New Developments in Greenhouse Technology can Mitigate the Water Shortage Problem of the 21st Century

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Abstract

The world's fresh accessible water situation is deteriorating at a dismal pace. Though the situation is already quite dramatic in Africa, the near future will bring us great problems in Asia as well, considering the pace at which the population is growing and the rise in water use per capita as the economy induces a raised demand. Agricultural consumption of fresh water is one of the main water uses world wide; however, it appears that protected cultivation of horticultural crops can alleviate the problem. Drip irrigation already reduces water use dramatically. However, novel high technological solutions in greenhouse production can lead the way to highly efficient water use production techniques. Adoption of more efficient water use techniques will contribute to sustainability, especially in highly populated urban areas. The novel Dutch technology of closed greenhouses could help develop water efficient production systems.

INTRODUCTION

The world's fresh water supply is diminishing at a dismal speed (UNESCO, 2006). As of ten years ago, 1.1 billion people already had no access to safe drinking water, and 2.6 billion people lacked access to basic sanitation (Gleick, 1998). Water needed for basic food production, in particular, is becoming scarce in many regions of our world (OECD, 1998), leading to future scenarios of regions or countries competing with each other for their basic water supply (Fig. 1). Although Africa is a continent notorious for its water problems, Table 1 shows that the main problems in the near future are to be expected in Asia, as the wealth of the population rises and water use grows exponentially. When people start to eat more meat, the water use will rise tremendously (Table 2). When we define Product Water Use (PWU) as the volume of water necessary during the entire production period to produce one kg of fresh product, we can study the influence of growth techniques on this efficiency (Hoekstra and Hung, 2005). It is clear that plants use much less water than animals (Table 2), when the plants consumed by animals are taken into account. However, arable crops still use massive amounts of water. Although horticultural crops tend to be rather efficient regarding PWU, the amounts of water needed for production can still be prohibitive in many areas in the world.

Managing the water and nutrient supply to greenhouse crops under adverse conditions, such as high electrical conductivity (EC) of water supply, requires new techniques in order to maintain high production levels and the desired produce quality. Under conditions of resource constraints, water loss should be minimized and nutrient emission to the surrounding environment should be abolished. In closed greenhouse systems, many processes are occurring and interacting in complex ways. Many of these processes can be described by mathematical models. Processes like crop growth and metabolite allocation with relation to climatic conditions (Heuvelink, 1996; Carvalho et al., 2002) and transpiration with relation to water and nutrient uptake (De Willigen et al., 2002) can be calculated in detail, based on measurements of several greenhouse parameters in combination with dynamic models. This leads to the possibility of

controlling growth and development of the crop through adaptive climate control and ion specific nutrient supply (Marcelis et al., 2000).

PRODUCT WATER USE (PWU) IN SEVERAL VEGETABLE CROPS UNDER DIFFERENT CULTIVATION PRACTICES

As a rule of thumb, only 10% of the water uptake of a crop plant produces a fresh weight increase, while 90% is transpired, raising the question of whether such a high transpiration rate is really needed for optimum yield. For tomato, we observed that a higher planting density resulted in a 10% yield increase (data not shown), whereas transpiration increased by 16% (Fig. 3). Hence, there is no strict relationship between transpiration and yield. Several experiments with greenhouse fruit vegetables conducted in the nineties have shown that transpiration can be reduced by 10-30%, without reduction in yield (Esmeijer, 1998).

As mentioned above, crop plants transpire at least 10 times more water than they fix into biomass (fresh weight), which is at least 10 times again more than plant dry matter. The ratio of fixed dry matter to water transpired is called transpiration efficiency. Considering that food-yield is usually a fraction of total biomass (harvest index), we see that agricultural production is unique among economic processes in having inherently low water use efficiency. An estimate of the amount of water necessary to produce a selection of basic foods is given in Table 2. From such data, it is estimated that the amount of water needed to produce a balanced diet would be 2000 m^3 per person per year, with 300 m^3 designated as irrigation water, on a world average (Klohn and Wolter, 1997). The product of the transpiration efficiency by the harvest index is called the water use efficiency (WUE) of a crop.

The harvest index is mainly a genetic factor, though crop management (sink/source manipulation) can have an effect on it. Varietal selection can also improve harvest index of crops: the harvest index of commercial winter wheat varieties introduced in France, for instance, has increased from about 30% to 50% between 1946 and 1992, an increase of 0.2% per year (Brancourt-Hulmel et al., 2003). Reduction of stalk height (short straw) was the main factor in this improved harvest index. Transpiration efficiency is also strongly affected by genetics. Compilation of measurements from the literature gives indicative values of 67 L of water per kg of dry matter in CAM-plants, 250 L· kg^{-1} in C_4 plants and up to 500 L· kg^{-1} in C_3 plants (E. Fereres and F. Orgaz, pers. comm., 2000).

