Ecosystem Modeling and Validation using Empirical Data from NASA CELSS and Biosphere 2

Grant Hawkins[1] and Ezio Melotti[2] and Kai Staats[3]
Over the Sun LLC, Phoenix, AZ, 85003

and

Atila Meszaros[4] and Gene Giacomelli[5]
University of Arizona, Tucson, AZ, 85719

Plant productivity varies widely based on the growing conditions. Controlled-environment experiments routinely outperform open-field agriculture yields by 10x or more by optimizing every resource: available light, atmospheric conditions, space, labor, nutrients and water, and by eliminating soilborne diseases, harmful pests and fungi. Dozens of mathematical and computer models of plant growth have been developed to explain and/or predict yield from growing conditions using discrete processes or functional structures, and their outputs are validated against one or more empirical studies. Validation data are typically selected based on the intended application of the model; for example, models for open-field agriculture will incorporate the range of conditions likely in the regions where a particular crop is grown and calibrated to experiments on that crop. In this study, we extend the Scalable, Interactive Model of an Off-world Community (SIMOC) with a highly generic plant growth model that incorporates 22 different plant species and validate it against two high-profile and dissimilar experiments: NASA's Controlled Ecological Life Support System (CELSS) and the Biosphere 2 Intensive Agricultural Biome (B2-IAB). Despite a difference in yield of >10x, our model predicts the outputs of both to be within range of experimental results, and the system-level behaviors of the B2 experiment are replicated by the simulation as well. Applications of this model include holistic cost-benefit comparison of widely dissimilar agricultural practices, optimization of long-term Biological Life Support Systems (BLSS), and public education.

Nomenclature

ECLSS	=	*Environmental Control and Life Support System*
BLSS	=	*Biological Life Support System*
B2	=	*Biosphere 2*
SIMOC	=	*The Scalable, Interactive Model of an Off-World Colony*
ABM	=	*Agent-Based Model*
CERES	=	*Crop Environment Resource Synthesis*
CELSS	=	*Controlled Environment Life Support System*
O_2	=	*Oxygen*
CO_2	=	*Carbon Dioxide*
PAR	=	*Photosynthetically Active Radiation*
f_{PAR}	=	*Factor of Photosynthetically Active Radation*
f_D	=	*Factor of Density*
f_{CM}	=	*Factor of Crop Management*
ppm	=	*Parts per Million*

---

[1] SIMOC Core Developer/Researcher, Ho Chi Minh City, Vietnam.

[2] SIMOC Lead Developer, Milan, Italy.

[3] Project Lead, Phoeniz, AZ, USA.

[4] PhD Candidate, Tucson, AZ, USA.

[5] Professor, Biosystems Engineering, Controlled Environment Agriculture Center, Tucson, AZ USA.

I. Introduction

Far away from farmland with expansive soil and fresh water, and outside of the breathable atmosphere astronauts and future citizen space explorers much bring all that is required to survive. In extreme environments such as Antarctica and the International Space Station, food is typically imported, and a physiochemical Environmental Control and Life Support System (ECLSS) maintains breathable air, potable water, and safe processing of human waste. In larger or more remote, near-future habitats a biological life support system (BLSS), could be an attractive or necessary alternative to mechanical ECLSS. Experimental data on BLSS is expensive and difficult to obtain, so research often utilizes simulations which are validated on experimental data from adjacent fields, such as controlled-environment agriculture and computational biology.

The largest experiments in closed-loop BLSS ever conducted were two human-in-the-loop, sealed missions at Biosphere 2 (B2 in Oracle, Arizona from 1991 to 1994. Biosphere 2 is an air-tight facility which includes 5 multi-acre biomes: rainforest, desert, savannah, ocean and intensive agriculture (controlled environment). A crew of 8 and 7 scientists and engineers lived inside the facility, growing all of their own food and maintaining the biomes, for periods of 2 years and 6 months, respectively. Scores of research papers were published in the ensuing years across a range of disciplines from agricultural productivity to ecosystem diversity to the aging of physical structures under extreme conditions. Research continues to this day on relevant topics like rainforest droughts and ocean acidification.

