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Plant factories; crop transpiration and energy balance

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ABSTRACT

Population growth and rapid urbanisation may result in a shortage of food supplies for cities in the foreseeable future. Research on closed plant production systems, such as plant factories, has attempted to offer perspectives for robust (urban) agricultural systems. Insight into the explicit role of plant processes in the total energy balance of these production systems is required to determine their potential. We describe a crop transpiration model that is able to determine the relation between sensible and latent heat exchange, as well as the corresponding vapour flux for the production of lettuce in closed systems. Subsequently, this model is validated for the effect of photosynthetic photon flux, cultivation area cover and air humidity on lettuce transpiration, using literature research and experiments. Results demonstrate that the transpiration rate was accurately simulated for the aforementioned effects. Thereafter we quantify and discuss the energy productivity of a standardised plant factory and illustrate the importance of transpiration as a design parameter for climatisation. Our model can provide a greater insight into the energetic expenditure and performance of closed systems. Consequently, it can provide a starting point for determining the viability and optimisation of plant factories.

1. Introduction

Expanding cities no longer derive their food supply from their hinterlands, but rely on the global food trade. Given the limited availability of land, water and nutrients, however, the sustainability of these networks is questionable (Newcombe & Nichols, 1979; Rosenzweig & Liverman, 1992; Kennedy et al., 2007; Lambin & Meyfroidt, 2011). Research on urban agriculture, plant factories and vertical farming has attempted to offer new perspectives for robust food production systems for cities. These systems generally focus on the development of local high-density production in closed plant production systems (Seginer & Ioslovich, 1999; Kozai et al., 2006; Kozai, 2013a, 2013b). These systems can also be integrated into (structurally vacant) high-rise buildings for vertical farming.

Agriculture always has relied on sunlight to power photosynthesis. Greenhouse horticulture uses solar energy both for photosynthesis and heating, by creating a (semi-)closed environment. This is one of the reasons for its productivity. Greenhouses create a controlled environment for plant production where excess (solar) energy is discharged by ventilation and deficits can be compensated by heating. As management of microclimate is fundamental to greenhouse agriculture, it relies on a broad body of knowledge, in particular with regard to the related energetic fluxes and requirements.

Commercial vegetable production in closed systems, however, is a relatively new issue. It focuses on the development of new typologies, such as plant factories and vertical farms (Goto, 2012). As a working definition, a vertical farm can be regarded as a multi-storey plant factory. In spite of the possible benefits, an obvious disadvantage of plant factories is the need for artificial lighting for photosynthesis and energy for air conditioning (cooling and vapour removal, both relying on forced air circulation). In particular, the combination of high-density crop production, limited dimensions and lack of natural ventilation is likely to result in a high demand for dehumidification.

The interior climate and the related energetic fluxes of plant factories have to be investigated in order to quantify these additional energy requirements. Closed systems limit the exchange of energy with the exterior climate. As a result, all energy entering the system has to leave the system through forced air circulation and conditioning. As cooling and vapour removal are quite different processes, however, the distribution between sensible and latent heat is a key factor. Therefore, the energy balance must be based on an accurate estimate of the crop transpiration coefficient, i.e. the fraction of the radiation load dissipated by the crop as latent heat.

To this end, it is essential to simulate the energetic behaviour of the crop – how it transpires, reflects light and exchanges heat and radiation. The results of research on the energy profile offer the starting point for

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the discussion on the possible benefits of plant factories compared with traditional greenhouses.

1.1. Objective

The main objective of this study was to explicate the energetic fluxes associated with the production of lettuce in plant factories. In particular, an approach for the estimation of transpiration was formulated and validated in order to illustrate the effect of the crop on the energetic distribution of sensible and latent heat.

1.2. Outline

We propose a model that is able to determine the relation between sensible heat and latent heat exchange and the corresponding vapour flux for the production of lettuce in closed systems. This model is validated by literature research as well as by experiments on the effect of photosynthetic photon flux density, cultivation area cover and vapour concentration deficit on lettuce transpiration. Subsequently the energy productivity of such a plant factory is quantified and discussed.

2. Theoretical background

This section addresses the energy balance and individual energetic fluxes resulting from closed plant production in a building structure. In particular, we specify our adaptation of the Penman-Monteith crop transpiration method, the 'big leaf' model.

2.1. Energy balance

Numerous models exist to analyse the energy balance in various greenhouse typologies, crops and production methods. It is necessary, however, to determine the impact of the plant factory typology on the various energy fluxes and the resulting interior climate. The plant processes play a key role in the total energy balance. In particular the crop transpiration is of paramount importance.

The following literature survey is intended to provide insight into the interdependency of various climatic variables. These data were used to formulate a model calculating the relative share of radiation load that is dissipated as sensible and latent heat.

2.1.1. Standard greenhouse energy balance

Using the greenhouse air as the control volume of interest, the control surface is composed of the glazing, the ground, components within the greenhouse and any open points of entry, including vents and gaps. The transfer of energy across these surfaces involves both sensible and latent heat exchanges (Boulard & Wang, 2000). The energy balance equation for greenhouses is adapted from Sabeh (2007) and is illustrated in Fig. 1 and represented by the following equation:

$$Q_R + Q_F + Q_{Comp} + Q_{Soil} + Q_{Plant} + Q_L + Q_{Vent} + Q_{Heat} = 0 \tag{1}$$

Q_R represents heat transfer by radiation. Q_F is the heat transfer across the glazing via conduction and convection. Q_{Comp} represents the heat transfer by the various greenhouse components, including structural components and production systems. Q_{Soil} is the heat transfer between the ground and greenhouse air. Q_{Plant} represents the heat transfer by the evapotranspiration of plants, which transfers latent and sensible heat energy to the greenhouse air. Q_L is the latent heat transfer of sensible energy in the air to water in the form of fog droplets. Q_{Vent} represents the heat transfer by natural and mechanical ventilation, which removes energy from the greenhouse via air exchange. Finally, Q_{Heat} is the energy added to the greenhouse using a heating system. This greenhouse energy balance represents a simplified, illustrative model and does not include elements of thermal inertia.

