Poly-Culture Food Production Mass Balances Prediction in a Semi-Closed Lunar Greenhouse Prototype (LGH)

G. Boscheri[1], M. Lamantea[2], C. Lobascio[3]
Thales Alenia Space, Turin, Italy, 10146

L. Patterson[4], E. Hernandez[5], T. Jensen[6], M. Kacira[7]
University of Arizona Controlled Environment Agriculture Center, Tucson, Arizona, 85719, USA

In 2010 Thales Alenia Space Italia (TAS-I) tailored and applied an existing plant growth model for application to the University of Arizona Controlled Environment Agriculture Center (UA-CEAC) Lunar Greenhouse Prototype (LGH). The activity was carried on in collaboration with UA-CEAC and Sadler Machine Co. (USA) in the framework of the NASA Ralph Steckler Phase I Space Grant effort. Starting from the results of that activity, the LGH facility data collection system in aid to the modelling effort has been improved through support by the NASA Ralph Steckler Phase II Space Grant and of a wider consortium. This paper will present the quantified mass balances and the flows of input resources (i.e. water, carbon dioxide, dry fertilizer salts) and output production (i.e. biomass, water condensate, oxygen) and their comparison to the values predicted by the plant growth model, developed starting from Cavazzoni's Modified Energy Cascade (MEC) model. Capability for reliable crop yield prediction will be discussed in the paper with main lessons learned from the activity.

Nomenclature

BLSS	=	Bioregenerative Life Support System
CEAC	=	Controlled Environment Agricultural Center
ESM	=	Equivalent System Mass
LGH	=	Lunar Greenhouse
MEC	=	Modified Energy Cascade (model)
MMEC	=	Modified MEC (model)
TAS	=	Thales Alenia Space
UA	=	University of Arizona

I. Introduction

BIOREGENERATIVE life support systems (BLSS) are among the key technologies to be developed in support of long term planetary exploratory missions, aiming at consumables reduction through resources loop closure. Higher plants as a mean to recycle carbon dioxide, treated organic wastes and not potable water into oxygen, food and potable water have been studied in integrated systems[1], in order to maximize Equivalent System Mass (ESM) efficiency[2]. Similar goals are aimed by the ongoing Lunar Greenhouse (LGH) project carried on at the University of Arizona Controlled Environment Agricultural Center (UA-CEAC)[3] under two distinct phases of the NASA Ralph Steckler Space Grant.

[1] Engineer at Life Support and Habitat, Turin, Italy
[2] Head of Life Support and Habitat, Turin, Italy
[3] Head of Space Flight Environment and Habitat, Turin, Italy
[4] Graduate Student, 1951 E. Roger Rd., Tucson, Arizona, USA.
[5] Undergraduate Student, 1951 E. Roger Rd., Tucson, Arizona, USA
[6] Undergraduate Student, 1951 E. Roger Rd., Tucson, Arizona, USA.
[7] Associate Professor, 1951 E. Roger Rd., Tucson, Arizona, USA.

In order to evaluate the performance of the LGH multi-crop system, an adequate plant growth model was necessary, capable of coping with the LGH the local microclimates, plants arrangements, and transient nature of the crop growing in the system.

With this goal in mind, the UA-CEAC has been collaborating with the Italian space company Thales Alenia Space Italia[4] and its Recyclab advanced life support research facility[5]. As a result of phase 1 of the project, we implemented a crop growth mass balance model that was developed tailoring Cavazzoni's Modified Energy Cascade (MEC) model on the LGH system. The product was validated with phase 1 results within the framework of the collaboration[6]. The study[6] highlighted the necessity to improve the data collection system of the LGH in order to better evaluate the environmental parameters driving the model predictions.

Therefore, the main objective of this paper is to report the applied system upgrades and the impact on predictive model accuracy.

