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# Modified energy cascade model adapted for a multicrop Lunar greenhouse prototype

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**Abstract**

Models are required to accurately predict mass and energy balances in a bioregenerative life support system. A modified energy cascade model was used to predict outputs of a multi-crop (tomatoes, potatoes, lettuce and strawberries) Lunar greenhouse prototype. The model performance was evaluated against measured data obtained from several system closure experiments. The model predictions corresponded well to those obtained from experimental measurements for the overall system closure test period (five months), especially for biomass produced (0.7% underestimated), water consumption (0.3% overestimated) and condensate production (0.5% overestimated). However, the model was less accurate when the results were compared with data obtained from a shorter experimental time period, with 31%, 48% and 51% error for biomass uptake, water consumption, and condensate production, respectively, which were obtained under more complex crop production patterns (e.g. tall tomato plants covering part of the lettuce production zones). These results, together with a model sensitivity analysis highlighted the necessity of periodic characterization of the environmental parameters (e.g. light levels, air leakage) in the Lunar greenhouse.
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*Keywords:* Bioregenerative life support system (BLSS); Crop models; Energy cascade model; Life sciences; Lunar greenhouse

## 1. Introduction

Future human colonization of the solar system will require the permanent presence of a large number of astronauts over great distances from Earth (e.g. Lunar and/or Martian outposts). The current practice of transporting and storing (i.e. resupplying) all the ingredients required to support human activities away from Earth must yield to a new system approach that involves extensive use of regenerative components (Barta and Henninger, 1994). Over the past two decades, bioregenerative life support systems (BLSS) emerged as the premiere approach to overcome the need to continuously resupply consumables from Earth (Mitchell, 1994). Such systems are generally able to (a) revitalize the atmosphere by giving out oxygen and storing carbon dioxide, (b) purify water and, most importantly, (c) provide edible fresh food (i.e. vegetables).

Generally, higher plants are extremely important because of their regenerative properties. Such biological systems are very effective in providing biomass and

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regenerate consumables. Indeed, higher plants as a mean to recycle carbon dioxide, treat organic wastes, extract oxygen, food and potable water have been studied in integrated systems (Wheeler et al., 1996). Most of studies have had the primary goal of maximizing the equivalent system mass (ESM) efficiency (Levri et al., 2003) which is a measure of resources produced over system cost (in terms of mass, volume, energy consumption and required crew time).

The Lunar greenhouse (LGH) project at the University of Arizona, Controlled Environment Agricultural Center (UA-CEAC) has similar goals which specifically include the development and characterization of a multi-crop, closed Lunar greenhouse prototype (Sadler et al., 2009). The LGH project comprises the development and characterization of a multi-crop closed planetary greenhouse testbed. Specifically conceived for future Lunar outposts that heavily rely on inflatable technology (Sadler et al., 2008), the proposed LGH system is comprised of four independent, cylindrical-shaped growth chambers each with approximately 19 $m^3$ of available volume. Whereas only one module is currently producing biomass, it is expected that the four modules will be made operational within the next six months. Each chamber is equipped with a cable supported recirculating nutrient delivery system, six water-cooled high pressure sodium lamps for illumination, and a recirculating air temperature control system with air diffusers located at the cable culture system level. Production of various NASA targeted crops has been achieved during the developmental period of the LGH, and now it has simultaneously grown lettuce, tomato, sweet potato, and strawberry within several system closure experiments which will be reported in this publication.

Modeling represents an integral component of the overall LGH biomass production and regenerative performance characterization. Models capable of accurately predicting mass and energy balance of the proposed LGH system are important to provide a critical link between collected data and overall system behavior. Control strategies capable of compensating the effects of environmental disturbances on crop growth can be more advantages and useful for advanced life support systems (Fleisher and Baruh, 2001). Most controllers are designed and work to maintain static setpoints in the production system. These setpoint values are typically derived from heuristic information and experiential studies for a given crop. Thus, environmental control tends to focus more on maintaining current setpoints with preset values without incorporating environmental disturbances and their effects on the crops in the control.

For many years, the development of system-level models for BLSS has been the major goal of the advanced life support (ALS) system and integration modeling and analysis project (SIMA) (Hanford and Gertner, 1998). Such community promoted the development of "energy cascade models," explanatory models also referred as mechanistic or process models based on an understanding of specific processes. Energy cascade model predicts crop productivity during crop growth and development based on analysis involving light absorption, canopy quantum yield, and carbon use efficiency. It evaluates time dependence and major features of the series of efficiencies in the crop's growth and development, these are the series called energy cascade. Energy cascade models can depict the overall photosynthetic $CO_2$ uptake during photo period and its liberation with respiration during dark period with five fundamental trends (Volk et al., 1995; Volk, 1996). These were explained as: a linear increase in photosynthetic photon flux density (PPFD) absorption to canopy closure, a constant canopy quantum yield until the onset of senescence, followed by a linear decline to the end of the life cycle, and lastly constant carbon use efficiency over the life cycle. Energy cascade models were initially calibrated for wheat (Volk et al., 1995), and following efforts extended model calibrations to other crops such as dry bean, lettuce, peanut, white potato, rice, soybean, sweet potato, tomato, and wheat (Jones and Cavazzoni, 2000). Eventually, the modeling effort culminated in the development and test of the modified energy cascade model (MEC) (Cavazzoni, 2001, 2004).

The MEC model is an explanatory crop model developed with sufficient detail, flexibility and generality for Advanced Life Support (ALS) systems studies, with the objective for the simplified crop models to be suitable not only for nominal conditions, but also for estimating the direction and magnitude of changes in off-nominal conditions. The term "explanatory" has been employed in alternative to process and/or mechanistic term because many mechanisms involving plant processes are either not well characterized or simply unknown (Cavazzoni, 2004). Indeed, the MEC model heavily relies on multivariate equations (generally polynomials) whose coefficients have been determined via ad-hoc curve fitting of experimental data (Cavazzoni, 2001).

