
10	CO_2—Fertilization	5

can contribute to a reduction of the energy consumption by 80–90 % and operate a greenhouse with minimum CO_2-emissions.

The Influence of Temperature on Plant Growth and Product Quality of Greenhouse Horticultural Plants

General

The "greenhouse effect" may have a positive effect on plants at higher latitudes; however, a negative effect on plant growth and development is also possible due to high temperatures in these latitudes. In general, the speed of all biochemical processes is temperature dependent and the reaction rate of different biological processes increases with increasing temperature. Afterwards, enhanced exposition duration and temperature intensity, the reaction rate decreases, because most enzymes lose their effectiveness or have been damaged resulting in reduced plant growth and development. Temperatures are highly affected by light intensity and to a lesser extent, by CO_2-concentration together with seasonal growth pattern and plant stage also needed to be considered (Gruda 2005).

Numerous studies have revealed optimum temperature range requirements for various plant species.

The optimum air temperature, regulation of the minimum air temperature and the commencement of cooling measures are three important aspects concerning air temperature regulation and control in protected cultivation. An optimum air temperature is crucial, due to regulation of the setting point of day temperature. As it was mentioned above, optimum temperature has to be regulated according to the particular plant species and/or cultivars and their subsequent development stages. Thus recommended temperatures for the germination of vegetables are higher than those for seedlings, transplants or for further cultivation. Optimum air temperatures are dependent on existing light intensity in protected cultivation. Plants grown under high radiant energy and low thermal energy become stocky, but grow and develop more slowly (Liu and Heins 2002). By contrast, plants grown under low radiant energy and high thermal energy grow and develop rapidly but become thin and weak. Moccaldi and Runkle (2007) reported that the flowering rate of salvia (*Salvia splendens*) and marigold (*Tagetes patula*) was primarily controlled by temperature within the experimental conditions provided with flowering decreasing from 42 to 24 days as temperature increased from 15 to 25 °C. Similarly, Blanchard et al. (2011) found the same trend for two petunia cultivars. (*Petunia* × *hybrida*). Although the flowering rate increased with temperature, plant quality parameters decreased, especially when the daily light integral (DLI) was low (Moccaldi and Runkle 2007).

In order to balance plant growth and development, during the European winter period, the optimum day temperatures in greenhouses have to be lower than in the summer months, with night temperatures generally to be kept lower than day temperatures in order to reduce respiration and heating costs. Minimum air temperatures are the lowest occurring plant-specific temperatures, which plants can tolerate in the short-term without permanent damage. For technical reasons frequently experienced in cold regions when it is snowing, the minimum temperature has to be regulated, so that snow can be defrosted by the greenhouse cover. The stage at which the grower commences cooling under increasing temperatures is of great importance, to avoid extreme heat stress situations. It is necessary to distinguish between optimal physiological and economical temperatures. Physiologically optimal air temperatures are temperatures at which, under the given irradiation, provide for maximum plant development per time-unit. By contrast, economically optimal air temperatures, take other features into account such as culture duration, yield, size, quality, and energy costs. Economically optimal air temperatures are frequently lower than optimal physiological temperatures with the differences usually a little higher for vegetables than for ornamental plants (Jansen et al. 1989).

New ways to increase energy efficiency and reduce costs of production include limiting the cultivation period to periods of adequate solar radiation, and lowering the economically optimal temperatures for heating and lowering the target temperature, to reduce energy consumption. For example, Elings et al. (2005) calculated that lowering day and night temperature set points for tomato by 1 °C lead to a reduction of 8 % per year energy consumption. However, lowering temperatures can adversely affect the leaf area development and light interception, resulting in lower production, extending the development time of the plant and adversely affecting product quality. This could be a problem especially for date cultures, e.g. poinsettia (*Euphorbia pulcherrima*), as well as early protected vegetables crops. Therefore, one of the main decisions that growers have to make is either to have a longer growth period, with lower energy requirements associated with often lower yields, or a shorter cultivation time with higher heating expenses and more often better returns by advancing the crop. Both cases incur additional costs that obviously will be higher for longer than shorter growth periods.

Day and Night Temperatures

Generally, a constant temperature is less favorable than a fluctuating one between day and night, when associated with high temperatures during the day and lower ones at night. Of importance here is the decrease in respiration at lower temperatures (night) and the increased photosynthesis at elevated temperatures (day).

The DIF-concept, or the difference between the day and night temperatures, was introduced in the horticultural literature in the 1990's. The DIF can be positive (day temperature = DT, is higher than night temperature = NT) or negative (DT is lower than NT). Langton and Cockshull (1997) reported that absolute day and night temperatures explained internode length rather than DIF, when an equal photoperiod of 12 h (day/night) was applied to chrysanthemum. Carvalho et al. (2002) went on to clarify the validity of the DIF concept by investigating cut chrysanthemums (*Chrysanthemum* cv 'Reagan Improved'), grown in growth chambers at 16 combinations of 4 day and night temperatures (16, 20, 24 and 28 °C) with a 12 h day length. The research group found that DIF could predict final internode length only within a temperature range 18–24 °C where the effects of DT and NT were equal in magnitude and opposite in sign. Internode appearance rate, as well as stem length formed during the experiment, showed an optimum response to DT, with the authors concluding that plants do not respond to DIF itself, but rather to the combination of independent effects of temperature measured during day and night periods.

Similarly a negative DIF strategy is still used, in order to reduce and substitute growth retardants used in controlling plant height or stem elongation of a number of different horticultural crops. Moe et al. (1992) reported that the most appreciable inhibitory effects on poinsettias were observed when lowering the growing temperature for 2–4 h before the dawn (cool morning strategy).

Peet and Bartholemew (1996) and Abdelmageed and Gruda (2009) emphasized the role of night temperatures on pollen characteristics and reported that total and percentage normal pollen grains were higher in tomatoes grown under normal night temperature than at high night temperatures. High day/night temperature differences or wide fluctuations in temperature can also induce disorders, like the cracking of tomato fruits (Peet 1992).

Low and High Growing Temperatures

Plastic greenhouses are also widely used for horticultural production in warm regions where high radiation and mild temperatures make production successful. By contrast, during the cold season, suboptimal temperatures and low irradiation can adversely affect growth and yield, and reduce the product quality of crops. Since warm-season crops are most likely cultivated under protected cultivation, damages could happen even at temperatures above freezing point. After long low temperature exposure leaves wilt and yellow and show various metabolic process disturbances. Furthermore, low temperature exposure has an influence on external and internal product quality.

Several authors have reported that low temperatures can cause fruit malformation and distortion, seedlessness, pericarp cracking, and pigmentation formation in various fruits and vegetables (Gruda 2005). Moreover, low night temperatures can reduce the number of pollen grains per flower and impair the germination ability of vegetables such as tomatoes and peppers with a tendency to develop parthenocarpic fruits.

Temperature can also influence the color intensity in most flower and fruits. Usually, low temperatures in combination with high light intensities hinder the coloring of flowers, bracts, and leaf parts, whereas some petunia cultivars show an increase in color intensity at higher temperatures. Fruits such as tomatoes, peppers and eggplants require relatively high temperatures for dye synthesis with color and color intensity interacting with growth factors, such as light (Jansen et al. 1989). For

Fig. 10.11 Anthocyanin formation on the underside of the tomato transplant leaves caused, due to a worse uptake of phosphorus at low temperatures. (Source: Gruda 2005, private collection)

instance, the red color of ripe tomato fruits is attributed to lycopene, a carotenoid synthesized and stored in the chromoplasts. Dumas (2003) reported that, except for *β*-carotene, greenhouse-grown tomato plants reduced carotene content of the fresh fruit under lower temperature regimes and at low air temperatures of < 12 °C may fully inhibit lycopene production. Moreover, Zipelevish et al. (2000) reported that eggplants (*Solanum melongena*) grown under cool winter conditions in unheated polyethylene covered greenhouses displayed a weaker intensity of fruit skin colour than during the normal hot growing period.

Low temperatures could also directly influence the organoleptic properties of vegetable products. For instance, low temperatures will produce less juicy tomato fruits with low acidity content and a mealy taste (Brückner et al. 2004) with Kano and Goto (2003) reporting a higher occurrence of bitter fruits in cucumber (*Cucumis sativus* cv. 'Kagafutokyuri') when grown under lower temperatures rather than higher temperatures. Both water and nutrient uptake can be inhibited at low temperatures. Jansen et al. (1989) reported that water absorption of cucumbers at 5 °C in the root zone is only about 10 % compared to that at 20 °C. In addition there can be a drastic reduction in absorption of nutrients at low temperatures in warm-season plants. Low temperature greenhouse grown tomato seedlings exhibited a lack of anthocyanin formation on the underside of the leaves due to a reduction of phosphorus uptake (Fig. 10.11). Once the seedlings are placed in the heated greenhouse, these symptoms gradually disappear.

Low temperatures make plants more susceptible to some pathogens and under such conditions inhibit the plant's defense mechanisms.

On the other hand, sub optimal low temperatures, when used appropriately, can sometimes improve fruit and vegetable quality. Ventura and Mendlinger (1999), for instance, reported that melon fruits from the unheated greenhouses were smaller and lighter than those from the heated greenhouse and had higher amounts of total soluble sugars (TSS), sucrose and fructose and tomatoes showed an improvement in fruit carbohydrate accumulation (fructose and glucose) when harvested under cooling growing conditions (Islam and Khan 2001).

Due to solar radiation and the "greenhouse effect" temperatures could sometimes rise above the optimal level for plant growth and development. Under such conditions many horticultural crops are exposed to a heat stress situation. Deleterious effects of high temperature can be direct or indirect. Direct temperature can damage cellular membranes, proteins, and nucleic acids. Indirect temperature effects can include inhibited pigment synthesis and thermal degradation of existing pigments as a result of sun scald or systems of sun burn (Kays 1999) as well as desiccate tissue and plant organs induced by water stress. In this case, internal fruit and vegetable temperature is more important than air temperature.

Physiologically high temperatures influence the photosynthesis process by inducing stomatal closure, increasing the rate of respiration and resulting in lowered biomass production and yield. Air temperatures do not only have an effect on plant growth and yield, but rather affect the development processes at different development phases. High temperatures result in "heat delay" a term that characterizes the effect of temperature, on delaying flower initiation. First in line are high night temperatures, but also day temperatures above the optimum for given species and cultivar leading to flowering delays. Warner and Erwin (2005), for instance, reported that high temperatures of 32 °C reduced the number of flower buds and resultant flowering in five annual herbaceous ornamentals, regardless of DLI.

Pollination, fruit set formation and horticultural products quality, are influenced by extreme high temperatures (Gruda 2005). For instance, Sato et al. (2002) reported that a continuous temperatures of 32/26 °C (day/night) led to the disruption of development in the pollen, endothecium, epidermis and stomium of anthers of tomato plants. Similar day/night temperatures reduced the percentage of germinated pollen of pepper plants compared with those at normal temperatures (26/22 °C) as well as fructokinase activity in mature pollen (Karni and Aloni 2002). Pollen grain release and germination has of course an effect on the ability of plants to set fruits. Abdelmageed and Gruda (2009) reported that heat stress associated with high day temperatures of 37 °C markedly decreased fruit fresh weight and the percentage of fruit set of tomatoes, as well as increasing the proportion of parthenocarpic fruits and aborted flowers. On the other hand reducing night temperatures from 27 to 22 °C had a positive effect on the number of pollen grains produced and released and fruit set percentage in the tomato. These results concur with Peet et al. (1997) who showed that low or optimal night time temperatures could compensate for high daytime temperatures in influencing pollen grain production in the tomato.

A combination of increased daily radiation and temperature has increased the incidence of blossom-end-rot (BER) of tomatoes, pepper and eggplant and tipburn of Chinese cabbage and lettuce. Taste, flavor and nutraceutical compounds of fruit and vegetables, grown under protected areas are also influenced by temperature. Gruda (2005) and Castilla and Hernandez (2007) reported that high temperatures can limit tomato fruit acidity, negatively influence taste and flavor, develop poor color and exhibit low lycopene content. Gross (1991) has shown that the optimal temperature range for lycopene formation in the tomato is between 16 and 21 °C, whereas temperatures between 12 and 21 °C favor best tomato fruit color (Dorais et al. 2001). However, both Dorais et al. (2001) and Dumas et al. (2003), agree that very high air temperature (30–35 °C and above) may drastically reduce or fully inhibit lycopene production in tomatoes. Liptay et al. (1986) stated that seasonal variations in the ascorbic acid content of the tomato cv. 'Jumbo' fruit ranged from 70 to 230 mg kg^{-1} fresh mass at the mature-green stage, and are directly correlated with temperature variations, when grown under greenhouse conditions.

Pardossi et al. (2000), Islam and Khan (2001), and Kano (2004) reported that sugar accumulation can be suppressed by high air temperatures when growing melons, cherry tomatoes, and watermelon, respectively. Moreover, preharvest temperatures can influence harvest quality and postharvest deterioration. For example, Kang et al. (2002) reported that cucumber fruit grown at a high average day temperature of 32 °C had a storage life of 16 days at 10 °C and did not exhibit chilling injury, whereas fruit grown at 27 °C developed symptoms of chilling injury after 12 days, at 10 °C. In addition during storage, firmness, vitamin C content, activity of superoxide dismutase, and catalase were higher in high temperature grown fruits than in control fruits.

Root-Zone Temperature

Root temperature is also known to have an effect on plant growth and product quality. Optimum root temperatures are known to stimulate constant new root growth and improve the uptake of nutrients and water in hydroponic or substrate culture systems, during the rapid development stage of the tomato, bell pepper, and cucumber fruits (Schnitzler and Gruda 2002).