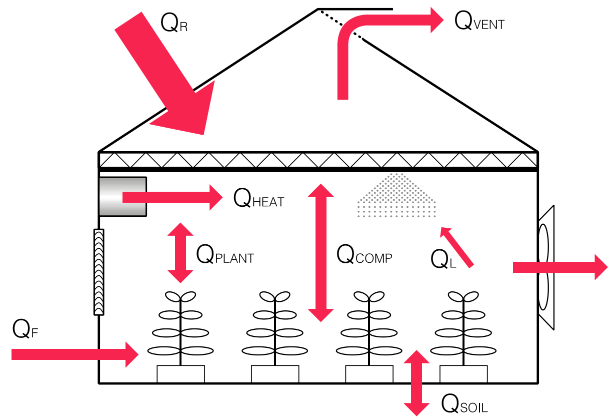

Fig. 1. Green house energy balance.
Adapted from Sabeh (2007).

2.1.2. Plant factory energy balance

The energy balance as stated in Eq. (1) applies to archetypical light-transmitting and naturally ventilated greenhouses, with solar energy as the exclusive source of photosynthetically active radiation (PAR). This equation has to be adapted in order to determine the energy balance for plant factories. The plant factory features a highly insulated construction, which limits thermal exchange with its surroundings. Therefore, the building structure can be considered as adiabatic; Q_{Soil} can also be omitted.

Other differences with the standard greenhouse energy balance include the exclusive use of mechanical air circulation and conditioning for heating and cooling; Q_{Vent} and Q_{Heat} become Q_{HVAC}. The influence of structural elements is integrated with Q_F to become $Q_{Façade}$. Finally, the energetic flux resulting from the inefficiency of production components/systems (e.g. artificial lighting) is redefined as Q_{Equip}. The energy balance for the plant factory is illustrated in Fig.2 and represented by the following equation:

$$Q_R + Q_{Façade} + Q_{Plant} + Q_L + Q_{Equip} + Q_{HVAC} = 0 \tag{2}$$

The share of Q_R and $Q_{Façade}$ in the total energy balance is likely to be reduced compared to standard greenhouses. This is the result of insulation properties and the relatively small surface area in plant factories, which usually consist of multiple layers. In the case of fully artificial production with an opaque façade the Q_R can be omitted, resulting in the following equation:

$$Q_{Façade} + Q_{Plant} + Q_L + Q_{Equip} + Q_{HVAC} = 0 \tag{3}$$

Closed production systems allow for a highly steady interior climate. Consequently, the influence of thermal inertia in the energy balance of the facility is very small and is not included in this simplified energy

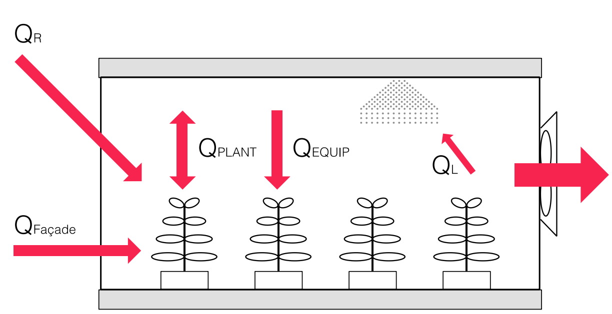

Fig. 2. Plant factory energy balance.

balance equation. Additionally, the transpiration model below is formulated as a steady state model, as opposed to dynamic.

2.2. Plant processes

The crop has a tremendous impact on its environment; it absorbs and emits radiation, exchanges heat with air and transpires. The crop transpiration coefficient, that is the fraction of the radiation load dissipated as latent heat, is key in quantifying the energy requirement of the system. In this study the Penman-Monteith approach, the 'big leaf' model, is used to estimate the transpiration and consequent energetic fluxes of the production of lettuce in the fully controlled conditions of a plant factory. This approach permits certain simplifying assumptions.

Since the first data on crop transpiration became available around 1920, it has been demonstrated that the data is far from constant (Clum, 1926). Penman demonstrated that crop transpiration primarily is a physical process. The components of this process are the energy available at the transpiring surface and the ability of air to extract vapour from this surface; it is partially influenced by the crop itself (Penman, 1947, 1948; Schofield & Penman, 1948). Monteith (1965) re-wrote Penman's equation, explicitly identifying the parameters that are affected by the crop.

The Penman-Monteith (PM) equation (Monteith, 1965) is based on the assumption that the three-dimensional crop canopy can be reduced to a one-dimensional 'big leaf' where net radiation is absorbed, heat is exchanged and water vapour escapes. This equation requires the crop to be homogeneous, level, continuous and extensive.

In a natural environment (open air) the sun is the only source of energy and the wind determines the removal rate of vapour from the transpiring surfaces. The PM equation describes this phenomenon and has been the basis of most crop transpiration models that were developed afterwards. A greenhouse, however, constitutes a peculiar environment. Therefore, there have been considerable research efforts to predict the (evapo)transpiration of greenhouse crops (Stanghellini, 1987; Boulard & Wang, 2000; Pollet et al., 2000)