Shoot environment (i.e., potential assimilation vs. potential evaporation), also has an effect on transpiration efficiency. Since assimilation has a saturating trend with respect to sun radiation, while potential transpiration does not, crops in temperate regions (with long summer days but lower peak radiation) generally have higher transpiration efficiency than in the tropics. This explains in part the fact that greenhouse production often has higher water use efficiency than field production. Altogether, however, this is the consequence of at least three factors, whose combined effect can increase water use efficiency several times (Table 3), namely:
1. reduced potential evaporation (less sun radiation; less wind and higher humidity)
2. increased production (better control of pathologies; better control of climate factors)
3. application of advanced irrigation techniques (drip irrigation; re-use of drain water)
In addition, substrate cultivation makes it possible to collect drain-water and re-use it in closed systems, which allows for some cost savings for fertilisers and water. Indeed, Dutch growers started to grow on closed systems for this purely economic reason (Ruijs and Van Os, 1991).

The water used in the production of a product is called the 'virtual water' contained in the product (Table 2). International trade brings along international water flows. Calculations of Hoekstra and Hung (2005) show that the global volume of crop-related international virtual water flows between nations was 695 km^3·yr^{-1} averaged over the years 1995-1999. For comparison: the total water use by crops in the world has been estimated at 5400 km^3·yr^{-1}.

A Cypriot study (Klohn, 2002) (Fig. 2), showed that protected cultivation is far more water use efficient then open field production, let alone meat production. We have done our own research into the product water use of the three main vegetable crops under glasshouse production in The Netherlands.

When we look at water use efficiency of horticultural produce in open field production, we are horrified at the amount of fresh water wasted in production. On average, a kilogram of tomatoes produced in the field will use about 200±100 L of water. At present in Israel, this is reduced to about 60 L kg^{-1} through drip irrigation. Greenhouse production reduces water use considerably (Table 3 and Fig. 2). In Dutch greenhouses with open irrigation systems, the average use is around 22 L kg^{-1} at present. With closed irrigation systems, the average is brought down to 15 L per kilogram product (KWIN, 2005). So re-use of drain water saves 7 L of water per kg tomatoes produced. In an experiment with a totally closed greenhouse in Naaldwijk (Wageningen-UR) in 2002 (Opdam et al., 2004; De Gelder et al., 2004; www.innogrow.nl), it was calculated that 40 to 50% of the water supplied to the crop was recovered by condensation of water vapour from the greenhouse air. The first commercial greenhouse of this kind (Themato BV in Berkel and Rodenrijs, The Netherlands), has been producing tomatoes for two years, produced bell peppers in 2006 and this year (2007) strawberries are being grown under closed greenhouse conditions. The entrepreneurs claim that for tomatoes, they actually did recover between 40 and 50% of the water supplied to the crop. If we assume that a crop is supplied with about 22 L kg^{-1} tomato produced and already 7 L are recovered from the drain, then the 11 L recovered from condensation, i.e., 50% of the supplied amount, in the climate treatment of the circulating air flow leaves us with a PWU of 4 L kg^{-1} tomato produced! This figure has not been rigorously substantiated, but is still above the theoretical limit of about 1.25 L of water per kg product. Tomato fruit represent about 80% of the total plant fresh biomass produced in a greenhouse (De Koning, 1993), meaning that 1.25 L of water per kg tomatoes is needed as a theoretical lower limit. As the closed greenhouse has not yet been optimized for water use efficiency (it is designed for energy use efficiency), it should be possible to reduce the PWU even further in practice. In the Watergy greenhouse in Spain (www.watergy.eu), also a closed greenhouse, 75% of the irrigation water has been recovered by condensation (Zaragoza et al., 2007).

When we need to apply active cooling to decrease the temperature in a conventional greenhouse, as is usually the case in arid and semi arid regions on the earth, the water use rises again tremendously, as is the case in experiments in Mexico (Loaiza-Mejia, 2005). In order to cool the greenhouse air, fogging and fan-and-pad systems are used in arid areas. In Mexico (Huejutla), a fogging system to keep greenhouse air temperature below 30°C during the entire year uses a calculated amount of 68 L·kg^{-1} tomatoes. To keep the temperature below 27°C this went up to 93 L·kg^{-1} tomatoes (including the rise in production). An experimental combined fan-and-pad and fog system to keep the temperature below 25°C is reported to use about 110 L·kg^{-1} tomatoes.