Calatayud et al. (2008a) found that rose roots growing in cold solution (10 °C) were thin, white, succulent, short and sparsely branched, whilst in warm solution (22 °C) roots were long, brown, thick and branched. In addition Kafkafi (2001) showed that at the same water potential gradients, and at constant light radiation and air humidity as well as canopy temperature, the rate of water flow through the stem in tomato was increased by 250 % when root temperature changed from 12 to 20 °C.

Studies with lettuce grown in a floating hydroponic system have shown that the head size, leaf color and thickness, as well as root structure, developed best at 24 °C water temperature, regardless of air temperature. Keeping water temperature at 24°C maintained the market quality of lettuce heads even at 31 °C air temperature (Thompson et al. 1998). Benoit and Ceustermans (2001) and Li et al. (2002) reported a much lower rate of BER of soilless culture sweet pepper plants grown on cooled slabs than on non-cooled slabs, possibly due to a higher root activity from better oxygen content in the root environment.

Suboptimal stress, on the other hand, can be used to improve the quality of vegetable seedlings. Chen et al. (1999), reported shorter and more compact plug-grown seedlings, which were irrigated with cold water (tomatoes 5–15 °C, cabbage 5 °C) compared with actively growing warm-season plants, e.g. cucumber, where irrigation with too much cold water sometimes cause irreparable damage from cold shock (Fig. 10.12).

Fig. 10.12 Cold shock of actively growing young cucumber plants due to cold water (< 10 °C). (Source: Technical University Munich, Germany, 1999)

Furthermore, irrigation with cold water makes the plants more predisposed to diseases, such as those caused by *Pythium* ssp., and *Rhizoctonia solani* (Jansen et al. 1989).

Humidity Modifications Under Cover and their Influence on Plant Growth and Product Quality of Horticultural Plants

Humidity is an important environmental factor which influences the water status of greenhouse vegetable plants and consequently affects all processes that are associated with transpiration such as the water balance, transpirational cooling and ion translocation (Bakker 1984). In the scientific literature, apart from *r*elative *H*umidity (rH) in percent, very often the term *V*apor *P*ressure *D*eficit (VPD) in kPa (kilo-Pascal) is used to characterize greenhouse humidity. VPD is the difference between the amount of water in the air of current air humidity and the amount by saturation at the same temperature. There are some factors that influence the humidity in greenhouses e.g. ET (i.e. soil evaporation plus plant transpiration) as well as air exchange with the atmosphere, water condensation at the roof level, as well as on plants. The air and crop temperatures also play a role in the control of VPD level. For example, warm air can hold more water vapor and it is more difficult to be saturated than cold air. High or low VPD will adversely influence the plant growth, yield and product quality, depending on the availability of water in the root zone, because in the end it's a question of plant water balance. For instance, in greenhouses with a high VPD, e.g. high outside temperatures in arid regions, the risk of drought stress might therefore be significant. This will increase for crops with high requirements on air humidity, such as cucumbers.

Interestingly, humidity is often neglected in protected cultivation, as long as diseases and pests do not appear. There are two main reasons for that: *firstly,* high humidity seldom causes any direct negative effect on plant growth and development. Grange and Hand (1987) found that vapor pressure deficit (VPD, 0.2–1.0 kPa) had almost no effect on the growth and development of horticultural crops. *Secondly,* until one or two decades ago, optimization of the greenhouse environment has been achieved traditionally by focusing on productivity, while product quality and quality parameters only given prominence in recent research studies (Mortensen 2000; Gruda 2005). On the other hand, according to Holder and Cockshull (1990) VPDs smaller than 0.2 kPa can only be induced for extended periods in modern glasshouses.

The management of humidity has two main purposes: maintaining crop transpiration within boundaries and preventing condensation on the crop. Excessively high or low rates of transpiration may result in local calcium deficiencies, loss of turgor, partial stomatal closure and loss of assimilation. Condensation is known to increase the incidence of disease causing organisms such as mildew and botrytis grey mould (Köhl et al. 2007; Stanghellini and Kempkes 2008). Whereas a high RH or respectively low VPD is successfully used for plant propagation and grafting. Three potentially harmful effects of extreme humidity on plants, can occur with heat damage is likely to occur because of the reduction of transpirational cooling, increased injury by air pollutants due to changes in stomatal resistance, and reducing the translocation of some ions from roots to shoots due to reduced transpiration rate under high humidity.

In the literature the information on the average weight of marketable fruits and fruit size of tomato and sweet pepper plants is inconsistent and contradictory (Gruda 2005). Mulholland et al. (2001), for instance, reported that fewer tomato fruits growing under low VPD may be due an increased rate of flower abortion and a reduction of pollen viability. In addition, the authors interestingly state that VPD of 0.1 kPa can severely reduce the K concentration in young leaves compared with standard air humidity.

Gruda (2005) has shown that controlling VPD could influence the excess or deficiency of calcium content in the fruits or in some fruit parts and consequently the occurrence of at least two related physiological disorders: "gold specks" and "blossom-end-rot" (BER). The physiological disorder known as "gold specks," is a consequence of an increased movement of calcium into the fruit and an accumulation of an excess of calcium, deposited as calcium oxalate, in cells below the epidermis (De Kreij et al. 1992; Adams 2002; Gruda 2005).

Different authors have shown that under conditions of low VPD, a reduction in the incidence of BER in tomato and sweet pepper is achieved (De Kreij 1996; Paiva et al. 1998; Li et al. 2002). High air humidity, especially during the night when the stomata are normally closed, appears to prevent calcium deficiency in lettuce (Collier and Tibbitts 1982). Cariglia and Stanghellini (2001), with Li et al.

(2001) suggested that there is an improvement of taste and flavor of tomato fruits by increasing the salinity, and applying the right humidity management program to the shoot environment. Lowering the transpiration rate can modify the effect of the root zone salinity, both by reducing the proportion of nonmarketable fruits, e.g. by the incidence of blossom end rot and reducing the decline in fresh weight. In general, manipulating the indoor climate, such as humidity, temperature and ambient CO_2 level, may offset the negative effect of high salinity on yield and fruit quality such as BER (Stanghellini et al. 1998; Dorais et al. 2001). These results were confirmed by Romero-Aranda et al. (2002) where greenhouse misting increased instantaneously improved the WUE of tomato yield and fruit size regardless of salinity.

On the other hand, low VPD can cause other disorders, such as, cracking and russeting (fine hairline cracks) of tomato and bell pepper fruits. According to Demers et al. (2007), a hypothesis could be drawn that low VPD decreases leaf transpiration but increases root pressure, which in turn increases fruit water supply and turgor pressure. Under such conditions, a greater stress would be applied to the fruit skin and cuticle, which would increase the likelihood of the development of cuticular and fruit cracking. Although, in this study, no significant effect of day/night RH regimes on fruit russeting was observed, it is reasonable to presume that the effect of high RH on russeting would be more pronounced if the high rH occurred at night, when leaf transpiration is already reduced.

By contrast with light and temperature, data concerning the influence of air humidity on internal greenhouse vegetable quality are generally scarce except for tomato fruits (Gruda 2005). Bertin et al. (2000) and Guichard et al. (2001) reported that, the dry matter and sugar concentrations of fruit exposed during their growth to high VPD was higher than those of fruit exposed to low VPD, apparently due to a decrease in water accumulation by the fruit which led to a 30% reduction in the net accumulation of water by the fruit (Guichard et al. 1999). Investigations by Mortensen and Fjeld (1998) with potted roses demonstrated that increasing air humidity reduced the vase life of roses from 8–13 to 2–5 days and caused the early onset of leaf drying and "bent neck" during the stage of shoot growth. According to Torre and Fjeld (2001) and Mortensen and Gislerod (2005) air relative humidity of 85–90% during active growth is a critical environmental factor that reduces the postharvest life of cut roses, mainly due to uncontrolled water loss from the cut shoot. Torre et al. (2003) reported that roses subjected to high RH showed differences in leaf anatomy; stomatal morphology and stomatal function, may explain the loss of water control from these plants. The authors concluded that stomatal ontogenesis should occur at RH conditions below 85% to secure roses with a high postharvest quality potential.

Air Flow and Ventilation

Greenhouses

One significant effect of covering crops is the modification in air movement near the canopy. The reduced air velocity may have positive or negative effects on crop production as it reduces physical damage to the foliage and fruit, increases the thickness of leaf boundary layers and suppresses the turbulence level of the flow, thus reducing the exchange rates of gases between leaves and their environment and allows for potential water savings. On the other hand, reduced air velocity may reduce the ventilation rate which may avoid sufficient supply of CO_2 for plant photosynthesis and adequate removal of excess heat and water vapor. Hence the design of any cover should take into account these effects on the crop.

Greenhouses are ventilated either by natural or by forced ventilation systems. Natural ventilation is generally a reliable, low-cost and maintenance and energy-efficient method to keep temperature and humidity inside agricultural buildings within safe and comfortable limits. Natural ventilation can be generated by two different effects. The first is the buoyancy force (stack effect) which results from density differences between the internal and external environment due to temperature and humidity differences. The second is wind-driven flow which may enhance or hinder the buoyancy-driven flow, depending on the locations and sizes of the openings and the wind speed and direction (Allard 1998). Natural ventilation systems are mostly used in greenhouses located at mild winter climates where climate control needs are moderate.

Forced ventilation systems in greenhouses are mostly based on mechanical fans with some optional cooling devices like a wet pad or a fogging system (Linker et al. 2011). Usually, in such systems, fans suck air out on one side and openings on the opposite side allow for air flow in. In order not to hinder interaction with wind-induced natural ventilation, it is preferable to install the fans on the leeward side of the greenhouse. In forced ventilation systems the air flow rate and hence the ventilation rate can be controlled; Teitel et al. (2004) showed that controlling fan motor speed saved electrical energy. Kittas et al. (2001) compared between forced and natural greenhouse ventilation systems and found that forced ventilation increased significantly the aerodynamic conductance, but did not influence significantly water consumption when compared with natural ventilation, because of the negative feedback between canopy-to-air VPD and stomatal conductance.

Natural ventilation processes in greenhouses were studied using experiments, modeling and Computational Fluid Dynamics (CFD) simulations. In the low investment greenhouses and plastic tunnels, natural ventilation is a cheap and dominant way to manage and control greenhouse climate, such as natural CO_2 enrichment to secure normal crop growth (Luo et al. 2005), and water vapor removal to reduce the risk of pest epidemics (Kofoet and Fink 2007).

Natural ventilation in greenhouses is applied through either roof or side openings, or both. Roof openings are usually applied in large greenhouses where ventilation

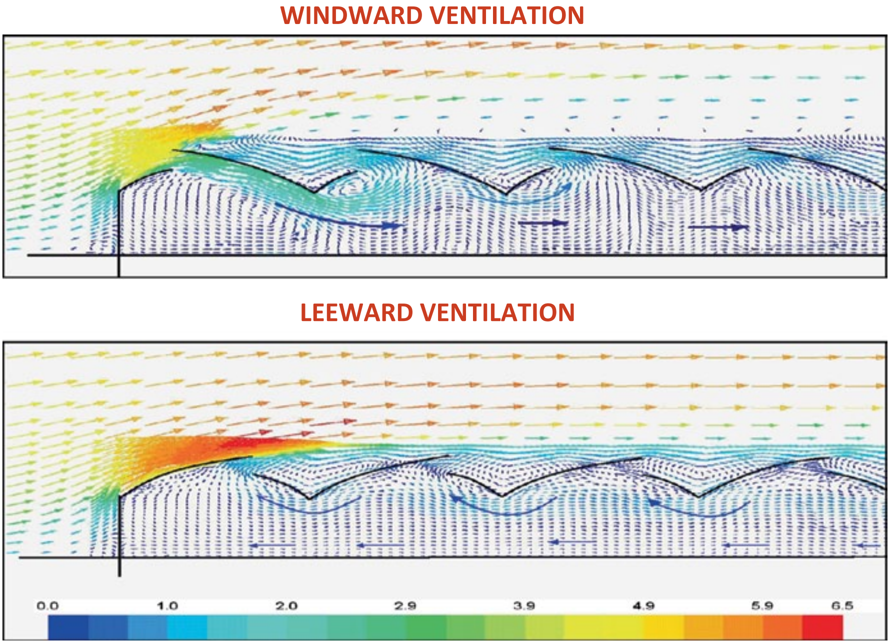

Fig. 10.13 A *C*omputational *F*luid *D*ynamic (CFD) simulation of air flow patterns in a greenhouse with roof openings under windward (*top*) and leeward (*bottom*) ventilation. (Source: Montero et al. 2011)

by side openings may not be sufficient. To protect the crop from insect invasion, roof and side openings are usually covered with insect-proof screens which not only reduce the ventilation rate, but also affect all other microclimatic variables (Teitel 2001, 2007; Teitel et al. 2006). Teitel et al. (2012) measured radiation distribution in three greenhouses with different roof configurations and clearly showed that roof openings, including the construction elements and insect-proof screens hindered the supply of sufficient radiation to the canopy.

Montero et al. (2011) indicated a significant difference between leeward and windward ventilation (Fig. 10.13), where the windward ventilation internal air flow was in the same direction as the external wind but in leeward ventilation the internal air flow direction was opposite to the external.

Teitel and Tanny (2005) have shown that in leeward ventilation, if the wind is not perpendicular to the plane of the openings there are outflow and inflow, at the windward and leeward edges of the openings respectively. A wind blowing from the back of the openings and nearly perpendicular to them reduced the mean air velocity at the two edges but did not change the turbulent velocity much. Teitel and Tanny (1999) demonstrated by experiments and theoretical models how the sudden opening of roof windows in a greenhouse affects the temporal variation in the inside temperature and humidity. The results showed that the effect of the ventilation (i.e. the reduction with time in the temperature and humidity ratio within the greenhouse) increases with the height of the window opening and the wind speed, and decreases with the solar radiation.