2.2.1. Crop energy balance

At equilibrium, the amount of energy arriving at the 'big leaf' surface must equal the amount leaving it. All fluxes of energy should be considered when deriving an energy balance equation. Energy directly related to photomorphogenesis, however, is limited (Ado et al., 1997) and can be considered negligible (Gates, 1965). The energy balance equation for a transpiring plant surface is then comprised of net radiation (R_{net}), sensible heat exchange (H) and latent heat exchange (λE):

$$R_{net} - H - \lambda E = 0 \tag{4}$$

R_{net}, the amount of radiation intercepted and absorbed by the crop depends on the amount of leaves present and how they are distributed. Lettuce crops consist of multiple, irregular, overlapping leaves. This results in an increased transpiring surface, with respect to the projected surface of the 'big leaf'. Therefore, leaf area index (LAI) plays an essential role in determining the energy balance. In this study LAI is defined as the ratio of leaf area divided by cultivation panel area. See Section 3.1.4 and below for how the LAI of the lettuce crop is incorporated into the equations for sensible and latent heat exchange. The equation for the transfer of sensible heat from the leaf canopy to the surrounding climate is:

$$H = LAI \cdot \rho_a \cdot c_p \cdot \frac{(T_s - T_a)}{r_a} \tag{5}$$

This equation demonstrates that the sensible heat flux is commanded by a single resistance, namely the aerodynamic resistance to heat (r_a). The sensible heat flux depends on the difference between the temperature at the transpiring surface (T_s) and in the surrounding air (T_a). In order to calculate the latent heat exchange it is necessary to determine the transfer of vapour. This transfer is represented by the following equation:

$$\lambda E = LAI \cdot \lambda \cdot \frac{(\chi_s - \chi_a)}{r_s + r_a} \tag{6}$$

This equation accounts for the fact that the vapour flux from the substomatal cavities to the surrounding 'free' air encounters two consecutive resistances: the surface (or stomatal) resistance (r_s) and the aerodynamic resistance (r_a) to vapour transfer. The latent heat flux depends on the difference between the vapour concentration at the transpiring surface (χ_s) and in the surrounding air (χ_a).

Penman (1948) added the imperative fourth equation by postulating that the transpiring surface is saturated at its temperature and Monteith (1965) applied only the first (linear) term of the Taylor's expansion of the saturation hypothesis, leading to the following equation:

$$\chi_s \cong \chi_a^* + \frac{\rho_a \cdot c_p}{\lambda} \cdot \varepsilon \cdot (T_s - T_a) \tag{7}$$

This allowed for the derivation of an analytical (PM) equation for crop transpiration that could be solved in a world still devoid of computer power. The limit to the applicability of the PM equation is the knowledge of the variables that have been introduced to describe the energy exchange of the 'big leaf'.

2.2.2. Add-ons to the 'big leaf' model

The transfer of heat and water vapour between the 'big leaf' and the surrounding air is governed by various functions relating to air movement, temperature, vapour pressure deficit and radiation. Applying this model to greenhouse crops, several studies have combined the PM equation with the thermal balance equation of the canopy and consequently the entire greenhouse energy balance (Boulard & Baille, 1993; Boulard & Wang, 2000). Models for greenhouse crop transpiration have been described by Stanghellini (1987), Chalabi & Bailey (1989), Aikman & Houter (1990) and Jolliet (1994). The main differences between these models pertain to the radiation absorption coefficient and the (stomatal and boundary layer) resistances. In order to use the Penman-Monteith equation in a predictive setting, methods for determining the aerodynamic resistance and the surface resistance (r_s) should be available (Alves et al., 1998; Alves & Pereira, 2000). The submodels for R_{net}, r_a and r_s are explained below.

3. Materials: model overview

This section addresses the submodels used in this study for net radiation, surface resistance and aerodynamic resistance. Consequently, we elucidate the MATLAB model that formulates the distribution of the sensible and latent component of the lettuce canopy.

3.1. Submodels

3.1.1. Submodel for net radiation

The net radiation (R_{net}) is the radiation ($I_{lighting}$) effectively absorbed by the crop, i.e. light that is intercepted (the ratio of projected leaf area to cultivation area, or cultivation area cover CAC) and not reflected (reflection coefficient ρ_r). This fraction generally depends on the amount of leaves, their distribution and orientation. The equation for the net radiation is:

$$R_{net} = (1 - \rho_r) \cdot I_{lighting} \cdot CAC \tag{8}$$

The reflection coefficient of lettuce for PAR, is reported to be 5–8% (Frantz et al., 2004). The present leaf area is either known or estimated as a function of degree-days. However, the correlation between leaf area and cultivation area cover is rather poor for closed crops such as lettuce. Pollet et al. (2000) confirm this by concluding that cultivation area cover (soil cover in traditional agriculture) was best estimated through imaging of the vertical projected leaf area. In lettuce, the cultivation area cover remains relatively constant throughout its development. The coverage expands rapidly in the early stages of growth, certainly under the relatively high temperatures of plant factories. This expansion is followed by densification of the crop within these boundaries, an increase in LAI. This results in a high and consistent percentage of cultivation area coverage (Tei et al., 1996). We recommend a value of 90% cultivation area coverage for predictive, static calculations.

3.1.2. Submodel for surface (stomatal) resistance

The surface resistance (r_s) represents the resistance of vapour flow through the transpiring crop, as well as from uncovered, evaporating soil surface (Allen et al., 1998). What is generally known is that stomata open under increasing photosynthetic photon flux densities (PPFD), resulting in a decrease of resistance. Therefore, applying a single value for r_s will reduce accuracy, and is not to be preferred, in spite of the standardisation, comparability, consistency and simplicity of calculations and simulations.

Several models for r_s in lettuce have been designed, based on experimental data (i.e. Alves et al., 1998; Alves & Pereira, 2000; Pollet et al., 2000). These empirical equations generally represent the influence of air temperature, vapour pressure deficit and PPFD on surface resistance, following the multiplicative method first proposed by Jarvis (1976). The relevance of additional factors beyond light has since been debated (Pollet et al., 2000), also in view of the limited validity of the multiplicative method outside the particular range for which parameters have been determined in each case (Jolliet & Bailey, 1992).

