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

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Plant productivity varies widely based on the growing conditions. Controlled Environment Agriculture (CEA) commercial production systems such as greenhouses routinely outperform open field agriculture by 10 times or more per unit area and per unit time 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*
CEA	=	*Controlled Environment Agriculture*
O_2	=	*Oxygen*
CO_2	=	*Carbon Dioxide*
f_{GL}	=	*Lifetime Growth Factor*
f_{GD}	=	*Daily Growth Factor*
f_{CU}	=	*Carbon Dioxide Uptake Factor*
f_{TE}	=	*Transpiration Efficiency Factor*

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ppm	=	*Parts Per Million*
C_i	=	CO_2 *Compensation Point*
ΔQ	=	*Biomass Accumulation*
Q_{Max}	=	*Maximum Lifetime Accumulated Biomass*
G	=	*Growth Rate*
E_T	=	*Transpiration-related Currency Exchanges*
E_P	=	*Photosynthesis-related Currency Exchanges*
PAR	=	*Photosynthetically Active Radiation*
f_{PAR}	=	*Factor of Photosynthetically Active Radiation*
f_D	=	*Factor of Density*
f_{CM}	=	*Factor of Crop Management*
Cb_{Max}	=	*Maximum Carbonation*
Gd_{CO2}	=	*Carbon Dioxide Gradient*
ΔCb	=	*Carbonation Rate*

I. Introduction

Far away from farmland with expansive soil and fresh water, and outside of the breathable atmosphere astronauts and future citizen space explorers must 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. At the time, Biosphere 2 was an air-tight facility which included 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 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.

The Scalable Interactive Model of an Off world Community (SIMOC) is a simulation platform which provides a testbed for BLSS research. SIMOC was designed originally based on an *ideal* scenario (NASA CELSS growth chamber experiments and the NASA BVAD document) and was calibrated so that the model reproduced the data from those experiments. The reality of a Moon or Mars habitat will be quite a bit different from the ideal, and the original Biosphere 2 missions offer a close approximation of those differences. In this paper, we add new degrees of freedom to the SIMOC plant model as well as other new agents such that it reproduces experimental data from both NASA *and* the original Biosphere 2 missions with a single model. By calibrating the model to these two extremes, we aim to grant researchers, students and citizen scientists greater insight into the historical data from both and the opportunity to evaluate and compare a wider range of different BLSS scenarios with higher accuracy.

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 for: development of human habitats beyond Earth; understanding the Earth's changing climate; and technology transfer from BLSS for improving food production systems on Earth within controlled environment agriculture (CEA). We aim to stimulate interest in these areas 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. Exchange values were based on experimental data from CELSS, so environmental conditions are ideal by default.

A. The SIMOC Plant Model

Plant agent definitions in SIMOC consist of a series of species-specific currency exchanges. These exchange values for all currencies are parameterized as their mean lifetime value (see Table 1) taken from experimental data, and a series of weights is applied at each step of the simulation to determine its current value. What follows is a summary of the weights used and their methods of calculation. The resulting timeseries values for a typical simulation are shown in Figure 1.
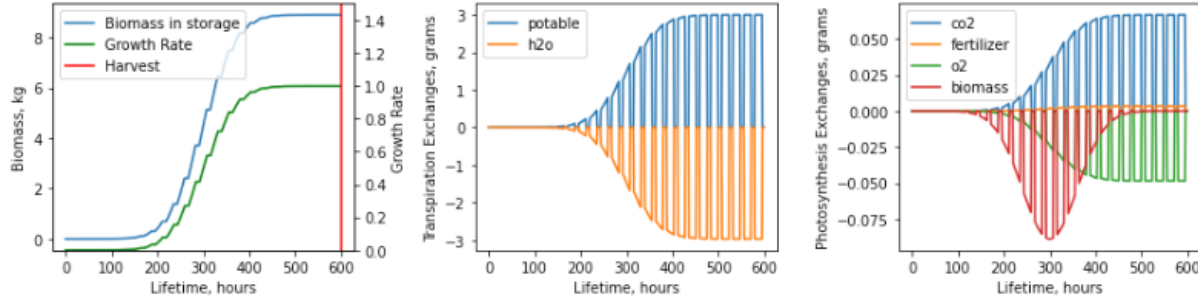

Figure 1. SIMOC plant model. *Based on 40 square meters of radishes grown with ideal potable water, CO_2 and fertilizer. From left to right: (a) total biomass in storage, matched with (calculated) growth rate; (b) inputs(outputs) related to transpiration. (c) inputs(outputs) related to photosynthesis.*