In this paper, the development of an energy cascade model for a multi-cropping system in a Lunar greenhouse prototype is reported. Our team, which involves a collaborative effort between the UA-CEAC, the Italian space company Thales Alenia Space Italia and its Recyclab advanced life support research facility, derived and simulated a crop growth mass balance model using a proposed modified version of the Cavazzoni's MEC model. The MEC model is an explanatory model developed for Advanced Life Support (ALS) systems studies, with the objective for using simplified crop models suitable not only for nominal conditions, but also for estimating the direction and magnitude of changes in off-nominal conditions. The MEC model in the current collaboration was further modified for predicting plant biomass production, oxygen and water generation, and carbon dioxide, water and plant nutrient consumption. The model predictions were calculated as a function of photosynthetic photon flux density (PPFD), carbon dioxide partial pressure, total atmospheric pressure, air temperature and relative humidity, and crop age and type. The MEC model was utilized within the validity

limits described by of Hanford (2004), however, several modifications were required for application to the LGH system. First, the multi-crop production was introduced in the MEC through independent application of single-crop models. Second, the different plant canopies of the multiple crops which were located at different positions within the volume space of the LGH were evaluated as independent layers within a three dimensional production volume, in order to evaluate their individual contributions to the overall performance of the system. Particular attention was given to the local microclimates, plants arrangements, and transient nature of the crop growing in the system. Third, the, mass exchange rates that were daily based in the original MEC, were changed to an hourly basis in the modified MEC to determine the day and night transition dynamics of the system. Such increased resolution would also help evaluate implications of off-nominal situations such as reduced plant transpiration or photosynthesis caused by short-term LGH system failures (e.g. lamp outage, power loss, etc). Furthermore, the proposed approach will help to determine the proper independent greenhouse unit sizes and redundancies to guarantee certain system performances. Model performance analysis and validation as well as the identification of the model output sensitivities to input parameters is executed using the LGH multi-crop testbed available at UA-CEAC.

This paper is organized as follows. In Section 2, the MEC model is briefly reviewed. In Section 3, the Modified MEC (MMEC) model algorithm and its equations are discussed in detail. In Section 4, the LGH system, which is employed as experimental setup to test and validate the proposed MMEC model is described. In Section 5, the results of the model validation based on LGH closure experiments is reported. Finally conclusions and future efforts are reported in Section 6.

## 2. The modified energy cascade model

The MEC model (Cavazzoni, 2004) originated from the "Energy Cascade" crop model used for ALS system studies by Jones and Cavazzoni (2000), which was developed for the wheat crop using data available in literature (Volk et al., 1995). The model had been demonstrated within several applications, in part, due to its simplicity (Pitts and Stutte, 1999). There was a need to expand the model to predict the growth of different crops, while accounting for the relevant controllable parameters in ALS plant growth facilities, such as radiation, temperature, humidity, pressure, and $CO_2$ partial pressure. Therefore, the MEC model was additionally developed for, soybean, white potato, lettuce, peanut, rice, sweet potato, dry bean and tomato. It was then expanded using literature data and descriptive models to predict oxygen production and plant transpiration.

The MEC model calculated plant growth in terms of biomass production using the daily carbon gain dependent on three basic parameters; the canopy light absorption, the canopy quantum yield (CQY), and the 24-hour carbon use efficiency ($CUE_{24}$). The biological and physical trends were predicted based on these parameters, and included: an increase in canopy light absorption from emergence through canopy closure; a constant (maximum) light absorption after canopy closure; a constant CQY through the onset of senescence, which then decreased linearly thereafter until crop completion; a $CUE_{24}$ similar to that of CQY for soybean, peanut and dry bean, and a constant life-cycle $CUE_{24}$ for all the non-legume crops. The biomass carbon fraction for the different crops was to calculate the daily oxygen production from daily carbon gains utilizing a plant biosynthesis model (after Penning de Vries et al., 1989). Descriptive models were developed to include the effects of air temperature on crop-specific values of the above-mentioned parameters. This allowed for consideration of different air temperature regimes. A multi-layer plant canopy photosynthesis model was used to generate multivariable polynomial regression equations for the calculation of maximum canopy quantum yield as dependent on irradiance and $CO_2$ concentrations. Finally, a crop transpiration component was added to the MEC model using relationships linking canopy stomatal conductance to canopy net photosynthesis (Monje, 1998).

## 3. The modified MEC (MMEC) model algorithm

The LGH system was created for optimum volume utilization and total mass minimization through resources recycling (Sadler et al., 2009). Therefore, it has several inherently difficult geometric and environmental challenges to overcome when modeled. The non-uniformity of environmental parameters (i.e. irradiance, air temperature and relative humidity) is inherent among the multi-layer

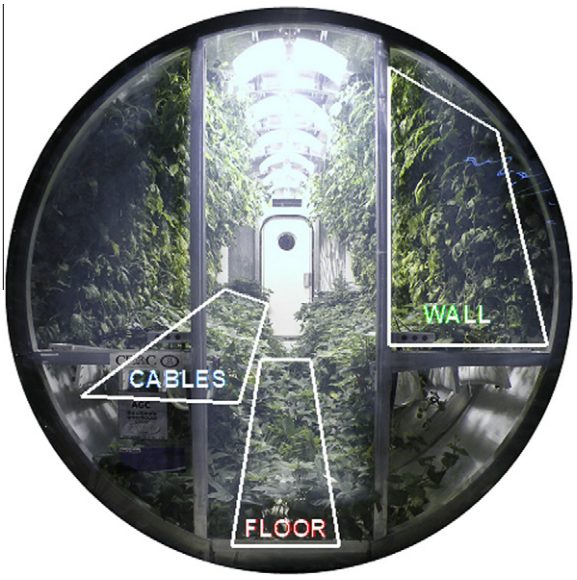


Fig. 1. End view of the multi-layer crop geometry within the LGH crop production module. Three distinct layers (floor layer; cable culture system layers; and wall layers) have been considered for separate environmental conditions within the MEC.

crop geometry (Fig. 1). These non-uniformities and their effects on plant response were incorporated into the modified MEC model. For instance, lettuce, tomato and sweet potato crop were simultaneously produced within the LGH at three distinct locations. These included: the cable-culture system level (CABLES layer), which was located adjacent to the air ventilation outlet diffusers and directly beneath the photosynthetic lighting; a tomato crop grown in the two rows locations along the chamber circumferential walls (WALL layer), which were further from the air outlet diffusers and, by virtue of their tall stature, much closer to the lamps; a sweet potato crop, which grew down toward the floor (FLOOR layer), into a less lighted region.