A. The UA-CEAC Lunar Greenhouse Prototype

The LGH project consists of the development and characterization of a multicrop closed planetary greenhouse prototype. The proposed LGH system is composed of four cylindrical shaped independent growth chambers each with a volume of 22 m^3. Only one module is currently under operation and 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. The LGH module's capability of simultaneously growing various NASA targeted crops (i.e. lettuce, tomatoes, sweet potatoes, strawberries) in growing surface areas planned from time to time to exploit maximum available volume has been tested with several system closure experiments .

B. The Modified MEC (MMEC) Model

The model exploited in this study, as adequately reported in Boscheri et.al 2010[6], is modified from Cavazzoni's Modified Energy Cascade (MEC) model[7]. The MEC model is an explanatory 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. As the MEC model, the modified model developed in the current study is aimed at predicting plants' biomass uptake, oxygen production, water transpiration and carbon dioxide consumption. In addition, water and nutrient use is considered for a complete mass balance analysis. The outputs are calculated as a function of Photosynthetic Photon Flux (PPF), carbon dioxide, partial pressure, atmospheric total pressure, temperature, relative humidity, crop age and type, within the same limits of validity of the MEC model[8]. However, mass exchange rates on hourly basis have been preferred to MEC's daily prediction rates in order to distinguish day and night dynamics in the system. This helped evaluating possible consequences (e.g. lower transpired water) of time-limited LGH system failures with its large canopy (e.g. a burned lamp, an energy loss).

II. NASA Steckler Phase 2 Relevant Results

A set of validation tests was performed on the MMEC model algorithm with data from different closure experiment results performed in 2009 and 2010 during project Phase I. A sensitivity analysis[6] on model output variability to inputs small variations highlighted the necessity of a periodic detailed characterization of the growth chamber to be modelled: the growth of crops along the chamber walls and floor alters sensibly the lighting pattern at canopy, as well as it creates variables microclimates in the different canopy layers, which affect the results.

The validation test results showed that the LGH experiment conditions and especially the complex geometry of the canopy growing area affected the modified MEC model prediction accuracy considerably. Indeed, when almost only lettuce was present in the LGH, growing on a flat surface at a defined distance from the chamber lamps, the results were satisfactory for the most mass-impacting model output parameters (biomass uptake and water exchange). Differently, the salts consumption and gasses exchange predictions were not apparently in accord with the measured results. Since the model CO_2 consumption prediction well matched with the calculation on the fixed carbon from the measured biomass uptake, an underestimation of the LGH growth chamber leakage was identified as the most likely source of error.

Given these conclusions, the modelling effort during phase II of the project was focused on improving the LGH facility environmental characterization and results evaluation capability exploiting the presented lessons learnt. The applied system upgrades and the impact on the model accuracy are reported in the following paragraphs.

A. The UA-CEAC LGH Relevant Upgrades

The main improvements of the faciltity monitoring capability were:

- a more refined mapping of illumination at multiple locations, in order to carefully address the model sensitivity to the light level at canopy
- on-line chamber leakage monitoring, in order to reduce the uncertainty of evaluation of crops' gas exchanges
- continuous environmental total pressure monitoring, since water evapo-transpired water model prediction is extremely sensible to this parameter
- detailed accidental water spillage recording, allowing evaluation of water and dry salts lost during operation, as well as in case of unexpected failures (e.g. drain clogging)
- carefull evaluation of canopy surface

PAR (photosynthetically active radiation) measurements were taken using a hand held sensor and measuring distance of the sensor from the light source. There are 7 spots of interest (at different distance from the lamps) in 11 ring sections (see Figure 1) of the chamber. Every other ring section contains a high pressure sodium lamp. Measured PAR at canopy was in the range of 120 to 440 $\mu mol_{photons}\ m^{-2}\ s^{-1}$.