This study aims to build a simulation of the plants and other primary components of B2 and recreate the historic experiments hour-by-hour. Simulations are be conducted in the Scalable Interactive Model of an Off-world Community (SIMOC), an agent-based model (ABM) built in Python. Agent models for the crew, plants, biomes, concrete, and mechanical ECLSS are calibrated against published data from the experiments, as is the higher-level behavior of the whole ecosystem.

After three decades, the images and story of B2 are still inspiring and thought-provoking. The lessons of BLSS at Biosphere 2 are as relevant today as ever, both for development of human habitats beyond Earth, and also for ?protecting ?understanding? the Earth's changing climate, and we aim to stimulate interest in both fields by making those experiments explorable via simulation.

II. Background

Computational models of plant growth emerged early in the information age. One of the first was Crop Environment Resource Synthesis (CERES), developed by the USDA and first published in 1983[1], for the purpose of predicting crop yields. It included two species-specific models, CERES-WHEAT and CERES-MAIZE, and simulated growth, phenology, water and nitrogen balance, and yield. Since then, several platforms have built or expanded on the CERES model: Agricultural Production Systems sIMulator (APSIM) integrates models of soil, weather and pests[2], and Decision Support System for Agrotechnology Transfer (DSSAT) provides a user-friendly interface for calibrating and measuring localized data.[3] One meta-analysis of 215 studies compared field-observed data to CERES model predictions and found on average 10-20% relative error on maize, wheat and rice crops. The average error was notably higher under extreme heat, cold, nutrient and water conditions.[4]

BLSS can use extreme conditions to their advantage.[5] By extending the growing period and optimizing water, nutrients and the air, growing conditions can be tuned to maximize yields and oxygen production. The NASA Controlled Environment Life Support System (CELSS) experiments from 1988-1996 used maximal lighting for each crop, elevated CO_2, and a nutrient-film hydroponic growing technique to achieve record production and take precise measurements of wheat, soybean, lettuce, potato and tomato plants.[6]

SIMOC is an ABM used to simulate habitats with BLSS.[7] ABMs are typically configured with certain agents (e.g. human, wheat, dehumidifier) which exchange currencies (e.g. oxygen, potable water, kilowatt-hours) with each other and their environment. SIMOC includes an agent library of humans, plants, mechanical life support, power and structures. Plants in SIMOC exchange oxygen (O_2), carbon dioxide (CO_2), fertilizer, potable water and water vapor with their environment, and accumulate biomass each step of the simulation (1 hour/step). Transpiration and photosynthesis rates are scaled to the amount of total biomass, resulting in a sigmoid-shaped growth curve for the exchanges. Environmental variables like CO_2 concentration affect the rate of biomass accumulation at each step, leading to a compounding effect over time. Exchange values were based on experimental data from CELSS, so growing conditions are ideal by default. Figure 1 shows an behavior of a SIMOC plant agent under ideal conditions.
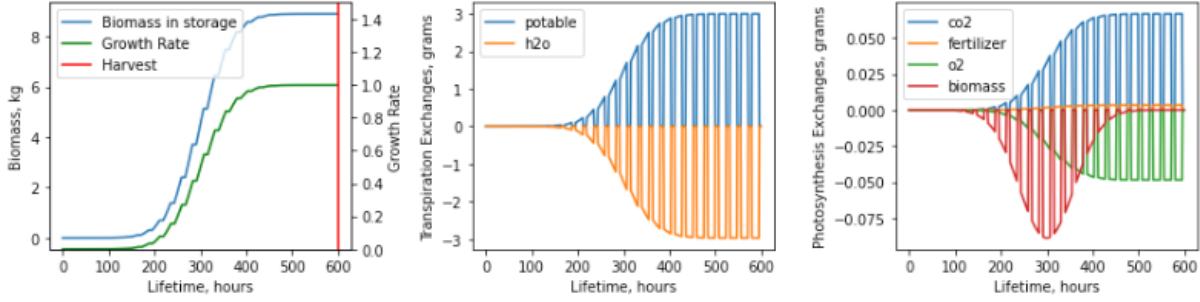
Figure 1. SIMOC plant model. *Based on 40 square meters of radishes grown with ideal potable water, CO_2 and fertilizer. From left to right: (a) total biomass in storage, matched with (calculated) growth rate; (b) inputs(outputs) related to transpiration;. (c) inputs(outputs) related to photosynthesis.*