Furthermore, the micro-environmental conditions changed in response to the growth stage of the plant, as the closure experiment progressed. For example, the tomato plants were trained to grow vertically upward being supported on string from above, and they gradually covered the outer walls of the LGH, thereby eliminating the portion of photosynthetic light reflected by the chamber cover to the lettuce plants below. Also as the lettuce filled the region adjacent to the air diffuser tube, air movement and distribution of the environmentally controlled air changed. In order to represent these micro-environmental characteristics and their effects on the model, more appropriately, the volumetric space of the growth chamber was divided into layers (Fig. 1). Each layer and specific crop was modeled as a mono-crop culture, with its own temporal-dependent microclimate parameters and intercepted light levels. The contribution of each crop layer for each produced and consumed resource was then summed to determine the totals as:

$$\mathrm{OUTPUTj}_{(t0,t1)} = \Sigma_i \int_{t0}^{t1} F\mathrm{j}(\mathrm{INPUTS}(\mathrm{t},i))dt \tag{1}$$

where $i$ is the mono-crop layer identification number; OUTPUTj is one of the model outputs (e.g. total oxygen produced); $F$j is one of the functions used to calculate model outputs from model inputs (specifically Eqs. (6), (8), (9), (11), (16)); and, INPUTS(t, $i$) are the $i$ crop layer model inputs parameters (e.g. air temperature) at time $t$. Each time dependant parameter was described by a staircase function, having step duration of two weeks. The step duration was determined as dependant on the variability of the parameters during the experiments, thus on the energy applied to the system. Each of the $F$j equations was based on the original MEC model equations, with the same limits and domain. Thus, the model generally applies over a range of PPFD from 200 to 1000 μmol $m^{-2}$ $s^{-1}$, relative humidity from 35 to 100%, and $CO_2$ from 330 to 1300 ppm. Differently, a time step of one hour was used for evaluating the mass exchange rates instead of the original MEC one day step. This allowed day to night environmental dynamic variations to be measured and evaluated, as well as, any short term LGH system inadequacies or even failures on the ALS system balances.

The modified MEC model and the resulting algorithm used in this study are detailed in the following section. Table 4 is presents full descriptions of the variables used in the model.

The MEC daily carbon gain (DCG) was scaled into hourly carbon gain (HCG), keeping the same MEC-model assumption to allocate the daily biomass uptake only for the photoperiod. Eq. (2) was used to determine HCG for each layer independently:

$$\mathrm{HCG} = \alpha \times \mathrm{CUE}_{24} \times A \times \mathrm{CQY} \times \mathrm{PPFD} \times I \tag{2}$$

where $A$ is the fraction of PPFD absorbed by the canopy (Eq. (5)), PPFD is the photosynthetic photon flux density from the lighting system, $I$ is equal to 1 and 0 during the photoperiod (day) and dark period (night), respectively, $\alpha$ is unit conversion factor. The canopy quantum yield (CQY) is defined by Cavazzoni (2004) as:

$$\begin{aligned}\mathrm{CQY} &= \mathrm{CQY}_{MAX} \quad \text{for } \mathrm{t} \leqslant t_Q \\ &= \mathrm{CQY}_{MAX} - (\mathrm{CQY}_{MAX} - \mathrm{CQY}_{MIN})(t - t_Q)(t_M - t_Q)^{-1} \quad \text{for } t_Q < t \leqslant t_M\end{aligned} \tag{3}$$

For most crops $\mathrm{CUE}_{24}$ is constant, while for legumes:

$$\begin{aligned}\mathrm{CUE}_{24} &= \mathrm{CUE}_{MAX} \quad \text{for } t \leqslant t_Q \\ &= \mathrm{CUE}_{MAX} - (\mathrm{CUE}_{\mathrm{MAX}} - \mathrm{CUE}_{MIN})(t - t_Q)(t_M - t_Q)^{-1} \quad \text{for } t_Q < t \leqslant t_M\end{aligned} \tag{4}$$

while

$$\begin{aligned}A &= A_{MAX}(t/t_A)^n \quad \text{for } t < t_A \\ A &= A_{MAX} \quad \text{for } t \geqslant t_A\end{aligned} \tag{5}$$

where $t_A$ is the time of canopy closure, and $n$ is a crop dependent exponent.

Therefore, it is possible to evaluate the hourly crop growth rate (HCGR), on a dry mass basis, as follows:

$$\mathrm{HCGR} = \mathrm{HCG} \times \mathrm{MW}_C \times \mathrm{BCF}^{-1} \tag{6}$$

where $\mathrm{MW}_C$ is the carbon molecular mass, and BCF is the biomass carbon fraction. The effective hourly crop growth rate (on a wet mass basis, HWCGR), is then calculated as:

$$\mathrm{HWCGR} = \mathrm{HCGR} \times (1 - \mathrm{WBF})^{-1} \tag{7}$$

The daily net oxygen production provided two contributions, including an hourly photosynthetic oxygen production (HOP, Eq. (8)), limited to photoperiod by HCG, and an hourly oxygen consumption from plant respiration (HOC, Eq. (9)), which contributed throughout the photoperiod and the dark period. The manipulation of the formula was justified by previously defined $\mathrm{CUE}_{24}$ parameter within the MEC, which represents the ratio of the daily net carbon gain to gross carbon photosynthetic assimilation. The oxygen consumption by respiration was evaluated as the difference between gross and net oxygen production throughout the photoperiod (H). This allowed evaluation of crop gas exchanges during failures in the environmental system for a short time period (i.e. a broken lamp), while providing the same daily results of the MEC model during nominal conditions. The following equations allow to distribute the contribution of plant respiration over the complete day.

$$HOP = HCG/CUE_{24} \times OPF \times MW_{O2} \quad (8)$$

$$HOC = HCG/I^{*}(1 - CUE_{24})/CUE_{24} \times OPF \times MW_{O2} \times H/24 \quad (9)$$

where OPF is the oxygen production fraction and $MW_{O2}$ is the oxygen molecular mass (32 g $mol^{-1}$).