Recently it has been shown that the spectral distribution may play a role in determining stomatal resistance. Wang et al. (2016) found that different red/blue ratios in particular influence the r_s of lettuce and illustrate the response of stomatal conductance to irradiance. After extrapolating their data, we formulated a general equation for r_s by fitting a rectangular hyperbola and approximating the parameters. This equation for r_s uses the light-dependent term PPFD in μmol/m^{2}s:

$$r_s = 60 \cdot \frac{1500 + PPFD}{200 + PPFD} \tag{9}$$

Faute de mieux, we adopted the hypothesis that r_s can be approximated by the photosynthetic photon flux density and is less dependent on any synergistic interaction of all variables. This will allow us to approximate r_s regardless of spectrum, lighting strategy and climate settings.

3.1.3. Submodel for aerodynamic boundary layer resistance

The aerodynamic boundary layer resistance influences the transfer of sensible heat and water vapour from the leaf surface into the surrounding air. To determine r_a, an analogy generally is made with the resistance to momentum transfer (Perrier, 1975; Allen et al., 1998; Alves et al., 1998). Aerodynamic resistance usually is described by an expression, derived from turbulent transfer and the assumption of a logarithmic wind profile (Thom, 1975; Monteith & Unsworth, 1990; Alves & Pereira, 2000). This approach is evidently unsuitable for closed environments.

In the controlled environment of a plant factory, the relatively high air circulation rate is what determines vapour and heat removal from the crop. The air is subsequently conditioned without the need for fresh air in the plant factory. Fuchs (1993) proposes a method that integrates the mean leaf diameter (l), the uninhibited air speed (u_∞) and LAI:

$$r_a = 350 \cdot \left(\frac{l}{u_\infty}\right)^{0.5} \cdot LAI^{-1} \tag{10}$$

It has frequently been shown (e.g. Stanghellini, 1987) that crop transpiration is only slightly dependent on the aerodynamic boundary layer resistance (as a consequence of the thermal feed-back). It is practical, however, to formulate standardised values for preliminary calculations, in order to improve their standardisation and simplicity. We recommend a LAI of 3 (Tei et al., 1996; Tuzet et al., 2003) and a mean leaf diameter of 0.11 (Ohashi-Kaneko et al., 2007) for predictive, static calculations. In this research we used two static values for r_a: 100 s/m with forced air circulation on and 200 s/m with forced air circulation off.

3.1.4. Transpiring leaf area

The leaf area index (LAI) of the lettuce crop is incorporated into the equations for sensible and latent heat exchange (Eqs. 5–6). As mentioned above the development and configuration of the leaves result in an increased transpiring surface. The LAI that is required in Eqs. (5)–(6) represents the 'effective' leaf area for latent and sensible heat transfer, as opposed to total leaf area. We estimated leaf area multiplying the accumulated dry weight by the specific leaf area (m^2/g) estimated as a function of days after emergence, determined by Tei et al. (1996).

3.2. Model overview

The MATLAB (2016) model executes an iterative process to simultaneously solve (Eqs. 4–7), processing the net PAR flux density, the surface and aerodynamic resistances as outlined above (Eqs. 8–10). The flows are denoted by a capital letter, followed by a subscript. The model parameters are listed in the list of symbols (Appendix A).

The iterative process is based on the aforementioned equations and is performed in a continuous loop. For each set interval of T_a, the model calculates the corresponding T_s at which the energy balance (R_{net}–H–λE) is closest to zero. The model utilises a continuous loop to approach this value at the set discretisation and consequently indexes the value closest to zero. Finally, the model lists the different variables congruent with this zero energy balance, in particular the quantity of the sensible (H) and latent (λE) heat exchange.

4. Methods: model validation

Our model was validated for three different interior climate regimes by separate experiments conducted in closed systems with artificial lighting. The first experiment (Wheeler et al., 1994) was conducted in NASA's Biomass Production Chamber at Kennedy Space Center. The second and third were conducted at Wageningen University & Research in the Netherlands as part of the Ground Demonstration of Plant Cultivation Technologies and Operation in Space (H2020 EDEN-ISS). A summary of the conditions of the experiments is in Table 1 and an extended description is given below.

4.1. Model validation for various photosynthetic photon flux densities

Our model was validated with the measured amount of transpired vapour at various photosynthetic photon flux densities (PPFD). Data were obtained in two LED-lighted climate chambers (2.88 × 2.20 × 3.06 m; 19.4 m^3 each) with lettuce in a hydroponic deep flow system. Nutrient solution volumes remained covered and were replenished every three days. Air temperature averaged 21 °C in light and 19 °C in dark conditions. Cooling and dehumidification were achieved by HVAC. Relative humidities averaged 73% in light and 82% in dark conditions. Air was continuously circulated in order to provide

Table 1
The location, crop production data and interior climate conditions for the experiments conducted at Wageningen UR and the Kennedy Space Center. The different sets of VCD are represented by numbers (0–4) and the different balances are represented by letters (A–F). Double values (e.g. 21/19) represent photo-/dark period, respectively.