B2 was the world's largest closed-environment agriculture experiment. Two full-scale experiments were conducted: Mission 1 from September 26, 1991, to September 25, 1993, and Mission 2 from March 6, 1994, to September 6, 1994.[9] These and later experiments yielded important insights into O_2 and CO_2 management, controlled-environment agriculture, soil community metabolism and more. In Ref 10, authors simulate the 5 major biomes of B2 during Missions 1 and 2 at two different levels of resolution using energy-balance models. Ref 11 details the behavior of the rainforest and desert biomes in isolated experiments conducted in 1996, and an experiment on carbon cycling in the ocean biome was conducted from 1995-1999.[12]

Two such studies will be used to validate our simulation. The first, Ref 13, is focused on the Intensive Agricultural Biome (IAB) during Missions 1 and 2. It includes measurements crop layout, internal sunlight and crop productivity. The second study, Ref 14, explores a discrepancy between expected and actual O_2 and CO_2 levels during the experiments and discusses the impact of soil respiration and concrete carbonation. Besides validating the accuracy of the simulation, it makes the studies more accessible for educational purposes by illustrating the same findings.

III. Methodology

To simulate the B2 experiments, the SIMOC plant agent model was updated, some new agents were added, and some existing agents were repurposed. The high-level approach was to (1) build and calibrate individual agents based on available reference data, (2) configure those agents simulations matching the historical missions, and (3) compare the emergent behavior of the simulation, namely plant productivity and O_2 and CO_2, to reference data. Plant productivity at B2 was 5-10x lower than at CELSS, as shown in Ref 13 Table 3. After discussion and further research, this was attributed primarily to three factors: differences in light, planting density, and mitigation of pests/weeds. These are added to SIMOC as new growth factors, which are applied as weights to biomass accumulation.

Light was incorporated into SIMOC as the currency Photosynthetically Active Radiation (PAR), in moles per square meter per hour. f_{PAR}, the factor of PAR, is calculated hourly based on current lighting:

$$f_{PAR} = min(1, \frac{P_a}{P_i})$$ (1)

where, P_i is the ideal PAR and P_a is available PAR. P_i is calculated using two new characteristics that were added to the plant specification from the CELSS data: 'photoperiod', or the number of hours per day of light, and 'par_baseline', or the ideal lighting intensity. P_a is determined by a connected 'light' agent, which is electric lighting by default. A new agent, 'B2 Sun', was created based on measurements of available PAR inside B2, with hourly variation throughout the day (Figure 2) and monthly variation for the dates 1/1/1991 - 12/31/1995 (Figure 4). Simulated PAR production by the B2 Sun compared with ideal (CELSS) PAR for selected crops is shown in Figure 2. The resulting f_{PAR} ranges from nearly 1 in lettuce to <0.2 for wheat.

