An agent-based model for high-fidelity ECLSS and bioregenerative simulation.

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Nomenclature

ABM	=	*agent-based model*
CO2	=	*carbon dioxide*
ECLSS	=	*environmental control and life support system*
H2O2	=	*hydrogen peroxide*
PAR	=	photosynthetically active radiation
PPFD	=	Photosynthetic Photon Flux Density
RO	=	reverse osmosis
µmol	=	micromole, 602 quadrillion photons, used to measure PAR

I. Abstract

Mathematical models can combine baseline assumptions about relatively simple, real-world systems into complex simulations, providing researchers with access to otherwise difficult to build or cost prohibitive environments. An agent-based model (ABM) employs the actions and interactions of individual and collective, autonomous agents such that their behavior, when allowed to unfold over a specified time, may exhibit non-linear, dynamic, and probabilistic behavior. SIMOC (a scalable, interactive model of an off-world community) is a Python agent-based model with both a research and educational component, developed to simulate hybrid ECLSS and bioregenerative closed systems, as those considered for long-term human habitation of the Moon or Mars. The SIMOC web-based agent editor enables rapid design of new agents to approximate real-world systems. While SIMOC was built upon data for both humans and plants extracted from the NASA Baseline Assumptions and Values Document, this publication sees first application of this novel approach to modeling the growth cycle of a single plant species in a semi-sealed, controlled environment, from seed to harvest, tracking air temperature, relative humidity, PAR, carbon dioxide, water run-off and biomass accumulation.

II. Introduction

In this NewSpace era, our species is once again preparing to venture beyond low Earth orbit (LEO) to the Earth's moon, and to Mars. In the long shadow of the Apollo era, advances in rocket propulsion, reusable heavy lift vehicles, and far larger human occupied space craft are being developed, in part, to give humans the capability for long duration missions.

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While the International Space Station has for nearly three decades provided the world's more collaborative laboratory for micro-gravity research, it has relied entirely on provisions brought from Earth. Physico-chemical based Environmental Control and Life Support Systems (ECLSS) have maintained breathable air and potable water for the human crew[1]. With the exception of a few experiments in growing edible plants[2], the multi-national astronauts have consumed food delivered from Earth by means of the NASA Space Shuttle, Russian Soyuz modules, and with a recent successful demonstration, in the near future the Space X Dragon.

The continuous supply of air, water, and food is sustainable in LEO and perhaps in orbit around or on the Moon, but at considerable cost. Current estimates suggest $20,000 USD[3] for each kilogram brought from launch pad into orbit. In order for humans to become interplanetary, to live for months, even years off-world it is imperative that hybrid systems enable a longer term sustainability. Bioregenerative life support systems, closed or semi-closed systems for food production and recycling of water and breathable air, working alongside, and ultimately without ECLSS is the logical, long-term goal[4].

As far back as the 1960s the Soviet Union was experimenting with wheat as a viable, plant-based CO2 scrubber. The BIOS experiments proved a viable means to provide sustained, breathable atmosphere[5]. Many more experiments, including Biosphere 2[6], NASA's LSSIF[7], the European Space Agency's MELiSSA[8], the University of Arizona's Lunar Greenhouse[9], and more recently the Chinese Lunar Palace 1[10] are demonstrations of various levels of bioregenerative life support systems. Biosphere 2 is a large-scale, earth science facility near Tucson, Arizona that encompasses 3.15 acres (1.27 hectares) of land and houses synthetic ecosystems within in a glass and metal shell. These communities have been in place for nearly 30 years and include analogues of rainforest, desert, savanna, marsh and ocean ecosystems.

With NASA's Lunar Gateway orbiter in development, preparation for mid-stay crew habitation (weeks or months)[11] is underway. Long-term habitation on Mars, as dictated by a once per two-year window for orbital alignment, will demand that some degree of bioregeneration be sustained. It is unnecessary, however, to conduct a full-scale, full-duration test of such a human-in-the-loop system on Earth if short- and mid-term studies generate ample data to support models and simulations.

III. SIMOC

SIMOC[5] is an agent-based model (ABM), a kind of computer model in which the actions and interactions of autonomous agents, individuals or collective entities, are given simple rules of engagement and then monitored to learn how they affect the system as a whole[12]. First conceived in the 1940s by Von Neumann and developed in the 1990s when computers provided the required computational power, ABMs have been used extensively to model systems in biology, ecology, and social science[13].

ABMs are typically composed of: (1) agents applied to various scales; (2) a capacity for decision-making; (3) learning rules or adaptive processes; (4) a topology for interaction; and (5) an environment in which to operate[14]. With SIMOC, the scale of the agents varies from a square meter of a plant, to a human, to a large-scale crop production system, as in a greenhouse. At this current phase of development, SIMOC agents do not make decisions, but do execute their functions based upon available resources. The topology is represented by a finite volume of space and associated, closed atmosphere including the components of crew quarters, greenhouse, airlocks, and with future versions, EVA suits and rovers.

While most computational models describe systems in states of equilibrium or moving between equilibria, ABMs can produce emergent behavior and build complex systems. With SIMOC, the agents are programmed to exchange solids, liquids, gases, and thermal and electric energy. One example is a square meter of a single plant species (one agent) absorbing CO2 (a currency of exchange) during the photosynthetic biochemical process. For each time step in the simulation (typically an hour), the simulator advances the interactions between all agents, in a random order.