An important issue in natural ventilation systems is the estimation of the ventilation rate, which is responsible for the adequate removal of excess heat and water vapor and supply of CO_2 (Boulard 2006). Boulard and Baille (1995) derived an expression for the ventilation rate, based on the Bernoulli equation, which depends on both the buoyancy and wind effects. Kittas et al. (1997) investigated the relative contribution of the two factors to greenhouse natural ventilation and found that under the conditions of their experiments, the wind effect predominated on the buoyancy effect when $u/\sqrt{\Delta T} > 1$, where u is external wind speed and ΔT is the temperature difference between inside and outside of the greenhouse.

In naturally ventilated greenhouses the control of CO_2 enrichment is largely related to the climatic conditions. For example, greenhouse CO_2 enrichment in warm climates is restricted by the need to ventilate, leading some growers to intermittent enrichment, where enrichment and ventilation alternate several times an hour. This strategy relies on the heat and CO_2 capacity of the system, characterized by a heating time constant of the order of 10 min, during which period ventilation may be suspended (Ioslovich et al. 1995). The latter authors have demonstrated that for slowly changing weather, the optimal CO_2 enrichment is basically not intermittent, but rather approximately stable. Seginer (1990) considered the combined effect of CO_2 enrichment and shading and concluded that under desert conditions, where ventilation is mandatory during most daytime hours, CO_2 enrichment was effective only during the morning, before ventilation rate had to be increased in order to cool the crop.

Screenhouses and Screen Covers

Another type of structures which become popular among growers in mild winter climates is the screenhouse or screen cover (Tanny 2013). These structures are much cheaper than greenhouses and under certain climatic conditions may provide the adequate protection for the crop. Since the screenhouse is a semi-open structure, air flow and ventilation are strongly influenced by the external climatic conditions. A major effect of porous screens is to increase the resistance to airflow which decreases the internal mean air velocity.

In an attempt to characterize the effect of horizontal screen covers or screenhouses on air velocity, several field measurements established relationships between inside air velocity and outside wind speed (e.g., Waggoner et al. 1959; Tanny et al. 2006; Siqueira et al. 2012; Tanny 2013). In few cases, the vertical gradient of air velocity was also considered (Allen 1975; Tanny et al. 2010). Obviously, denser screens with lower porosity would induce higher resistance to air flow and hence will diminish inside air velocity more than screens with higher porosity. However, Tanny (2013) suggested that several additional factors (e.g. screen deployment configuration, crop height, velocity measurement height and the travel distance of air, or fetch) affect the inside air velocity in screenhouses.

Tanny et al. (2006) have shown that several important turbulence characteristics were essentially unchanged from their external values, in a large screenhouse in which banana was grown (Fig. 10.9). Tanny et al. (2010) and Siqueira et al. (2012) demonstrated that the friction velocity, which is a measure of the turbulent transport of momentum, was nearly constant with height in the air space between the crop and the screen. Tanny and Cohen (2003) and Tanny et al. (2009a) investigated the boundary layer properties of the air flow above the screen, which controls the exchange of gases and heat between the canopy and atmosphere and showed that screens may inhibit these exchange processes, including ET, and hence lead to water saving.

Screenhouses of relatively light shading screens reduce the absolute velocity of the approaching external wind but preserve the wind direction, and the turbulence properties of the boundary layer (Tanny et al. 2006, 2010). This contrasts with insect-proof screenhouses, which induce a more complicated internal air flow pattern (Möller et al. 2003) where in part of the screenhouse the air flow direction was opposite to the external wind. This latter finding was similar to roof ventilated greenhouses under leeward ventilation (Fig. 10.13).

Ventilation rate of screenhouses was investigated using the water vapor as a tracer in two insect-proof screenhouses in which pepper and banana was grown separately. Tanny et al. (2003) have shown that ventilation rate depended on external wind speed, was significantly reduced as compared to open field conditions, and was non-uniform within the screenhouse, demonstrating a higher ventilation rate closer to the side walls than the center of the house. Ventilation rate estimates were in the same order of magnitude for both crops (Tanny et al. 2006). Teitel and Wenger (2010) have shown the effect of screenhouse roof shape on the ventilation rate, using CFD simulations. Their analysis showed that using pitched roofs increased the ventilation rate as compared to flat roofs, due to higher penetration of air into the house.

Modifications of CO_2 in Protected Environments, CO_2 Enrichment and Distribution and the Influence on Plant Growth and Product Quality

Carbon dioxide (CO_2) is a crucial component of photosynthesis used for biomass production, and is indispensable for plant growth. Plants take in CO_2 through the stomata by diffusion so the concentration of CO_2 in the greenhouse atmosphere strongly influences CO_2 uptake by the plant. On the other hand, according to Frantz (2011) the CO_2 concentration in the greenhouse can be reduced during the day to levels as low as 175 ppm (the normal atmospheric CO_2 concentration is about 390 ppm) and this in turn leads to photosynthesis reduction. When greenhouse windows are closed and no ventilation takes place a CO_2 supply from the atmosphere can happen only from leaks through the greenhouse envelope. If the internal air circulation is very low, the remaining CO_2 deficit is not recoverable.

Whereas the traditional straw bale cultural technique for cucumbers is one of the oldest and simplest methods of CO_2 enrichment in greenhouses, its importance has increased with the trend towards producing crops in nutrient film, rockwool, and other substrates, where natural CO_2 concentration is small compared to CO_2 coming from the soil profile. Indeed, in greenhouses, the soil is frequently covered with plastic sheets when alternative soilless media are used (Hicklenton 1988; Slack 1986a). On the other hand, CO_2 enrichment methods have continued to develop sources of nonpolluting CO_2 (Mortensen 1987), so that the negative effects associated with the burning of hydrocarbons have been reduced (Gruda 2005).

Maintaining high levels of CO_2 is sometimes difficult, when solar radiation and/or inside air temperatures are high inside the greenhouse, because roof and/or side windows need to be opened, to ventilate the greenhouse in order to reduce the air temperature and/or regulate the VPD at optimal values. New perspectives recently developed closed and semi-closed greenhouses which reduce the energy consumption. In such greenhouses window ventilation is usually reduced or replaced by an active cooling system. In addition, energy saving measures have been implemented where excess solar energy is collected and stored, in order to be reused at night or in periods in which the solar radiation is limited, e.g. in cloudy days or in the winter. Under these conditions it is possible and preferable to keep high CO_2 concentrations even at high light levels.

Generally, concentrations of 800–1,000 μmol mol^{-1} in greenhouse atmosphere are used for different plants in the daytime, in order to promote photosynthesis and inhibit light respiration. According to Drake et al. (1997) elevated CO_2 reduces stomatal conductance as well as transpiration rate and improves WUE, while at the same time stimulates higher rates of photosynthesis and increases light-use efficiency. Many studies reported these positive effects on physiology, growth, and productivity of plants. Besford et al. (1990), for instance, found more than double photosynthetic rates in mature leaves of tomatoes, an increase of the fresh weight per unit area of leaf, and in general increases of crop yields, due to an increase of CO_2 concentrations to 1,000 μmol mol^{-1}. Mortensen (1987) reported that horticultural greenhouse plants exhibited positive effects due to CO_2 enrichment by increasing dry weight, plant height, number of leaves, and lateral branching, whereas Mortensen and Moe (1995) found that the development rate of miniature roses could be accelerated by 4–5 days at elevated CO_2. Plant quality of ornamentals, expressed by growth habit and number of flowers, is often enhanced by CO_2 enrichment. Peet and Willits (1987) reported that CO_2 enrichment significantly increased the yield of cucumbers. Mortensen (1994) showed that increasing CO_2 concentration in plastic “field chambers” from ambient to 800–900 μmol mol^{-1} could increase the dry weight of lettuce, carrot, and parsley by 18, 19, and 17%, respectively. Enrichment with CO_2 (900 μmol mol^{-1}, 8 h day^{-1}) and supplementary lighting for approximately 3 weeks before transplanting, increased accumulation of dry matter in shoots by 50% for tomato and pepper seedlings, as compared with the control group. Furthermore, the early yield after transplanting to the field was improved (Fierro et al. 1994). Some more examples of benefits for other vegetable crops are compendiously presented by Gruda (2005).

Carbon dioxide enrichment could have a positive effect on plant propagation and promoting the rooting of cuttings. Even at low irradiance growth promotion can be achieved by CO_2 enrichment, due to inhibition of photorespiration and the associated reduction of the light compensation point. This is of great benefit in winter/spring period in higher latitudes when light levels are low. The negative effects of low light conditions (Fierro et al. 1994), low temperatures (Frantz 2011), high salinity levels in irrigation water available in Mediterranean countries (Romero-Aranda et al. 2002) or high electric conductivity (EC) levels of nutrient solutions (Li et al. 1999) can be diminished by CO_2 enrichment. Supplementary CO_2 boosted total leaf number and mass of lettuce even though temperatures were maintained at 1.67 °C (3 F) lower than in a traditionally well insulated greenhouse without added CO_2 at a commercial facility (Frantz 2011).

There is less information on the effect of CO_2 concentration as an elicitor on the internal quality of vegetables with most publications reporting no effect on product quality (Gruda 2005). However, there is evidence that the enhanced rate of photosynthesis observed during short-term exposure to high CO_2 may not be sustained over long periods (Drake et al. 1997; Frantz and Ling 2011). Besford et al. (1990) summarized that growth for a number of weeks in high CO_2, involving several vegetable crops and tobacco did not maintain the photosynthetic gain, when plants were measured at normal CO_2 ambient condition. This process is defined as the photosynthetic acclimation to high CO_2 concentration. Similarly, Frantz and Ling (2011), recently observed a positive effect of CO_2 on leaf and flower mass after 5 weeks on the growth of *Petunia × hybrida* (second harvest), but there was no CO_2 effect on growth with the last harvest. These results show that long-term exposure to elevated CO_2 doesn't always lead to enhanced biomass production. Moreover photosynthetic acclimation can lead to adverse effects on the ornamental value of plants (Croonenborghs et al. 2009) such as higher carbohydrate concentration, lower concentration of soluble proteins and RuBisCo, and inhibition of photosynthetic capacity (Drake et al. 1997).

Indeed higher amounts of carbohydrates can lead to a problem of source/sink balances and sink strength. Arp (1991) analyzed the relationship between rooting volume, or the size of the container, and acclimation of photosynthesis of plants in elevated CO_2 concentrations and found that plants grown in small containers (< 10 L), were sink limited because of root zone restrictions. These results were in agreement with a survey of 163 studies by Drake et al. (1997), where the assimilation remains the same for plants grown in both elevated and ambient CO_2 concluding that the restriction of rooting volume on acclimation is probably confounded with effects of nutrient availability on photosynthesis.

Other factors, such as available nutrients, also could reduce sink strength (Drake et al. 1997). Qian et al. (2012) found that fruit load is important as well. By investigating different fruit loads of tomato in a semi-closed greenhouse and a conventional modern greenhouse it was found that the increase of dry matter production in the semi-closed greenhouse was mainly explained by a higher CO_2 concentration when compared to an open greenhouse. Similarly, Dannehl et al. (2012) showed that a combined application of a high pressure fog system and CO_2 enrichment in a semi-closed greenhouse were adequate to accelerate plant growth, increase the dry matter in leaves, and promote the formation of fruit set per truss, as well as increase in the maximum total yield by 20 % as well as fruit size. On the other hand, the occurrence of blossom-end rot in tomato fruit was reduced when compared to those grown under conventional climate conditions. Qian et al. (2012) concluded that the photosynthetic acclimation to elevated CO_2 concentrations depended on the source-sink balance and a continuously high CO_2 concentration in a semi-closed greenhouse does not cause feedback inhibition in high producing crops, because these plants have sufficient sinks (fruits) to utilize extra assimilates.

Water Supply, Irrigation Management and Systems and their Effect on Plant Growth and Development

General

Water is one of the most important factors influencing plant growth, productivity, and quality and is the main component of plant cells and total fresh biomass content of plants. Typical greenhouse grown vegetables such as tomatoes, cucumbers, peppers, and lettuces may contain 90–96 % or even more water. For protected crops, irrigation and its management have a special importance since natural precipitation is excluded and if soilless culture systems (SCSs) are used, often the groundwater sources are unavailable. Moreover, greenhouse plants are not exposed to drastic changes of environmental conditions. For example, Huang and Snapp (2004) reported a very consistent association between the incidence of shoulder check or russeting of tomatoes grown in the open and precipitation events followed by periods of hot, dry weather during rapid fruit expansion. In addition resultant fruit quality was higher and the incidence of defects lower in fruit produced under plastic rain covers than in open field-grown tomatoes.

Water supply is significantly higher in protected cultivation than in the open field, mainly due to the intensity and quantity of year-round biomass production. High temperatures, which can be reached in greenhouses during summer, may also increase water demand. On the other hand, the requirements on water quality are considerably higher. Generally, the majority of protected crops is warm-season species that are sensitive to low temperatures. Therefore water temperature must be as close as possible to the plant root temperature. Increased salinity in the irrigation water is more likely to have a more negative impact than in the open field, over all in a closed loop-system.

Either too much or too little water can induce plant stress. For instance, a typical disorder of tomato fruits is blossom end rot—usually occurring due to water deficit, whereas cracking is due to an excess of water supply. According to Peet and Willits (1995), the application of excess irrigation water to greenhouse tomatoes induced a two-fold higher incidence of radical cracking in fruit compared to the recommended water regime. Photosynthesis and transpiration are negatively affected by water and/or drought stress. Most of the water consumed by plants is used in the transpiration process, as well as regulation of internal temperature. Plants react to water fluctuations firstly by stomata regulations with stomata closing during the night and opening at dawn (light-induced stomatal opening). Transpiration increases with increasing temperature until midday and decreases significantly by cooling, due to a gradual closing of stomata.

