BIOSPHERE 2 STRATEGIC RESEARCH PLAN (Draft September 20, 2022)

Mission:

Biosphere 2 advances our understanding of natural and human-made ecosystems through integrated research and development of scalable interventions that increase the resilience and sustainability of Earth systems and human societies. We foster research in our unique facilities, conduct interdisciplinary science education, and lead in developing solutions for our planet and beyond.

Vision:

By 2030, Biosphere 2 will be a global center for resilience solutions to humanity's grand challenges of climate change, biodiversity loss, and sustainable development. We will be a collaborative and inclusive hub in a network that provides education, ideas, research and innovations for sustainability from the University of Arizona campus to the entire globe.

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Executive Summary

Biosphere 2 (B2), a campus of the University of Arizona (UA), engages in world-class environmental research, education, and entrepreneurship leading to solutions for humanity's grand challenges of climate change, biodiversity loss and sustainable development, on Earth and beyond. The core research facility of the B2 campus is the world's largest indoor controlled environment for ecological and climate change research across multiple biomes. The campus also boasts a growing number of specialized research spaces, including facilities dedicated to development of co-located food and photovoltaic energy production and a human-habitat analog for the Moon and Mars that emphasizes research on life support systems and astronaut training. The B2 campus hosts a UA Center for Innovation incubator, a Visitor Center that attracts and educates nearly 100,000 visitors annually, and a 100-person conference and retreat center.

Over the last decade, B2 has built its fundamental research and core educational programs and expanded its portfolio beyond these efforts. To enhance our impact still further, our strategic plan for the next five years rests on five pillars, closely linked to the UA strategic plan: **Sustainability research, Resilience solutions, Our region, Tomorrow's leaders, Networks**. These pillars are underlain by two foundations essential for everything we do: **excellence in operations** and **justice, diversity, equity and inclusion**.

Pillar #1: SUSTAINABILITY RESEARCH

Advancing the science of sustainability and resilience of natural and human-designed systems.
The main research facility at B2 has a unique role in better understanding how ecosystems respond to global climate change. The controlled environment allows us to separately manipulate key variables such as temperature and atmospheric greenhouse gasses, and the size allows us to monitor responses of entire, complex ecosystems. This **unique balancing of control and complexity** enables us to address the following Grand Challenges across all the research systems at B2:

1. *Enhancing restoration and adaptation of natural ecosystems by deeper understanding of how and why they respond to changing environments*
2. *Improving local-to-global Earth system models to predict impacts of human activities on natural systems*
3. *Designing and testing interventions to enhance resiliency of ecosystems to climate change and increasingly extreme environments*
4. *Developing novel technologies to monitor environmental change and mitigate its negative impacts*

At B2, UA faculty lead broadly based research teams of students and collaborators to address these challenges. We will increase institutional and external support and expand communication of B2 science to expand the research scope and collaborative network of B2 science.

Objective: *Increase the impact and scope of Earth systems science, sustainability and resilience research and expand use of B2 facilities by the national and international community of researchers in these areas.*

Assessment: *Shorter-term success will be assessed by growth in standard measures of research productivity and impact (publications, citations, collaborations, grant funding, patents), and by the growth in number and diversity (geographic, demographic) of collaborators and students. Longer-term assessment will address intellectual leadership and recognition.*

Pillar #2: RESILIENCE SOLUTIONS

Translating science to generate innovative solutions to humanity's urgent problems

Applications-oriented work at B2 focuses on translation of Earth system science and engineering into solutions addressing the UN Sustainable Development Goals and resilience of local communities and environments on Earth and in space. In addition to B2 research directed towards these goals, a growing number of entrepreneurs in sustainability and resilience are hosted at B2 through a branch of the UA Center for Innovation. Similarly, a growing number of industrial partners are using B2 facilities to develop and test technologies relevant to sustainability and resilience. To further link B2 scientists and students with private sector R&D and businesspeople, we will foster an inclusive campus culture of interdisciplinarity and innovation, instituting formal and informal networking, workshops, symposia and other opportunities. All of our translational activities will seek to mitigate the disproportionate impacts of climate change and other environmental issues on marginalized communities.