The transpiration model was adapted to provide hourly transpiration rates (HTR) as:

$$HTR = \beta \times (MW_w) \times gc \times (VPD/P_{atm}) \quad (10)$$

where the constant ß is used to convert rates from second to hours; MWw is the molecular weight of water; $g_C$ is the canopy surface water vapor conductance (Eq. (11)); $P_{atm}$ is the BLSS atmospheric pressure; and, VPD is the vapor pressure deficit (Eq. (12)). VPD and $g_C$ were the same as defined in the original MEC model.

$$g_C = (g_A \times g_S)(g_A + g_S)^{-1} \quad (11)$$

where $g_A$ (BLSS water vapor aerodynamic conductance) and $g_S$ (canopy water vapor stomatal conductance) are defined for horizontal planar canopies, such as lettuce, soybean, sweet potato as:

$$g_S = (1.717 \times T - 19.96 - 10.54 \times VPD) \times (P_{NET}/[CO_2])$$

$$g_A = 2.5$$

while for vertical canopies, such as for tomato:

$$g_S = 0.1389 + 15.32 \times RH \times (P_{NET}/[CO_2])$$

$$g_A = 5.5$$

and

$$VPD = VP_{SAT}(1 - RH) \quad (12)$$

$$VP_{SAT} = 0.611 \times \exp[(17.4 \times T)/(T + 239)]$$

where, $T$ is the air temperature; $VP_{SAT}$ is the saturation vapor pressure; $[CO_2]$ is the BLSS carbon dioxide concentration; RH is the relative humidity. The canopy net photosynthesis ($P_{NET}$) is calculated as:

$$P_{NET} = A \times CQY \times PPFD \quad (13)$$

In addition, simplified equations were used to model $CO_2$ consumption, water and nutrients use, which were not part of the MEC models, but were necessary for a complete mass balance. Hourly carbon dioxide consumption by photosynthesis ($HCO_2C$), as well as, carbon dioxide production by respiration ($HCO_2P$) were included, and were considered as per Hanford (2004) to equal the moles of oxygen of the photosynthesis and respiration reactions (Eq. (8) and (9)):

$$HCO_2C = HOP \times MW_{CO2} \times MW_{O2}^{-1} \quad (14)$$

$$HCO_2P = HOC \times MW_{CO2} \times MW_{O2}^{-1} \quad (15)$$

where $MW_{CO2}$ is the carbon dioxide molecular mass.

The hourly plant macronutrients uptake (HNC) was evaluated dependent on the plant dry biomass generation rate (Hanford, 2004):

$$HNC = HCGR \times DRY_{fr} \times NC_{fr}$$

where $DRY_{fr}$ is the crop-dependent dry over wet biomass fraction (Hanford, 2004, Table 4.2.7), and $NC_{fr}$ is the fraction of nutrient consumed for gained dry mass (Hanford, 2004, Table 4.2.10). Finally, Hourly Water Consumption (HWC) was computed to complete the mass balance:

$$HWC = HTR + HOP + HCO_2P + HWCGR - HOC - HCO_2C - HNC \quad (16)$$

The MEC model calculated resource exchanges per unit time and per unit crop growing surface, assuming a fixed reference planting density for each crop. The LGH with its multi-cropping and multi-layer growing procedures required the use of various planting densities in the model. Thus, the evaluation of the growing area in the model was completed by dividing the number of plants of each single crop by the MEC reference planting density.

## 4. Experimental design of the UA-Lunar greenhouse (LGH) system

### 4.1. LGH system

The prototype LGH is a demonstration of a lightweight membrane hydroponic crop production system, called Cable Culture (Giacomelli, 1987) within a closed environment that exhibits a high degree of future planetary mission fidelity (Sadler et al., 2008). The LGH complex was designed and constructed for a four person crew based on NASA estimates that 28 to 40 $m^2$ of crop production area per crew member would generate 50% of the total caloric intake (Wheeler, 2003). The current LGH in operation was envisioned to be one of four LGH greenhouse units within a proposed Lunar habitat in a hub and spoke arrangement (Sadler et al., 2008). The single LGH unit was 2.1 m in diameter and 5.5 m in length, and was constructed of rigid aluminium frame and thin film surface cover (F-Clean ETFE, AGC Inc., Japan), with a capability to be stored in a collapsed position for transit (Fig. 1). When deployed the LGH had the hydroponic and the crop lighting systems in place for immediate operation, and it provided an interior volume of 19 $m^{-3}$ and 11.1 $m^2$ of canopy area when configured with a horizontal, single plane growing system. When vertical crops cover the perimeter area of the walls, an additional vertical growing area was achieved; this depended upon the poly-culture crop distribution and the specific cultivars that were utilized. The environmental conditions of the LGH were maintained by an air conditioning system using a heat exchanger to cool and de-humidify the atmosphere within a closed loop design. Plant growth lighting was provided by six, 1000W HPS water-jacketed lamps developed by the Sadler Machine Company (Giacomelli et al., 2003). The lighting fixtures were mounted on the folding upper connecting links of the structural support rings of the LGH frame. The lamps consist of a luminaire and a bulb enclosed within a quartz glass, double-walled annulus with

de-ionized cooling water provided by a heat exchanger located outside of the LGH. The lamp ballasts were also located outside of the LGH. The readers are referred to Sadler et al. (2008, 2009) for further details of the LGH system hardware.