With inadequate water supply, or extreme heat and drought, the stomata close much earlier with negative consequences for gas exchanges and CO_2 assimilation. Because of the reduction in CO_2 assimilation in leaves, the metabolic processes are impacted resulting in many of the integrated physiological and biochemical processes that cause yield and quality reduced. The loss of turgor pressure in the cells leads to wilting that initially manifests in a withering of leaves followed by leaf necrosis and plant desiccation.

According to Bolla et al. (2009) greenhouse water shortages in roses can have a negative effect on photosynthesis with a simultaneous reduction in the photosynthetic rate and a significantly lower quantum yield of photosystem II, without any limitation made on the intercellular CO_2 concentration levels. This, as well as the increase in carbohydrate content (glucose, fructose and sucrose) and inorganic solutes (potassium) of the stressed plants during the dry-down period indicate that the plants are able to maintain their metabolic and physiological function. Apart from the stomatal closure the ability to continue functioning also plays a role, by means of turgor maintenance and osmotic adaptation.

Niu et al. (2008) also indicated that during dry-down, fluorescence measurements indicated some damage in the photosystem II of four clones of oleander plants (*Nerium oleander*). In addition, shoot dry weight was reduced, while root-to-shoot dry weight ratio was increased; as substrate volumetric moisture content decreased from 30 %, leaf net photosynthetic rate, ET rate, and stomatal conductance decreased in all clones.

Plants express a response to water stress by changes in their morphology such as decreasing leaf area, in order to regulate water loss and prevent further dehydration (Gruda and Schnitzler 2000a), or by an adaption in their root system. According to Kulkarni and Phalke (2009), under drought stressed conditions, plants would increase their water uptake from deeper soil layers by restricting the horizontal proliferation of lateral roots in the topsoil and allocating more resources to the growth of primary roots. The plant can be considered a hydraulic system, connecting water in the soil, or in the case of SCS the substrate or nutrient solution, with the water vapor in the atmosphere (Taiz and Zeiger 2010). In the literature, sometimes the term "soil-plant-atmosphere continuum" is used to characterize the water pathway. The water movement processes are explained using the water potential concept (negative pressure). The factors influencing water movement along this pathway are water tension in the root zone, soil or substrate type, physiological plant status and atmospheric water demand. Hence, greenhouse environmental conditions, such as air temperature, radiation, air movement and air VPD will directly or indirectly influence water movement. This sub-section only considers soil water and its effect on protected crops.

In greenhouses, plants obtain water mainly from the soil. Thus, the regulation of soil moisture is very important. Excessive amounts of water, due to an incorrect irrigation can result in nutrient losses by leaching, particularly of nitrogen. Moreover, overwatering should be avoided, because of a likely oxygen deficiency and a probable production of other adverse gases in the soil such as methane and/or carbon dioxide. In this case the roots may not successfully uptake water and nutrients. The optimum water content in greenhouses is in the range of field capacity, and sometimes higher, with substrate cultures with a high pore volume. The regulation of soil moisture is also important for microbial transformation in the soil, for mobilization of nutrients from the soil organic matter, and for solubility of nutrients. For instance, adequate soil moisture is necessary to facilitate diffusion of potassium (K^+) to plant roots for uptake which according to Lester et al. (2010) accounts for >75 % of K^+ movement. Therefore, soil moisture deficits can limit soil K transport as well as uptake into the plant, thereby causing K deficiency.

Simulated drought conditions are sometimes used as a tool to control plant habit and generative development. As it was stated earlier, one of the quality requirements for ornamentals is to be compact plants and to possess a good number of buds and blooms at sale time and where the stature of the plant benefits the consumer and grower; namely, a high-quality product, and savings in production and transportation costs, less water and space requirements. Different methods have been developed to induce compact morphology. The inhibition of growth with chemical agents is certainly one of these methods. Very limited licenses as well as an increased consumer consciousness however have led to increasing pressure in developing alternative methods for growth inhibition. The use of techniques for lowering temperatures and/or "cool morning", and thigmomorphogenesis and restrictive water management are some of these alternative methods. Röber et al. (1986) demonstrated that decreasing moisture leads to a reduction of height, diameter, and leaf area of ornamental plant species. Precisely performed induced sub-drought stress can produce compact high quality plants, comparable to those treated with growth inhibitors. Liptay et al. (1997) reported that carefully regulated, moderate stress can slow down growth of vegetable transplants under certain circumstances without influencing yield or product quality loss. Gruda and Schnitzler (2000b) have proved that size differences in head lettuce transplants, induced by variable irrigation levels and different organic substrates, were no longer detectable 3 weeks after transplantation. In addition, moderate stress can reduce susceptibility to pathogens, such as *Pythium ultimum* (Schnitzler and Gruda 2002). A modification of water availability can also be achieved by adjusting the concentration of nutrient solution in soilless culture and this is used by growers in order to improve the quality of some fruit vegetables, such as tomato.

Crop Water Requirements and Evapotranspiration

Water scarcity has become a significant limitation in agricultural production worldwide. Hence it is necessary to accurately estimate the crop water needs, or whole canopy ET, under different conditions in order to optimize irrigation and increase the water saving.

Evapotranspiration can be either measured or estimated by models, the common measurement techniques being the lysimeter and sap flow gauges. One lysimeter application is based on installing several planted pots on load cells and continuously monitoring their weight. From this data, and knowledge of the irrigation, the amount of water consumed by the plant during a certain time period can be extracted which can then be used to guide the next irrigation. The lysimeter technique is useful for small and moderate size plants but for large plants or trees it is rarely used due to obvious technical limitations (Ghavami 1973; Israeli and Nimri 1986). Sap flow gauges are based on measuring the sap flow rate in the stem using stem temperature variations induced by sap flow. Common sap flow techniques are the heat-pulse (Cohen 1994) and thermal dissipation (Granier 1985). In recent years the use of the eddy covariance technique to measure whole canopy ET was examined in screenhouses, and is discussed below.

Crop water requirements for protected crops can be estimated using the well-known Penman-Monteith (PM) equation, which is derived from principles of energy balance and transport processes. The general expression for the PM equation is (Allen 1998):

$$ET = \frac{\Delta(R_N - G) + \rho_a C_p (e_s - e_a)/r_a}{\Delta + \gamma^*} \quad (10.1)$$

in which

$$\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right).$$

In Eq. 10.1, ET is the evapotranspiration (W m^{-2}), Δ is the slope of the saturation vapor pressure-temperature curve (kPa K^{-1}), R_N is the canopy net radiation (W m^{-2}), G is the soil heat-flux density (W m^{-2}), ρ_a is air density (kg m^{-3}), C_p is air specific heat at constant pressure (J kg^{-1} K^{-1}), e_s and e_a are the saturated and actual vapor pressure (kPa), γ is the psychrometric constant (kPa K^{-1}), r_a is the aerodynamic resistance (s m^{-1}), and r_c is the canopy resistance (s m^{-1}).

A common method for estimating crop water requirements for canopies in open field conditions is to use the concept of reference evapotranspiration, ET0, and then apply a crop coefficient, Kc, which is an empirical parameter, specific for each crop and growth stage (Allen et al. 1998). The ET0 is calculated for a well irrigated and uniform reference grass crop at a height of 0.12 m, conditions which dictate certain values for the resistance terms, r_a and r_c, in Eq. (10.1). Substituting these values in Eq. (10.1) results with the equation of daily ET0 (Allen et al. 1998):

$$ET0 = \frac{0.408\Delta(R_N - G) + \gamma \dfrac{900}{(T_{mean} + 273)} u(e_s - e_a)}{\Delta + \gamma(1 + 0.34u)} \tag{10.2}$$

where u is air velocity measured at 2 m above the ground. Details for calculations of daily values of the other parameters in Eq. 10.2 are given in Allen et al. (1998).

Obviously the conditions of most protected crops are significantly different from those of the reference grass for which Eq. 10.2 was derived. Therefore adjustments should be made according to actual climatic conditions and canopy properties in order to obtain the actual crop evapotranspiration (ETc). For mild climates, von Zabeltitz (2011) suggested increasing daily mean maximum and minimum temperatures by 4 and 2 °C, respectively, using mean relative humidity of about 75–80 %, and assuming transmittance of the global radiation by the cladding material (mostly for plastic greenhouses) of about 0.6–0.7. In addition, recommendations for actual crop coefficient (Kc), relative area of crop to ground and irrigation loss are given (von Zabeltitz 2011).

Fernandez et al. (2009) demonstrated the use of the ET0 approach (Eq. 10.2) for an unheated plastic greenhouse in Almeria, Spain using two sub-models: one for radiation and the other for the crop coefficient for pepper cultivation. They conducted experiments in a naturally ventilated greenhouse in the Almeria region in which pepper was grown. The measurements included inside and outside climatic variables, and ETc was measured by lysimeters. Good agreement was obtained regarding estimated and measured values of ET0, ETc and Kc.

In an attempt to optimize water use in greenhouses, several studies measured crop ET, mainly by the lysimeter technique, and compared the measurements with theoretical models, adapted to the greenhouse conditions. For example, Jolliet and Bailey (1992) examined the effects of inside climatic conditions on tomato transpiration and compared their transpiration measurements with five transpiration models. Their results showed that transpiration rate increased linearly with solar radiation, VPD and air velocity; however air temperature and CO_2 concentrations had no significant influence on crop transpiration. Among the five transpiration models they investigated, they found two (Stanghellini 1987 and Jolliet and Bailey 1992) to be in best agreement with the measurements as these two models represented most accurately the solar radiation and VPD effects on the stomatal conductance.

A different approach in simulating the ETc in Mediterranean plastic greenhouses was examined, by Boulard and Wang (2000). They suggested that unlike north-European glasshouses, Mediterranean plastic greenhouses are strongly coupled with the external environment, such that ET modeling can be based on the relationships between the external and internal greenhouse conditions. Their results showed that when the greenhouse was closed, i.e., strongly decoupled from the external environment, ET predictions based on external conditions deteriorated in comparison with periods when the greenhouse was well ventilated. This was due to strong interaction between inside and outside in the ventilated greenhouse. In their model, Boulard and Wang (2000) applied the general Penman-Monteith equation (Eq. 10.1)

Fig. 10.14 Two eddy covariance systems installed in a large banana screenhouse, located at the Western Galilee of northern Israel. The systems measure whole canopy turbulent fluxes of water vapor, heat and CO_2. Their deployment above the canopy does not interfere with the crop. (Source: Tanny 2007, private collection)

using specific expressions for the different parameters, based on the greenhouse ventilation rate, specific stomatal resistance and leaf boundary layer resistance. Experiments conducted in a greenhouse with a tomato crop resulted with very good agreement between estimated and measured (by lysimeters) ETc.

The use of evaporative cooling devices like pad and fan or fogging (see Sect. 3.1) increase the greenhouse air water vapor concentration and hence should be taken into account when crop water requirement is considered. For example, Fuchs et al. (2006b) demonstrated in a rose crop that operating the wet pad cooling system reduced transpiration. Such result may have implications on irrigation needs of greenhouse crops. Although crop transpiration is reduced, the additional water is supplied through the wet pad, such that the total amount of water required is not changed much. The operation of the wet pad also cools down non-transpiring organs of the plants like flowers or fruits, which is an advantage.

In fan ventilated greenhouses, and provided there is no water condensation, the total amount of crop transpiration can be measured through a mass balance of the water vapor (Teitel et al. 2010), implemented between air inlet and outlet. In screenhouses this approach cannot be implemented. Therefore, Tanny et al. (2006, 2010) and Dicken et al. (2013) have examined using the Eddy Covariance technique to measure whole canopy ET in large screenhouses. In this technique, vertical air velocity and water vapor concentration are measured at a high sampling rate, usually 10 Hz; the covariance of these two variables is the net vertical turbulent flux of water vapor, i.e., ET.

Usually air temperature is also measured at high frequency such that sensible heat flux can be obtained as well. If CO_2 concentration is also measured at high frequency, its vertical flux can also be determined by this approach. This latter measurement also facilitates the calculation of the water use efficiency as the ratio between CO_2 and water vapor fluxes. Eddy covariance sensors are installed within the air boundary layer above the canopy, so this approach has the advantage that there is no interference with the crop or the soil (Fig. 10.14).

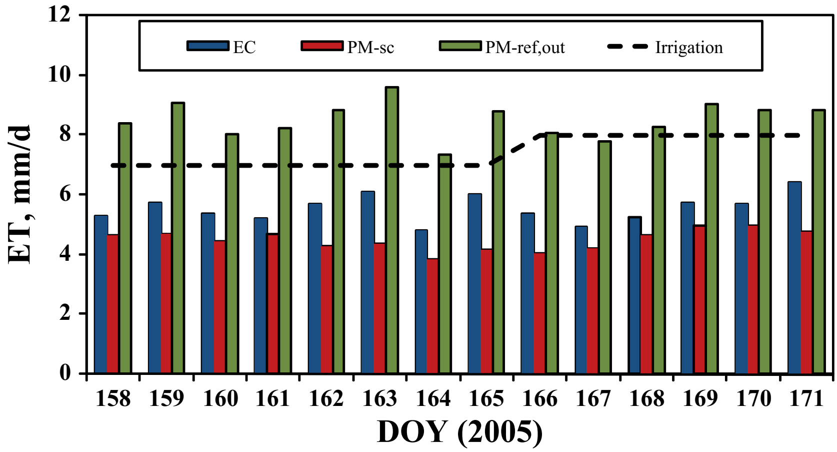

Fig. 10.15 Total daily evapotranspiration as measured by the Eddy Covariance technique (*black bars*) and estimated by two models. *PM-sc*: screenhouse evapotranspiration model (*gray bars*); *PM-ref, out*—reference evapotranspiration for external conditions (*empty bars*). The *dashed horizontal line* is the irrigation supplied by the grower. *JD*: Julian Day. (Source: Tanny et al. 2012)

To model ET accurately in screenhouses, Möller et al. (2004) suggested a modified Penman-Monteith model which includes an additional boundary layer resistance due to the boundary layer occupying the air gap between the canopy top and the screen. They measured transpiration of pepper plants in an insect-proof screenhouse, using sap flow and eddy covariance techniques; they found good agreement between the two measurement approaches and between the measurements and the newly derived model.