The lifetime growth factor (f_{GL}) represents the proportion of growth that occurs during each stage of a plant's life. It is modeled using a normalized Gaussian function to capture the plant's growth pattern, which is fastest in the middle of its life and slowest at the beginning and end. f_{GL} is shown as Equation 1, where r is the rate of the plant's life stage, ranging from 0 (brand new) to 1 (ready to harvest):

$$f_{GL}(r) = \frac{2\, G(r, 0.5, \frac{\pi}{10})}{G(r, 0.5, \frac{\pi}{10})} \tag{1}$$

In Equation 1, $G(r, 0.5, \pi/10)$ represents the Gaussian function with a mean of 0.5 and a standard deviation of $\pi/10$, evaluated at the given rate r. The denominator, $G(0, 0.5, \pi/10)$, serves to normalize the Gaussian function, ensuring that the growth factor peaks at a maximum value of 2, and results in a mean value of $\cong 1$. The lifetime for each plant is taken from Ref. 6, and shape of the curve resulting from the standard deviation was validated by experimental data as described in Ref. 7.

The daily growth factor (f_{GD}) represents the proportion of growth that occurs during each hour of the day (h), taking into account the photoperiod of the plant, scaled such that the mean value over 12 hours is equal to 1. f_{GD} is shown in Equation 2. The photoperiod (P) represents the number of hours of light exposure the plant receives daily; it is measured in hours and centered about noon.[6]

$$f_{GD}(h) = \begin{cases} \frac{24}{P}, & \left(12 - \frac{P}{2}\right) \leq h \leq \left(12 + \frac{P}{2}\right) \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

The CO_2-response mechanism in SIMOC consists of a carbon dioxide uptake factor (f_{CU}) and a transpiration efficiency factor (f_{TE}). f_{CU}, shown in Equation 3, represents increased rate of photosynthesis due to elevated CO_2 and is calculated using a baseline CO_2 concentration of 350 parts per million (350), the current CO_2 concentration (ppm), and the CO_2 compensation point (C_i) with a constant temperature (T) of 25 degrees Celcius, Equation 4. f_{TE} represents the increased water-use efficiency due to elevated CO_2, and is shown in Equation 5 The SIMOC CO_2-response mechanism is described in detail in Ref. 8.

$$f_{CU}(ppm) = \frac{(ppm - C_i)(350 + 2C_i)}{(ppm + 2C_i)(350 - C_i)} \tag{3}$$

$$C_i = \frac{163 - T}{5 - 0.1T} \tag{4}$$

$$f_{TE}(ppm) = \begin{cases} 1, & ppm \leq 350 \\ 0.73, & ppm \geq 700 \\ 1 - \left(0.27 \times \frac{ppm - 350}{700 - 350}\right), & otherwise \end{cases} \tag{5}$$

Hourly new biomass accumulation (ΔQ) is weighted by f_{GL}, f_{GD} and f_{CU}. The instantaneous rate of biomass accumulation at each step in the model is expressed by Equation 6.

$$\Delta Q = \Delta Q_{mean} \times f_{GL} \times f_{GD} \times f_{CU} \tag{6}$$

The rates of transpiration and photosynthesis are then determined by the total accumulated biomass: small plants require fewer resources, large plants require more. The exchange values for potable water, h2o (water vapor), fertilizer, CO_2 and O_2 are likewise parametrized as their mean lifetime value, and weighted at each step to determine their current value. Each is weighted by the factor of daily growth (f_{GD}) as well as the growth rate (G).

The growth rate (G), shown in Equation 7 represents the ratio of currently accumulated biomass (Q_i) to ideal lifetime accumulated biomass (Q_{Max}). Q_{Max}, shown in Equation 8, is simply the mean rate of biomass accumulation multiplied by the lifetime of the plant, in hours (L).

$$Q_{max} = \Delta Q_{mean} \times L \tag{7}$$

$$G = \frac{Q_i}{Q_{max}} \tag{8}$$

Since biomass accumulation follows a normal distribution, cumulative biomass (its integral) is sigmoid-shaped. Since the mean of an unskewed sigmoid curve is half of its maximum value, after weighting exchange values by G, they are multiplied by 2, so that its lifetime mean is 1. The resulting 'sigmoid-shaped' values were also validated in Ref. 7. This applies to transpiration-related exchanges (E_T) of potable water and water vapor, and photosynthesis-related exchanges (E_P) of carbon dioxide, fertilizer and oxygen, as expressed by Equations 9 and 10, respectively.