### 4.2. Crop growing system

Cable culture (Fig. 2) is a soil-less hydroponic crop growing system compatible with the LGH folding structure architecture. Plants were grown in the flexible plastic film envelope where the envelope was suspended from a cable supported at each end of the LGH; the envelope was formed around the cable and held closed by a Velcro-like attachment, allowing the plant stem to extend out of the top of the envelope while keeping the roots enclosed; the hydroponic nutrient was introduced at both ends of the envelope and flowed along the plant roots to the mid-span of the cable-supported envelop, where it discharged from the envelop and returned to the reservoir (Sadler and Giacomelli, 2007). The plants were germinated within 20 $cm^3$ rock wool growing media (Grodan Inc.) to start the seedling within a nursery located outside the control volume of the LGH. Once established, the roots have no additional media or physical support except for the enclosure of the envelope. Cultivars grown in the project period included NASA candidate crops such as lettuce (*Lactuca sativa L.*, cv. 'Cos'), strawberry (*Fragaria X ananassa L.*, cv. 'Seascape'), sweet potato (*Ipomoea batatas L.*, cv.'Beauregard'), and tomato (*Lycopersicon esculentum L.*, cv. 'Clermon'). An in-row spacing of 15 cm for lettuce, 20 cm for strawberry, 20 cm for sweet potato, and 30 cm for tomato was used. Row-to-row spacing was 20 cm, for all rows, and a 50 cm walkway separated the production area into two half production zones. The seedlings of each crop species were seeded and rooted within a nursery located outside the LGH located in the LGH lab. Then, the seedlings were transplanted into the LGH's cable culture system at the beginning of the closure experiment period. The nutrient solution (modified one-half strength Hoaglands solution) was controlled to 6.0 pH and 1.8 dS $m^{-1}$ for the lettuce and strawberry, and at 6.5 pH and 1.8 dS $m^{-1}$ for the sweet potato and tomato.

Fig. 2. Cable culture soilless hydroponic system deployed inside the LGH. Flexible plastic film envelopes were suspended from both ends of the LGH with a cable.

### 4.3. LGH environmental control and data acquisition systems

The LGH has a computerized climate control and data collection system to monitor and maintain plant microclimate and hydroponic nutrient solution electrical conductivity (EC) and pH. Makeup water was automatically added and monitored to replace plant evapotranspiration water. In addition, water condensation from the heat exchanger was also monitored. The hydroponic nutrient system consisted of two independent systems allowing for two separate nutrient formulations for each of the eight plant rows. The system consisted of three 400 L nutrient solution storage tanks, pumps and distribution plumbing to each row of plants within the LGH. The nutrient solution continuously flowed and was monitored and controlled using a data logger which operated peristaltic pumps for delivery of concentrated stock solution and acid or base to the nutrient reservoirs. Dissolved oxygen (CS512, Campbell Scientific Inc., Logan, UT, USA) was monitored in the nutrient solution and aeration was continuously provided by an air compressor and a distribution system of air bubbler stones. Aeration was provided from the atmosphere within the LGH to maintain a closed system. High pressure bottled $CO_2$ was added to maintain atmospheric carbon dioxide concentration at 1000 ppm during the photosynthetic lighting periods. Climates ontrol system maintained a 17/7 h photo period/dark period, respectively. The average air temperature and relative humidity during the photoperiod and dark periods were 20.5 °C/65% and 18.5 °C/70%, respectively. Atmospheric $CO_2$ was elevated to 1000 ppm during the photoperiod. The average photosynthetic active radiation measured at the height of the cable culture zone was about 400 μmol $m^{-2}$ $s^{-1}$.

Data collection included measurement and recording of the nutrient solution EC (HI 3001, Hanna Instruments Inc., Ann Arbor, MI, USA), pH (HI 1001, Hanna Instruments Inc., MI, USA), and oxygen concentration (OMT355, Vaisala Inc., Woburn, MA, USA), as well as carbon dioxide (GMT220, Vaisala Inc., Woburn, MA, USA) from both the LGH interior environment and the laboratory environment exterior to the LGH. The LGH interior and exterior air temperatures and relative humidity (HMP50, Vaisala Inc., Woburn, MA, USA), as well as, interior photosynthetic active radiation (LiCor190SA, LiCOR, Lincoln, NE, USA), and lamp water cooling system temperatures (Thermocouple Type-T) were monitored and stored. An electronic load cell weighing system (RL1800, Ricelake Weighing Systems, Ricelake, WI, USA) was installed underneath the entire LGH, which monitored bio-

mass production rates, as measured by daily increase in absolute weight of the LGH and its crops. This weighing system was also used to determine the amount of labor time used throughout the production period. These were indicated by abrupt increases, followed by decreases in total LGH system weight, indicating that someone had entered the LGH, and determining the amount of time required for performing the work task. A data logger (CR3000, Campbell Scientific Inc., Logan, UT, USA) scanned all the sensors every second and stored ten minute averaged data for further analysis. The sensors used were purchased brand new and were factory calibrated except the EC and pH sensors were calibrated in the lab with standard calibration solutions prior to the experiments as well as periodically during the experimental period.