Planting density was incorporated as f_D, the factor of Density, which is also used to ?weigh?weight? biomass accumulation. f_D is set to 0.5 for SIMOC-B2. Pest/Weed issues are cited as a reason for poor yields in Mission 1 compared to Mission 2. We spoke with Tilak Mahato, a crew member on Mission 2. Due to the complexity of the issues and interventions, a single variable f_{CM}, the factor of Crop Management, was incorporated to represent the combination of practices which improve production. f_{CM} is also used to weight biomass accumulation and is set to 1 by default. The input (In) and output (Out) exchanges and parameter characteristics for plant species used in SIMOC-B2 are shown in Table 1.
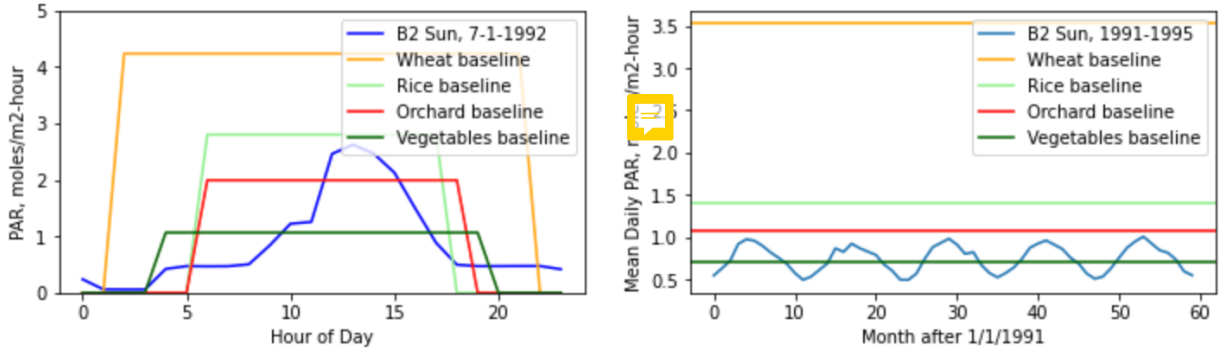
Figure 2. B2-Sun PAR production vs. ideal. *PAR output from the B2 Sun agent (blue)is compared with PAR baseline for 4 staple crops across the daily (left) and annual (right) cycles.*

The distribution of crop species inside B2 is based on Ref 13 Figure 1(a). In this study and others,[15] the total growing area cited is much larger, and includes many more different types of plants. Due to the limited availability of validation data, just use the plants in the table, and scale them proportionally to the growing area.

Concrete and soil were also primary contributors to the O_2 and CO_2 balance within B2, as identified by Ref 14. Agents representing them were added to SIMOC as well. Concrete, besides curing, undergoes a process of carbonation, where internal calcium hydroxide is combined with CO_2 to form calcium carbonate and retain moisture. At elevated CO_2 concentrations like those in B2, this process occurs much faster, and for much longer.[16] The SIMOC Concrete agent uses a modified diffusion function to simulate this process, calibrated to estimates provided by Ref 14. Figure 3 shows the behavior of the SIMOC concrete agent inside B2 compared to reference scenarios.
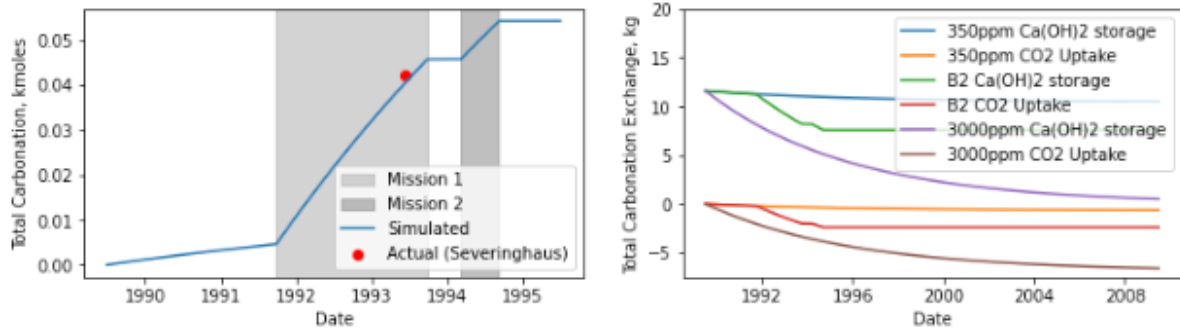
Figure 3. SIMOC concrete model. *1 m^2 of concrete shown in 3 different CO_2 scenarios*