SIMOC is at present able to simulate a closed, human-in-the-loop system that employs ECLSS, bioregeneration, or a combination of both. With the physical crew quarters, greenhouse, lights, each human, each square meter of plants, and each ECLSS module being an agent, the currencies exchanged by all agents engaged in the model, at each time step, include: oxygen, carbon dioxide, free hydrogen, methane, nitrogen, phosphorous, potassium; water (potable, gray, waste, vapor); edible and inedible biomass; and electric power (generated, stored, and consumed). Figure 1 provides the SIMOC user work flow.

5 SIMOC is a pilot project of the Interplanetary Initiative, Arizona State University, School of Earth & Space Exploration.

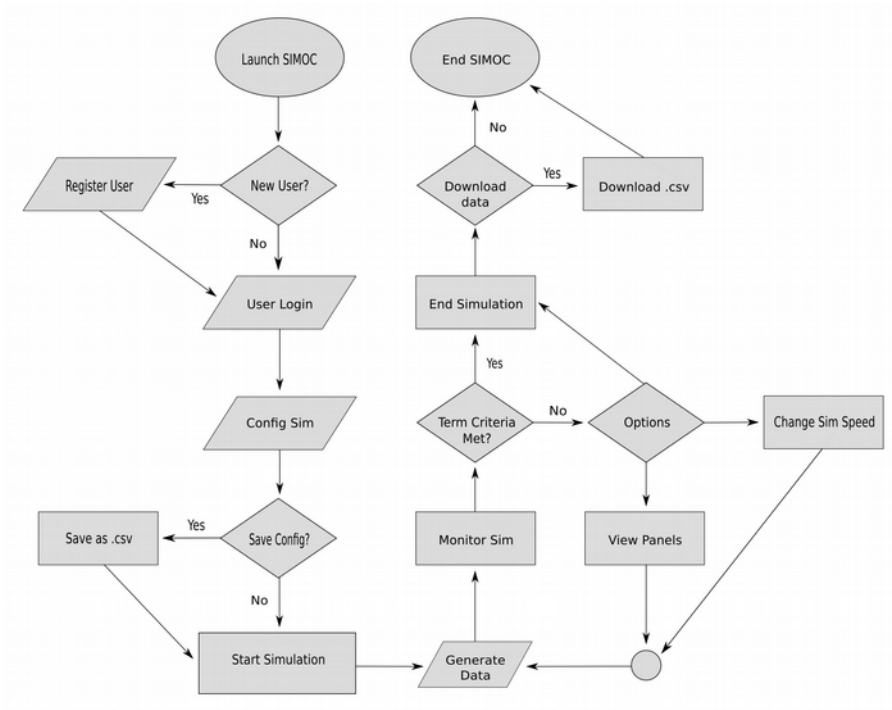

Figure 1: The SIMOC user work flow.

Much of the data that guides the current SIMOC model was obtained from the NASA Baseline Values and Assumptions Document (BVAD)[15]. BVAD data is primarily composed of a starting and ending value for a plant's biomass or respiration cycle, resulting in a linear average per time step. However, the photosynthetic biochemical process, biomass accumulation, and growth cycles are best described by non-linear, even compound functions over the course of a day, season, and life cycle as respiration biochemical regulation counteracts the tendencies in the physico-chemical determined rate of reaction. This results in a better supply of energy at low temperatures, while the slower rise in respiration rate at higher temperatures permits more economical consumption of metabolites[16].

As such, it was known that SIMOC would benefit from the introduction of agents that incorporate non-linear functions in their exchange of the currencies in order to more closely represent observed, real-world biological systems. This research simulated the results obtained from the experiment conducted at the Biosphere 2—and thereby introduce to SIMOC the first non-linear plant growth functions.

SIMOC is composed of two principal components: a back-end server and a front-end web interface. Built upon the computer language Python, the server manages the interaction of the agents in each given time step, monitors the currencies of exchange, and delivers content to the web interface. The server can be run with or without the web interface. The web interface is built upon the computer languages Javascript and CSS. SIMOC is designed to operate on a single computer CPU, on a single server, or across massively scalable, distributed systems such as Amazon or Google web services. SIMOC can be engaged by a single user, or many users at one time, each engaged in their own, independent session. A single user can engage SIMOC by means of the web interface to run a single simulation, or multiple, simultaneous simulations to test various hypotheses.

The agents are defined by a single Javascript data file stored in the JSON format, and collectively referred to as the *agent library*. This agent library contains all parameters that define the actions and interactions of all agents. In parallel with the physical experiment central to this body of research, the SIMOC team introduced advanced functions available to all agents, including log, exponential, normal, and sigmoid. Multiple functions may be engaged for a single agent, as is demonstrated in section VII. Table 1 provides a simplified example of the *agent_description.json* file used to model the experiment described herein. An example of the Python code employed to process the functionality of the agent described in Table 1 is given in Table 2.

```
Plant type: barley

Input:

h2o_potb: 0.097 kg per hour

enrg_kwh: [not applied] kWh
   growth_daily: step
      min_threshold: 8.0
      max_threshold: 18.0
      noise: false

Output:

atmo_co2: ___ kg per hour
   growth_lifetime: sigmoid
      noise: true

   biomass_totl: ___ kg per day
      growth_lifetime: sigmoid
      noise: true

h2o_wste: ___ kg per hour
   growth_lifetime: norm
      center: 4.0
      min_value: 0.00
      invert: true
      noise: true

Characteristics:

   category: food_cereal
   lifetime: 11.0 days
   reproduce: false
```

