**Plant Growth 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 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 10% [TENTATIVE] of experimental results. 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

*A* = amplitude of oscillation

*a* = cylinder diameter

*Cp*= pressure coefficient

*Cx* = force coefficient in the *x* direction

*Cy* = force coefficient in the *y* direction

c = chord

d*t* = time step

*Fx* = *X* component of the resultant pressure force acting on the vehicle

*Fy* = *Y* component of the resultant pressure force acting on the vehicle

*f, g* = generic functions

*h* = height

*i* = time index during navigation

*j* = waypoint index

*K* = trailing-edge (TE) nondimensional angular deflection rate

# Introduction

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# Background

Computational models of plant growth emerged early in the information age. One of the first was Crop Environment Resource Synthesis (CERES) which was expanded to CERES-WHEAT and CERES-MAIZE in 1985 and 1986. Several modern platforms are built on the CERES model: Agricultural Production Systems sIMulator (APSIM) integrates models of soil, weather and pests, and Decision Support System for Agrotechnology Transfer (DSSAT) provides a user-friendly interface for calibrating and measuring localized data. 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.

Biological Life Support Systems (BLSS), or artificial ecosystems used to support human crew in extreme environments, use extreme conditions to their advantage. By extending the growing period and optimizing water, nutrients and the air, ecosystems 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 CO2, and a nutrient-film hydroponic growing technique to achieve record production and take precise measurements of wheat, soybean, lettuce, potato and tomato plants.

The Scalable Interactive Model of an Off-world Community (SIMOC) is an agent-based model used to simulate habitats with BLSS. In addition to humans, mechanical life support, power and structures, SIMOC includes plant agents which exchange O2, CO2, fertilizer, potable water and water vapor with their environment. Plant growth is controlled by accumulated 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. Figure 1

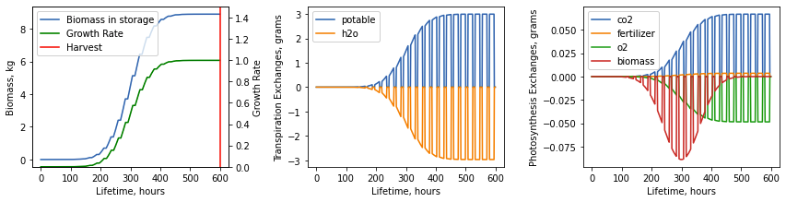


Figure 1. SIMOC plant model. *Based on 40 m2 of radishes grown with ideal potable water, CO2 and fertilizer.*

Biosphere 2 (B2) is 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. These yielded important insights into O2 and CO2 management, controlled-environment agriculture, soil community metabolism and more. In the following years, smaller, isolated experiments were performed on the effects of drought on rainforests, elevated CO2 on coral reefs, and baseline productivity of different biomes.

# Methodology

First, two of the Biosphere 2 studies were selected for validation. One study is focused on the Intenstive Agricultural Biome (IAB) during Missions 1 and 2. It includes crop layout as well as measurements of sunlight and crop productivity. The other study looks at the overall behavior of O2 and CO2 levels during Mission 1, and relates it to soil respiration and concrete carbonation.

Our approach was to (1) calibrate SIMOC plants model using sunlight and productivity data, (2) simulate the Biosphere 2 experiments in SIMOC, and (3) compare simulated plant productivity and overall levels of O2 and CO2 to actual (measured) levels. Table N shows that plant productivity at B2 was ~10x lower than in the CELSS experiment. After discussion, we chose differences in lighting, planting density and pest/weed mitigation as the factor we would use to account for this difference.

Chart, line chart, histogram

Description automatically generatedFigure 2. B2-Sun PAR production vs. ideal.

Lighting was incorporated into SIMOC as variable fPAR, the factor of Photosynthetically Active Radiation (PAR), which is used to weight biomass accumulation.

()

where, Pi is the ideal PAR and Pa is available PAR. Pa is determined by a connected ‘light’ agent, which is electric lighting by default. For SIMOC-B2, a ‘B2 Sun’ agent was created based on measurements of available PAR inside B2, with hourly variation throughout the day, and monthly variation for the dates 1/1/1991 - 12/31/1995. The resulting fPAR ranges from nearly 1 in lettuce to <0.2 for wheat. Figure 2

Planting density was incorporated as fD, the factor of Density, which is also used to weight biomass accumulation. fD 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 fCM, the factor of Crop Management, was incorporated to represent the combination of practices which improve production. fCM is also used to weight biomass accumulation and is set to 1 by default.