Soil contains respiring microorganisms, and the soil inside B2 was especially rich. Soil was distributed across different biomes, each of which has a specific rate of soil respiration, as well as a community of vegetation performing photosynthesis. In SIMOC, each biome is modeled as a separate agent with fixed rates of O_2 and CO_2 exchange, based
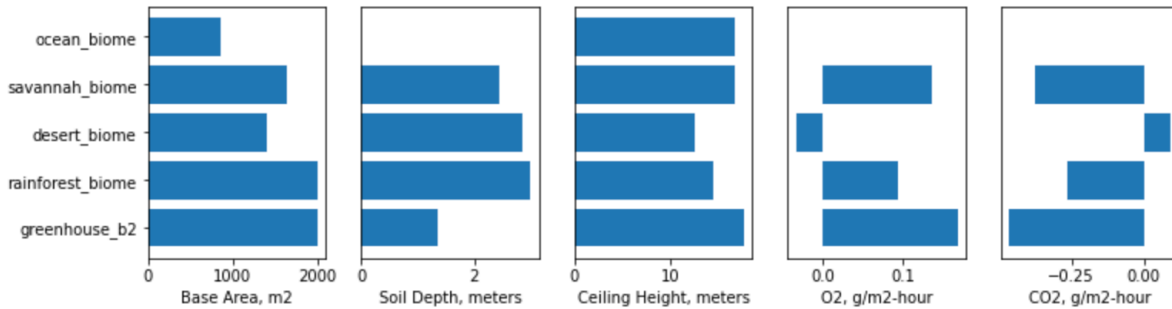
Figure 4. SIMOC Biomes specification.

on experimental data of the rainforest and desert biomes.[11, 15] The combined effect of biome soil respiration and plant photosynthesis was calibrated to match the soil exchange in Ref 14. These are compared in Figure 4.

Several general agents from SIMOC are used in the Biosphere simulations as well. Human agents are copied, but food consumption is reduced by 50% to account for the crew's calorie-restricted diet, as compared to the calorie-rich astronaut diet on which SIMOC was based. The ECLSS for B2 consists of a dehumidifier, CO_2 removal system, O_2 resupply system, and water and waste recycling. Also included are the power generation and storage required by the ECLSS.

Finally, these agents are configured into SIMOC simulations. A base configuration, shown in Table 2, was created with default agents, amounts and parameters. Then three scenarios were created to represent historical Missions 1 and 2. Mission 1 was split into 2 configurations in order to include supplemental oxygen and changes in operation made during Mission 1:

- *Mission 1a*: The beginning of Mission 1 (9/26/1991) up until the point when supplemental O_2 was added (1/12/1993). The CO_2 management system is set to limit CO_2 to 2,500 ppm but has a maximum rate of sequestration.
- *Mission 1b*: From the end of Mission 1a to the end of Mission 1 (9/25/1993) , with changes to base configuration:
  - Starting atmosphere in the biomes, crew habitat and lungs is set to the ending atmosphere of Mission 1a: 14.95% O_2, 0.32% CO_2, 0.9% H_2O, and 83.83% N_2.
  - Concrete carbonation is set to the ending carbonation of Mission 1a: 0.0296.
  - O_2 management system (storage and makeup valve) is added. 11,288 kg of O_2 are available in storage, and the O_2 lower limit is set to 20%. This will begin immediately adding oxygen to the atmosphere.
  - Crop areas are adjusted such that red beet, sweet potato and dry bean make up 65% of the total area (split evenly between the 3), and the remaining crops are scaled proportional to their amount in the base configuration.
- *Mission 2*: Biosphere Mission 2, from 3/6/1994 to 9/6/1994, with changes to base configuration:
  - Human amount reduced to seven.
  - Concrete carbonation is set to Mission 1b ending carbonation: .0401.
  - Crop management factor is increased to 1.5

Attribute	In	In	In	Out	Out	Out	Char	Char	Char	Char
Type	CO_2	Potable Water	Fertilizer	O_2	H_2O	Biomass	PAR Baseline	Photo-period	Lifetime	Harvest Index
Unit	g/m^2	g/m^2	g/m^2	g/m^2	g/m^2	g/m^2	moles/m^2-h	hours	days	
wheat	2.55	188.49	0.11	1.85	187.64	1.65	3.53	20	84	0.29
soybean	0.53	188.49	0.06	0.38	188.38	0.31	1.54	12	90	0.38
sweet potato	1.90	85.14	0.10	1.38	84.49	1.27	1.17	12	85	0.45
peanut	1.28	457.90	0.14	0.93	457.63	0.76	1.13	12	35	0.25
rice	1.57	116.29	0.07	1.14	115.76	1.02	1.40	12	45	0.3
dry bean	1.42	508.55	0.16	1.04	508.25	0.84	1.01	18	28	0.4
red beet	0.51	22.70	0.03	0.37	22.53	0.34	0.72	16	38	0.6
sorghum	2.55	188.49	0.11	1.85	187.64	1.65	3.53	20	84	0.29
vegetables	0.44	64.07	0.04	0.32	63.93	0.30	0.71	16	35	0.81
corn	2.55	188.49	0.11	1.85	187.64	1.65	3.53	20	84	0.29
orchard	0.97	117.18	0.07	0.70	116.87	0.64	1.08	13	57	0.45

Table 1. SIMOC-B2 Plant Specification.