Chamber Door	1. Light	2. No light	3. Light	4. No light	5. Light	6. No light	7. Light	8. No light	9. Light	10. No light	11. Light

Figure 1: LGH PAR map measurement sections identification

In order to frequently evaluate the LGH growth chamber leak rate, the system was equipped with a NO_2 injection and monitoring system. NO_2 partial pressure decay measurements during time were exploited to evaluate leakage of carbon dioxide to the outside enviroment. A careful evaluation of the CO_2 leak was necessary not only for evaluating its consumption, but also for calculating properly the effective LGH oxygen production. The global leak rate was measured during Phase II test campaign as variable from 75 to 200 m^3_{air}/day.

B. Phase II Modeling Preliminary Results

A considerable number of closure experiments were carried on during Phase II of the project, from March 2012 to present. The Main LGH Chamber is composed of eight full-chamber-length envelopes that are divided in the center by drains (see Figure 2). With four envelopes on either side of the walkway and the divisions created by the drains, we have divided the chamber into four quadrants with 4 envelope sections in each. Position is denoted by using North, South, East, and West to specify which quadrant and which number envelop in that quadrant. The total horizontal growing area is about 10 m^2.

South West West West West (S4W) .744 m^2		North West West West West (N4W) .744 m^2
South West West West (S3W) .498 m^2		North West West West (N3W) .496 m^2
South West and South West West Rows 1.24 m^2		North West and North West West Rows 1.24 m^2
South East and South West West Rows 1.24 m^2		North East and North East East Rows 1.24 m^2
South East East East (S3E) .496 m^2		North East East East (N3E) .496 m^2
South East East East East (S4E) .744 m^2		North East East East East (N4E) .744 m^2

Figure 2: LGH growth chamber division into 4 quadrants with 4 envelope sections in each

The following crops were grown, not always simultaneously, with multiple combinations:

- Red Oakleaf Lettuce (Lactuca Sativa variety)
- Green Oakleaf Lettuce (Lactuca sativa variety)
- Sweet Potatoes (Ipomoea batatas, Louisiana Beauregard potatoes)
- Red Basil (Ocimum basilicum variety)
- Strawberries (Fragaria spp. Sarian F1 day neutral variety)

Since the MMEC model was validated only for lettuce and sweet potato crops, the multi-crop configurations where also basil and strawberries were grown have not been yet analyzed. Thus, a limited set of closure experiments were identified with only about 5 m^2 of lettuce and 5 m^2 of sweet potatoes allocated within the greenhouse. The collected data were processed and averaged in order to evaluate the main mass balance (biomass uptake, gas exchange, water/nutrient consumption and evapo-transpioration) and compare the results with the predictive model output. Table 1 reports the model accuracy evaluation of a set of closure experiments that were performed from August 2012 to January 2013. The deviation of expected performance with respect to actual results ranges from a 3.4% error on dry salts consumption to a 21.4% for gas exchange (O_2 production/ CO_2 consumption).

Table 1: Phase II closure experiment with only lettuce and sweet potato crops averaged results

PARAMETER	CLOSURE TEST RESULTS	MODEL RESULTS	% OFF
Biomass harvested [kg/week]	7.68	8.63	+12.5
Oxygen produced [kg/week]	0.94	1.14	+21.4
Condensate prod. by plants [kg/week]	177	182	+2.4
Water net plants consumption [kg/week]	208	190	-9.0
CO_2 net plants consumption [kg/week]	1.29	1.57	+21.4
Dry salts added [kg/week]	0.28	0.29	+3.4

Although the presented Phase II results have been obtained from a single experiment, the model accuracy appears generally improved with respect to what was obtained during Phase 1, which is summarized in Table 2. A major positive note is given by the gas exchange evaluation, which was about 67% off during Phase 1 test campaign. Nutrient consumption also presents appreciable improvements (from about 45% to 3.4% error). Moreover, looking at phase 1 closure experiments CE1 and CE3 (Table 2) it is evident that the water balance is much better predicted in the Phase II test campaign.