In a study conducted in a large banana screenhouse near the Sea of Galilee in northern Israel, ET was measured by an eddy covariance system (Tanny et al. 2006) and the measurements were compared with two types of models; the Penman-Monteith model of ET0 (Allen et al. 1998) under external meteorological conditions, and the modified ET model for internal screenhouse conditions. Figure 10.15 presents the results of measurements over a period of 14 days in June 2005. The results show that the screenhouse model is somewhat lower than the measurements. The model for ET0 is significantly higher however, illustrating the effect of the screenhouse in reducing ET. The results of Fig. 10.15 show that irrigation (dashed horizontal line) was consistently higher than the actual crop water use. Note that this irrigation level was already about 70 % of the irrigation supplied to open banana plantations in this region and that although irrigation was increased from JD (Julian day) 166, actual crop water consumption did not change suggesting the possibility of water savings.

Box 1 *Water use efficiency*

Water use efficiency (WUE) of agricultural and horticultural production can be generally defined as the ratio of the volume of water used productively (Stanhill 1986). It is also termed as water productivity and expressed in units of product weight per volume of water applied. From a physiological point of view, WUE can be defined as the ratio between CO_2 assimilation flux, and transpiration rate on the plant level. It can also be defined as the ratio between CO_2 flux and the rate of water applied.

As reviewed by Castilla (1999), protected cultivation can improve the water productivity due to the ET reduction, and using advanced technologies like drip irrigation, sophisticated climate control and soilless culture. Pardossi et al. (2004) summarized typical values of WUE for Mediterranean greenhouse crops. Mean values presented were 21.8, 14 and 30.3 kg m^{-3}, for tomato, cucumber and sweet pepper, respectively (Pardossi et al. 2004 and von Zabeltitz 2011). These values were lower by more than 50 % than corresponding values of 58.2, 28 and 77 kg m^{-3}, obtained for the same crops in sophisticated greenhouses in the Netherlands. Van Kooten et al. (2004) reported that for a kilogram of tomatoes produced in the field, on average used about 200 ± 100 L of water. Using drip irrigation, this amount is reduced to about 60 L per kg, (e.g. in Israel). In high-tech greenhouses in The Netherlands, the average use at that time was approximately 20 L per kg. However, applying new techniques and new irrigation methods as well as modifying the environmental management can significantly improve water use efficiency. The techniques include the use of light selective shading or movable screens as well as the use of the evaporative cooling system. According to van Kooten et al. (2004), it is possible to get WUE of 1.5 L water per kg tomato by closing the greenhouse and regaining the condensed evaporated water.

Water use efficiency of screenhouse crops was estimated as the ratio between yield and applied irrigation. In an irrigation trial conducted in a large banana screenhouse in the Jordan Valley, different levels of irrigation were applied (100, 85, 70 and 55 %) and yield measured for each treatment. The 100 % irrigation level was actually 70 % of the irrigation supplied to open banana plantations in this region. The results of Tanny et al. (unpublished data) showed that at 85 % irrigation the yield did not decrease as compared to the 100 % level. Irrigation at 70 % reduced the yield but this reduction was statistically insignificant. The lowest irrigation level of 55 % did cause a significant reduction in yield. Hence, the results showed that water use efficiency can be increased by about 20–30 % by growing the banana in screenhouses in this region of the country.

Dicken et al. (2013) defined WUE of a screenhouse banana plantation in two ways. One definition was the ratio between total daily values of net CO_2 uptake and ET as measured by the Eddy Covariance system (WUE_{ET}), and the second was the ratio between total daily net CO_2 uptake and applied daily irrigation (WUE_{irr}). Results showed that $WUE_{ET} > WUE_{irr}$ due to the fact that measured ET was less than the daily irrigation. Results also showed that the ratio between the two fluxes, namely, WUE_{ET}, was essentially unchanged with plant growth (with an average of 0.00894 for small plants and 0.00946 for large plants). On the other hand, WUE_{irr} (based on irrigation) increased with plant growth suggesting that the crop was over-irrigated during its initial growth stage. This finding may be important for improving irrigation management and increasing water savings. Dicken et al. (2013) also presented diurnal courses of the WUE_{ET} (daily values only, 10:00–17:00) for small and large banana plants in the screenhouse. Larger plants' WUE_{ET} was essentially unchanged during the day whereas for the smaller plants a small increase (not significant) of WUE was observed during the day. The results also showed that during the morning hours (10:00–12:00) WUE_{ET} for the larger plants was significantly higher than that for the smaller plants. This, together with the observation by Dicken et al. (2013) that photosynthesis per leaf area was about the same for both cases may indicate over-irrigation of the smaller plants in the early morning. Such observations could assist growers in increasing water use efficiency of screenhouse banana plantations by fine tuning irrigation during the morning hours.

Irrigation Management

Irrigation management includes all measures that guarantee sufficient water supply for plants. One could assume that for a specific plant species "only" the right water demand should be ensured and generally, the amount of evapotranspired water should be compensated. However, customizing irrigation is a multi-faceted activity and the amount of water used in protected crops is still higher than the theoretical calculated values. For instance, Fuchs et al. (2006a) reported that roses grown in greenhouses on artificial substrates transpire annually an estimated 1,500 mm of water in Israel. However, in order to prevent solute accumulation in the root medium, growers use nearly twice this amount for irrigation. The excess water leaches out, leading to a considerable waste of water and fertilizer (for water use efficiency (WUE), see box 1; and for fertilizer use efficiency (FUE), box 2).

Questions like "how long?" (= duration), "how often?" (= frequency), and "how much?" (= water amount), deserve answers to greenhouse management (climate conditions) for each plant's growth phases (young or ripening stage), particularly, to control the water status of a crop for a proposed level of plant performance. According to Saha et al. (2008) targeted performance levels and optimizing irrigation input can be used to either maximize yield or economic return, or increase the WUE.

Different irrigation controls range from hand irrigation through to simple timer-based to computer-based monitoring and control systems. In commercial

Fig. 10.16 Examples of drip irrigation systems in protected crops, (**a**) by ornamental plants, (**b**) strawberry, and (**c**) tomatoes. (Source: Gruda 2005, private collection)

Fig. 10.16 (continued)

greenhouses, irrigation is usually automated and water supply adapted for plant need. According to Savvas et al. (2013), the common approaches in irrigation control are the use of timer-based, sensor-based or model-based irrigation control methods. Whereas the timer-based method involves using a timer, sensor-based control depend on water status measurement, either in the soil/substrate or in the plant, model-based control methods depend on the estimation of plant water loss related to one or more environmental or crop variables.

Past research and practical experience has shown that irrigation management practices must be simplistic, useable, flexible within the existing system design and maintenance constraints, and understandable by growers, in order for them to be widely adopted and used. Therefore, it is not surprising that the predominant irrigation scheduling method is decision making by the growers, based on their own experience (Warren and Bilderback 2004).

Irrigation Systems

From a spatial point of view and according to Savvas et al. (2013), greenhouse irrigation systems can be categorized in: (i) overhead surface, (ii) surface and (iii) subsurface or sub-irrigation system.

Overhead surface irrigation is based on a top-down principle and involves overhead nozzles, where the water is sprayed onto the plants. The nozzles are installed either in static pipes or in rigs, so called automatic irrigation booms, which move through the greenhouse above the plants. Overhead irrigation is appropriate for watering plants with low stature and at a similar uniform growing stage. In addition, it is of benefit for plants that like regular cooling, such as different lettuces and salad greens, spinach or seedlings. These systems have relatively low installation costs. The irrigation uniformity and WUE are however low by these systems. In addition, the risk for residue on leaves and flowers as well as the risk for spreading diseases is high, because the water is applied to the aerial part of plants.

The most popular irrigation system in greenhouses is the surface system or drip irrigation (Fig. 10.16), mainly due to high efficiency and uniformity. In addition, drip irrigation is easy to install and design, as well as being precise with less run-off of water. One of the great advantages of drip irrigation is that it can be used to deliver nutrient solution as well as plant protecting agents. Drip irrigated water with or without fertilizer is delivered slowly where needed, through the soil or substrate surface to the plant roots. Apart from low-pressure irrigation, pressure compensating emitters are used, in order to deliver a constant water-amount per time unit. One of the disadvantages of drip irrigation is the clogging of emitters.

Subsurface or sub-irrigation systems provide plants with water through the base of pots and/or other containers used, and include capillary mats, troughs, ebb-flood benches as well as flooded floors. In this system water reaches the roots mainly by capillary forces. Ebb-flood benches are generally used for production of pot ornamentals and seedling plants, troughs are used for pot plants and vegetables grown in substrates, and flooded floors for seedling production and large ornamental plant production. One of the disadvantages of this system is the accumulation of salts in the upper layers of the soils or substrates. Sometimes pipes that are usually used in drip irrigation, e.g. porous pipes, are installed in the soil in form of a sub-irrigation system. By an appropriate use, the WUE could be improved.

Impact of Irrigation on Crop Yield and Quality

Producing high quality horticultural products requires a proper efficient irrigation management. Generally, supplying optimal water amounts improves growth and yield of protected crops. However, according to Gruda (2009), high yields do not automatically imply high quality; therefore, a compromise needs to be established. For instance, increasing water availability in tomato enhances fruit size and acidity. On the contrary, fruit quality of tomatoes can be significantly enhanced in terms of dry matter, TSS (total soluble solids), and sugar content in the fruit when plants are grown under moderate water stress conditions, with no significant yield loss (Pulupol et al. 1996; Wu et al. 2004). Moderate deficit irrigation is useful not only in reducing production costs, but also in preserving water consumption and minimizing leaching of nutrients and pesticides into the groundwater (Pulupol et al. 1996).

Furthermore, water shortage might increase the content of so called nutraceutical or health-promoting substances. Mattheis and Fellman (1999) and Kleinhenz et al. (2003) reported that water availability relative to crop development may also influence the flavor of vegetables. In a review article concerning the antioxidant content of tomatoes, Dumas et al. (2003) reported that, depending on cultivars, water shortage generally tends to increase the ascorbic acid content of the fruits. Moreover, a higher color intensity and lycopene content of tomato fruits were found under water shortage (Wu et al. 2004); Dorais et al. (2008), and Dumas et al. (2003) reported conflicting results concerning the lycopene levels depending on cultivar as well as other growth conditions.

Several aspects of plant development and physiology are controlled by root-sourced chemical signals in contact with drying soil. These signals, carried by the xylem, can act to modulate growth and gas exchange in the shoot (Davies et al. 2002; Campos et al. 2009). On this basis, an irrigation approach called "partial root zone drying" (PRD) has been developed, where half of the root system is kept near field capacity, and the other half is kept under water deficit. In an investigation with tomatoes, Campos et al. (2009) found that yield, number of fruits and total soluble fruit solids content were similar among the control and PRD-treatments with an increase of 25 % in the fruit titratable acidity reached in one PRD treatment. Fruit firmness, was increased up to 31 % in PRD treatments. In addition, PRD treatments allowed a water irrigation saving of up to 46 %.

According to Kader (2008), the key for growers to adopt appropriate cultural practices is encouraged by the willingness of consumers to pay a premium price for preferred products, essentially compensating the producer for the loss in yield. Reducing water availability as a method to achieve positive effects on yield and product quality of vegetables should not be applied however in all protected crops. For instance, Mediterranean greenhouse growers of watermelon and green bean crops tend to slightly reduce the soil water availability during the flowering phase to enhance fruit number and yield. González et al. (2009) investigated this deficit irrigation strategy and found that overall, mild water deficits, during the flowering of watermelon and green bean crops grown in Mediterranean greenhouses, did not improve the final fruit number or the yield of these crops, but reduced vegetative growth. Continuous water stress throughout the season can also diminish leaf area, fresh and dry weight, but did not hasten ripening, necessary for mechanical harvest, but rather delayed fruit maturation in relation to other treatments. Water deficit, either sustained or applied at the fruit ripening phase, was detrimental to commercial yields of pepper (González-Dugo 2007). Patanè et al. (2011) also reported that full irrigation is required to maximize marketable yield in processing tomatoes cultivated in semi-arid climate conditions. The authors stated however that an adoption of deficit irrigation strategies could be considered, especially in areas such as those of the Mediterranean basin, where water resources are increasingly scarce. Indeed, besides the conspicuous irrigation water savings (up to 48 %), full irrigation resulted in a yield reduction proportionally less than the water deficit (Patanè et al. 2011).