Table 1: A subset of SIMOC agent_description data file, describing the single agent barley. The standard JSON file has been simplified to produce a more readable body of text.

```
Method: get_sigmoid_step

def get_sigmoid_step(step_num, mean_value, num_values, min_value=0,
max_value=None, center=None, steepness=None, noise=False, noise_factor=20):
    center = center if center else int(num_values / 2)
    max_value = max_value if max_value else (mean_value * 2) - min_value
    steepness = steepness if steepness else 10. / float(num_values)
    y = np.arange(num_values)
    y = ((max_value - min_value) /
         (1. + np.exp(-steepness * (y - center)))) + min_value
    if noise:
        y += np.random.normal(0, y.std() / noise_factor, num_values)
    y = np.clip(y, min_value, max_value)
    return y[step_num]
```

Table 2: A sample of a Python method used to process the agent function.

IV. The Body of Research

It was the intent of this body of research to conduct an experiment that generates a dataset of six (6) parameters, for the growth of a single plant species, barley, from seed to fodder:

1. air temperature (degrees C)
2. relative humidity (%)
3. photosynthetically active radiation, or PAR (μmoles)
4. carbon dioxide, or CO2 (ppm)
5. biomass, or wet weight (grams)
6. water added to the system (milliliters)

SIMOC was then configured to approximate the parameters of the experiment and set in motion for a simulated duration that matches that of the real-world barley growth, running start to finish in just a few seconds. The outcomes of the real world and simulated, seed-to-fodder growth cycle are then compared.

Barley was selected for this experiment for its rapid growth cycle (8-12 days)[17] without need for soil, added plant nutrient, excessive light, nor maintenance of a highly consistent air temperature. This experiment is not concerned with the nutritional value of the plant employed, nor the CO2 sequestering for atmospheric recycling. Rather, the specific goal is to demonstrate that the configuration of a simple data file can invoke the desired output of a simulation, and when compared to the data captured in the real experiment, is a reasonably close approximation.

While all six of the aforementioned parameters are correlated in the real world, and do contribute to the overall performance of the plant's growth cycle[18], the parameters of interest were CO2, water run-off and biomass accumulation. Air temperature, relative humidity, and PAR were recorded to support the observed trends in CO2 and biomass, and for potential use in subsequent simulations and publications.

CO2 is measured in parts per million (ppm), as a function of plant respiration. Biomass is defined within SIMOC as the progressive accumulation of total mass, independent of the ratio of plant material versus water retention. CO2 and biomass are simulated within SIMOC to a close proximity of the nonlinear, compound functions recorded during the experiment and subsequently captured in the dataset. A more in-depth explanation of each of these parameters, the means by which they were recorded, the means by which SIMOC produces the simulation, and the findings are discussed in this Experimental Procedure and and Simulation Procedure.

V. Experiment Procedure

The experiment was housed at the University of Arizona's Biosphere 2 research facility, near Oracle, Arizona, where both short- and long-term research projects are hosted as part of a growing science incubator program. This experiment benefited from fairly stable light intensity, day to day, air temperature, and relative humidity, and twenty-four hour access to the growth chambers, supporting a routine in data collection and watering for the duration of the principal experiment (10.25 days) and the prolonged evaluation of the barley fodder once watering was terminated, for an additional six days).

Whole grain barley seed, as is standard from any feed and grain store, was selected for its abundance and common use in fodder experiments. Four units of 800 grams (~1 liter) seeds were measured. They were then washed in a bath of 3 ml H2O2 dissolved into 4 liters reverse osmosis (RO) water to reduce the proliferation of fungi and mold. Each unit was rinsed in RO water (which was discarded) and then soaked for 12 hours in RO water, more than ample to than accommodate the absorption by the seeds. The amount of initial water uptake (retention) by the barley seeds was calculated by the difference in measured mass of the dry seeds (800g) vs each of the four soaked seeds, per the four germination trays, prior to sealing the growth chambers.

Two grow chambers, A and B respectively, were designed and built by Dr. Dragos Zaharescu[19]. They are composed of a clear polycarbonate shell with three horizontal levels, two of which reside below the primary chamber. For this experiment, the primary chamber was sealed from the lower two through the addition of a sheet of corrugated polycarbonate, penetrated only by the holes required to provide power to the digital scales, sensor cables, and a water drainage system. The areas of penetration were sealed with self-adhesive tape, allowing only a nominal amount of air to pass. The total volume of each chamber was 0.49 cubic meters. The continuously operating DC fans sealed to the intake of the chambers enforced a positive airflow with no known, additional inlets. The DC fan moved a linear 0.5 meters per second through an opening 3.8 cm diameter, or 0.138 cubic meters per minute. The airflow at the outlet was measured to be above 90% at the inlet. As air temperature, relative humidity, and CO2 were measured at the chamber outlets, a totally sealed environment was not as important as a constant, positive pressure and airflow.