Agent	Amount		Agent (continued)	Amount
human_agent	8		south_lung*	1,800
rice	530		ocean_biome*	863
wheat	370		savannah_biome*	1,637
sorghum	261		concrete†	15,800
peanut	168		b2_sun	1
corn	488		co2_storage	1
dry_bean	222		co2_removal SAWD‡	5
sweet_potato	261		dehumidifier	50
vegatables	348		solid_waste_aerobic_bioreactor	1
soybean	326		urine_recycling_processor_VCD	1
orchard	646		multifiltration_purifier_post_treatment	50
greenhouse_b2*	2,000		water_storage *(potable: 10,000)*	50
crew_habitat_b2*	1,000		nutrient_storage *(fertilizer: 10,000)*	50
rainforest_biome*	2,000		food_storage§	1
desert_biome*	1,400		b2_power_gen	1
west_lung*	1,800		power_storage	1

Table 2. SIMOC-B2 Base Configuration. *Initialized with earth-normal atmosphere. †Initialized with carbonation: 0.00458, after 2 years @ 350ppm. ‡CO_2 upper limit: 2,500ppm. §Initialized with 500kg food: each crop type, proportional to their amounts.

IV. Results

Simulated crop yields during the B2 Missions were compared to reported yields for wheat, rice, corn and sorghum in Ref 13 Table 3. The mean relative error across all yields was 37% (excluding M1a and M1b corn). The error was smallest in Mission 2, averaging 10%, and greatest in Mission 1b, with an average of 97%. Productivity at CELSS was 80-90% higher than the Biosphere 2 configurations. All crop species showed season variation in yield proportional to the change in sunlight. In Mission 1a, total food production is barely sufficient to cover the crew's diet; at certain
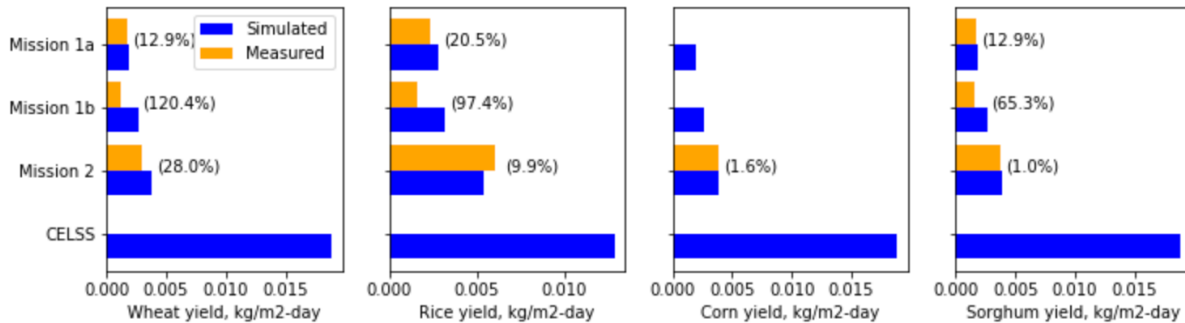

Figure 6. Simulated vs. Measured Crop Productivity (Relative Error). *Measured data from Marino Table 3.*

times, do to the overlaying of crop growth cycles, the crew doesn't have edible food for a day or two, but they recover and survive.