Objective: *Increase collaborations involving the B2 campus community and other scientists, engineers, businesses, funders, NGOs and local communities to create and implement resilience solutions across the globe.*

Assessment: *Short-term, we will measure the numbers and progress of patent disclosures and new technologies and innovations for possible suites of solutions and of quality partnerships with implementers. Longer-term, we will collaborate with social scientists and partner with local communities to assess the solutions' long-term adoption and impact on the communities' development and resilience.*

Pillar #3: OUR REGION

Using community expertise and demonstrations to advance resilience of arid lands

Arid lands constitute a substantial portion of the lands on Earth (35%) and are expanding with climate change. Southeastern Arizona has long been a powerhouse of expertise on desert environments, based on traditional knowledge of the Native Nations, the many NGOs and federal/state agencies located here, and of course the expertise of the UA campus. UA has a deep history of excellence in the study of arid lands, with global leadership in areas such as hydrology, ecology, climate, and controlled-environment agriculture. B2 will build on this convergence of our desert southwest location and this vast regional expertise to develop case studies in resilience. Such projects are valuable opportunities for UA researchers and students to collaborate closely with communities throughout our region and other arid lands. For example, planned projects will demonstrate the synergy between controlled environment agriculture and agrivoltaics to reduce energy and water use and intensify production of many crops at the Yuma branch of the UA Experiment Station, and to experiment with crop resilience under expected climate change in the B2 controlled environment including those from native seeds. Longer-term, B2 will become a demonstration net zero community where the students and the public can observe and experience implemented solutions.

Objective: *Build upon UA and regional strengths through strong partnerships to enhance the quality of life and resiliency locally and in ways relevant to other arid communities. The UA/B2 will be increasingly recognized as an international hub of excellence, providing examples of and solutions for resilience in arid lands.*

Assessment: *Short-term success will be measured by the number, quality, and longevity of partnerships for resilience of arid lands and the number and progress of demonstration projects and case studies. Longer-term, we will measure how our case studies and demonstrations are used to stimulate new projects and their impact inside and outside our region.*

Pillar #4: TOMORROW'S LEADERS

Preparing the next generation of leaders in resilience science and solutions

The unique facilities and rich intellectual environment at B2 provide exciting research and hands-on learning experiences for students, local community members, and tourists from around the globe. We will build interest in STEM fields and sustainable development for undergraduate students at UA and internationally by creating engaging, hands-on courses using B2 research and facilities and meaningful and inclusive research experiences. Graduate students and trainees will gain valuable experience in transdisciplinary problem-solving by incorporating diverse viewpoints from across disciplines and across life experiences. Experiential learning opportunities for regional K-12 students and teachers will inspire problem solvers of the next generation. As a Hispanic-serving institution, UA is particularly well-poised to diversify the next generation of resilience leaders. The visitors who tour B2 will come away with a deeper understanding of the importance of sustainability and resilience research and a sense of empowerment to make their own contributions to environmental and social resiliency.

Objective: *To increase the educational activities and curricula tied to B2 research, more fully integrate diverse undergraduates in B2 activities, and become a major attractor for UA students and students from across the globe.*

Assessment: *Short-term, we will collect data on the number of courses taught, the number and demographics of students involved in different programs, student outcomes such as majors and graduation rates, and the quality of visitor experiences. Longer-term assessments in collaboration with educational researchers will investigate the role of B2 in attracting excellent and diverse students to UA and the consequences of B2 engagement for careers and public understanding of science.*

Pillar #5: NETWORKS

Deepening connections to national and global networks of science, innovation, and education

We will leverage national and international partnerships to maximize impact and convene thought leaders in sustainability from across the globe. Our many existing and planned partnerships place B2 as a growing node in a network of similar-minded researchers, educators, and innovators focused on local solutions to sustainable development challenges worldwide. For example, one rapidly expanding set of partnerships harnesses food-energy-water solutions to build resilience in communities in the Americas, Europe, the Middle East, and Africa. Another set of international partnerships will use the B2 Ocean to discover strategies to create resilience in coral reef ecosystems. A multidisciplinary consortium across the UA and CNRS, the national laboratory system of France, is developing a holistic understanding of terraformation with funding from the National Science Foundation and the recently launched France-Arizona Grand Challenge Institute of CNRS. An emerging partnership with multinational companies will generate solutions for human survivability and resilience in space and on other planets. A new partnership is emerging to create a four-continent (Americas, Middle East, Europe and Africa) International School of Agrovoltaics, targeted to graduate students and farmers.