## 5. MMEC model evaluation based on LGH plant growth experiments

Model applications are restricted to the environmental ranges, plant cultivars, and planting densities based on the data sets from which they are developed. Thus, a sensitivity analysis of variation of model outputs to model inputs due to expected variability during the plant growth experiments was initially performed to identify an adequate MMEC model validation strategy. The necessity was driven by the temporal and geometric variability of the environmental data observed during the 2009 LGH plant growth experiments (now labeled "closure tests"). Depending on crop position and size, the environmental parameters used as model inputs varied considerably around set-points, as reported in detail in Table 1. The model inputs were atmospheric temperature, relative humidity, total pressure, $CO_2$ concentration, and PPFD. The model outputs were net oxygen production, net carbon dioxide consumption, water and dry nutrients consumption, crop transpired water and wet biomass production. The sensitivity analysis compared the model outputs with the LGH set-point parameters as inputs. The results were obtained by changing one input parameter at a time across its variability range and the resulting output variation was determined. The results showed that various model outputs were impacted by the variation of inputs ranging from complete independence, and up to an order of magnitude change. Table 1 provides the results of the sensitivity analysis. The observed behaviors for each input parameter were qualitatively differentiated as "none", when the output was independent of the input; "low" when the output variation was lower than 20%; "medium" when between 20% and 70%; "high" when variations impacted on an order of magnitude of change. The data revealed that the model outputs such as biomass produced, net $O_2$ produced, net $CO_2$ consumed and dry salts consumed were highly sensitive to light intensity. Both air temperature and relative humidity showed a strong effect on evapotranspiration rate and water consumed. Overall, the results indicated that variability of light intensity, air temperature and relative humidity impacted the predicted outputs the most. Therefore, it was concluded that these three input parameters had to be carefully considered in the model validation process.

Extensive data mining was then performed on the LGH operational data to provide comparison with those computed by the model, and concentrating on the parameters highlighted as critical by the sensitivity analysis. The sensitivity analysis concluded that a series of hardware and monitoring system improvements had to be completed before 2010 closure tests started. The most critical needs were to quantify the system air leakage rate, the light intensity at different crop layers, and the biomass production.

A gas infiltration test was performed on the LGH after additional sealing was completed and when it was without plants, using $CO_2$ as the indicator gas. The leakage rate was $4.2\ m^3\ h^{-1}$, or the LGH module gas volume was exchanged 4.4 times per 24 hour period. This information was used together with $CO_2$ added and the $CO_2$ concentration in the atmosphere to compute the carbon dioxide consumption of the plants. In addition, the plant transpiration was calculated based on the air infiltration rate, the water condensate collected and air RH measurements.

Fleisher (2002) indicated that the combination of both the magnitude of the light disturbance and duration of disturbance had the greatest effects on lettuce yield loss in growth chamber studies. The study showed that the timing

Table 1
Sensitivity of MMEC model outputs to model input variables based on 2009 closure experiment data variability. "None" represents no output variation, "low" is used if output variation is lower than 20%, "medium" if between 20% and 70%, and "high" if greater than 70%.

| | PPFD ($\mu mol\ m^{-2}\ s^{-1}$) | $CO_2$ concentration (ppm) | Relative humidity (%) | Total atm. pressure (kPa) | Air temperature (°C) |
|---|---|---|---|---|---|
| *Model INPUTS* | | | | | |
| Minimum | 200 | 330 | 35 | 100 | 17 |
| Set-point | 300 | 1000 | 50 | 101 | 21 |
| Maximum | 1000 | 1300 | 95 | 102 | 28 |
| *Model OUTPUTS and sensitivity to above INPUT parameters* | | | | | |
| Biomass produced (units) | High | Medium | None | None | None |
| Net $O_2$ produced | High | Medium | None | None | None |
| Water (evapo)transpiration | Low | Low | High | Low | High |
| Water consumed | Low | Low | High | Low | High |
| Net $CO_2$ consumed | High | Medium | None | None | None |
| Dry salts consumed | High | Medium | None | None | None |

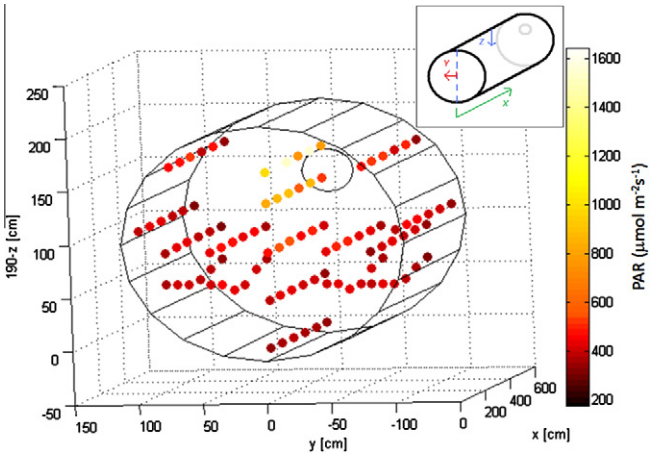


Fig. 3. 3D mapping of LGH photosynthetic photon flux density (PPFD). Measurements recorded at plant canopy within the different growing layers (cable culture system, floor, and walls).

Table 3
Comparison of 2010 plant growth experiment measured results with MMEC model predictions. Results obtained from three, short term closure periods (column 1, March 19 to April 12; column 2, May 11 to June 1; column 3, June 1 to July 12) are compared to results including the entire 6 month time period (column 4, March 13 to August 20). Positive numbers are used for model output overestimation; negative numbers are used for model output underestimation.

| 2010 closure test date | Model prediction error [%] | | | |
|---|---|---|---|---|
| | 3/19 to 4/12 | 5/11 to 6/1 | 6/1 to 7/12 | Overall 3/13 to 8/20 |
| Biomass produced | −8.9 | +7.6 | −31.9 | −0.7 |
| Net $O_2$ produced | −39.4 | −11.9 | −70.9 | −67.5 |
| Water (evapo)transpiration | −51.6 | +10.7 | −46.1 | +6.3 |
| Water consumed | −48.3 | +4.0 | −44.7 | +0.5 |
| Net $CO_2$ Consumed | −39.4 | −11.9 | −70.9 | −67.5 |
| Dry salts consumed | −24.6 | +46.6 | −51.9 | −45.1 |

of the disturbance had no effect on yield with respect to changes in the magnitude of the light intensity disturbance. In the current study, photosynthetic photon flux maps were measured at the plant canopy level during the plant growth stages to characterize the shading effect of the tall crops on the other layers during the closure test period. Fig. 3 is a graphical representation of one of the many maps created during plant growth stages. It indicates magnitude, position and variability of light within the LGH (also see Fig. 2). The measurements showed that the PPFD level was not same on different growing zones in the LGH (between 250–550 µmol $m^{-2}$ $s^{-1}$ at production zones). Light mapping helped to use actual values of light available for the crops growing in different parts of the LGH for calculations in the MMEC model.