$$E_T = E_{Tmean} \times f_{GD} \times f_{TE} \times G \times 2 \tag{9}$$

$$E_P = E_{Pmean} \times f_{GD} \times f_{CU} \times G \times 2 \tag{10}$$

Additionally, the output exchanges of each process (water vapor for transpiration and oxygen for photosynthesis) are scaled by the proportion of actual to available inputs. For example, if potable water availability is only 50% of the target value for a given step, water vapor production will be 50% of its target value as well. Finally, when a plant reaches the end of its lifetime, its internal biomass is converted into edible food and inedible biomass based on the harvest index, also specified in Ref. 6.

B. Biosphere 2 Reference Data

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) update or add individual agents and calibrate to 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, so the plant model was updated. Concrete and soil were also primary contributors to the O_2 and CO_2 balance within B2, as identified by Ref. 14, so they were add.

A. Updates to SIMOC the Plant Model

After discussion and further research, the difference in plant productivity was attributed to three independent 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 currency exchanges.

Lighting requirement for plants is typically expressed in terms of Photosynthetically Active Radiation (PAR), a waveband of photosynthesis, and Photosynthetic Photon Flux Density (PPFD), with units in Mol m^{-2} s^{-1} as measured by a quantum sensor (though in practice, PAR is often used as shorthand for PPFD). Lighting requirement over the course of a day is expressed as Daily Light Integral (DLI), the summation of PPFD for the photoperiod (Mol m^{-2}) and is used to indicate the amount of light energy received by the quantum sensor. DLI's are known for many crops, for example 15-17 Mol m^{-2} is common for lettuce, and 25-35 Mol m^{-2} is common for tomatoes.

In SIMOC, for simplicity, light energy was incorporated as the currency PAR with units Mol m^{-2} s^{-1}. f_{PAR}, the factor of PAR, is calculated as the ratio of available PAR (P_a) to ideal PAR (P_i) as expressed by Equation 11.

$$f_{PAR} = \min(1, \frac{P_a}{P_i}) \tag{21}$$

P_i is calculated using two characteristics from the CELSS data: 'photoperiod', or the number of hours per day of light (also used above to calculate f_{GD}), and 'par_baseline', or the ideal lighting intensity. P_a is determined by a connected 'light' agent. For CELSS-type simulations, an electric light agent matching each plant's ideal conditions. For B2, a new agent, 'B2 Sun', was created based on measurements of available PAR inside B2 by sensors located just above the planting surface thus accounting for the shading effects of the ceiling, with hourly variation throughout the day (Ref. 13 Figure 2), and monthly variation for the dates 1/1/1991 - 12/31/1995 (Ref. 13 Figure 4). Simulated PAR production by the B2 Sun compared with ideal PAR for selected crops is shown in Figure 2, with P_i ranging from 0.7 for lettuce to 3.53 for wheat, the resulting f_{PAR} ranges from 1 for lettuce to <0.2 for wheat.

Planting density was incorporated as the factor of density(f_D), which is also applied as weights to biomass accumulation. f_D is set to 0.5 for SIMOC-B2, indicating that planting density at B2 is 50% of ideal. Pest/Weed issues are cited as a reason for poor yields in Mission 1 compared to Mission 2.[17] Due to the complexity of crop production practices and the variety of crop species, a single variable f_{CM}, the factor of Crop Management, was incorporated to represent the combination of practices which maintain crop production. f_{CM} is likewise applied as a 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.
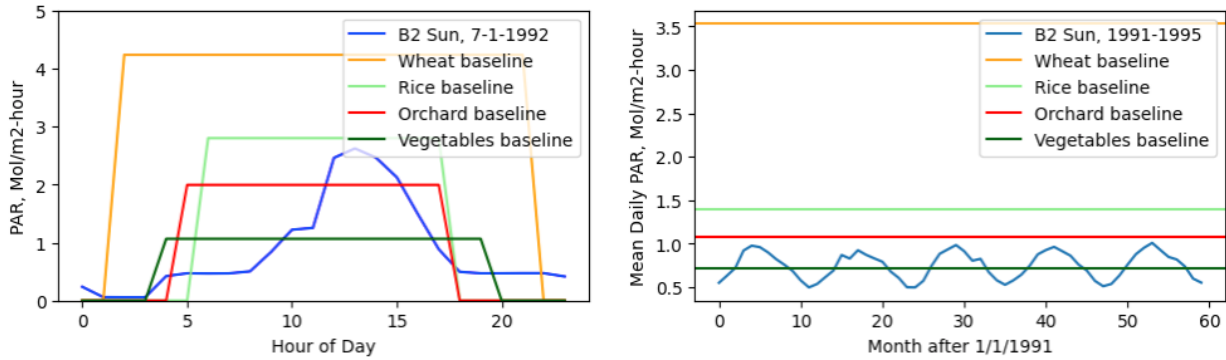
Figure 2. B2-Sun PAR production vs. ideal. *PAR output from the B2 Sun agent (blue)is compared with PAR baseline for 4 staple crops across the daily (left) and annual (right) cycles.*