Objective: *To increase and strengthen long-lasting and impactful partnerships addressing Earth's greatest challenges. B2 will become recognized globally for its collaborative research and educational initiatives and its role in convening thought leaders to impactfully address global grand challenges.*

Assessment: *Short-term, we will evaluate the number and quality (including outputs) of partnership convenings and conferences at B2 and B2 leadership roles in national and global networks. Longer-term, we will assess the longevity and impact of B2 partnerships on innovation in science, education, and sustainable development.*

Foundation: Excellence in operations

Foundational to all the pillars in support of the B2 mission is excellence in operations. B2 already has a world-class staff. **However, the current operating budget is insufficient to fully support existing operations, let alone the ambitious objectives described above.** During the first year of this five-year strategic plan, we will develop detailed operational plans to fully support the five pillars; this process will involve all staff to ensure broad understanding of the goals and buy-in as to how they will be achieved.

Foundation: Justice, equity, diversity and inclusion

A diverse workforce, equitable distribution of resources, and an inclusive climate are all essential to achieve the foundational objectives that we describe for each of the pillars. Yet, B2 does not yet have a workforce that is representative of the greater Arizona or US population, nor has the workforce climate and resource distribution been rigorously assessed. In the first year of this strategic plan, we will engage all researchers, students, staff and administration at B2 to propose specific JEDI goals and develop concrete plans to achieve them. Such broad involvement in detailed planning is essential to ensure complete buy-in and commitment by everyone at B2. **The administration of B2 commits to allocating up to 2% of its operating budget each year towards achieving the JEDI goals that will be thus defined.**

Introduction

Biosphere 2 is a rapidly evolving campus of the University of Arizona (UA) that encompasses a broad array of facilities focused on Earth system research and entrepreneurship (Fig. i.1). Activities at B2 span the continuum from advancing fundamental understanding of Earth system processes all the way to developing commercial and scalable solutions that increase the resilience and sustainability of Earth systems to address the UN Sustainable Development Goals. Global partnerships further leverage this work in local communities throughout the world, with an emphasis on under-served people. Numerous undergraduate and graduate students are deeply engaged in ongoing research at B2 and the Biosphere 2 campus is also an iconic regional attraction that connects with over 100,000 visitors per year, permitting the general public and K-16 students to learn about the cutting-edge research in and around the facility and its history. The campus includes a 100-room dormitory complex that serves as a conference and retreat center.

Figure i.1. Main features of the B2 campus near Oracle, AZ.

The Biosphere 2 campus is anchored by the iconic structure built over 30 years ago to research and develop self-sustaining space-colonization technology (Fig i.2). This structure is world-famous for two missions in the 1990's in which a group of research volunteers were sealed inside to monitor and demonstrate how humans could sustain life in a closed atmosphere, water and food system with only energy and information exchange with the outside. Since that very public-facing experiment, the iconic B2 structure has been turned into a unique laboratory where scientists can conduct research that can be done nowhere else on earth. The meso-scale synthetic ecosystems inside this core research facility include the world's largest controlled systems of tropical rainforest, ocean, fog desert, savanna, and mangroves (Fig. i.3). Also inside the main research structure is the Landscape Evolution Observatory (LEO; Fig. i.3), the world's largest laboratory experiment in the

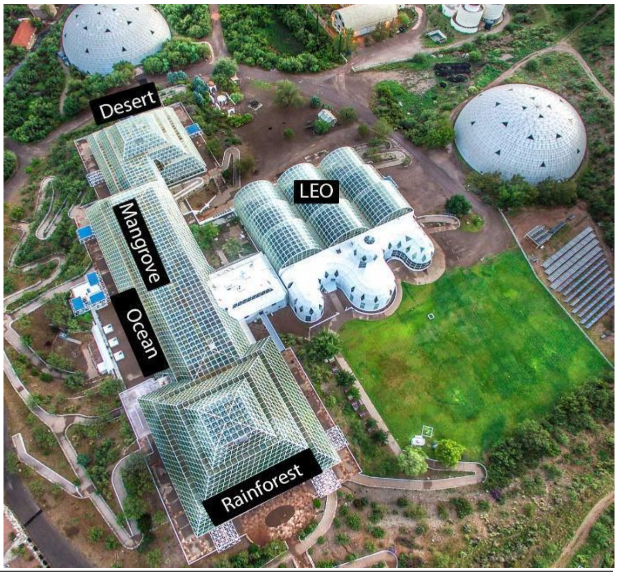

Figure i.2. Main research structure of the B2

Figure i.3. Photos of the five major research systems of the B2 campus (see Appendix III for details).

interdisciplinary Earth sciences, consisting of 3 artificial, highly instrumented landscapes that started in 2011 with bare rock. The goal is to observe each step in the landscapes' evolution, or terraformation, from purely mineral and abiotic substrate to living, breathing landscapes and soil that support microbial and, ultimately, vascular plant communities.