Oxygen in the Root Environment

Optimal root development requires a sufficient oxygen supply. In soilless cultures, oxygen deficiency in the root environment causes root dysfunction, with negative consequences for water and nutrient uptake (Morard and Silvestre 1996; Gislerød et al. 1997). According to Schapira et al. (1990), the oxygen dissolved in the nutrient solution of the cucumber crop was depleted within approximately 60 min (25 g fresh roots per liter nutrient solution at 20 °C). This process, which is driven by root respiration and microbial activity, is affected by factors such as the nutrient solution temperature, root biomass, light and CO_2 concentration (Schnitzler and Gruda 2002) as well as the stage of plant growth. Whereas, for instance, young tomato plants were able to adapt to hypoxia in the root environment and survive, mature plants wilted 2 days after aeration interruption in a hydroponic system and consequently died rapidly. Hypoxia in the root environment can result in decrease in leaf photosynthesis, changes in the transpiration rates and efficiency of the photosystem II and a slow change in leaf diffuse reflectance (Kläring and Zude 2009).

Morard and Silvestre (1996) reported that root asphyxiation is difficult to carry out in a substrate culture as plants exhibit considerable tolerance to temporary hypoxia and anoxia (several hours) and greenhouse growers have expressed concern that the oxygen content of nutrient solutions may be sub-optimal for plant growth (Ehret et al. 2010). Ehret et al. (2010) investigated the oxygen enrichment of the irrigation solution of cucumbers and pepper, grown in sawdust, and found that in only one instance out of three trials enrichment increased the yield of cucumbers and that there was no effect of enrichment on the pepper yield. Gruda et al. (2008) reported that individual factors such as organic substrate, irrigation, and aeration caused changes in CO_2 concentrations in the root zone of tomatoes and cucumbers.

Plant Nutrition, Nutrient Management and their Effect on Plant Growth and Development in Soilless Culture

General

Correct crop nutrition is essential for successful plant production (Bailey and Nelson 2012) and even more for protected crops. The nutrient uptake of the protected plants is generally higher compared with field cultivation, because of high production intensity and potentially higher yields. For instance, yields of more than 500 t ha^{-1} a^{-1} are not an exception for tomatoes and cucumbers produced in High-Tech greenhouses. Since harvest residues are totally removed from the greenhouse the nutrients used for biomass production of follow-up crops have to be fully compensated by the fertilizer and if high temperatures are encountered, the mineralization rate of organic matter in the greenhouses is higher than in the open field. Similarly, the movement of nutrients in soil is high particularly potassium and nitrogen levels, and leaching losses are often high, due to frequent watering and the attempt to keep up soil moisture. Special attention needs to be paid to the control of nutrient and salt contents in soil and soilless culture systems in protected cultivation. Appropriate fertilization (especially with nitrogen) requires more frequent analyses in shorter intervals, e.g. once in every 4 weeks. A combination of both *ferti*lization and irri*gation* is sometimes used. This combination process is known as "*fertigation*" and such systems are "*fertigation systems*". If fertigation systems are used, soil analysis has to be limited to the wetted root zone. Particularly important is the nutrient control in soilless culture, because their restrictive root volume and a very low buffer capacity. Here, at least daily analyses of EC- and pH-values of the nutrient solution are required. Since fertigation management in such systems is usually carried out by computer programs these two characteristics are however continuously controlled: some equipment allows separate management for each element. In all cases nutrient solution has to be tested periodically. Another way to control the nutrients is to analyze crop leaves where young leaves from the same age are used (Drews and Fischer 1992).

In soil culture, preplant and post-planting fertilization have to be differentiated (Bailey and Nelson 2012), however, in soilless culture only a post-planting fertilization or an accompanied fertigation with a nutrient solution is provided. Dolomitic limestone is often added to raise the pH of peat and other acid substrates (Jackson et al. 2009).

Soilless Culture

The term "soilless culture" is defined as the cultivation of plants in systems without soil "*in situ*" and this method is the most intensive and effective in today's horticultural industry. In recent years, a multitude of innovative cultivation procedures using bags, mats, and containers, in addition to nutrient solutions, have been developed. These growing methods include systems without a solid medium, as well as aggregate systems, in which inorganic or organic substrates are used (Gruda 2009). The distinction between soilless culture and other systems is sometimes blurred. For instance, the growth and maintenance of indoor ornamental pot plants or the outdoor production of hardy nursery plants in containers is considered soilless culture. On the other hand, the supply of nutrient solution to plant roots has become a custom cultural practice for soil-grown greenhouse crops as well, similar to using drip irrigation in outdoor horticulture.

Soilless cultural systems (SCS) offer significant advantages in comparison to direct cultivation in soil. These include cultivation of protected crops independent from soil characteristics. Therefore they exhibit a great degree of flexibility, even in areas with poor or adverse growing conditions, such as poor soil structure or high soil salinity. The main reason for using soilless culture however is the reduction of soil-borne pathogens and the control over water and nutrient supplies. The majority of nutrients used in such systems is soluble or in liquid form applied in a nutrient solution. In soilless culture either a liquid or aggregate medium is used. Such production systems and mainly the liquid method are called hydroponic systems as well, whereas periodically spraying plants with a nutrient solution is called aeroponic.

The main characteristic of SCS is the restricted volume of a rooting medium in comparison to soil-grown crops. The common issue in this system is the precise amount and ratio of the desiderated nutrients. In case of liquid systems and the use of inorganic substrates no interference of organic matter or cation exchange capacity (CEC) in the soil is observed. There has been an improved product quality however through more precise dosage of water and nutrients within closed systems (Gruda 2009). In Europe, Canada, and in the large horticultural industry complexes in the U.S., 95 % of greenhouse tomatoes are produced in SCSs (Peet and Welles 2005). Despite the considerable advantages of commercial soilless culture, there are still some disadvantages, such as higher costs that are normally required for their initial installation and increased technical skills that are needed to cope with its installation and management (Savvas et al. 2013).

Savvas et al. (2013) classified soilless culture and growing media systems into water/hydroponic culture and/or deep water culture, float hydroponics, nutrient film technique (NFT), deep flow technique, aeroponics, and substrate/aggregate culture. Gruda et al. (2013) differentiated between inorganic and organic growing media, where inorganic growing media included rockwool (the most used substrate in soilless culture), perlite, tuff, volcanic porous rock, expanded clay granules, vermiculite, zeolite as well as some other synthetic materials, sand and gravel. Organic growing media included peat, composts, bark, coir, and wood fibers as well as other wood residuals. In addition, several peat substitute/alternative growing media have been introduced worldwide, due to an increased environmental awareness of consumers, the constant dismantling of ecologically important peat bog areas and pervasive waste problems. Recently, biochar, a form of charcoal which is manufactured from organic matter by heating in an anoxic situation (pyrolysis), has been used in agriculture and introduced in horticulture as a growing medium as well (Gruda 2012; Gruda et al. 2013). Each substrate

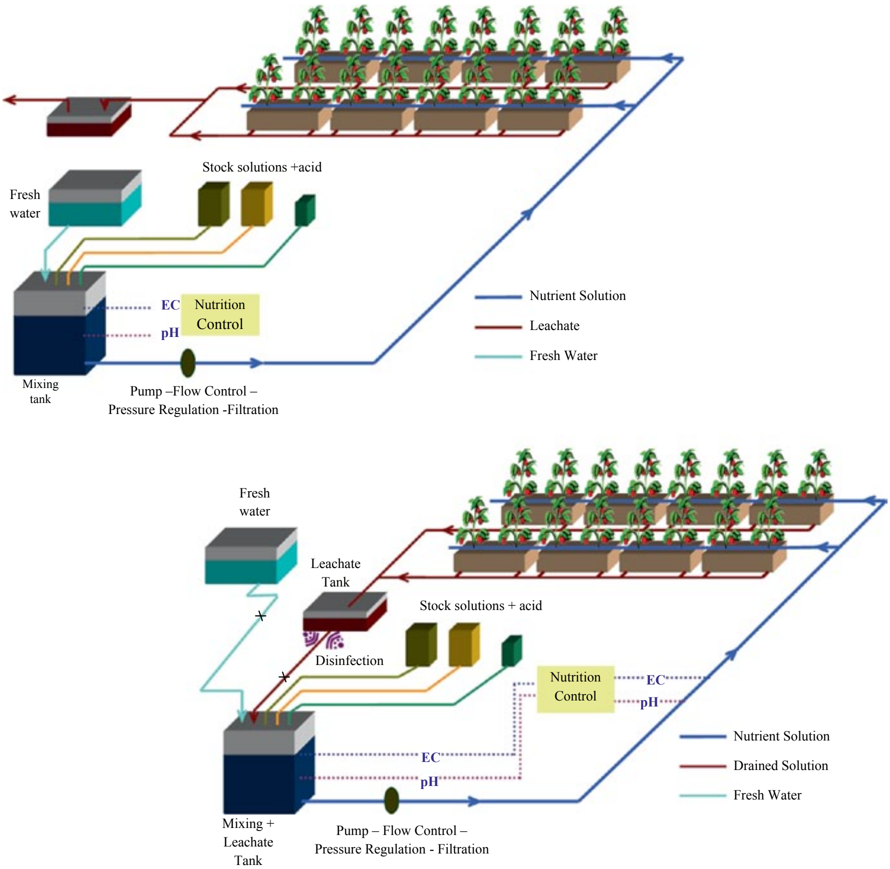

Fig. 10.17 Schematic diagram of a simple open- (*top*), and closed-loop (*bottom*) soilless culture system. (Source: ecoponics, In: Food and Agriculture Organization of the United Nations, Savvas et al. 2013. Reproduced with permission)

requires its own optimum growing technology and management approach with an adapted fertigation system (Gruda 2009).

Open and Closed-Loop Culture Systems

In soilless culture, methods of fertigation management and the recycling of nutrients in solution are categorized as either an open or a closed-loop system (Fig. 10.17). In an open system, any excess water and nutrients is drained to waste and not recycled. In a closed-loop system any drainage is captured, recovered and recycled. Closed systems also increase the risk of spreading root diseases through the system; hence treating the captured drainage water before recycling has to be considered (Wohanka 1992; van Os et al. 1999). Most pure hydroponic systems are inherently closed systems, but some aggregate systems were open until recently. When drip irrigation is used (which is most common) overwatering to the extent of 20–30 % is common, in order to prevent drying of the substrate and salt accumulation. In an open system this results in an expensive loss of water and fertilizer and a potential source of nutrient pollution of the environment (for WUE, see box 1; and for FUE, box 2). Many recent installations are closed systems and this will become mandatory in the future as nutrient management planning is implemented in many countries. A closed system requires higher water quality to prevent a build-up of unwanted ions. It also means that the composition of the nutrient top-up solution has to match nutrient ratios closely when taken up by the crop. In the past, nutrient top-up has been done on the basis of electrical conductivity measurement but in the future this may be replaced by the use of specific ion sensors (Inden et al. 1999; Gieling et al. 2001).

According to Papadopoulos et al. (1999) and Tüzel et al. (2001), there were no significant differences between open and closed-loop culture systems in tomato fruit quality due to applying adequate culture practices. Similarly Raviv et al. (1998) found no differences in rose production or quality when comparing open-loop systems with three different recirculation techniques.

In experiments with *Chrysanthemum indicum* hybrids, carnations (*Dianthus caryophyllus*), *Gladiolus* hybrids (Leinfelder and Röber 1987, 1989, 1991) and *Gerbera* spp. (Özçelik et al. 1999) no differences were found in terms of flower quality between diverse substrates in closed-loop culture systems. Rodriguez et al. (2006) investigated different combinations of media (coarse perlite, medium perlite, and pine bark) and containers (polyethylene bags and plastic pots) used in the production of 'Galia' muskmelons (*Cucumis melo*) and found that fruit yield and fruit quality were not affected by any combination of media and containers. Similarly, Serio et al. (2004) investigated the use of washed disposal of the posidonia (*Posidonia oceanica*)—a marine species belonging to the *Potamogetonaceae* family and found no differences in total yield of cherry tomatoes grown in this substrate or rockwool.

Plant in Soilless vs. Soil Cultures

Gruda (2009) points out that the only reliable way to compare soil with soilless systems is to place both systems under the most optimal growing conditions for the same crop. In soilless culture, higher yields and earliness of cropping can be achieved when compared to soil cultivation. For example Selma et al. (2012) showed that a growth period of 102 d was needed for fresh-cut lettuces (*Lactuca sativa*) to reach the same maturity stage in soil compared to 63 d in soilless culture. According to Gruda (2009) using SCSs does not automatically guarantees high-quality vegetables. Numerous studies confirm that SCS enables growers to produce vegetables without quality loss compared to soil cultivation. An adaptation of the cultural management to a specific cultural system, as well as the crop requirements, can further result in improving the quality of the horticultural product.

Effect of Nutrition on Plant Growth and Development

Either a deficiency or an excess of any nutrient will deteriorate plant growth. For instance, among the many plant mineral nutrients, potassium is one of those cations that has a strong influence on quality attributes that determine fruit marketability, consumer preference, and the concentration of critically important human-health associated phytonutrients (Lester et al. 2010). Growers and researchers should consult general plant nutrition literature for any given species (e.g. for tomato plants, Passam et al. 2007). Schnitzler and Gruda (2002) provide a detailed review of different nutrient elements and their effects on the product quality of ornamentals and vegetables.

Commercial greenhouse growers use nutrient concentrations based on the plant species needs in order to maximize crop yield. Strategies need to change however where high irrigation frequencies and high levels of nutrients are sometimes delivered to the plant roots, to avoid salt accumulation in soil, and where we have limited growing media volumes and restricted root mass. Recent investigations have shown that these strategies do not present an economically optimized production and excessive nutrients do not necessarily translate into higher yields (Rouphael et al. 2008). For instance, Siddiqi et al. (1998) have shown that reductions of macronutrient concentrations from 50 to 25 % of the control level can be applied without any adverse effect on growth, fruit yield and the quality of tomatoes. Similarly, Zheng et al. (2004) and Rouphael et al. (2008) demonstrated that current nutrient application rates can be reduced by at least 50 % without any detrimental effect on growth and quality of potted gerbera and geranium, respectively. On the other hand, high concentrations of different elements can be detrimental to plant growth and development as well.