CONCLUSIONS

Protected cultivation appears to be not only useful for keeping plant-harmful events out, e.g., insects, cold temperatures and fungi, but also to keep in the plant's benefits. This allows us to minimize resource usage of energy, nutrients and water. The new techniques for optimizing resource usage in The Netherlands were mainly aimed at reducing energy use and preventing expulsion of waste water. However, they are also extremely useful in reducing water usage for the production of basic food products. These are in high demand in densely populated, i.e., urban areas, where the demand on fresh clean potable water is concomitant. On the one hand, it is possible for breeders to try to enhance the water use efficiency of crops, but the gains obtained from this within the 3 photosynthesis groups (CAM, C_4 or C_3) are negligible compared with the gains obtained from technical advances in climate control. However, these solutions are practical only in situations where the producer is able to invest large sums of money in production

facilities, which is not the case in most horticultural production sites in the world today. However, as the clean water shortage becomes more apparent in the world by e.g., the exhaustion of fossil water supplies (for example in the Alméria production area, about 35,000 hectares of protected vegetable production in Spain) or the emptying out of river water for surface irrigation as in China (more than 2 million hectares of protected cultivation at present), the demand for highly technical growth facilities will increase and the price of these products will likely increase as well.

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Tables

Table 1. Percentage of the total world accessible fresh water supply and percentage of the world population per continent (UNESCO, 2006).

Continent	Accessible fresh water supply (%)*	Population (%)*
North and Central America	15	8
South America	26	6
Europe	8	13
Africa	11	13
Asia	36	60
Australia and Oceania	5	<1

* = % of world total

Table 2. Product water use of different agricultural products (from Hoekstra, 2003).

Product	PWU ($L \cdot kg^{-1}$)*
Beef	15,977
Pork	5,906
Cheese	5,288
Eggs	4,657
Poultry	2,828
Rice	2,656
Soybeans	2,300
Wheat	1,150
Milk	865
Maize	450
Potatoes	160

* = $L \cdot kg^{-1}$ fresh product

Table 3. Amount of irrigation water required to produce 1 kg of fresh marketable produce in several climates and growing systems.

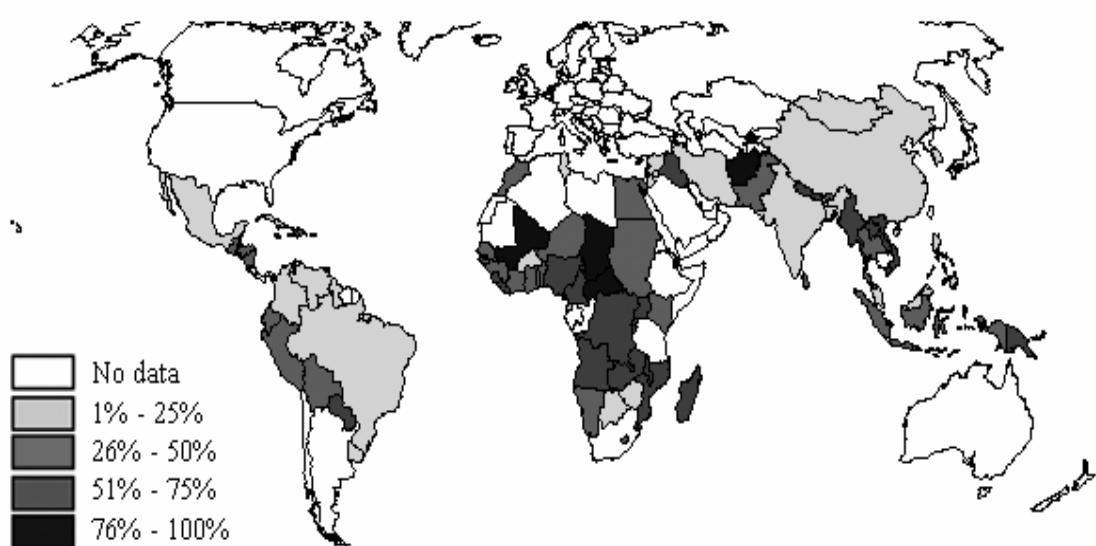| Climate and growing system	Tomato	Sweet pepper	Cucumber
Open field production	60 (Israel)	300 (Spain)	600 (Turkey)
Spain, unheated plastic "parral"	40		
Israel, unheated glass	30		
Spain, unheated "parral", regulated ventilation	27	74	
Holland, climate-controlled glass, CO_2 enrichment	22		
Holland, as above, with re-use of drain water	15	22.8	14