Each germination tray was temporarily affixed to heating pads which were permanently affixed to press board. The press board was part of a fabricated, sloped construct which itself was fastened to the metal top tray of the scale. The germination trays were of the standard 48x22 cm, placed at a slope of 2.5 cm over the entire run. Evenly spaced drainage holes were introduced at the bottom of each tray which fed into a PVC basin, fabricated to capture all water run-off without loss, and to restrict air flow from the upper to the lower chamber, to a minimum.

Each of the 4 germination trays, 2 per chamber, with water capture, heating pads, and sloped constructs, one for each of the measured units of barley seed, were set upon a laboratory grade, digital scale[6] with 0.5g resolution in the range of 0-10kg. At the start of the experiment, prior to sealing the ends of the chambers, each scale was tared (reset to zero) with the application of the sloped construct and heating pads, the mass of the germination trays and seeds prior to their soaking were known, measured quantities and removed in subsequent calculations. The scales remained active and illuminated throughout the entire experiment, and therefore did not need to be reactivated in any manner to provide the current reading.

Four glove ports allowed for ready access to the germination trays, two per chamber, with a gravity fed water line composed of flexible vinyl introduced through the passive outlet to each chamber. Prior to watering the mass of each of the four trays was manually recorded. A single catch basin on the mid-level of each Chamber A and B captured run-off from the prior watering, from both trays, A1 + A2 and B1 + B2 respectively. The volume was measured by means of an external, graduated cylinder, and then discarded. After eight hours no further water was actively draining from the germination trays, thereby providing the mass of the plant and retained water at that time.

Each of the four trays was given 775 ml of RO water three times daily, at 8:00 AM, 4:00 PM, and 00:00 AM for the duration of the experiment, with two exceptions: a) the first 24 hours period when the soaked seeds were allowed to lay without additional water; and b) mid-run, a three-days modified schedule withheld the midnight watering to learn if uptake the following 8:00 am would fully compensate, by volume.

In the initial, principal experiment (10.25 days) the scales provided a measure of the wet biomass accumulation. For the subsequent six days, both trays were left in Chamber A to dry by natural process, their biomass loss captured. Tray 2 of the Chamber B was removed, sorted, and blades separated from root mass. It was dried in a laboratory oven to return the biomass to a fully dry state for comparison to the original, dry seeds (see close of Section VIII, Findings).

Full spectrum, florescent grow lights, 2 per chamber, provided a source of light for a period of 13 hours per day, augmented by note worthy ambient light (see Figure 5). Light was measured by means of Quantum sensors that report the Photosynthetic Photon Flux Density (PPFD), corresponding to micromoles of photons per meter squared per second (μmol m-2 s-1). The Vernier brand Quantum sensor supported a range from 0-2000 μmol m-2 s-1 in full sun, with an absolute Accuracy of ±5%, wavelength range: 410 nm to 655 nm, and resolution of 1 μmol m-2 s-1. Carbon dioxide was measured by means of a Vernier brand Go Direct CO2 Gas Sensor with integrated air temperature and humidity monitoring. In the range of 0-100,000 ppm, the CO2 sensor provides an accuracy of ±100 ppm for 0 to 1,000 ppm and resolution of 1 ppm. The integrated air temperature sensor provides an accuracy of ±0.5°C at a resolution of 0.1°C. The integrated relative humidity sensor provides an accuracy of ±5% at a resolution of 0.1%.

Quantum and GoDirect sensors were attached to LabQuest 2 portable recording units[7], one set for each Chamber A and B respectively, for the automatic recording of PPFD, C, RH, and CO2 at the chamber air flow outlets. Data was acquired once per minute for the duration of the experiment. A third CO2 sensor[8] was placed at the inlet to each chamber where it monitored the shared airspace, as the chambers were perpendicular to each other. The Vaisala CO2 sensor captured a single data point six times each minute.

6 by Goldenwall

7 by Vernier

8 by Vaisala GMP222

VI. Data Reduction

As previously noted, all Vernier data was recorded automatically at a rate of once per minute, for a total of 14,780 data points. The Vaisala CO2 sensor was introduced 49 hours and 10 minutes into the experiment, and recorded data once every ten seconds, or six times a minute, for a total of 71,760 data points. The water in, water out, and biomass were recorded three-times daily [08:00, 16:00, 00:00] for a total of 30 data points during the principal investigation.

The Vernier data was down sampled 10:1 using a sliding window averaging function, resulting in a data point once every 10 minutes for PAR, air temperature, relative humidity, and CO2. The Vaisala CO2 sensor was down sampled 60:1 to match the Vernier averaged rate, and then shifted to match the date-time stamps of the Vernier units. The biomass data was not reduced.

While air temperature and relative humidity were recorded by the Vernier instruments, they are treated as independent variables in SIMOC at this time, and therefore were not simulated. The data will be retained for future modeling and associate publication.

A total of thirty data points were generated by SIMOC to approximate the 30 biomass accumulation data points generated by the experiment. SIMOC was configured to simulate the CO2 cycle at a data rate of once per hour, or six times fewer data points than that resulting from the data reduction, as described above. Therefore, the CO2 data (internal, external) is again reduced by means of a sliding window average to match that of the once per hour rate, as shown in Figure 6.

VII. Simulation Procedure

A SIMOC simulation is configured within the SIMOC agent configuration file *agent_description.json*, an industry standard JSON file in which agents are defined by a series of parameters. Parameters include initial and final mass, a daily and lifetime growth curve, CO2 sequestration, and water uptake. The configuration file can be edited through the use of a text editor or a web interface to define the agents prior to a simulation run. From the command line or SIMOC web interface, the quantity of human, structure, physico-chemical and bioregenerative agents are selected for a given duration, and the model is set in motion.