The first validation test of the model was completed using the data obtained from the previous LGH closure test in 2009 (Sadler et al., 2009) to highlight how the LGH characterization and facility improvements of 2010 impacted the model validation results. Only lettuce was grown and evaluated for a two week period in 2009. The data acquisition system did not allow at that time for an exact mass balance, since data on chamber air leak rates were not available. The validation test was performed in two steps. In the first step, only the average values for the growth chamber environmental parameters (e.g. PPFD, air temperature, and relative humidity) were used. Model simulations were in good agreement with the measured data for biomass production (error less than 5%), water consumption and condensate production (error approximately 15%). The model predictions were poor for oxygen production and carbon dioxide consumption (error approximately 70%). The negative result for gas exchange was attributed to the experimental procedure of the tests, which did account for the LGH system gas infiltration and reporting only the actual system $CO_2$ consumption and not its use by the plants. The ratio of the oxygen produced over the carbon dioxide consumed was the same as the ratio of the molecular masses for both modeled and real calculated results, since it was calculated in the same way in both situations. No data for dry salts consumption were available for the reference closure experiment during 2009. Since the sensitivity analysis results (Table 1) showed among all a high impact of small variations of LGH temperature and RH on model outputs. Thus, in the second validation test, the temperature and RH variation was considered in the dynamic model. There was an improved prediction of water consumption and condensate production, as the error was reduced to approximately 10% (Table 2).

Table 2
Comparison of 2009 closure experiment measured results (column 1) with MMEC model predictions (columns 2 and 4) and associated differences (error) (columns 3&5). Two different comparisons are reported. The first one uses the average environmental data, and the second one incorporates variability of environmental parameters from the same data set reported in Sadler et al. (2009).

| 2009 1st closure test | Growth experiment results | Predicted with avg. data only | | Predicted with avg. data and stddev | |
|---|---|---|---|---|---|
| | Results [kg] | Results [kg] | Error [%] | Results [kg] | Error [%] |
| Biomass produced | 23.5 | 22.3 | 4.9 | 22.3 | 4.9 |
| Net $O_2$ produced | 4.4 | 1.4 | 67.2 | 1.4 | 67.2 |
| Water (evapo) transpiration | 244 | 281 | 15.0 | 272 | 11.3 |
| Water consumed | 256 | 289 | 13.1 | 280 | 9.5 |
| Net $CO_2$ consumed | 6.0 | 2.0 | 67.1 | 2.0 | 67.1 |
| Dry salts consumed | N.A. | 0.5 | N.A. | 0.5 | N.A. |

The model validation was subsequently evaluated with data from the recent closure tests of 2010, which occurred after upgrading the LGH system and the experimental procedure. The primary LGH system design and operation improvements were the reduction of the LGH air infiltration, the addition of automated nutrient solution pH control, and an improved control strategy for the environmental parameters. Moreover, the LGH monitoring system was improved, providing redundant sensors and measurement procedures for all of the critical experimental parameters, including the load cell system to automatically monitor biomass production. The system was also better characterized in terms of PPFD levels at the canopy height during the experiment and for gas exchanges due to leakage.

The 2010 closure tests were performed with a mixed canopy of lettuce, tomatoes, strawberries and sweet potatoes. Table 3 illustrates the comparison of the model predictions with the experimental results for the different closure tests between March 13th and August 20th 2010. The results showed improved predictions of the LGH expected overall output for the experiments, for example, for biomass production (underestimated 0.7%), and water consumption and transpired water (overestimated by 6.3% and 0.5%, respectively). In the first two closure tests, lettuce was grown and harvested, while tomatoes and sweet potatoes were present but not at maturity for harvest. The harvested lettuce biomass matched well with the model predictions (error less than 10%). Prediction of gasses exchange improved as expected compared to the previous tests, where LGH system infiltration rate was not considered. A reduction in the prediction of water consumption and condensate production was observed in this test, where the EC control system of the nutrient solution had a small failure. This is justified by the high sensitivity of crops water uptake with respect to nutrient solution electrical conductivity (Schwarz and Kuchenbuch, 1998), together with the absence of reference EC values in the MEC models. The nutrient consumption was overestimated by 25% compared to the model prediction, but again a reference nutrient solution recipe is not mentioned in the MEC models. In the third closure tests, the tomatoes and sweet potatoes had a greater impact on the whole canopy, and the result was a decrease in modeling precisions, especially for the expected biomass production, which was underestimated by 30%.

Table 4
Modified MEC model nomenclature.