Salinity

The accumulation of salts on the soil can be an important issue during hot and dry conditions most notably in arid or semi-arid regions, where there is a high crop evaporative rate. Due to water movement and capillarity action the upper soil layer can be over-salted. The use of poor irrigation water with high salt content and an inadequate irrigation system may aggravate this problem. Under such conditions plants suffer from a high osmotic potential, due to impaired water absorption. Moreover, certain ions, such as chloride, borate, and sodium ions can provide specific phytotoxic effects. The accumulation of sodium in the soil, and the availability of the exchange complex with sodium, can reduce flocculation and impair soil structure.

As noted earlier, water quality is very important in greenhouse management. Poor quality water, both chemically and biologically, has an adverse effect on production and product quality. According to Lycoskoufis et al. (2005) the growth of pepper at high salinity levels (60 mM NaCl, 8 dS m^{-1}) was affected through stomatal closure, presumably due to high salt concentrations in the leaf apoplast, inhibition of photosynthesis at chloroplast level, which is partly associated with reduced chlorophyll concentration, and alterations in carbon allocation and utilization aimed at the adaptation of plants to a saline environment. Grieve (2010) reported that some plants can adjust osmotically within hours, where cell volumes and turgor are restored, but irreversible damage has already been done. Cell elongation and cell division are reduced, and, as a result, shoot growth decreases. Roots are also reduced in length and mass. Moderate salinity levels, which are crop depended, usually restrict growth without any overt injury symptoms and the plants appear normal, but stunted.

Even in SCSs, high salinity levels can be detrimental to plant growth. Rouphael et al. (2008) investigated the growth and quality of zonal geranium (*Pelargonium* × *hortorum* 'Real Mintaka') in closed soilless systems, in order to evaluate the effects of the irrigation system (drip and sub-irrigation) and nutrient solution concentration under various conditions of radiation and temperature. The authors found that the ECs during the spring season at the end of the growing cycle was two-fold higher than that observed in the winter season, due to higher solar radiation and higher air temperature, and was almost double in a full than in a half strength nutrient solution. Consequently, plant growth with sub-irrigation using a full strength nutrient solution during spring season resulted in lower shoot biomass, growth and quality index than those grown using drip-irrigation. Similar results were obtained by Santamaria et al. (2003) with cherry tomatoes and Rouphael and Colla (2005) with zucchini squash. The increase of EC in the upper layer of the substrate reduced the fruit yield of both crops cultivated in sub-irrigated systems. In other trials, however closed-cycle sub-irrigation systems were successful for tomato production using saline water (Incrocci et al. 2006; Montesano et al. 2010). According to Incrocci et al. (2006), the process of fast water salinization made it necessary to flush out the nutrient solution in six different occasions in a closed-loop aggregate culture using the drip irrigation system, with a subsequent loss of water and fertilizers. On the contrary, in sub-irrigation culture, the upward water movement in the substrate, coupled with selective mineral uptake by the roots, caused salinity build-up and sodium accumulation in the upper region of the substrate. Here the authors conclude that sub-irrigation conducted with saline water can be a tool to reduce water consumption and nutrient runoff in closed-loop substrate culture of tomatoes and retain fruit yield and quality of tomatoes.

Improvement on Product Quality Due to a Moderate Salinity Stress

According to Grieve (2010), moderate salinity can improve the quality of vegetables, due to changes in two classes of phytochemicals: compatible osmolytes and antioxidants. Many investigations have shown that using solutions with moderate electrical conductivity, achieved by adding sodium chloride or nutrients, the first one being more common due to economic concerns, can improve the tomato fruit quality, in terms of organic acidity and total soluble solids (Mizrahi and Pasternak 1985; Sonneveld and Welles 1988; Adams and Ho 1989). These results are in agreement with Serio et al. (2004), who found an improvement of organoleptic quality and nutraceutic properties of cherry tomatoes and also intrinsic the quality parameters of dry matter, total soluble solids, vitamin C and α-tocopherol, and antioxidative potential. According to Hasegawa et al. (2000) and Plaut et al. (2004), an increase in the dry matter of tomato fruits occurred under high saline conditions due to an active osmotic adjustment of plants to guarantee further water uptake. Furthermore, the correlation network analysis showed that compared to other traits, sugar is one of the key traits for an improvement of tomato fruit quality (Zushi and Matsuzoe 2011). Sato et al. (2006) however found an increase not only in sugar content, but also in organic and some amino acids. The authors reported that taste panels indicated that NaCl treatment increased sweetness, acidity, umami (i.e. the taste of deliciousness), and overall preference. Hexose concentration of the fruit grown on NaCl treated plants significantly increased. At the same time, chloride ions, organic and amino acids had higher concentrations in sodium chloride treated plants than in the control group. A review of these effects is presented in Dorais et al. (2001), Gruda (2009) and Schnitzler and Gruda (2002).

Recently, consumer awareness increased concerning health promoting compounds and properties that can act in an antioxidant capacity and improve nutritional value in vegetables (D'Amico et al. 2003; Dumas et al. 2003, Gruda 2009). Krauss et al. (2006) investigated the influence of three different salt levels (EC = 3, 6.5, and 10 dS m^{-1}) on tomato growth and yield. Rising EC-values of the nutrient solution increased vitamin C, lycopene and ß-carotene (the precursor to vitamin A) in fresh fruits by up to 35 %. Phenol concentration was tendentiously enhanced, and the phenols' antioxidative capacity and carotenoids increased on a fresh weight basis. Since the authors did not record any change in dry weight basis, they suggested that the observed increase of lycopene was due to the concentration—caused by reduced water flux to the fruit. However, Wu et al. (2004) reported an increase of lycopene (34–85 %) for five cultivars tested under high EC compared to low EC, while the increase of total soluble solids was only 12–22 %, suggesting that the lycopene increase might be due to a plant stress response to osmotic and/or salt stress rather than the result of high concentration caused by reduced water content of the fruit. These results are in concordance with the results of Fanasca et al. (2006) where these authors observed an increase in lycopene concentration on both a fresh weight and dry weight basis in tomato by raising the EC from 2.5 to 8 dS m^{-1}. However other authors (Krumbein et al. 2006; Fernández-García et al. 2004) did not find differences in lycopene content, when plants were grown under high EC-values. According to Wu and Kubota (2008a) the reason is the time of analysis because the physiological status is very important, in respect to parameters of product quality (Schnitzler and Gruda 2002). According to Wu and Kubota (2008a), lycopene analysis should be done throughout the fruit ripening process (from late green to the fully ripened stage) rather than at the last stage of ripeness to better understand lycopene synthesis since lycopene concentration in the tomato fruit increases rapidly during the process. Therefore, Wu and Kubota (2008a) carried out a study where lycopene content was analyzed at six tomato ripeness stages and found that the

Table 10.2 Effects of EC and application timing of EC on lycopene content of tomato fruits at different ripeness stages. (According to Wu and Kubota 2008a)

Treatment	Lycopene concentration (mg g^{-1} DW)			
	G	B and T	P and LR	R
High EC	ND	0.07	0.39 a	1.39 a
Delayed high EC	ND	0.10	0.32 b	1.29 a
Low EC	ND	0.08	0.25 c	0.99 b
ANOVA ($P=0.05$)	–	NS	*	*

The six fruit ripeness stages characterized by color development, which include green (G), breaker (B), turning (T), pink (P), light red (LR) and red (R) (USDA 1976). Low and high EC were 2.3 and 4.5 dS m^{-1}, respectively. The high EC and the delayed high EC treatments were applied immediately after anthesis and 4 weeks after anthesis, respectively. ANOVA, Analysis of Variance for treatment significance: * or NS at $P=0.05$. Means with the same letters are not significantly different according to a Tukey HSD test at $P=0.05$. NS = no significance. ND = not detected. DW = dry weight (Source: Wu and Kubota 2008a)

lycopene content of tomato, *cv*. 'Durinta', increased 12–20-fold as fruits developed from the breaker/turning stages to the red stage (Table 10.2).

Wu and Kubota (2008a) suggested that ethylene synthesis triggered by osmotic and/or salt stress is central to the increase in lycopene concentration within the tomato fruit. The reduced water flux is linked to an increase in TSS and under these environmental conditions tomatoes mature earlier and accumulate more lycopene during the pre-harvest time.

Similar results, where an increased EC-value enhanced health-promoting substances, were also obtained for sweet pepper, cucumber (Sonneveld and van der Burg 1991; Trajkova et al. 2006), eggplant (Savvas and Lenz 1994), celery (Pardossi et al. 1999), watermelon (Colla et al. 2006), as well as zucchini squash (Rouphael et al. 2006). Seo et al. (2009) reported that the EC-value of the nutrient solution as well as the concentration of S and P can strongly influence the concentration of sesquiterpene lactones; and therefore have an effect on bitterness and acceptability of lettuce.

Adjusting the salinity of the nutrient solution allows growers to modify water availability to the crop and hence improve the quality of tomato fruits. However, increasing the salinity, limits marketable yield, increases the incidence of BER, and reduces fruit size (Dorais et al. 2001; Gruda 2009). For instance, although cherry tomatoes are considered to be more tolerant in respect to adverse effects of EC-values, the total yield of cherry tomatoes was reduced at a higher salinity (6 dS m^{-1}) in comparison to 3 dS m^{-1} (Serio et al. 2004). One of the disadvantages of increasing TSS by a high EC treatment is the reduction in fruit size due to a reduction of water content in the fresh fruit (Adams and Ho 1989) where fruits were smaller, mainly due to a reduction in fresh weight (Ehret and Ho 1986). This resulted in total yield reductions and an increased occurrence of the physiological disorder blossom-end rot (BER) (Petersen and Willumsen 1991), caused by a reduction of calcium absorption by the roots and increased resistance to xylem transport inside the fruit (Ho and Adams 1989). According to Ho et al. (1999), accelerated fruit enlargement may be the principal cause of BER in tomatoes, even when the uptake of calcium by the plants seemed to be adequate.

Dorais et al. (2001) and Wu and Kubota (2008b) examined the effects of electrical conductivity (EC) on tomato fruit yield and found that it is not reduced when EC was increased moderately to approximately 5 dS m^{-1}. Wu and Kubota (2008b) reported that for all cultivars tested the plant physiological response under elevated EC was cultivar and growth-stage specific, and increasing the inflow EC to moderate levels during the reproductive growth stage did not adversely impact photosynthesis, transpiration, and leaf conductance of tomato plants. According to Zushi et al. (2009), salt stressed fruit developed protection mechanisms against salt-induced oxidative stress during the ripening in both the pericarp and pulp. In addition, the growers and investigators have developed some growing strategies to overcome or mitigate the detrimental effects of salinity.

Strategies to Overcome or Mitigate Salinity Stress

Numerous strategies have been tested for minimizing crop yield loss due to salinity, and at the same time maximizing inner (nutrient value, taste, texture) and outer (appearance, color, firmness, shelf life, aroma) quality characteristics of the marketable product. Those management practices include nutrient management of salt-stressed crops, timing of salinity application or withdrawal, method and scheduling of irrigation, and the choice of rootstock (Grieve 2010). Generally, it could be said that high water supply has a mitigation effect on salinity, and vice versa: drought situations increase these effects. The important fact is however the choice of the right cultivar. Salt tolerant cultivars are the best tool to avoid or mitigate this kind of stress, e.g. in semiarid greenhouse conditions and with limited environmental control capacity.

There are other irrigation and agronomic strategies that can also minimize salinity damage. One of these strategies involves crop spraying or the application of supplemental nutrients, fluctuating EC-values and the use of a split root system with unequal ECs. For instance, Tuna et al. (2007) reported that salt stress significantly decreased plant growth and fruit yield. Supplementary calcium sulphate was added however to the nutrient solution and it significantly improved plant growth and fruit yield and improved membrane permeability.

Buck et al. (2008) lowered the EC-values during the midday, in order to mitigate high water stress on the tomato plant, and achieved a premium-grade tomato yield comparable to the high EC-treatment. These results are in agreement with those of Santamaria et al. (2004) where the authors found that a 2 dS m^{-1} daytime EC combined with 6 dS m^{-1} nighttime EC level did not affect total yield, fruit number, fruit weight, or plant water consumption in the cherry tomato. This strategy makes sense for use in semiarid greenhouse conditions with limited controlled-environment technology. Sonneveld (2000), Mulholland et al. (2002), Tabatabaie et al. (2004), and Lycoskoufis et al. (2005) suggested for crop growing in soilless culture an unequal EC, achieved with a “split-root” system, in order to avoid or mitigate high salinity issues, and as a consequence, to improve both

Table 10.3 Yield and fruit weight of tomato, cv. 'Counter', on a split-root system whereby the two halves were supplied with nutrient solutions of the concentrations indicated. (According to Sonneveld 2000)

EC value	Yield (kg m^{-2})	%	Fruit weight (g)	%
2.5/2.5	24.0	100	77	100
5.0/5.0	21.1	88	71	92
2.5/5.0	23.7	99	80	104

Box 2 *Fertilizer use efficiency (FUE)*

Efficient use of fertilizers has become of economic and environmental importance in greenhouse production. One can calculate fertilizer use efficiency as the ratio of marketable yield to total fertilizers used. Greenhouse production can be very intensive and there are great differences between the fertilizer usage in an open field and the greenhouse. Similarly, the loss of fertilizer could be drastically reduced, using closed production systems. Marcelis et al. (2000) estimated the data for both, an open and a closed production system. They noted that whereas in standard greenhouses in many Mediterranean countries the yearly losses were approximately 300–350 kg N and 125–300 kg P, in a "closed loop" greenhouse production system, in north Europe approximately 120 kg N and 20 kg P per ha and year can be lost. It is now clear that fertilizer losses can be reduced even further.

yield and product quality. This system is similar to a 'partial root-zone drying' irrigation system (with the difference that instead of different soil moisture, different osmotic potentials are realized). In this case, the most favorable part of the root system experienced the largest water absorption, the plant as a whole does not show any restriction and the yield and fruit weight was nearly the same as in normal EC-value (Table 10.3).