O_2 and CO_2 concentrations inside B2 are shown in Figure 5. Simulated O_2 concentration closely tracked the measured level throughout Missions 1 and 2: starting from the earth-normal ratio of 19%, it fell steadily throughout Mission 1a to a low of 15% in winter 1993. Then, at the start of Mission 1b, they rise steadily back to their baseline rate, and begin falling again. Simulated CO_2 levels fluctuate less than those measured, but show the same seasonal variation in the winter of 1992/93: with less sunlight, plants grow more slowly and consume less CO_2.
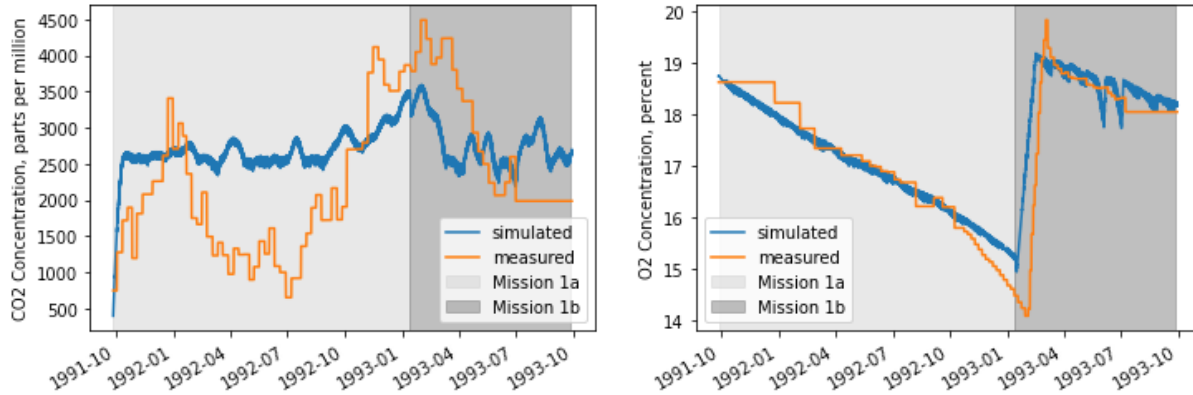
Figure 5. Simulated vs. Measured CO$_2$ and O$_2$ levels.

The total exchanges of the ECLSS, concrete and soil (biome) agents are shown in Table 3, as compared to measured data in Ref 14 Table 1. O$_2$ exchanges due to resupply and soil respiration have a relative error of ~1%. CO$_2$ exchanges from soil respiration and concrete carbonation had a relative errors of 6% and 9%, respectively, and the CO$_2$ scrubber error was 18%.

Field	Measured, kmoles	Simulated, kmoles	Relative Error
Pure O$_2$ added on days 475 - 494	7,055	6,978	-1.09%
Total CO$_2$ taken up by scrubber	-4,313	-5,069	17.53%
Soil respiration O$_2$[1]	-11,327	-11,190	-1.21%
Soil respiration CO$_2$[1]	29,135	30,782	5.65%
CO$_2$ captured by concrete	-24,205	-22,121	-8.61%

Table 3. Simulated vs Measured Ecosystem Exchanges.

V.   Discussion

The results of the simulation are directionally accurate, but with a low degree of precision. Relatively few measurements of plant productivity are available from the B2 experiments, and SIMOC's other validation reference is a highly dissimilar experiment. To improve precision of the plant model, we make the following recommendations:
- Include fruit trees and other perennial plants in addition to vegetables. These made up a large part of the B2 crew's actual diet, and follow a different growth cycle.
- Model the impact of specific pests and parasites. As records allow, match periods of low productivity for specific plants with their causes – most often fungi or mites. In the case of corn, no edible food was produced in Mission 1a and 1b because it is wind-pollinated, and there was no wind inside the structure. This and other species-specific behaviors could increase the accuracy as well as the educational potential of SIMOC.
- Include some metric of human wellness besides simple survival. Some of the difference in plant productivity between Missions 1 and 2 can be attributed to crew energy levels and morale. Taking into account nutrition, workload, variety of diet, etc. and giving an overall indication of crew's well-being will be useful in optimizing these systems, and for making the simulations more engaging.

Despite this imprecision, the measured system-level behaviors of the B2 missions are observable in the simulation. By making adjustments the base configurations, users can also observe the following phenomena:
- Plant growth can be increased by adding supplemental lighting (at the cost of increased electric consumption), or decreased by reducing CO$_2$ setpoint to <700ppm.