These 3 factors are incorporated into the plant model as shown in Equations 12, 13 and 14, which replace Equations 6, 9 and 10, respectively.

$$\Delta Q = \Delta Q_{mean} \times f_{GL} \times f_{GD} \times f_{CU} \times f_{PAR} \times f_D \times f_{CM} \tag{12}$$

$$E_T = E_{Tmean} \times f_{GD} \times f_{TE} \times G \times 2 \times f_{PAR} \tag{13}$$

$$E_P = E_{Pmean} \times f_{GD} \times f_{CU} \times G \times 2 \times f_{PAR} \tag{14}$$

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, we us only those plants listed in the reference, and scale them proportionally to the growing area.

Attribute	In	In	In	Out	Out	Out	Char	Char	Char	Char
Type	CO_2	Potable Water	Fertilizer	O_2	H_2O	Wet 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/m²-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.

B. The SIMOC Concrete Agent

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 concreate agent includes a 'carbonation' attribute with unit moles, which is updated each step of the model by the carbonation rate using a modified version of Fick's diffusion law.

The carbonation rate (ΔCb) represents the amount of carbonation with unit moles per hour. The first step in calculating ΔCb is to determine the CO_2 saturation point in moles (S_M) for the current ambient CO_2 level (ppm). S_M is determined by interpolating ppm between two reference points, taken from Ref. 14 Figure 2. The lower reference point is equal to the integral of saturation of the Outside concrete, which we estimate to be 12.7 %-cm at 350ppm. For the upper reference point, we use the Inside concrete, which we estimate to be 35 %-cm at 3000ppm, and divide by 0.3, on the assumption that it was only 30% of maximum saturation at the time of measurement. This assumption is based on the carbonation process being said to last up to 20 years[16], and that the data from inside Biosphere 2 indicate that the rate of CO_2 absorption continued to be significant after the reference data were collected. When S_M is established, it is multiplied by the density of carbonatable material (D_{CO2}), which is given as 1.21 g/cm^2 in Ref. 14 Table 2, and divided by 1000 to convert from grams to kg, to determine the maximum carbonation (Cb_{MAX}). The process is expressed by Equation 15.

$$Cb_{MAX}(ppm) = .00121 \times \begin{cases} 12.7, & ppm \leq 350 \\ 116.6, & ppm \geq 3000 \\ 12.7 \div \left(103.9 \times \frac{ppm-350}{3000-350}\right), & otherwise \end{cases} \tag{15}$$

Next, we determine the carbon dioxide gradient (Gd_{CO2}) as the difference between the current carbonation (Cb_i) and Cb_{MAX} or 0, whichever is greater. Finally, ΔCb is calculated as the product of Gd_{CO2} and the diffusion rate (Df_{CO2}) of .000018, which was determined by fitting the preceeding equations to the experimental data from Ref. 14. These are shown in Equations 16 and 17, respectively.