Jokinen et al. (2011) also reported that the split root fertigation approach provided complementary benefits over traditional fertigation, in terms of water and nutrient uptake and ultimately yield improvement. The peat-based split root fertigation (SRF) method improved cucumber yield in both open (21 %) and semi-closed (17 %) greenhouse conditions over the traditional fertigation method. This indicates that the response is governed by root exposure to high sodium chloride concentrations and not by water absorption inefficiency of the roots (Lycoskoufis et al. 2005).

Moreover, better root aeration (enhancing oxygen supply to root cells) may considerably enhance salinity tolerance of tomatoes in heavy clay and saline soils (Bhattarai et al. 2006).

More detailed information concerning soilless culture apart from Savvas et al. (2013) and Gruda et al. (2013), can be found in Resh (2012), Savvas and Passam (2002) and Raviv and Lieth (2008) and for information concerning plant nutrition of greenhouse crops, the book by Sonneveld and Voogt (2009) is recommended.

Some Agronomical Aspects and Cultural Practices

Genotypes and Cultivar Choice

Sources of genetic material have a great influence on yield and product quality of protected crops. Different tolerances between hybrids and genotypes have been documented for temperature (Ventura and Mendlinger 1999; Abdelmageed and Gruda 2009), drought stress conditions, water shortage (Dumas et al. 2003; Niu 2008) and salt stress and fertilizer level (Wu et al. 2004; Wu and Kubota 2008b; Zushi and Matsuzoe 2011). In the future, plant breeding will form a strategy on its own, adding to growth conditions improvement. Breeders can address improvements of tolerance to diverse stress situations, as well as improvements in respect to yield, earliness, and product quality. For example, Higashide and Heuvelink (2009) investigated yield improvement of tomatoes and found that an increase in yield over the past 50 years in Dutch tomato production was caused by an increase in light use efficiency of tested genotypes, resulting from a decrease in the light extinction coefficient (a morphological change) and an increase in the leaf photosynthetic rate (a physiological change).

Grafting

Although less frequent than the well-known fruit tree grafting, vegetable grafting is getting more and more important. Interestingly, the early use of grafted vegetables was associated with protected cultivation which involves successive cropping, and is currently being globally practiced (Lee et al. 2010). The majority of grafted plants belong to the *Solanaceae* and *Cucurbitaceae* families where the rootstocks of plant genotypes have shown resistance to different soil-borne diseases. Since wild species possess these properties, they are used as rootstock as well. By contrast, the scions are usually used good productive and high qualitative genotypes. Although first used to avoid serious problems caused by soil-borne diseases (Bletsos 2006; Lee et al. 2010; Louws et al. 2010) this practice has been used to increase plant vigor and yield (Lee et al. 2010; Gisbert et al. 2011), reduce stress situations caused by adverse environmental conditions such as low soil temperature (Lee et al. 2010), high salinity (Colla et al. 2010), high temperatures (Abdelmageed and Gruda 2009; López-Marín et al. 2012), inadequate fertilization (Savvas et al. 2010) and water stress and organic pollutant challenges (Schwarz et al. 2010). Recently, Flores et al. (2010) and Rouphael et al. (2010) also reported an influence of grafting on vegetables product quality. Despite these advantages, some disadvantages are noted such as high costs of grafting seedling and sometimes low earlier yield. In order to cut high costs, vigorous rootstocks are so far used in two and sometimes three-or-four-stem-pruned-systems in tomato greenhouses. According to Lee et al. (2010), research has been focused on developing efficient rootstocks and handy grafting tools as well as grafting machines or robots to reduce the higher price of grafted seedlings.

Fig. 10.18 Single stem tomatoes in (**a**) non-lowering system and (**b**) lowering system. (Source: Gruda 2010, 2011, private collection)

Plant Density

Plant density depends on plant species, the cultivar or the genotype used, and the associated environmental and agronomic conditions. An increase in plant density is to some extent positively correlated with yield, however negatively correlated with the size of the marketable plant part. The reason for that is thought to be the insufficient supply of photo-assimilates caused mainly due to a competition for light interception, influencing the photosynthetic rate and carbohydrate distribution.

Plant Training

Training is applied to indeterminate vegetable crops such as the tomato, pepper, and cucumber where the main objective (through a combination of plant density and pruning) is to improve light interception of leaves. In addition, the positive effects on air movement can also influence disease spread and control. For instance, tomato plants are supported by plastic twines and are hitched around a wire (Papadopoulos 1991; Schwarz 1995) (Fig. 10.18a). However, in modern soilless greenhouses with supporting wires of 2 m or higher, as tomato plants reach the wire, they are untied which allows the plants to be lowered and grown horizontally to the slabs or system ground. The green slip is hanging vertically from the wire and has very good assimilation conditions (Fig. 10.18b). With this training system the plant length of tomatoes can reach more than 12 m and if environmental conditions are adequate to plant growth, spring cropping can be extended to a single full cultivation period (or in a so called one-crop-per-year). However, in areas with hot summers, usually a two-crops-per-year production strategy is applied. In some regions, a single-cluster strategy or five-crops-per-year is used as well (Logendra et al. 2001).

The prevalent system practiced on greenhouse cucumbers is V-training or the umbrella system which involves removal of all emerging flowers and laterals up to the 8–9th node (approx. lowest 60 cm of the main stem). Thereafter, just one fruit per lateral is allowed for the next 60 cm of the main stem. One fruit and one lateral are allowed to grow from each leaf axis on the rest of the main stem. After the main stem reaches the wire, the growing point is pinched out allowing an extra 2 or 3 leaves above the wire. Afterwards, the two strongest laterals from the top of the plant are allowed to grow over the wire and then to hang down. The next steps differ depending on plant variations described by Papadopoulos (1994). In addition, the author recommends the control of fruit numbers due to selective fruit thinning, in order to avoid plant exhaustion and to improve fruit quality.

Similarly, pepper plants can be trellised to the Dutch "V" (a two-stem pruned) system or to the "Spanish" (non-pruned plants) system. Jovicich et al. (2004) compared the "V" with the "Spanish" trellis system and found no differences in total marketable fruit yield. Labor requirements for the Spanish system were reduced however by at least 75 % compared with the "V" trellis system.

Pruning

Pruning is a (manual) operation used to support training, with the aim of improving light relationships, equilibrating plant growth and development, providing for a better control of diseases with consequences in minimizing yield losses, and improving product quality. Pruning helps to facilitate cultural operations in the greenhouse. Both vegetative (e.g. 'leaves' by tomato and cucumber, 'new side shoots' by tomato and pepper, 'shoot apices' by tomato and cucumber) and generative organs (e.g. 'flower removal' by roses, and 'fruit thinning' by tomatoes) are pruned.

Navarrete and Jeannequin (2000) investigated the frequency of lateral shoot pruning in greenhouse tomato crops, and found that the de-shooting frequency affected both vegetative growth and yield and pruning time. When de-shooting was performed every 21 days, the stem diameter and the number of fruits per m^2 was also reduced, leading to a significantly lower yield in comparison with a 7 day deshooting cycle. Moreover, the tomato harvest was delayed, presumably due to dry matter partitioning and better light interception due to the pruning process.

Plants, such as roses, possess high plasticity, rapid and dynamical acclimation in response to changes in incident sunlight established by pruning (Calatayud et al. 2007). Similarly, roses showed a higher maximum efficiency of photosystem II (PSII) in dark-adapted leaves, a higher actual quantum yield and a higher proportion of open PSII reaction centers when pruned. They also showed lower non-pho-

Fig. 10.19 Bumble bees, ready for pollination application in a greenhouse. (Source: Gruda 2013, personal archive)

tochemical quenching, indicating a lower energy dissipation in heat, compared to non-pruned plants. The results related to chlorophyl-a fluorescence, indicate that pruned plants have a higher capacity for better promoting a photosynthetic light reaction than non-pruned plants (Calatayud et al. 2008b).

In addition Cockshull and Ho (1995), found that tomato fruit production and fruit size can be adjusted to the level of available photo-assimilates if cluster pruning is coordinated with the growing period. The number of fruits (fruit load) as well as the fruit to leaf ratio are important in fruit vegetables. Logendra et al (2001) reported 25 % higher tomato yields at single-cluster plants pruned to allow two leaves above the cluster than plants pruned directly above the cluster. Furthermore, both fruit yield and harvest index were greater for all single-cluster plants at a higher light level. According to Ho (1992) however since fruit constitute a major portion of photo-assimiliates, the variation in number will influence their size rather than the fruit to leaf ratio. On the other hand, according to Dorais et al. (2001) severe deleafing of plants reduces photosynthetic capacity of the canopy and the remobilization of mobile elements. Therefore, Slack (1986b) recommended that deleafing in commercial tomato crops should not exceed the level of ripening fruits.

Pollination

For a range of greenhouse vegetables such as melons, pepper, tomato, eggplant, zucchini, and strawberry, extra pollination is needed to assure good fruit setting and productivity. Pollen quality can be adversely affected by high temperatures, limited air movement and high humidity in greenhouses. Since most cucumber cultivars are parthenocarpic they do not need extra pollination. Plant pollination can be enhanced by using a mechanical (vibration) or biological method (e.g. bumble bees, Fig. 10.19). The latter used more frequently in greenhouses because they are natural agents of pollination and growers benefit because of lower production costs, increased yields, and improved fruit quality (Velthuis and van Doorn 2006).

Integrated Plant Management and Plant Hygiene

Optimal climatic conditions under protected cultivation are not only favorable for growing crops, but also for the development of pests and diseases. Therefore, integrated plant management and plant hygiene in greenhouses are of utmost importance. Generally, plant protection in greenhouses is applied according to the principles of the integrated pest management or organic production principles. Both these methods aim to reduce pest and disease incidences in greenhouses crops due to a minimal use of pesticides or application of alternative methods to control pest and diseases, respectively. Moreover, both these methods are oriented towards an adaption of sustainable greenhouse production.

The Interaction of Factors, their Multiplicity and Effects on Plant Growth and Development

Many specific environmental and agronomic factors influence plant growth, yield and product quality of protected crops. Only when all these factors are in optimal level, in balance, and well managed and sustainable can it be expected that plant growth and development will be at its best. Liebig's Law of the Minimum, states that growth is controlled not by the total amount of resources available, but by the scarcest resource available (limiting factor). Optimum growth and performance will be a function of the genotype used, with the developmental and maturity stages, and a function of interaction between all environmental conditions and agronomical measures. Furthermore, according to Raviv et al. (2008), when multiple factors are limiting, the interacting effects are more complex than simply suggesting causality of suboptimal production to the most-limiting factor. This is particularly important in practice because it is extremely rare that all production factors can be simultaneously optimized in a living system.

Increased light intensity leads to an increase of the photosynthesis rate until light saturation level. However, under high CO_2 concentrations, light saturation may shift to higher light levels. Similarly, optimum temperature of the net photosynthesis rate can increase by increasing light intensity. Optimum temperature of net photosynthetic rate is also affected by CO_2-concentration. Similarly knowledge of greenhouse design and the technology are associated with effective crop management. Singular actions such as these are extended into complex questions of entire measures, in order to improve the sustainability of such systems. Based on advanced sensors and robotics, it is possible to involve all environmental factors in greenhouse climate control. Sustained efforts to balance the greenhouse climate conditions with other factors such as outside conditions, weather forecasts, light and energy efficiency, water and fertilizer use efficiency must be undertaken. In turn, these factors could be integrated together with crop management and plant growth rate to optimize the greenhouse utilization.

Many possibilities exist to increase yield, reduce production costs per unit area or plant, retain the longer cultivation period long, and improve the product quality of greenhouse crops. This is due to an introduction of innovative approaches (originated in horticulture and other activity fields), and the use of a combination of optimum performance measures associated with protected cultivation.

Conclusions

There is a wide spectrum of approaches in protected cultivation that enable growers in different climatic regions to adopt and adjust the preferred technology for each specific crop. High-tech greenhouses produce high yields but also require high initial cost whereas the naturally ventilated plastic tunnels and greenhouses, as well as screenhouses, are a low-cost alternative suitable for growers with limited capital or in regions with a fluctuating demand.

Significant progress has been achieved in both practical application and basic understanding of protected cultivation principles and practices. Due to the energy crisis and the increasing price of fuel, growers now need to adopt climate control approaches that reduce conventional energy consumption, and increase the use of renewable energy sources like solar, or geothermal. Researchers and growers need to fine tune the irrigation needs to meet the exact needs of horticultural crops in close consideration with a climate control strategy.

The use of sophisticated materials and additives in order to fine tune the radiation intensity and spectrum are becoming important in efficiently utilizing the heat associated with solar radiation and reducing the cooling requirements in mild climates to increase the energy savings. Advances in genetics and molecular biology are leading to the development of crops that are much less prone to stresses and hence can be grown in many different regions in terms of climates and soils.

Future research will focus on more durable and efficient structures, sustainable covering and substrate materials, more efficient climate control systems that increase energy savings, the breeding of varieties that are more resistance to biotic and abiotic stresses, and improving the development of production management strategies. These studies are needed in order for the horticultural industry to meet the growing food demand under future uncertainties such as climate change and changing global economies and markets.

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