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Plant factories versus greenhouses: Comparison of resource use efficiency

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ABSTRACT

Research on closed plant production systems, such as artificially illuminated and highly insulated plant factories, has offered perspectives for urban food production but more insight is needed into their resource use efficiency. This paper assesses the potential of this 'novel' system for production in harsh climates with either low or high temperatures and solar radiation levels.

The performance of plant factories is compared with cultivation in traditional greenhouses by analysing the use of resources in the production of lettuce. We applied advanced climate models for greenhouses and buildings, coupled with a lettuce model that relates growth to microclimate. This analysis was performed for three different climate zones and latitudes (24–68°N).

In terms of energy efficiency, plant factories (1411 MJ kg^{-1} dry weight) outperform even the most efficient greenhouse (Sweden with artificial illumination; 1699 MJ kg^{-1} dry weight). Additionally, plant factories achieve higher productivity for all other resources (water, CO_2 and land area). With respect to purchased energy, however, greenhouses excel as they use freely available solar energy for photosynthesis. The production of 1 kg dry weight of lettuce requires an input of 247 kWhe in a plant factory, compared to 70, 111, 182 and 211 kWhe in greenhouses in respectively the Netherlands, United Arab Emirates and Sweden (with and without additional artificial illumination).

The local scarcity of resources determines the suitability of production systems. Our quantitative analysis provides insight into the effect of external climate on resource productivity in plant factories and greenhouses. By elucidating the impact of the absence of solar energy, this provides a starting point for determining the economic viability of plant factories.

1. Introduction

By midcentury, the number of people living in cities is likely to reach the level of the world's total population in 2002; the urban population is expected to increase from 3.6 billion in 2011 to 6.3 billion in 2050 (UN, 2014). The supply chains to feed the expanding cities will become increasingly complex, which will have a major impact on urban and rural areas (Newcombe and Nichols, 1979; Rosenzweig and Liverman, 1992; Kennedy et al., 2007; Lambin and Meyfroidt, 2011). It has often been suggested that urban agriculture could ensure a supply of locally produced, fresh food. Given the financial value of urban space, an economically viable venture would require exceptionally high productivity.

One proposed solution is the use of closed production systems such as plant factories and vertical farms (Seginer and Ioslovich, 1999; Kozai et al., 2006; Kozai, 2013b). A vertical farm can be considered as a multi-storey plant factory. Closed systems are designed to maximise production density, productivity and resource use efficiency (Kozai, 2013a). High productivity is achieved by adapting the interior climate to achieve uniform lighting, temperature and relative humidity through minimising the interaction with the exterior climate. Limiting this interaction can also benefit the efficient use of energy, water and CO_2 (Goto, 2012).

The evident shortcoming of this typology is the high energy (electricity) demand for artificial illumination, which is needed for photosynthesis. Furthermore, the combination of high-density crop production, limited volume and lack of natural ventilation is likely to induce a high demand for cooling and vapour removal (Graamans et al., 2017).

In contrast, greenhouse horticulture consists of a (semi-)controlled environment which uses primarily solar energy for photosynthesis as well as for heating. Excess energy can be discharged by ventilation and any deficits or surplus can be compensated by heating or cooling. The

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transparent, conductive design of greenhouses is a trade-off between solar energy and the influence of the exterior climate. The relation between the costs (heating and cooling) and benefits (solar radiation) of greenhouse production largely depends on the latitude and external climate conditions of the site (Kozai, 2013b). It can be expected that at high latitudes solar radiation no longer offsets the energy being lost through the greenhouse cover. The opposite may occur at low latitudes, where the incoming solar energy cannot be discharged by natural ventilation. In these situations evaporative and/or active cooling would become necessary.

Plant factories are now being used for the commercial production of leafy greens, but their potential remains uncertain. In order to achieve economic viability, the increased resource productivity and/or the value of additional services would have to outweigh the disadvantage of the absence of solar energy.

1.1. Objective

The objective of this study is to quantify the resource requirement for lettuce production in greenhouses and plant factories and to analyse how this requirement is affected by external climate conditions.

1.2. Outline

We couple an established model for lettuce growth with accepted models for the simulation of climate and resource requirements in either plant factories or greenhouses. Subsequently, we calculate and analyse the resource requirement of lettuce production in the two growing systems, each in three climates.

2. Methodology

This study consists of a performance analysis of plant factories and greenhouses at three different locations. To this end, we analyse resource expenditure for lettuce production. The resource expenditure of each facility is the result of internal and external gains as well as the use of electricity, water and CO_2. These figures were calculated and compared. Greenhouse and building simulation software had to be used, since the two typologies require a different format. Ultimately, the production output, climatic performance and related resource consumption were analysed for each facility.