Inspired by the cutting-edge research ongoing in this core structure, an entire campus network has evolved that includes additional research infrastructure, industrial partners, international NGOs, educational and visitor programs, and communities within the region. This surrounding campus is dedicated to enhancing ongoing fundamental research and building on it to develop real world solutions to our urgent environmental problems. New facilities outside the core structure include innovative research and development to co-locate food and renewable energy production (Agrivoltaics) and a space analog for habitats on the Moon and Mars for research into mechanical and bioregenerative systems, as well as astronaut training (SAM) (Fig. i.3). An Analytical Laboratory has state-of-the-art capabilities for chemical analysis of samples for researchers. The B2 campus also hosts a UA Center for Innovation incubator through a cooperative agreement with Tech Launch Arizona, where entrepreneurs can interact with the researchers, students, and staff of B2 (see chapter 2).

The rapid growth of this broader Biosphere 2 campus over the last few years means that we are now poised to take Biosphere 2 to the next level of global impact. To move to this new level of world-class excellence, in 2021, the B2 executive team, researchers, staff, along with the Advisory Board and a new Science Advisory Board, embarked on a strategic planning process (Appendix I).

In this document, we present the outcome of this process, developed around five interconnected strategic pillars, linked to the pillars of the University of Arizona strategic plan: 1. Sustainability research, 2. Resilience solutions, 3. Our region, 4. Tomorrow's leaders, and 5. Networks. In Chapters 1-5, we define these Pillars, the strategic objectives for those Pillars, and the activities to meet those objectives, keeping in mind that most activities contribute towards meeting the objectives of multiple pillars For example, the basic and use-inspired research described under Pillar 1 blends into the translation of that research into solutions to improve environmental and social resiliency, as described under Pillar 2. The focus on regional expertise and case studies for resilience of arid lands in Pillar 3 is based on the science and its translation in Pillar's 1 and 2. Our educational and outreach initiatives described under Pillar 4 are both based on and contribute back to Pillars 1-3. And finally, all of this work positions B2 to be a leader in national and global networks of research, education, and innovation as described under Pillar 5. The next phase of planning will involve detailed planning for the foundations that underlie all these strategic pillars: Excellence in operations and Justice, equity, diversity, and inclusion in everything we do. In Chapters 6 and 7, we describe the next steps needed to improve these essential foundations.

Background for the strategic pillars is included in appendices, including a history of the B2 campus (Appendix II), a description of each of the research systems of B2 (Appendix III), and highlights of the impact of past B2 research (Appendix IV). In addition, each of the major research systems has developed a detailed strategic research and education plan, which are described in Appendices V-IX.

Chapter 1. SUSTAINABILITY RESEARCH (Pillar 1)

Advancing the science of sustainability and resilience of natural and human-designed systems.

The iconic structure that anchors the B2 campus creates a rich array of opportunities to advance sustainability and resilience science in ways that can be done nowhere else on earth. As the world's largest indoor controlled-environment facility for ecological research, this core B2 research facility enables a high level of control of environmental factors while still supporting entire ecosystems of interacting organisms. Thus, **Biosphere 2 can uniquely contribute to answering questions about how organisms interact with the environment because of its unique balancing of control and complexity** (Sagarin et al. 2016; Figure 1.1). Small to mid-scale environmental chambers such as Ecotrons (Lawton et al. 1993) or facilities such as greenhouses can have extraordinary levels of control of multiple factors and thus can contribute to deep understanding of the patterns and mechanisms by which individual organisms or small numbers of interacting organisms interact with the environment. However, the scale of such experiments means that relatively few individuals and species can be included, eliminating phenomena that only emerge at the population and community level of organization, in more heterogeneous environments, or at larger spatial scales. At the other extreme, field studies in nature are obviously more realistic with much more complex and variable environments and a rich diversity of taxa and ecological functions. Hence, field studies incorporate multitudes of direct and indirect interactions among organisms and with their environment. Experiments in the field that