	EXP-1 – PPFD Wageningen UR		EXP-2[a] –CROP COVER Kennedy Space Center	EXP-3 –VCD (control) Wageningen UR	EXP-3 –VCD Wageningen UR	
Latitude	51.9865374 °N		28.590181 °N	51.9865374 °N	51.9865374 °N	
Longitude	5.6634339 °E		-80.659198 °E	5.6634339 °E	5.6634339 °E	
Typology	CPPS with DFT		CPPS with NFT	CPPS with DFT	CPPS with DFT	
Dimensions	1.44 m^2 in 19.4 m^3		20 m^2 in 113 m^3	0.72 m^2 in 19.4 m^3	0.72 m^2 in 19.4 m^3	
Cultivar	Batavia		Waldmann's Green	Batavia	Batavia	
Cycle duration	3 days		28 days	8 days	8 days	
Cultivation area cover [%]	100		0–95	91	82–95	
LAI	3.0		0–4.3	(A) 3.0 (B) 3.0 (C) 2.9	(D) 3.2 (E) 3.2 (F) 3.4	
Mean air temperature [°C]	21/19		22.6/22.4	(0) 21/19	(1) 17/15 (2) 17/15	(3) 25/23 (4) 25/23
Relative Humidity [%]	73/83		71/75	(0) 76/86	(1) 75/82 (2) 78/96	(3) 79/86 (4) 89/93
VCD [g/m^3]	5.0/2.8		5.9/5.0	(0) 4.4/2.7	(1) 3.7/2.3 (2) 2.3/0.5	(3) 5.2/3.5 (4) 3.3/3.3
CO2 levels [μmol/mol]	700–800		1000	700–800	700–800	
Lighting system	LED		HPS	LED	LED	
PPFD [μmol/m^2s]	(A) 140 (114–166) (B) 200 (170–254) (C) 300 (262–338)	(D) 400 (300–477) (E) 450 (396–594) (F) 600 (506–691)	293	(A) 140 (126–148) (B) 300 (283–324) (C) 600 (550–651)	(D) 140 (123–147) (E) 300 (278–321) (F) 600 (555–645)	
PAR flux density [W/m^2]	(A) 28.2 (B) 41.0 (C) 58.6	(D) 79.6 (E) 90.8 (F) 118.8	58.89	(A) 28.2 (B) 59.2 (C) 119.6	(D) 27.8 (E) 59.6 (F) 119.8	
Photo-/Dark period [h]	16/8		16/8	16/8	16/8	
r_s [s/m]	(A) 289/450 (B) 253/450 (C) 218/450	(D) 190/450 (E) 179/450 (F) 158/450	218/450	(A) 289/450 (B) 217/450 (C) 158/450	(D) 290/450 (E) 217/450 (F) 157/450	
r_a [s/m]	100/100		100/200	100/100	100/100	

[a] As reported by Wheeler et al. (1994).

a mixed atmosphere. This required approximately 4000 m^3/h or approximately 200 volume exchanges per hour. The individual climate chambers featured either high (400–600 μmol/m^2 s) or low (100–300 μmol/m^2 s) PPFD and the illumination on each balance was carefully adjusted to have three PPF densities within each range (Table 1).

A set-up of six independent digital balances (60 kg, 2 g accuracy) was used to determine transpiration. The total weight of the crops, production system and nutrient solution was measured and documented by each balance every 30 s. The transpiration rates were determined by calculating the slope of the (decreasing) weight in time. Two distinct and precise slopes (photo- and dark period) could be determined, due to the steady climate in the cells and the large number of measurements.

The experiments used transplanted Batavia lettuce, 60 days after sowing, with a cultivation area cover of 100%. LAI was not measured but estimated based on literature. Tei et al. (1996) reported a LAI of 4.4 for Saladin lettuce at 60 days after sowing. Batavia lettuce, however, has less overlapping, non-effective leaves. Consequently, we presumed a LAI of 3, following Tuzet et al. (2003).

From this experiment we used two data sets; the transpired vapour and fresh weight.

4.2. Model validation for a range in cultivation area cover

Our model was validated with evapotranspiration rates throughout the development of the crop and the corresponding cultivation area cover as reported by Wheeler et al. (1994). They produced lettuce in a closed chamber using a hydroponic nutrient film technique. The objective of that study was to track gas, water and nutrient balances in relation to the productivity of lettuce from seeding to harvest. Evapotranspiration rates were daily assessed by recording the replenishment of the nutrient solution reservoirs.

The air temperature averaged 22.6 ± 0.4 °C in light and 22.4 ± 0.2 °C in dark conditions. The relative humidity averaged 71 ± 3% in light and 75 ± 2% in dark conditions. Air was continuously circulated in order to provide a mixed atmosphere. From this experiment we used three data sets; the canopy cover, evapotranspiration rate and dry mass accumulation. The LAI was considered to be variable in accordance with Wheeler et al. (1994).

4.3. Model validation for various vapour concentration deficits

The model was validated with a second experiment in the climate cells, following the same set-up described in Section 4.1. Nutrient solution volumes remained covered and were replenished every three days and aerated daily. The experiments used transplanted Batavia lettuce, 45 days after sowing. The specific leaf area (SLA) relationship (Tei et al., 1996) was applied to estimate the LAI from weight at harvest. The LAI varied between 2.9 and 3.4 (Table 1). The other specifications correspond to the boundary conditions mentioned in Section 4.1.

The objective of this experiment was to have two sets of pre-fixed levels of vapour concentration deficit (VCD). The first chamber (control) was continuously maintained at 21/19 °C and 75% RH (VCD 4.4/2.7 g/m^3). The climate settings of the second chamber were changed stepwise every two days in order to attain a range of vapour concentration deficits. However, we discovered that our control of the humidity was very limited at each temperature set-point, which resulted in four separate levels of VCD (Table 1). Within each chamber we had three different PPFD on the three scales.

5. Model results & discussion

Sections 5.1–5.3 present the validation results and discuss them with respect to model performance for the transpiration rate. In Section 5.4 the energy balance and distribution in closed plant production systems has been illustrated and discussed for a standard production climate.

5.1. Model validation for photosynthetic photon flux densities

In this experiment transpiration rates were continuously registered throughout the day for a full canopy cover illuminated under various PPFD. The average slope of the decline in weight of each set-up was used to determine transpiration rates at light and dark.

Our experiment resulted in a 24 h average transpiration rate of 0.032 g/m^2 s (115 g/m^2 h). The model calculated a 24 h average transpiration rate of 0.030 g/m^2 s (108 g/m^2 h). The corresponding root mean square error (RMSE) is 0.004 g/m^2 s (15.87 g/m^2 h). The simulated transpiration rate in our model has a considerable correlation with the experimental data as far as figures during light are concerned (Fig. 3). In contrast, the simulated transpiration rate at dark was less consonant with the experiment: 0.011 g/m^2 s (40 g/m^2 h) versus 0.016 g/m^2 s (58 g/m^2 h), respectively.