Figures

Fig. 1. Percentage of population without access to safe drinking water. From: The World's Water – The Biennial Report on Freshwater Resources (Gleick, 1998).
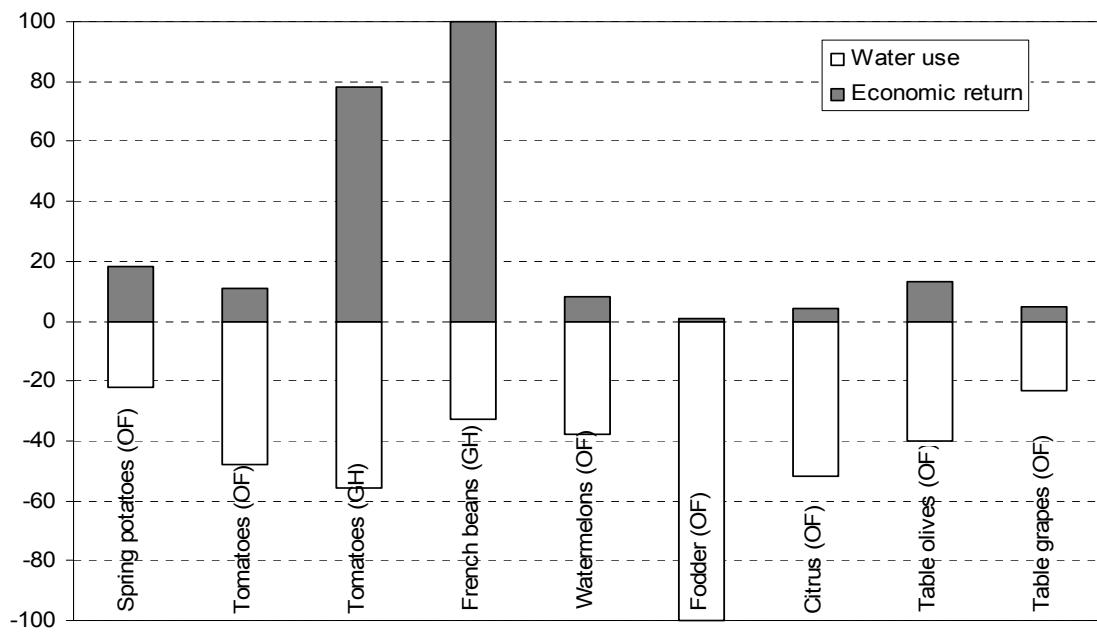
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Fig. 2. Comparison of crop cultivations for their value obtained (Cy£·m^{-3} water) and their water requirement (m^3·ha^{-1}) from a Cypriot study (Klohn, 2002). (Values expressed as percentage of the highest value; OF = Open Field, GH=Greenhouse).
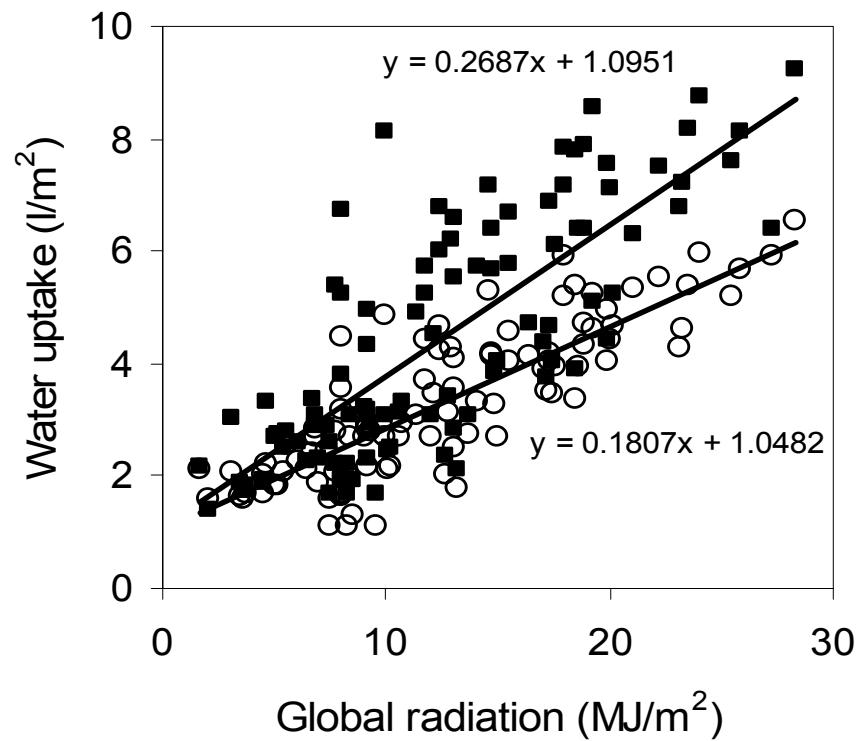

Fig. 3. Relationship between daily global radiation and water uptake for a tomato crop at two in-row planting distances (○ 0.50 m; ■ 0.33 m).