Once the experiment was designed, constructed, and executed and the data recorded, reduced, and analyzed, the procedure for preparing the SIMOC simulation was as follows:

1. Discover the underlying functions for CO2 production, biomass accumulation and water retention by means of regression and/or experimental averaging and comparative median.
2. Configure the SIMOC *agent_description.json* file to approximate the discovered functions (1).
3. Execute SIMOC against the configuration.
4. Collect the data generated by SIMOC as recorded in a .csv file.
5. Compare the original data collected in the experiment to that generated by SIMOC, using the *coefficient of determination*, or R^2 to determine the quality of fit.

In the SIMOC simulation, additional, active agents include the greenhouse, power generation, storage, and consumption, where generation was assumed to be continuous and storage a one hundred percent pass-through from generation to consumption. A buffer between the output of one agent and the input of another storage agent was employed for CO2, water, and electrical power as is standard for all SIMOC currencies of exchange. These have no affect on the outcome of the data, for this model configuration.

VIII. Findings

As noted in Section V, the instruments recorded air temperature, relative humidity, PAR, CO2, water run-off and biomass accumulation. As shown in Figure 2, the barley wet biomass was recorded for Chamber A, trays 1 and 2, from dry seed to a plateau of biomass accumulation (day 10), and for a subsequent six days natural drying period while remaining in the unaltered chamber. Tray B2 was removed at the close of the principal experiment in order to dry in a laboratory oven (see close of Section VIII, Findings). Tray B1 remained in-chamber until it was also removed at which point Chamber B data collection was terminated.

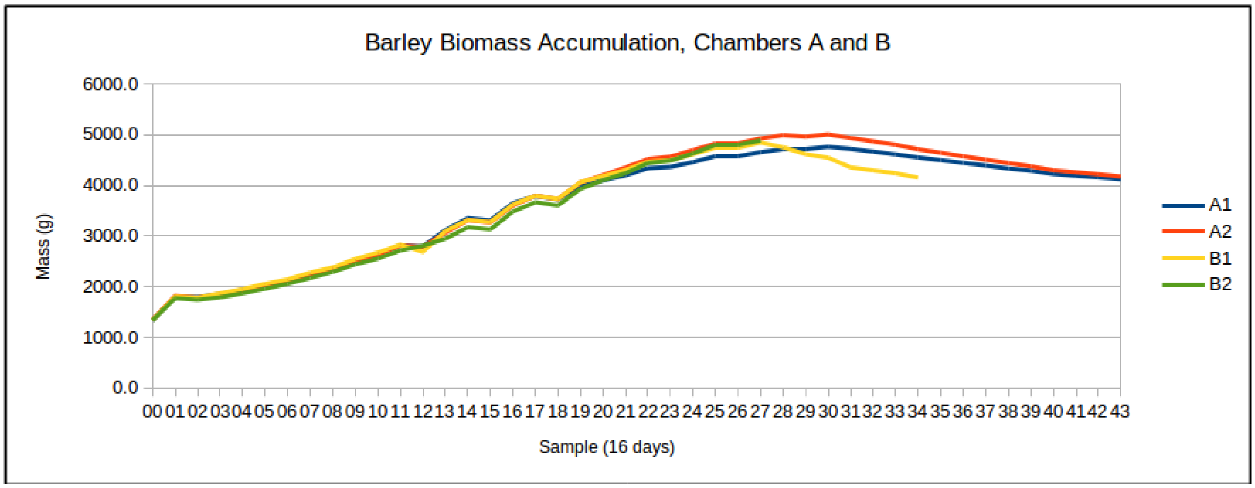

Figure 2: Wet barley biomass accumulation and loss for the full duration of 16 days for Chamber A. Trays B2 and B1 were removed to be dried for pre- and post-experiment dry mass measures.

The watering regime was changed on three of the midnight watering events. For each, no water was applied, resulting in the noted "dips" in Figure 2 at samples 12, 15, and 18. The next morning at 8:00 am, very close to twice as much water was retained by the barley, resulting in a nearly unaltered continuation of the biomass accumulation function. While skipped water events are not currently simulated in SIMOC, this does lay a foundation for future simulation configurations in which random events result in loss of power or water to the simulated bioregenerative ecosystem. Further literature review and possible, future experiments will build upon this experience for an even higher fidelity agent-based model.