Table 2: Phase I closure experiments results summary – Model results vs measurements

PARAMETER	CE1: March 19th to April 12th % off	CE2: May 11th to June 1st % off	CE3: June 1st to July 12th % off	Overall March 13th to August 20th % off
Biomass harvested	+8.9	+7.6	-31.9	+0.7
Oxygen produced	+39.4	+11.9	+70.9	+67.5
Condensate prod. by plants	-51.6	+10.7	+46.1	+6.3
Water net plants consumption	-48.3	+4.0	+44.7	+0.5
CO_2 net plants consumption	+39.4	+11.9	+70.9	+67.5
Dry salts added	+24.6	+46.6	+51.9	+45.1

III. Conclusion

Significant improvements were implemented on the UA-CEAC lunar greenhouse during NASA Steckler Space Grant Phase II activities. These upgrades to the input data measurement strategy allowed increasing the accuracy of the modified MEC model developed during Phase I[6]. A refined mapping of illumination at canopy and a carefull evaluation of growth surface led to a biomass uptake evaluation accurate at about 12.5%. On-line leakage evaluation through NO_2 pressure decay measurements reduced the uncertainty of evaluation of crops' gas exchanges (about 21% accuracy). Finally, detailed accidental water spillage recording, as well as continuous environmental total pressure monitoring, allowed a refined evaluation of water balance (more than 9% accurate) and dry salts consumption during operations (only 3.4% off).

Acknowledgments

The authors wish to thank NASA and the Ralph Steckler Space Grant endowment for their generous support that was provided to the Arizona Space Grant Consortium, Timothy Swindle, Director and Susan Brew, Program Manager. We also wish to thank Dr. Raymond Wheeler, NASA Technical Advisor. Finally, we wish to acknowledge the great collaborative effort of our great team of international students, academia and industries.

References

[1]Wheeler, R.M., Mackowiak, C.L., Stutte, G.W., et al. "NASA's biomass production chamber: a test-bed for bioregenerative life support studies," *Adv. Space Res*. 18 (4/5), 215–224, 1996.

[2]Levri, J.A., Drysdale, A. E., Ewert, M. K., Fisher, J. W., Hanford, A. J., Hogan, J. A., Jones, H. W., Joshi, J. A., Vaccari, D. A. "Advanced Life Support Equivalent System Mass Guidelines Document", NASA/TM-2003-212278, 2003

[3]Sadler, P., Giacomelli, G., Furfaro, R., Patterson, R. L., Kacira, M., "Prototype BLSS Lunar Greenhouse,", *39th International Conference on Environmental Systems*, SAE Paper No. 2009-01-2484, Savannah, Georgia, USA, 2009.

[4]G. Boscheri, R. Furfaro, L. Grizzaffi, G. Giacomelli, M. Kacira, M. Lamantea, C. Lobascio, L. Patterson, P. Sadler, "Evaluation of Bio-regenerative Life Support Systems in the frame of a Concurrent International Cooperation", *40th International Conference on Environmental Systems*, AIAA Paper No. AIAA-2010-6202, Barcelona, Spain, 2010b

[5]Grizzaffi, L., Lobascio, C., Rampini, R., Saverino, A., "Recyclab, a Laboratory for Regenerative Life Support Development", *37th International Conference on Environmental Systems*, SAE paper No. 2007- 01-3250, 2007

[6]Boscheri, G., M. Kacira, L. Patterson, G. Giacomelli, P. Sadler, R. Furfaro, C. Lobascio, M. Lamantea, L. Grizzaffi. "Modified energy cascade model adapted for a multicrop lunar greenhouse Prototype", *Advances in Space Research*, 50(7):941-951, 2012.

[7]Cavazzoni, J., "Using explanatory crop models to develop simple tools for Advanced Life Support system studies," *Adv. Space Res*. 34 (2004) 1528–1538, 2004.

[8]Hanford, A. J. "Advanced life support baseline values and assumption document". JSC 47804 (CTSD-ADV-484), National Aeronautic and Space Administration, Lindon B. Johnson Space Center, Houston, TX, USA, 2002.