As most transpiration occurs under light, this error will only have a limited bearing on the dimensioning of HVAC systems for plant factories. The discrepancy is likely caused by the stomatal resistance; at dark it is set at 450 s/m (Eq. 9). Adaptation of the equation on the specific or cultivar level might improve correlation.

5.2. Model validation for crop cover

In the study of Wheeler et al. (1994) ET rates were daily registered and the development of canopy cover and the accumulation of dry mass were periodically assessed. Their data were transcribed to determine the dry mass development in relation to canopy cover. The SLA relationship (Tei et al., 1996) was applied to estimate the development of LAI as a function of canopy cover.

The experiment resulted in an average ET rate of 3991 g/m^2 d, of which Wheeler et al. (1994) estimated that 1000 g/m^2 d was free evaporation from exposed water surface. They obtained this estimate by extrapolating measured ET rates to zero crop cover. In order to compare transpiration rates, we show our calculated values and the experimental data thus corrected (Fig. 4). The RMSE is 361 g/m^2 d (15.04 g/m^2 h).

5.3. Model validation for vapour pressure deficit

In this experiment transpiration rates were continuously registered throughout the day for a full canopy cover illuminated under various PPFD. Scheduled changes to air temperature and RH offered insight into the effect of vapour concentration deficit on ET. Transpiration rates were determined as described in Section 5.1.

The experiment resulted in a wide range of transpiration rates. The simulated transpiration rates in our model have a fair correlation with the experimental data. Similar to Section 5.1, the correlation is greater under light than at dark (Fig. 5). The RMSE under light is 15.96 g/m^2 h, whereas at dark it is 18.06 g/m^2 h.

5.4. Distribution of energetic fluxes

We have simulated four sets of climate conditions in order to illustrate the variable distribution of energetic fluxes in a plant factory, as determined by plant processes. The differences between the sets of conditions are limited to temperature and PPFD (Table 2). The efficiency of the LED-lighting system (the conversion of electric power to $I_{lighting}$) of each experiment was set at 52% (Royal Philips N.V., 2015). These simulations provide insight into the influence of temperature and PPFD on transpiration and the distribution of latent and sensible heat.

The Sankey diagram (Fig. 6) illustrates the simulated fluxes and consequently the importance of transpiration as a design parameter for climatisation. Firstly, the latent heat flux constitutes the largest single flow of energy in each simulation and even exceeds the input energy at lower PPFD (140 μmol/m^2 s). Secondly, we can see that the relative share of the latent heat flux increases with higher air temperatures.

Plant factories are closed systems that generally rely on relatively high PPFD and temperatures to shorten production cycles. Following our simulations, the cooling demand of these plant factories is presumably relatively high, as a result of the increased sensible heat exchange with the lighting system and the decreased sensible heat exchange with the (cooling) plant canopy. The most important finding, however, is that the latent heat flux can even exceed the input energy in certain situations. This impact is greater than expected and necessitates an a

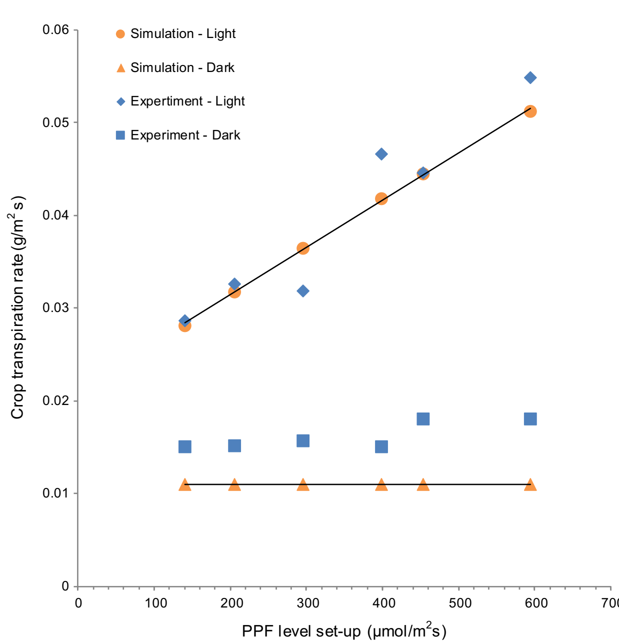

Fig. 3. The simulated transpiration compared to measurements for various PPFD. Measurements are represented by diamonds (photoperiod) and squares (dark period), simulations by circles (photoperiod) and triangles (dark period).

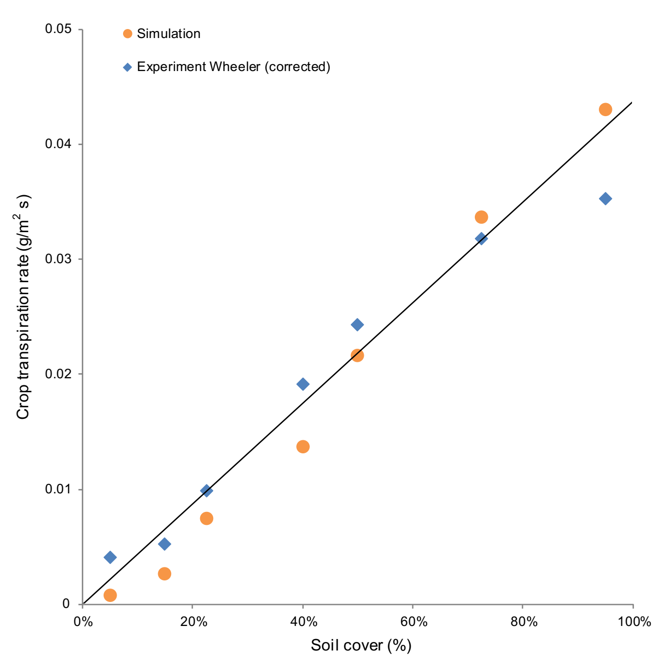

Fig. 4. The simulated crop transpiration compared to measurements for various cultivation area cover percentages. Measurements are represented by diamonds, simulations by circles.