The distribution of crop species inside B2 is based on Marino X. In this study and others, 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. Table 1.

Concrete and soil were also primary contributors to the O2 and CO2 balance within B2, as identified by Severinghaus. Agents representing them were added to SIMOC as well. Concrete, besides curing, undergoes a process of carbonation, where internal calcium hydroxide is combined with CO2 to form calcium carbonate and retain moisture. At elevated CO2 concentrations like those in B2, this process occurs much faster, and for much longer. The SIMOC Concrete agent uses a modified diffusion function to simulate this process, calibrated to estimates provided by Severinghaus.

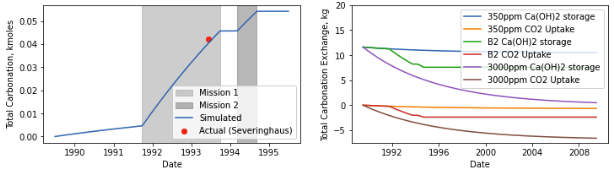


Figure 3. SIMOC concrete model. *1 m2 of concrete shown in 3 different CO2 scenarios: the B2 habitat at 350 before, after and between missions and 3000ppm during (left, right), is compared with constant 350ppm and 3000ppm (right).*

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Attribute | In | In | In | Out | Out | Out | Char | Char | Char | Char |
| Type | CO2 | Potable Water | Fertilizer | O2 | H2O | Biomass | PAR Baseline | Photo- period | Lifetime | Harvest Index |
| Unit | g/m2 | g/m2 | g/m2 | g/m2 | g/m2 | g/m2 | 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.

Soil contains respirating microorganisms, and the soil inside B2 was especially rich. It was spread throughout 4 different biomes along with vegetation. SIMOC agents representing the combined soil respiration and plant photosynthesis of each were created for the Rainforest, Desert, Savannah and IAB (soil only).  The Biome paper + Severinghaus figures. Figure 4

Several general agents from SIMOC are used in the Biosphere simulations as well. The Environmental Control and Life Support System (ECLSS) in SIMOC-B2 consists of a dehumidifier, CO2 removal system, O2 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. Table 2 A base configuration was created with default agents, amounts and parameters. Then three scenarios were created, representing 3 segments of the historical Biosphere 2 missions:

* *Mission 1a*: The beginning of Mission 1 (9/26/1991) up until the point when supplemental O2 was added (1/12/1993).

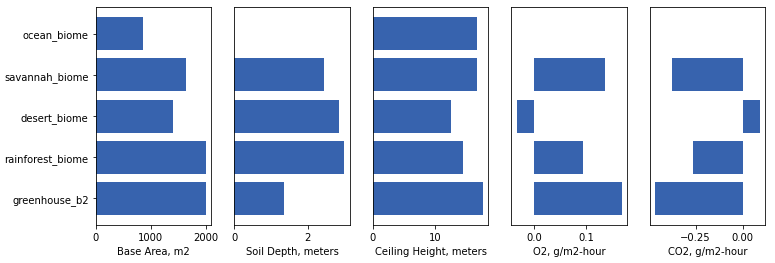


Figure 4. SIMOC Biomes specification.

* *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% O2, 0.32% CO2, 0.9% H2O, and 83.83% N2.
  + Concrete carbonation is set to the ending carbonation of Mission 1a: 0.0296.
  + O2 management system (storage and makeup valve) is added. 11288 kg of O2 are available in storage, and the O2 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 7.
  + Concrete carbonation is set to Mission 1b ending carbonation: .0401
  + Crop management factor is increased to 1.5

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Agent | Amount |  | Agent (continued) | Amount |
| human\_agent | 8 |  | south\_lung1 | 1,800 |
| rice | 530 |  | ocean\_biome1 | 863 |
| wheat | 370 |  | savannah\_biome1 | 1,637 |
| sorghum | 261 |  | concrete2 | 15,800 |
| peanut | 168 |  | b2\_sun | 1 |
| corn | 488 |  | co2\_storage | 1 |
| dry\_bean | 222 |  | co2\_removal\_SAWD3 | 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\_b21 | 2,000 |  | water\_storage *(potable: 10,000)* | 50 |
| crew\_habitat\_b21 | 1,000 |  | nutrient\_storage *(fertilizer: 10,000)* | 50 |
| rainforest\_biome1 | 2,000 |  | food\_storage4 | 1 |
| desert\_biome1 | 1,400 |  | b2\_power\_gen | 1 |
| west\_lung1 | 1,800 |  | power\_storage | 1 |

Table 2. SIMOC-B2 Base Configuration. 1Initialized with earth-normal atmosphere. 2Initialized with carbonation: 0.00458, after 2 years @ 350ppm. 3CO2 upper limit: 2,500ppm. 4Initialized with 500kg food: each crop type, proportional to their amounts.

