Journal of Horticultural Science & Biotechnology (2012) **87** (3) 193–202

An overview of climate and crop yield in closed greenhouses

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(Accepted 21 February 2012)

SUMMARY
The closed greenhouse is a recent innovation in the horticulture industry. Cooling by ventilation is replaced partly (in semi-closed greenhouses) or completely (in closed greenhouses) by mechanical cooling. Excess solar energy is collected and stored to be reused to heat the greenhouse. In temperate climates, this concept combines improved crop production with energy savings. This paper presents an overview of climate, crop growth and development, and crop yield in closed and semi-closed greenhouses. The technical principles of a closed greenhouse are described and the macroclimate and microclimate arising from this are studied. The consequences of the typical growth conditions found in closed greenhouses for crop physiology and crop yield are examined. Finally, the experiences of commercial growers are presented. In temperate climates, closed greenhouses can reduce the use of fossil fuel-derived energy by 25 – 35%, compared with open greenhouses. With high global radiation, the climate in closed greenhouses is characterised by high CO_2 concentrations, high air humidity, improved temperature control, and a vertical temperature gradient. An annual increase in production of 10 – 20% is realistic, with reduced amounts of supplied CO_2. The yield increase is primarily obtained through increased rates of photosynthesis due to the higher CO_2 concentrations in closed greenhouses. To introduce this innovation into practice, knowledge transfer was a key factor for its implementation and the realisation of increased production levels. Future trends will require minimising the use of fossil fuels and increasing the level of control of the production process. Closed and semi-closed greenhouses fit seamlessly into this trend as they allow for a more controlled climate and higher levels of production, combined with savings in fossil fuel use.

Greenhouse systems have been developed to protect crops from unfavourable environmental conditions, thereby extending the growing season. Improved growth conditions have significantly increased product quality and production (Dorais *et al.*, 2001). An analysis of the statistical data on tomato, sweet pepper, and cucumber reveals that annual production per unit greenhouse area (kg m^{-2}) for tomato in The Netherlands increased by 113% over the last 27 years, while sweet pepper production increased by 90%, and cucumber production by 35% (Figure 1). This increase was due to several factors, including improved climate conditioning (Montero *et al.*, 2011), improved cultivars (Higashide and Heuvelink, 2009), improved crop and pest management, and better control of the rooting medium. Although the energy used per unit of production decreased by 70% between 1980 and 2008, the greenhouse industry still has a large demand for fossil fuels (Van der Velden and Smit, 2010). According to the Kyoto Protocol from 1997, greenhouse horticulture must contribute to a reduction in CO_2 emissions, which can be realised by reducing fossil fuel consumption. For the Dutch greenhouse industry the goal is a reduction in CO_2 emissions of 48% by 2020, compared to 1990 levels (Anon, 2008).

Recently, a number of greenhouse concepts were developed with the primary aim of reducing energy consumption. Bot (1992) described the perspectives of the closed greenhouse to greatly reduce CO_2 emissions and improve crop and pest management. Later a number of other concepts were described, such as the solar greenhouse (Bot *et al.*, 2005), the closed greenhouse (Opdam *et al.*, 2005), Watergy (Buchholz *et al.*, 2005), the energy-producing greenhouse (Bakker *et al.*, 2006), the sunergy greenhouse (De Zwart, 2011), and the low energy greenhouse (Tantau *et al.*, 2011). In each of these

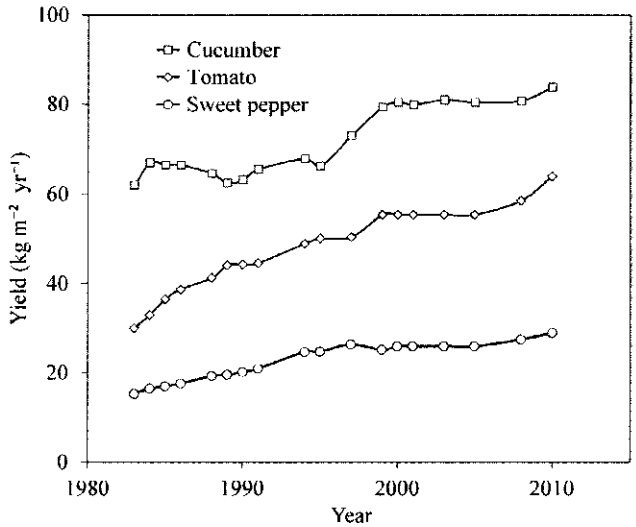

FIG. 1
Average annual yields for cucumber (open squares), tomato (open diamonds), and sweet pepper (open circles) in Dutch greenhouses. Data were derived from statistical overviews between 1983 (Croque and Nienhuis, 1983) and 2010 (Vermeulen, 2010).

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