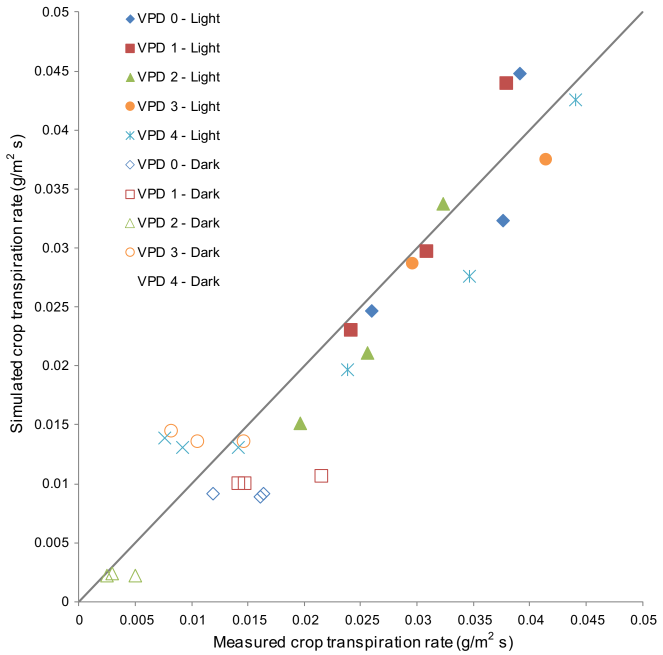

Fig. 5. The simulated transpiration compared to measurements for various vapour concentration deficits. Results under light are represented by solid markers and results in dark are represented by outlines. Diamonds represent the (control) VCD Set 0 (4.4/2.7 g/m^3), squares represent VCD set 1 (3.7/2.3 g/m^3), triangles represent VCD set 2 (2.3/0.5 g/m^3), circles represent VCD set 3 (5.2/3.5 g/m^3) and stars represent VCD set 4 (3.3/3.3 g/m^3).

priori assessment of the energetic fluxes for the design of plant factories. Our model can be used for such an assessment.

6. Outlook

6.1. General considerations

The aim of this study was to explicate the energetic fluxes associated with the production of lettuce in plant factories. Validation results showed that our model predicted the transpiration of the lettuce crop with great accuracy for different lighting intensities, air humidities and stages of development (cultivation area cover and LAI). No additional calibration was deemed useful.

The presented model offers two key advantages for the design of plant factories and vertical farms.

Firstly, our model offers a prospective and rather accurate insight into the role of plant processes in the total energy balance. The (evapo)-transpiration is an important design parameter that has been frequently neglected in research on closed climate production.

Secondly, our model is versatile enough to be applied to different crops, types of growing environment and interior climates. We have demonstrated the accuracy of the model under a broad range of climate conditions (PPFD, temperature, RH) and crop development stages.

We envisaged designing this model as a simple and useful tool for the energetic optimisation of plant factories. In this process oversimplification might have played a role and relevant aspects may have been neglected. For example, the performance of the transpiration model can still be improved by implementing dynamic LAI and cultivation area cover models. This allows for a more accurate simulation throughout the different stages of crop development and for an optimisation of crop respacing. Predicting the transpiration of a fully developed crop may suffice for the design of plant factories, however, as HVAC systems are generally dimensioned according to the highest load. In this respect, other simplifications may prove to be non-critical as well, such as the obvious weakness of having empirical, crop specific parameters in the estimate of the surface (stomatal) resistance.

Given these results, the model is considered to be appropriate for a realistic simulation of the vapour flux associated with the production of lettuce in plant factories.

6.2. Total energy requirement for plant factories

The vapour flux and consequent dehumidification relatively require a large amount of energy. The other influential processes are artificial illumination and climatisation. Light for photosynthesis has to be artificially supplied in plant factories. Additionally, the need for forced air circulation and conditioning results in higher energy costs. Finally, the design and efficacy of plant factories will depend on economic consequences as well. The benefits of plant factories compared to traditional greenhouses have to compensate for these additional costs.

6.3. Comparison with greenhouses

We simulated the energy requirement of the production presented by Wheeler et al. (1994) and compared this to the requirement of standard greenhouse production in the Netherlands (Vermeulen, 2014). Global solar radiation in the Netherlands is 3.54 GJ/m^{2}y (KNMI, 2014) and we assume a greenhouse transmissivity of 65%. No whitewash is applied. In addition to solar radiation, the greenhouse production of lettuce requires gas for heating (94 kWh$_E$/m^{2}y), storage and steaming (52 kWh$_E$/m^{2}y), as well as electricity for various other uses (5 kWh$_E$/m^{2}y) (Vermeulen, 2014). Without solar energy, greenhouses approximately require 1.55 kWh$_E$ to produce a single crop of lettuce (average fresh weight 289 g). When we integrate solar energy, however, one crop of lettuce requires approximately 8.08 kWh$_E$. In the aforementioned plant factory a single crop with the same fresh weight would approximately require 7.57 kWh$_E$.

Apart from lighting, greenhouses rely more on natural ventilation for dehumidification, whereas plant factories rely solely on mechanical air conditioning. As a result, the vapour flux and the consequent latent cooling load are a significant factor in the total energy consumption of plant factories.

Table 2
The specific sets of crop production data and interior climate conditions used in determining the distribution of energy fluxes from the crop (and lighting system) to the surrounding air via simulation. Double values (e.g. 21/19) represent photo-/dark period, respectively.