# Results

[Wheat productivity charts, CELSS vs B2]

[Table with productivity comparisons and error]

Chart

Description automatically generated

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

[Other agents, severinghaus table]

|  |  |  |  |
| --- | --- | --- | --- |
| **Field** | **Measured, kmoles** | **Simulated, kmoles** | **Relative Error** |
| Pure O2 added on days 475 - 494 | 7,055 | 6,978 | -1.09% |
| Total CO2 taken up by scrubber | -4,313 | -5,069 | 17.53% |
| Soil respiration O21 | -11,327 | -11,190 | -1.21% |
| Soil respiration CO21 | 29,135 | 30,782 | 5.65% |
| CO2 captured by concrete | -24,205 | -22,121 | -8.61% |

Table 3. Siulated vs Measured Ecosystem Exchanges. *Measured data from Severinghaus Table 2*

[O2 and CO2 charts, actual vs simulated]

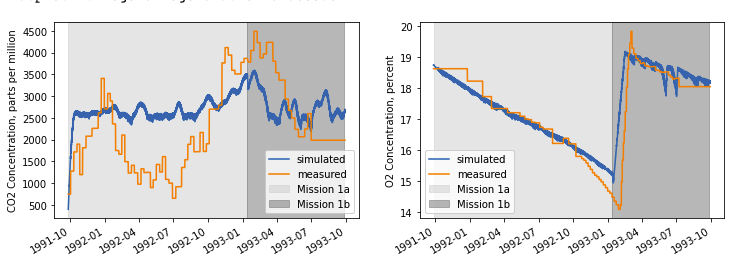


Figure 5. Simulated vs. Measured CO2 and O2 levels. *Measured data from Severinghaus Figure 1.*

# Discussion

Discussion: An interpretation of the results, an analysis of the implications and significance of the findings, and a comparison with the existing literature.

# Conclusion

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# Acknowledgments

Tilak, Ray, SIMOC, John, Tyson

# References

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2Dornheim, M. A., “Planetary Flight Surge Faces Budget Realities,” *Aviation Week and Space Technology*, Vol. 145, No. 24, 9 Dec. 1996, pp. 44-46.

3Terster, W., “NASA Considers Switch to Delta 2,” *Space News*, Vol. 8, No. 2, 13-19 Jan. 1997, pp., 1, 18.

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*Books*

4Peyret, R., and Taylor, T. D., *Computational Methods in Fluid Flow*, 2nd ed., Springer-Verlag, New York, 1983, Chaps. 7, 14.

5Oates, G. C. (ed.), *Aerothermodynamics of Gas Turbine and Rocket Propulsion*, AIAA Education Series, AIAA, New York, 1984, pp. 19, 136.

6Volpe, R., “Techniques for Collision Prevention, Impact Stability, and Force Control by Space Manipulators,” *Teleoperation and Robotics in Space*, edited by S. B. Skaar and C. F. Ruoff, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1994, pp. 175-212.

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8Chi, Y., (ed.), *Fluid Mechanics Proceedings*, SP-255, NASA, 1993.

9Morris, J. D. “Convective Heat Transfer in Radially Rotating Ducts,” *Proceedings of the Annual Heat Transfer Conference*, edited by B. Corbell, Vol. 1, Inst. Of Mechanical Engineering, New York, 1992, pp. 227-234.

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12Tseng, K., “Nonlinear Green’s Function Method for Transonic Potential Flow,” Ph.D. Dissertation, Aeronautics and Astronautics Dept., Boston Univ., Cambridge, MA, 1983.

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13Richard, J. C., and Fralick, G. C., “Use of Drag Probe in Supersonic Flow,” *AIAA Meeting Papers on Disc* [CD-ROM], Vol. 1, No. 2, AIAA, Reston, VA, 1996.

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16TAPP, Thermochemical and Physical Properties, Software Package, Ver. 1.0, E. S. Microware, Hamilton, OH, 1992.

Include a version number and the company name and location of software packages.

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17Scherrer, R., Overholster, D., and Watson, K., Lockheed Corp., Burbank, CA, U.S. Patent Application for a “Vehicle,” Docket No. P-01-1532, filed 11 Feb. 1979.

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