| Parameter | Definition |
|---|---|
| $\alpha$ | Conversion constant (0.0036 s $h^{-1}$ mol $\mu mol^{-1}$) |
| ß | Conversion constant (3600 s $h^{-1}$) |
| A | Fraction of PPFD absorbed by the canopy |
| $A_{MAX}$ | Maximum fraction of incident irradiance absorbed by the canopy |
| BCF | Biomass carbon fraction |
| CQY | Canopy quantum yield ($\mu mol_{carbon.fixed}$ $\mu mol^{-1}{}_{Absorbed.PPFD}$) |
| $CQY_{MAX}$ | CQY until $t_Q$ |
| $CQY_{MIN}$ | CQY at $t_M$ |
| $CUE_{24}$ | 24-h Carbon use efficiency (a fraction) |
| $CUE_{MAX}$ | $CUE_{24}$ until $t_Q$ |
| $CUE_{MIN}$ | $CUE_{24}$ at $t_M$ |
| $DRY_{fr}$ | Crop dry over wet biomass fraction ($g_{dry}$ $g^{-1}{}_{wet}$) |
| $g_A$ | BLSS aerodynamic water vapor conductance ($mol_{Water}$ $m^{-2}$ $s^{-1}$) |
| $g_C$ | Canopy surface water vapor conductance ($mol_{Water}$ $m^{-2}$ $s^{-1}$) |
| $g_S$ | Canopy stomatal water vapor conductance ($mol_{Water}$ $m^{-2}$ $s^{-1}$) |
| H | Photoperiod (hours $day^{-1}$) |
| HCG | Hourly carbon gain ($mol_{carbon}$ $m^{-2}$ $h^{-1}$) |
| HCGR | Hourly crop growth rate (g $m^{-2}$ $h^{-1}$), on a dry basis |
| $HCO_2C$ | Hourly carbon dioxide photosynthetic consumption (g $m^{-2}$ $h^{-1}$) |
| $HCO_2P$ | Hourly carbon dioxide respiration production (g $m^{-2}$ $h^{-1}$) |
| HNC | Hourly macronutrients uptake (g $m^{-2}$ $h^{-1}$) |
| HOC | Hourly respiration-caused oxygen consumption (g $m^{-2}$ $h^{-1}$) |
| HOP | Hourly photosynthetic oxygen production (g $m^{-2}$ $h^{-1}$) |
| HTR | Hourly transpiration rate ($g_{water}$ $m^{-2}$ $h^{-1}$) |
| HWC | Hourly water consumption ($g_{water}$ $m^{-2}$ $h^{-1}$) |
| HWCGR | Hourly wet crop growth rate (g $m^{-2}$ $h^{-1}$) |
| I | I is respectively equal to 1 and 0 during day and night time |
| $MW_C$ | Carbon molecular mass (12.0107 g $mol^{-1}$) |
| $MW_{CO2}$ | Carbon dioxide molecular mass (44.010 g $mol^{-1}$) |
| $MW_{O2}$ | Oxygen molecular mass (31.9988 g $mol^{-1}$) |
| $MW_W$ | Water molecular mass (18.0153 g $mol^{-1}$) |
| $n$ | Crop dependant exponent |
| $NC_{fr}$ | Nutrient consume fraction for gained dry mass ($g_{nut}$ $g^{-1}{}_{drymass}$) |
| OPF | Oxygen production fraction ($mol_{O2.produced}$ $mol^{-1}{}_{carbon.fixed}$) |
| $P_{atm}$ | BLSS atmospheric pressure (kPa) |
| $P_{NET}$ | Canopy net photosynthesis ($\mu mol_{carbon}$ $m^{-2}$ $s^{-1}$) |
| PPFD | Photosynthetic photon flux density ($\mu mol_{photon}$ $m^{-2}$ $s^{-1}$) |
| RH | Relative humidity (fraction) |
| $T_{LIGHT}$ | Mean air temperature during the light-cycle (°C) |
| $t$ | Time from experiment start (days) |
| $t_A$ | Time of canopy closure (days after emergence, DAE) |
| $t_M$ | Time at harvest or crop maturity (DAE) |
| $t_Q$ | Time of onset of canopy senescence (DAE) |
| VPD | Vapor pressure deficit (kPa) |
| $VP_{SAT}$ | Saturation vapor pressure (kPa) |
| WBF | Water biomass fraction |

## 6. Conclusions

An improved explanatory model based on the previously developed MEC model for crop growth was evaluated for prediction of system outputs from the multi-crop Lunar greenhouse prototype at the UA-CEAC. The model provided a tool not only to verify LGH input and output resources, but also for future advancements of the control strategies in the LGH system. Modifications of the original MEC model included completing the resources mass balance, allowing modeling of limited system failures (e.g. short power losses), modeling environmental parameters variations during the experiments due to the evolving chamber volume occupation and to the control strategy, and allowing for use within a multi-layered and multi-crop production system. A set of experiments have been performed on the improved model with data from various closure tests performed in 2009 and 2010. A sensitivity

analysis on the output variability of the model to input variations highlighted the necessity of a detailed characterization of the LGH system and its climatic variables. These included consideration of the growth of crops along the chamber walls and floor, and how the canopy lighting pattern, as well as, varying microclimates in the different canopy layers would affect the results. The model validation test results showed that the complex geometry of the canopy growing area affected the modified MEC model prediction accuracy. When having a simplified canopy, such as only lettuce, providing a relatively uniform flat canopy surface at a known distance from the lamps, the results were highly satisfactory for the most model output parameters, including biomass production (accurate within 9%), and water exchange (accurate within 11%). However, the consumption of fertilizer salts and the gasses exchange predictions were not accurately determined, sometimes being more than 50% different from the measured results. The model predicted $CO_2$ consumption does match with the estimation based on the fixed carbon required for the measured biomass production, suggesting an underestimation of the LGH growth chamber infiltration losses as the most likely source of error. When the tomato and sweet potato crops are included and to grow on the walls and the floor layers, the geometry becomes much more complex to model and becomes less accurate on the model predictions (e.g. prediction of biomass production accurate within 42%, and water exchange within 46%). The main reason is in estimating the PPFD expected for each plant layer during the different growth stages.

The goal of the current study aimed at evaluating and validating the modified MEC model with four different closure experiments (almost at steady-state) with multi-crops. The study evaluated the capabilities and limitations of the modified model for predicting biomass growth, transpired water, oxygen generation, $CO_2$ consumption, and dry salts used. There is a need to further improve the model. For instance, characterization of the chamber environmental parameters can be improved, and the focus should be to estimate the PPFD at the canopy during the different growth stages with different plants and their combined production in the LGH system. It will be necessary to develop and couple mathematical crop models which could predict effects of various environmental disturbances on plant growth and development during the production cycle. This would help develop better understanding of the plant responses to off-nominal disturbances and under system failures. In addition, the effect of nutrient solution EC and pH in the model must be investigated, since these parameters are expected to impact nutrient and water consumption rates. It will be advantages to conduct further closure tests with the same crops and under various climatic conditions to validate the modified model which is underway within the scope of the Phase II NASA Steckler Project efforts.

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