2.1. Model selection

2.1.1. KASPRO for greenhouses

Given the differences in the construction of greenhouses and plant factories, different simulation models had to be applied. The design of greenhouses implies considerable interaction with the exterior climate. This causes substantial fluctuations in the interior climate, since control actuators have limited capacity. Therefore, a dynamic model is needed to calculate these variations. In this study we used KASPRO (De Zwart, 1996), an advanced, dynamic model to calculate the climate in greenhouses. It consists of sub-models that are based on the energy and mass balance of the greenhouse elements. The model takes full account of the interdependence of the greenhouse characteristics and the various climate control actuators, accounting for their limited capacity. More details of this model are described by De Zwart (1996), Luo et al. (2005a), Luo et al. (2005b) and Katsoulas et al. (2015).

2.1.2. DesignBuilder for plant factories

Unlike greenhouses, plant factories are closed systems, consisting of a highly insulating and airtight structure (Kozai, 2013a). Detailed dynamic greenhouse models, such as KASPRO, are less suitable for calculating the limited interaction between the interior and the exterior climate as well as the high internal heat loads. Furthermore, calculating the energetic requirements of plant factories in KASPRO would require considerable modification and validation of the energy balance. Therefore, we selected EnergyPlus in combination with DesignBuilder (2016).

EnergyPlus is a building energy simulation program with three basic components – a simulation manager, a heat and mass balance simulation module and a building systems simulation module (Crawley et al., 2001). We used DesignBuilder (2016) for simulating the energy consumption of the plant factory, as this program is considered the most complete graphic user interface for EnergyPlus.

DesignBuilder is not a dynamic simulation model. This is not a limitation, as plant factories have just two states (photo-/dark period), each with a constant climate throughout. It is essential to calculate the energetic behaviour of the crop in both states – how it transpires, reflects light and exchanges heat and radiation. Cooling and vapour removal are quite different processes and the relation between sensible and latent heat is a key factor in the energy demand. Therefore, the energy balance must be based on an accurate estimate of the crop transpiration coefficient, i.e. the fraction of the radiation load that is dissipated by the crop as latent heat. We have integrated the energetic behaviour into the simulations, following the method described by Graamans et al. (2017). We have taken into account an average LAI of 2.1, according to Tei et al. (1996), in order to represent a facility where all stages of development are simultaneously present, as is common in actual practice.

The energetic behaviour of lettuce was calculated for the conditions of photo- and dark periods (Table 1). The various positive energetic fluxes were set as equipment gains in DesignBuilder; the negative sensible heat transfers were set as process gains. The cooling load for maintaining a constant temperature of the nutrient solution (Section 2.3.4) was calculated manually and integrated into the total sensible cooling load. We used Fourier's law of heat conduction to calculate the heat transfer across container and cover. For this calculation we assumed a constant temperature of the nutrient solution of 24 °C, air temperatures of 30/24 °C during photo − /dark periods, a conductive surface area of 2.2 m^2 per m^2 cultivation area, a thickness of 50 mm and a U-value of 0.03 $W\ m^{-2}\ k^{-1}$. The conductive surface area is based on suspended, extruded containers with a rectangular cross section of 850 × 130 mm and a nutrient solution depth of 125 mm.

2.2. Lettuce production in relation to climate

Differences between the interior climates of greenhouses and plant factories result in differences in plant production. The production in both types of facility determines their respective energetic performances. To this end, the model described by Van Henten (1994) was implemented in computational software (MATLAB, 2016). This is a dynamic growth model that simulates various physiological processes in butterhead lettuce (*Lactuca sativa* var. *capitata* L.). The model determines crop growth rate by distinguishing between growth of structural (e.g. glucose, sucrose, starch) and non-structural (e.g. cell walls, cytoplasm) dry weight. Non-structural dry weight is calculated as a function of gross canopy photosynthesis, respiration and transformation into structural material. Structural dry weight is a function of non-structural dry weight and canopy temperature. We took total dry matter (shoot and root) as the most adequate indicator of production in different conditions. This method negates the effects of commercial and crop management strategies, as well as possible variations in dry matter partitioning between root and shoot. In practice the roots contain approximately 8% of the total dry matter (He and Lee, 1998a, 1998b; Frantz et al., 2004). Furthermore, we assumed a fixed dry matter content of 7% (Koudela and Petříková, 2008; Gent, 2014), an average LAI of 2.1 (Section 2.1.2) and an initial dry weight of 0.48 $g\ m^{-2}$ cultivation area.

The Van Henten (1994) model reduces the three-dimensional crop canopy to a single plane (cultivation area), though it does not address the plant density. This limitation inhibits modelling the transplanting and the respacing of crops. Respacing is done in plant factories and