	Set A –high PPFD & low temperature	Set B–high PPFD & high temperature	Set C–low PPFD & low temperature	Set D–low PPFD & high temperature
Cultivation area cover [%]	95	95	95	95
LAI	3.0	3.0	3.0	3.0
Mean air temperature [°C]	21/19	25/23	21/19	25/23
Relative Humidity [%]	73/83	73/83	73/83	73/83
VCD [g/m^3]	5.0/2.8	6.3/3.5	5.0/2.8	6.3/3.5
PPFD [μmol/m^{2}s]	600	600	140	140
PAR flux density [W/m^2]	120	120	28	28
R_{net} [W/m^2]	108.3	108.3	25.3	25.3
r_s [s/m]	158/450	158/450	289/450	289/450
r_a [s/m]	100/100	100/100	100/100	100/100

Fig. 6. The distribution of energy fluxes from the crop (and lighting system) to the surrounding air, following four different climate sets. The diagrams illustrate the results at a PPFD of 600 μmol/m^2 s or 140 μmol/m^2 s and a temperature regime of 21/19 °C or 25/23 °C. Positive fluxes are represented in solid red, negative fluxes in cross-hatched blue. Please refer to the web version of this article for interpretation of the references to colour in this figure legend.

However, the plant factory could also present several benefits in other fields. The main differences in the total energy consumption between greenhouses and plant factories are the result of envelope design and plant processes. The exterior climate has a significant impact on the heating load in greenhouses due to heat transfer across the building envelope. In plant factories, however, the exterior climate has a much smaller effect than the internal loads imposed by lights and plants (Harbick & Albright, 2016). Katsoulas et al. (2015) show that the highest attainable water use efficiency decreases with the coupling of greenhouse environment to the outside air (an indicator of ventilation requirements). They found that water use efficiency increased significantly in closed systems as the result of two processes: (1) the increased productivity due to a more adequate microclimate with a higher CO_2 concentration and (2) the ability to collect and reuse transpired water condensing at the cooling element. The high water use efficiency, CO_2 efficiency and production density of closed production systems offer perspectives for locations where resources such as land or water are scarce.

7. Conclusion

In this study a crop transpiration model was developed and validated. It describes the energetic fluxes associated with the production of lettuce in closed plant production systems. The model illustrates the energetic distribution of sensible heat and latent heat and the corresponding vapour production. This offers insight into the role of plant processes in the total energy balance of production in plant factories and vertical farming facilities.

The presented model can be used to analyse and optimise the design of plant factories. The model does not require extensive empirical data and can therefore readily provide an accurate estimate for a range of closed production climates. Models may be developed for high-density production in isolated systems, systems integrated into (structurally vacant) buildings or even as an integral part of the city. Transpiration can be integrated effectively as a design parameter and the total energy profile of plant factories can be assessed in detail. Future research can adapt our model as input for more extensive analyses and calculations with regard to production output, production climate and energetic performance.

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Appendix A. List of symbols

Symbol	In model	Description	Unit
CAC	–	cultivation area cover percentage	[%]
c_p	–	specific heat of air	[J/kg °C]
e^*	e_sta	saturated vapour pressure [kPa]	[kPa]
EB	E_b	energy balance	[–]
H	H	sensible heat flux	[W/m^2]
$I_{lighting}$	–	irradiance of photosynthetically active radiation	[W/m^2]
l	–	mean leaf diameter	[m]
LAI	LAI	active leaf area index	[m$^2_{leaf}$/m$^2_{cultivation}$]
$PPFD$	–	photosynthetic photon flux density	[μmol/m^{2}s]
r_a	R_a	aerodynamic boundary layer resistance	[s/m]
RH	RH	relative humidity	[%]
R_{net}	R_netto	net radiation	[W/m^2]
r_s	R_s	surface (stomatal) resistance	[s/m]
T_a	T_a	air temperature	[°C]
T_s	T_s	crop canopy temperature	[°C]
u_∞	–	uninhibited air velocity	[m/s]
Q_R	–	heat transfer by radiation, per façade	[W/m^2]

(continued on next page)

Appendix A *(continued)*

Symbol	In model	Description	Unit
		surface area[a]	
Q_F	–	heat transfer across greenhouse glazing, per façade surface area[a]	[W/m^2]
Q_L	–	latent heat transfer of sensible energy, per greenhouse surface area[a]	[W/m^2]
Q_{Comp}	–	heat transfer by the various greenhouse components, including structural components and systems, per component surface area[a]	[W/m^2]
Q_{Equip}	–	internal heat load from the equipment, per component surface area[a]	[W/m^2]
$Q_{Façade}$	–	heat transfer across the façade, per façade surface area[a]	[W/m^2]
Q_{Heat}	–	heat added to the greenhouse using a heating system, per greenhouse surface area	[W/m^2]
Q_{HVAC}	–	additional heating or cooling by Heating, Ventilation, Air-Conditioning (HVAC) systems, per greenhouse surface area	[W/m^2]
Q_{Plant}	–	heat transfer by plant processes, per canopy surface area[a]	[W/m^2]
Q_{Soil}	–	heat transfer between the ground and air, per greenhouse surface area	[W/m^2]
Q_{Vent}	–	heat transfer by natural and mechanical ventilation, per greenhouse surface area	[W/m^2]
δ	Delta	relationship between saturation vapour pressure and air temperature	[kPa/°C]
ε	Epsilon	vapour concentration (slope of the saturation function curve)	[−]
λ	Lambda	latent heat of the evaporation of water	[J/g]
λE	La_E	latent heat flux	[W/m^2]
ρ_r	–	reflection coefficient of the crop	[%]
ρ_a	–	density of air	[kg/m^3]
$\rho_a\, c_p$	Rc	heat capacity of air	[J/kg°C]
χ	–	vapour concentration	[g/m^3]
χ_a	X_t_a	vapour concentration of the air	[g/m^3]
χ_a^*	X_sta	saturated vapour concentration of the air	[g/m^3]
χ_s	X_sts	vapour concentration at the canopy level	[g/m^3]
γ	Gamma	psychometric constant of 66.5	[Pa/K]

[a] These values have to be normalised for greenhouse surface area in order to be used in the total energy balance.

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