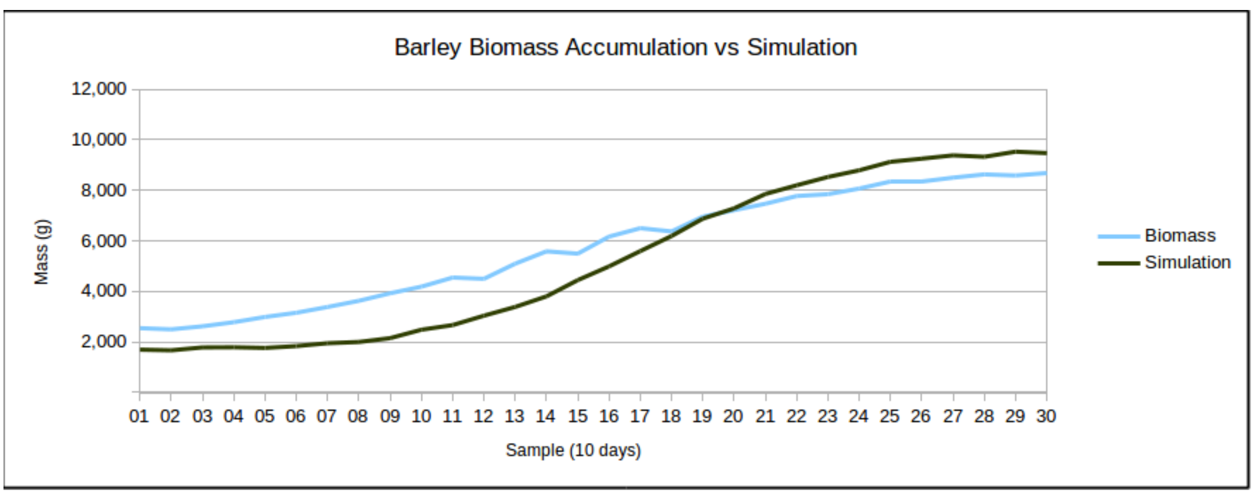

Figure 3: Wet barley biomass accumulation measured in Chamber A vs the simulation generated by SIMOC. The coefficient of determination (R^2) was 97%.

In Figure 3, wet barley biomass accumulation in Chamber A is represented as a sum of barley trays 1 and 2, less the original dry mass of the seeds (800g) and the mass of each germination tray, respectively. The SIMOC simulation effectively approximated this growth function, with an R-squared value of 97% for the set of 30 data points.

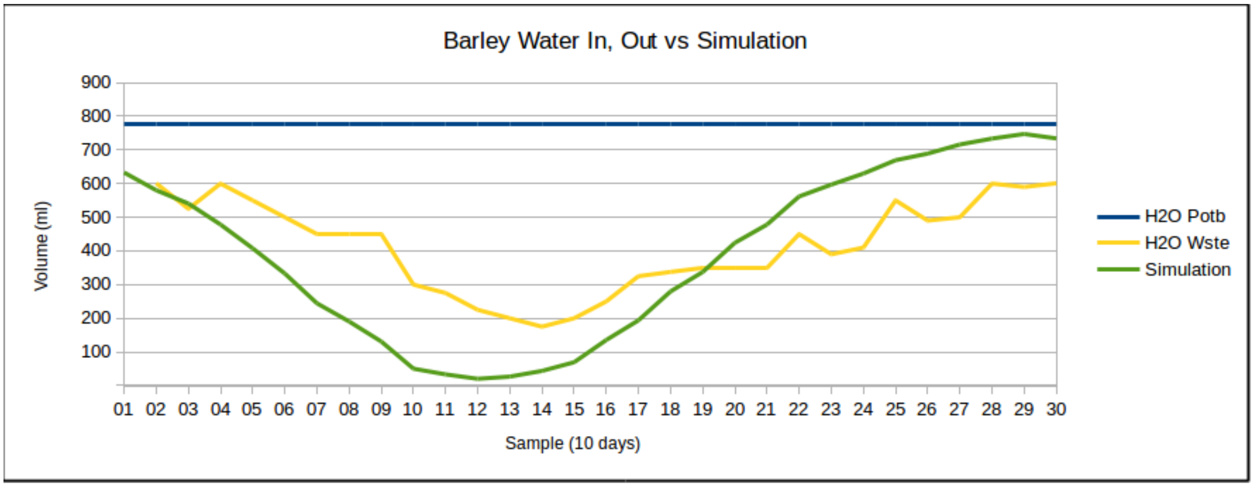

Figure 4: The water added (H2O Potb) and run-off (H2O Wste) measured for both trays 1 and 2 combined in Chamber A versus the simulation generated by SIMOC. The coefficient of determination (R^2) was 64%.

Water allocation is an important function in a closed ecosystem where potable or gray water used to support the plants ultimately moves through ECLSS or bioregenerative reprocessing. In Figure 4, given a constant water input ("H2O Potb") of 775 ml per watering, SIMOC approximated ("Simulation") the water run-off ("H2O Wste"), the water not absorbed by the plant, for each of the 30 waterings during the 10 days experiment. The R-squared value for this simulation was 64%, which is notably low due to the variation invoked by the altered watering schedule.