$$Gd_{CO2} = \max (0, Cb_{MAX} - Cb_i) \tag{16}$$

$$\Delta Cb = Gd_{CO2} \times Df_{CO2} \tag{17}$$

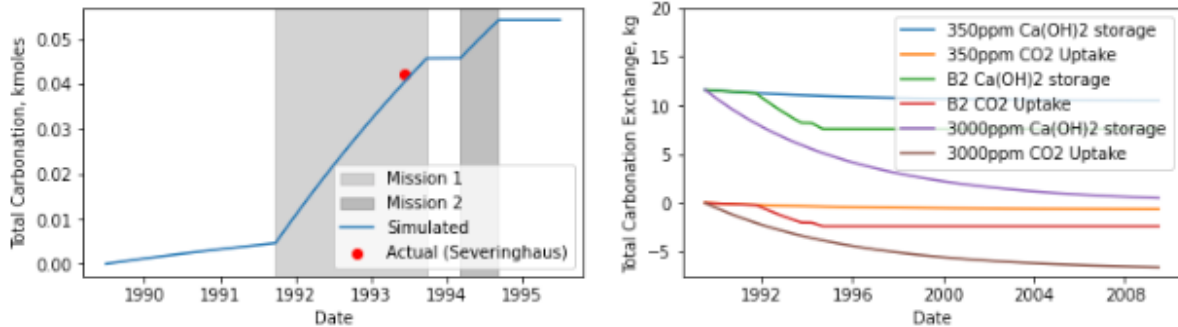The behavior of the concrete agent over time and under different scenarios is illustrated in Figure 3.

Figure 3. SIMOC concrete model. *1 m^2 of concrete shown in 3 different CO_2 scenarios.*

C. The SIMOC Biome Agents

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 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.

D. Other Agents

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
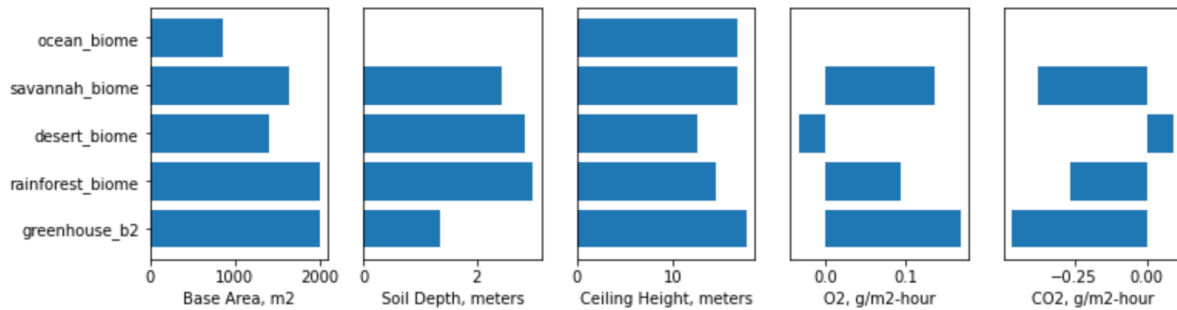
Figure 4. SIMOC Biomes specification.

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.

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
vegetables	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.

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.

- o 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:
  - o Human amount reduced to seven.
  - o Concrete carbonation is set to Mission 1b ending carbonation: .0401.
  - o Crop management factor is increased to 1.5.

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, and are shown in Figure 5. 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 times, due to the overlaying of crop growth cycles, the crew doesn't have edible food for a day or two, but they recover and survive.
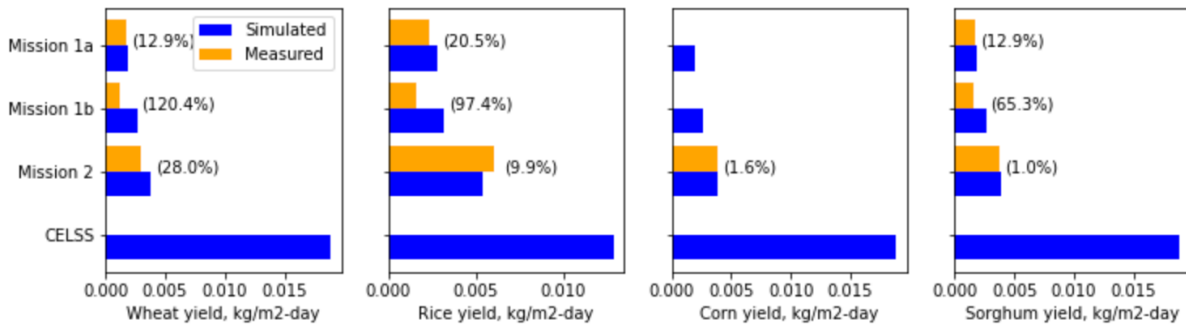

Figure 5. Simulated vs. Measured Crop Productivity (Relative Error). *Measured data from Marino Table 3.*