> ***Pillar 1: SUSTAINABILITY RESEARCH***
>
> ***Objective**: Increase the impact and scope of Earth systems science, sustainability and resilience research and expand use of B2 facilities by the national and international community of researchers in these areas.*
>
> ***Assessment**: Shorter-term success will be assessed by growth in standard measures of research productivity and impact (publications, citations, collaborations, grant funding, patents), and by the growth in number and diversity (geographic, demographic) of collaborators and students. Longer-term assessment will address intellectual leadership and recognition.*

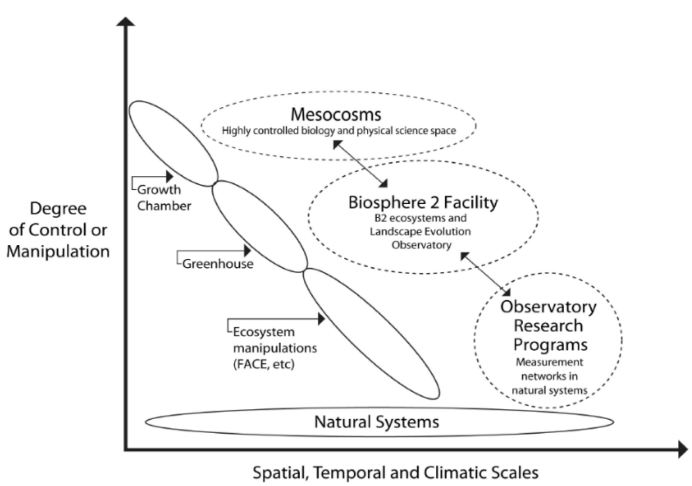

Figure 1.1. Tradeoffs between system complexity and ability to control and manipulate environmental factors to understand their impact.

manipulate one or a few environmental factors or organisms can help establish causality of some outcomes, but inevitably have results that are somewhat context dependent because of our inability to control all potentially influential factors.

The controlled environment facility at B2 thus represents a bridge between the exquisite control but ecological simplicity of microcosms such as ecotrons at one extreme and the realism but extraordinary complexity of field studies at the other. The B2 synthetic ecosystems provide some core aspects of the natural world without the vast detail found in real ecosystems and can be especially useful in testing specific questions about mechanisms rather than cataloging complexity *per se*. More specifically, the core B2 research facility incorporates:

- Capability for precisely controlling environmental conditions, including rates of change, at scales involving multiple organisms and environmental gradients. Thus, results incorporate indirect, as well as direct, effects of environments.
- Capability for disentangling effects of multiple environmental factors that may be correlated in nature, as well as simulating non-analog environments that do not (yet) exist on Earth.
- Capability for precisely monitoring and modeling whole-system environmental conditions, organismal processes, and ecosystem functions at multiple scales through "sensors everywhere."
- Capability for controlling and monitoring inputs and outputs to the entire system.
- Capability for assembling and manipulating novel combinations of species and genotypes that could not be done in real-world conditions because of concerns about potential invasions and genomic mixing.

These valuable capabilities of the core research facility at B2 are inevitably accompanied by some tradeoffs. Most notably, the larger spatial scale that enables examining responses of complex ecosystems means that replicates at this scale are lacking. B2 researchers have minimized the impact of these limitations by practices such as replication in time (before-after designs), time series analyses, and combining experiments using the synthetic ecosystems in the core facility with both microcosm and field studies (see Appendix X for more detail).

Grand Challenge questions for B2

The combination of strengths and limitations of the synthetic ecosystems of the core facility described above mean that an important focus of B2 research in these systems is on **elucidating mechanisms and processes**, especially in response to changing environmental conditions, and on **constraining and calibrating models**. The systems external to the core facility are designed more for translational research to apply these lessons and develop solutions to make human-designed systems more resilient.

Specifically, B2 research addresses the following Grand Challenges:

1. ***Enhancing restoration and adaptation of natural ecosystems by deeper understanding of how and why they respond to changing environments***

Many of the experiments conducted in the core facility study how novel assemblages of organisms acclimate and adapt to changing environments, including expected future climate scenarios and novel combinations of environmental factors. For example, research is planned for the B2 Ocean to assemble novel combinations of corals from around the globe to test how different assemblages will respond to higher ocean temperatures and acidification; such combinations are too risky to assess in the field because of potential consequences such as invasive species, genetic pollution, symbiont shuffling, and pathogen introduction. Further, the large scale means that it is possible to measure the consequences of these new environments for ecosystem processes such as carbon cycling across scales from individuals to landscapes.