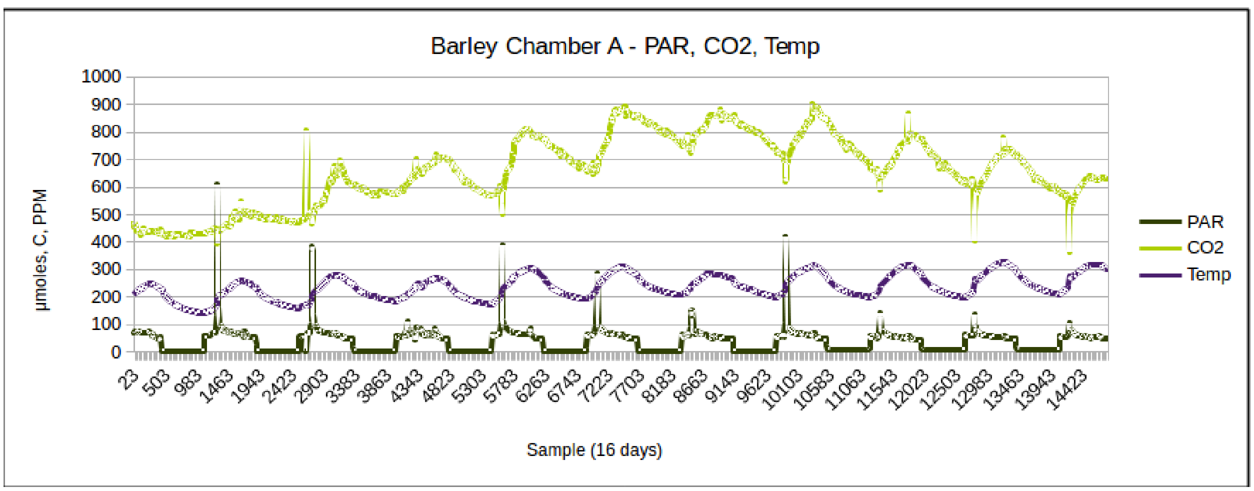

Figure 5: CO2 (ppm) displayed against the measure of PAR (amplified 2x) and air temperature (amplified 10x), for Chamber A.

PAR, CO2, and temperature were recorded to validate the experiment configuration and environmental control, but not simulated. Future applications of SIMOC may return to this data for comparison and publication. As is made evident in Figure 5, daily CO2 production is directly proportional to temperature (amplified 10x) and correlated to light (PAR amplified 2x) with the obvious, matching spikes, a brief period in each day when sunlight fell directly upon the experiment chambers, invoking a momentary increase in CO2 sequestration.

It is important to note that during the principal 10 days of barley growth the experiment saw an overall rise in CO2 production, where it was anticipated the photosynthetic activity of the barley would have reduced the concentration. Additional observation of the milky white, sweet smelling water in the catch basin suggested that the initial seedbed was made too thick and the lower layers sustained aerobic germination.

In an off-world habitat, production of excess CO2 could imbalance the breathable atmosphere to the detriment of the human occupants. While not the anticipated outcome of the experiment, this will benefit SIMOC in its ability to simulate both correct and incorrect configuration of growth chambers. As such, SIMOC was configured to approximate the CO2 function with an R-squared value of 87%, as in Figure 6, as one possible outcome.

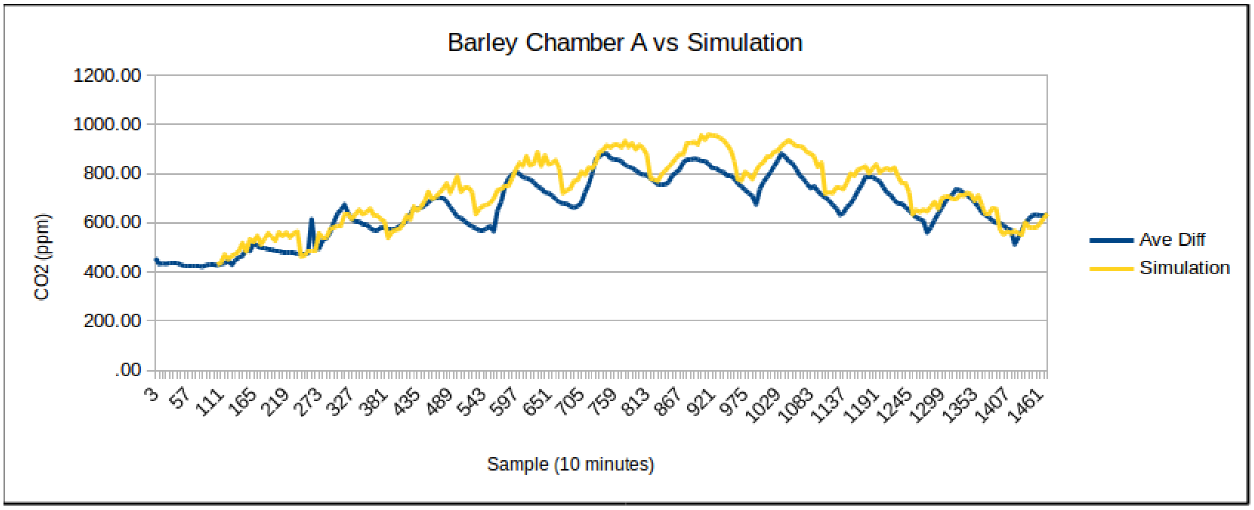

Figure 6: CO2 recorded in Chamber A versus the simulation generated by SIMOC. The coefficient of determination (R^2) was 87%.

While not integrated into the SIMOC simulation at this time, it was found that the 800 grams of dry seed which accumulated wet biomass in excess of 4kg per tray was reduced to just 450 grams after two days drying in a laboratory oven at 100C.

IX. Conclusions

As was given foundation in the Apollo era, our species is once again poised to venture beyond low Earth orbit to the Earth's moon, Mars, and beyond. In order to make this tremendous leap forward, we will carry with us both mechanical and biological life support systems proved in analogs, rigorous test environments, and computer simulations.

