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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