2. ***Improving local-to-global Earth system models to predict impacts of human activities on natural systems***

The controlled environments and high density of atmospheric, soil, and in-organism sensors facilitates assessing assumptions about processes, functional forms, and parameters in the Earth system models that are the essential tools for predicting future states of Earth systems on various scales. For example, recent research in the Tropical Rain Forest has shown that atmospheric dryness is a much more significant limitation on whole-system carbon fluxes than are high temperatures *per se* (Smith et al. 2020); this has been impossible to separate in the field where high temperatures inevitably increase atmospheric water limitation as well and carbon fluxes.

3. ***Designing and testing interventions to enhance resiliency of ecosystems to climate change and increasingly extreme environments***

For example, agricultural systems are highly vulnerable to increasing temperatures and drought. Research in the Agrivoltaic system is showing that combining sustainable energy production and agriculture can make both systems more efficient. Research in the B2 Ocean is testing novel combinations of coral species that will be more resilient to increasing acidity and temperature in oceans. Research in SAM will help design better human life support systems by moving beyond mechanical to more sustainable biological life support systems.

4. ***Developing novel technologies to monitor environmental change and to mitigate its negative impacts.***

For example, novel installations in LEO of the same kind of remote sensing instrumentation used on satellites to monitor the earth's surface allow much more precise tests of how these technologies work to monitor key environmental parameters such as land surface temperature and wetness, and critical plant processes such as photosynthesis. The Tropical Rainforest is being used to test new instrument configurations for measuring methane (an important greenhouse gas) and methane isotopes that will then be moved to the floodplain forests of the Amazon Basin of South America.

The scientific research at B2 is primarily organized around five major research systems (Appendix III), each of which has been assigned a UA Research Director. Three of these are synthetic ecosystems in the core controlled-environment facility (the Landscape Evolution Observatory (LEO), the Ocean, Tropical Rain Forest) and two are external to this facility: Agrivoltaics and SAM (Space Analog for the Moon and Mars). The Research Directors of each of these systems worked with their collaborators and liaisons on the B2 Science Advisory Board to develop system-specific strategic research plans around the B2-wide Grand Challenges described above. These plans are in Appendices V-IX and will also be on the B2 website, for communication with potential collaborators and students. Because involvement of students and justice, equity, diversity, and inclusion (JEDI) are essential foundations for achieving excellence in scientific research, each of the system-specific strategic research plans includes sections on education and JEDI.

The smaller synthetic ecosystems in the core controlled-environment facility (desert, savanna, thorn forest, and mangroves; see Appendix III) have had less research activity in recent years compared to the tropical rainforest, ocean, and LEO and do not now have UA-appointed Research Directors. Over the next 1-3 years, we plan to host a series of targeted workshops with invited researchers from UA and externally to brainstorm and plan future use of these systems, whether in their current form or completely transformed for other uses (as the temperate forest plantations were transformed into LEO). In addition, we will expand use of the natural ecosystems around the B2 campus for ecological research and education, starting with a BioBlitz to introduce UA and local researchers, educators, and students to the setting and available support for activities.

While ongoing research by B2-affiliated faculty already involves numerous collaborations with scientists from around the globe, there is considerable room to expand use of the facilities through more formal and systematic approaches to enlarge and diversify these collaborative networks still further. For example, starting in 2022, B2 will host an annual symposium, involving plenary talks by high-profile researchers to provide context and inspiration for work at B2, talks on the specific research occurring at B2, and sessions for the general public that highlight some of the ongoing research at B2 in a less technical format. B2 researchers will also be encouraged to organize symposia at national and international conferences that explicitly highlight opportunities at B2, as well as their own research accomplishments. Similarly, researchers giving seminars or talks on their research at other institutions will also provide information on opportunities for others. B2 will also host workshops/think tanks on more focused topics that could lead to important results in their own right, but also broaden exposure by participants to the research opportunities available at B2. For example, as part of the France-Arizona Institute of Global Grand Challenges (see chapter 5), we are planning a series of think tanks to be held at the B2 conference center. The first topics will be: 1) One health: humans, environment, animals, emerging diseases 2) Networks of intelligent and integrated environmental monitoring, and 3) Water and carbon as public goods to transform to a circular and sustainable economy, including an international school on agrivoltaics. In all symposia and workshops organized by B2, explicit attention will be paid to ensuring diverse speakers and participants.