SIMOC is an agent-based computer model that enables the user to configure combinations of physico-chemico and/or bioregenerative life support systems and then execute fast-forward, times-series simulations. Initially built upon historic, linear data generated in NASA and university experiments, this research saw the growth of barley from seed to fodder in 10 days, with air temperature, relative humidity, PAR, CO2, water run-off and biomass accumulation recorded. The data was processed to expose the inherent, non-linear functions for CO2 and biomass accumulation. Water run-off was also simulated as an important aspect of a closed ecosystem. The SIMOC agent-based model was then configured to approximate each of these parameters and a simulation was set in motion.

A comparison of the SIMOC simulation to barley wet biomass accumulation is given an R-squared value of 97%; for water run-off, 64%; and for CO2, 87%. The water run-off is notably low due to the intentional modification of the watering schedule. Tighter simulations can be generated by SIMOC as defined by the user configurable agent description file. As with any model, a balance must be found between under- and over-fitting.

In conclusion, SIMOC was successfully programmed to generate its first non-linear simulations and produce data that approximated the associated, real-world functions captured in the course of an experiment in barley fodder production. With normal, log, exponential, and sigmoid functions now readily defined in the SIMOC agent configuration file, any number of mechanical or biological agents built upon non-linear functions may be introduced.

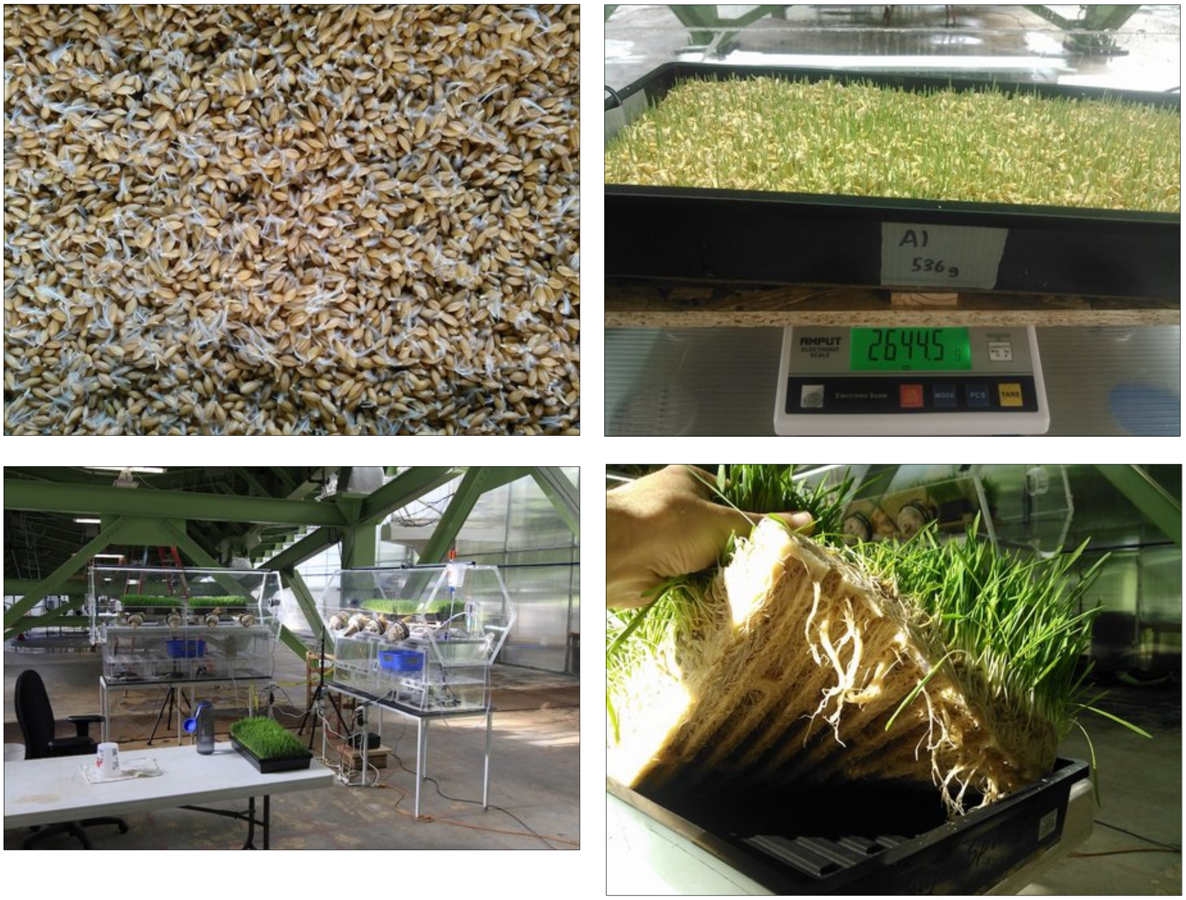

Figure 7: The barley experiment at Biosphere 2, from seed germination to fodder.

Immediately following the conclusion of this experiment, SIMOC was used by a team from Dartmouth College to model seven additional plants integral to their human-scale Marsboreal greenhouse design. Dartmouth was announced the winning team of the fourth annual NASA Breakthrough, Innovative and Game-changing (BIG) Idea Challenge, April 24, at NASA's Langley Research Center in Hampton, Virginia. [9] These seven additional plants were added into the SIMOC agent library, thereby further improving the fidelity of this tool for simulation.

9 NASA BIG Ideal Challenge

Acknowledgments

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