- Crop layouts can be adjusted to add higher-yield crops, or crops which transpire and photosynthesize at different rates, affecting overall gas balances.
- The starting concrete carbonation rate can be adjusted, which affects the rate at which it consumes CO_2. This is also affected by the ambient CO_2 levels, with lower rates of carbonation when CO_2 levels are lower.
- Adjusting the areas of each biome impacts (1) the size of the air sink, and therefore the overall changes in concentrations, (2) O_2 and CO_2 exchanges, as each biome has a different rate.

VI. Conclusion

The Biosphere 2 experiments are the most significant application of a man-made biological life support system to date. The data generated and lessons learned are as useful today as ever for addressing climate change and designing habitats beyond Earth, and for inspiring the next generation of scientists and engineers to build them....as well as improving CEA crop production, resource use efficiency and decreased environmental impact of food production on Earth.... By building and conducting simulations of the original experiments, we aim to build a research and educational platform to serve that purpose.

Acknowledgments

References

[1]Jones, C. A., et al. "The CERES wheat and maize models." *Proceedings of the International Symposium on Minimum Data Sets for Agrotechnology Transfer, ICRISAT Center, India*. 1983.

[2]Zheng, Bangyou, Karine Chenu, Alastair Doherty, and S. Chapman. "The APSIM-wheat module (7.5 R3008)." *Agricultural Production Systems Simulator (APSIM) Initiative* 615 (2014).

[3]Liu, H. L., et al. "Using the DSSAT-CERES-Maize model to simulate crop yield and nitrogen cycling in fields under long-term continuous maize production." *Nutrient cycling in agroecosystems* 89 (2011): 313-328.

[4]Basso, Bruno, Lin Liu, and Joe T. Ritchie. "A comprehensive review of the CERES-wheat,-maize and-rice models' performances." *Advances in agronomy* 136 (2016): 27-132.

[5]Mitchell, C A. "Bioregenerative Life-Support Systems." *The American Journal of Clinical Nutrition*. Oxford University Press (OUP), November 1, 1994.

[6]Wheeler, R. M. *Crop production for advanced life support systems-observations from the Kennedy Space Center Breadboard Project*. 2003.

[7]Staats, Kai, et al. "An agent-based model for high-fidelity ECLSS and bioregenerative simulation." 49th International Conference on Environmental Systems, 2019.

[8]Hawkins, Grant, Kai Staats, Ezio Melotti. "Responses to Elevated CO2 on Food Production and Life Support Systems in a Mars Habitat." 51st Internatinoal Concerence on Environmental systems, 2022

[9]Marino, Bruno DV, and Howard T. Odum. "Biosphere 2. Introduction and research progress." *Ecological Engineering* 13.1-4 (1999): 3-14.

[10]Engel, Victor C., and H. T. Odum. "Simulation of community metabolism and atmospheric carbon dioxide and oxygen concentrations in Biosphere 2." *Ecological Engineering* 13.1-4 (1999): 107-134.

[11]Lin, Guanghui, et al. "Ecosystem carbon exchange in two terrestrial ecosystem mesocosms under changing atmospheric CO 2 concentrations." *Oecologia* 119 (1999): 97-108.

[12]Langdon, Chris, et al. "Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef." *Global Biogeochemical Cycles* 14.2 (2000): 639-654.

[13]Marino, Bruno DV, et al. "The agricultural biome of Biosphere 2:: Structure, composition and function." *Ecological Engineering* 13.1-4 (1999): 199-234.

[14]Severinghaus, Jeffrey P., et al. "Oxygen loss in Biosphere 2." *EOS, Transactions American Geophysical Union* 75.3 (1994): 33-37.

[15]Silverstone, S. E., and M. Nelson. "Food production and nutrition in Biosphere 2: results from the first mission September 1991 to September 1993." *Advances in Space Research* 18.4-5 (1996): 49-61.

[16]Pommer, Kirsten, and Claus Pade. *Guidelines: uptake of carbon dioxide in the life cycle inventory of concrete*. Nordic Innovation Centre, 2006.