O_2 and CO_2 concentrations inside B2 are shown in Figure 6. 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.
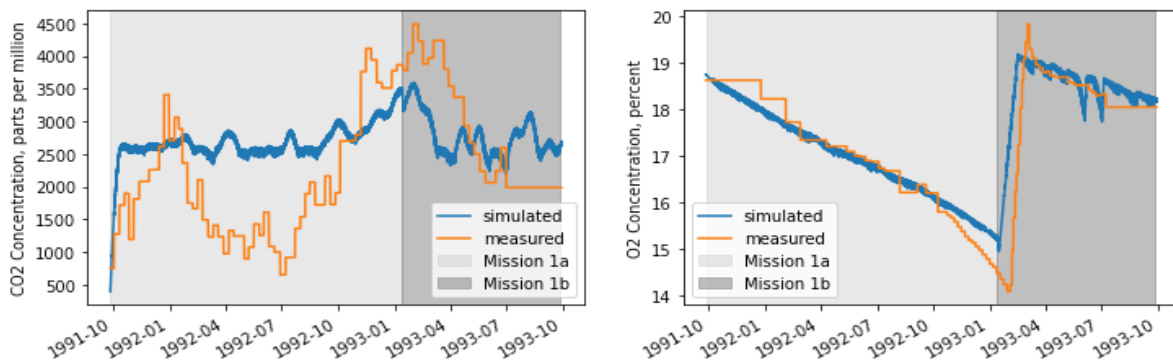

Figure 6. Simulated vs. Measured CO_2 and O_2 levels.

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 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%
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. An overview of the configurable metrics in SIMOC versus the actual experiments is given in Table 4.

Domain	Biosphere 2 Actual	SIMOC Configurable
Crop Selection	• Grains (3 species), Starchy Veg (4), Legumes (5), Vegetables (20), Fruit (9), Animal Products (6)[15] • Mix of annuals and perennials.	• Grains (3), Starchy Veg (2), Legumes (4), Vegetables (14), Fruit (2) • Annuals only.
Crop Layout	• Select quantity and location. • Several discrete growing areas with unique lighting and soil characteristics • Intercropping (Mission 2)	• Select quantity. • No distinction between growing areas • Use composite crops (vegetables, orchard) to represent intercropping
Lighting	• Sunlight with hourly, seasonal and annual variation • Occlusion from B2 superstructure • Shading due to row spacing and weeds	• Sunlight with hourly variation based on a typical day, and monthly variation based on monthly mean. • Measurements taken at ground level to account for occlusion. • Optional supplemental lighting
Crop Wellbeing Factors	• Pests and parasites have crop-species-specific effects at different stages of growth. • Fungi kill large swaths of crops and spread via contaminated tools. • Inhabitants' crop management rigor varies based on mood, nutrition, etc.	• Crop Management Factor (default=1) applied to biomass accumulation rate for all plants.
Human Wellbeing Factors	• Diet: nutrition, variety, quantity • Atmosphere: low oxygen levels cause fatigue, nausea, lack of motivation • Workload: varies based on growing season, one-off events, sickness, etc. • Interpersonal factors	• Survival: die from lack of food, water or oxygen, or from high carbon dioxide levels
Biomes	• Fixed area of each biome with unique lighting and soil characteristics. • A community of plants and soil microorganisms with daily/seasonal variation in currency exchanges • Health/well-being varies, requires human input	• Variable area of each biome • Biome-specific, non-variable oxygen and co2 exchanges • No environmental response

Table 4. Case Matrix. Comparison of selected factors which contribute to the success or failure of a mission.

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. This could be due to several factors, including low lighting, seasonal variation in light, and a lack of wind for natural pollination.[17] 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. (Though it should also be noted that crop management practices based on experience and attention to detail have a significant impact as well).
- 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

Biological life support systems are essential for maintaining human life on Earth and enabling the expansion of civilization beyond our planet. The Biosphere 2 experiments stand as the most significant application of a BLSS to date. By integrating the configuration and experimental results of Biosphere 2 with those from highly controlled and optimized NASA experiments into a single model, we can explore a wider range of scenarios and improve the accuracy of extreme conditions where innovative solutions are most likely to emerge.

The data generated and lessons learned hold relevance for addressing climate change, designing extraterrestrial habitats, and inspiring the next generation of scientists and engineers to build them. These insights can also contribute to Controlled Environment Agriculture (CEA) crop production by enhancing resource use efficiency and reducing the environmental impact of food production on Earth. By building and conducting simulations that incorporate the original experiments, we aim to create a research and educational platform that serves this purpose.

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