This pillar fits under the UA strategic pillar Grand Challenges: environment.

Chapter 2. RESILIENCE SOLUTIONS (Pillar 2)

Translating science to generate innovative solutions to humanity's urgent problems

This pillar is focused on translation of science into solutions for sustainable development and resilience for local communities around the globe in support of the UN Sustainable Development Goals and extending into human colonies in space. We aim to create a *culture of science, technology, and innovation* on the B2 campus involving interactions among its diverse stakeholders. These stakeholder groups include B2 researchers working on basic and use-inspired science, students and interns, entrepreneurs leading startups, technical staff from established companies using B2 facilities to test new technologies, along with businesspeople and social scientists who focus on deployment of new technologies and approaches. Having all these groups with diverse perspectives and expertise on the B2 campus has the potential to create a rich intellectual ecosystem that can inspire new ideas and approaches and new collaborations. However, interactions among these groups must also be actively nurtured. Physical co-location (as with the start-up incubator described below) is a first step, but we will also develop regular events where all these groups come together. Possibilities include the annual symposium highlighted in Chapter 1, weekly B2-wide brown-bag seminars and discussions that highlight ongoing work at B2 in all these spheres, and more focused workshops on themes relevant to multiple groups working at B2.

> ***Pillar 2: RESILIENCE SOLUTIONS***
>
> ***Objective:*** *Increase collaborations involving the B2 campus community and other scientists, engineers, businesses, funders, NGOs and local communities to create and implement resilience solutions across the globe.*
>
> ***Assessment:*** *Short-term, we will measure the numbers and progress of patent disclosures and new technologies and innovations for possible suites of solutions and of quality partnerships with implementers. Longer-term, we will collaborate with social scientists and partner with local communities to assess the solutions' long-term adoption and impact on the communities' development and resilience.*

B2 researchers are already using their science in B2 facilities to support increased resilience of communities and have plans to increase these efforts. For example, Diane Thompson is collaborating with coral reef restoration organizations to test novel assemblages of coral reef species to determine those best adapted to the warmer, higher-CO_2 conditions of future oceans (Appendix VI). Greg Barron-Gafford is investigating what crops are best able to grow under photovoltaic panels and collaborating with solar companies, as local UA extension and farmers, on the optimal design of solar installations for both energy production and crop growth (Appendix VII). Gene Giacomelli is leading a new effort in controlled environment agriculture. As work at B2 on the nexus of food, energy, and water increases, B2 will set up a center to solidify its intellectual leadership in this area of growing global importance. B2 will work with researchers to find additional NGO and commercial partners to take all this translational research to the next stage of implementation in the real world.

For even more immediate solutions, B2 is increasing its connections to both new startups and established commercial ventures to use B2 facilities and benefit from the rich intellectual ecosystem at B2. A substantial step toward this end was completed in April 2022 with the co-location of the University of Arizona Center for Innovation (UACI) at B2 in collaboration with UA TechParks. Biosphere 2 already has four startup companies co-located on the grounds to make use of the expertise at B2 and UA and the ability to showcase their technologies and solutions to the 100,000+ annual visitors at B2. By establishing first this UACI satellite location at B2, and then moving to a full-fledged Tech Park, we intend to co-locate innovative companies, larger corporate R&D, and create more industry and national lab partnerships with UA and B2 researchers for demonstrating and commercializing sustainable and resilience solutions at scale. A formal arrangement for hosting companies will become more important as we focus on scaling solutions that will work globally, especially in economically disadvantaged areas of the US and developing countries, where bringing these solutions to market will require local community engagement, local companies and local champions. In the future we will seek partnerships with technology accelerators in economically disadvantaged regions of the US and developing countries to create local companies to create jobs and provide capacity building to enhance their economies.

In addition to hosting startups and demonstrations of resilience solutions, B2 has, and is developing many more, partnerships with industrial partners based elsewhere–a list is in Appendix XI. For example, a developing partnership with Seeds will potentially test probiotics for coral resilience in B2O, and a partnership with Heliae will potentially analyze soil microbiome samples from the synthetic ecosystems under the spaceframe. SAM, itself a partnership with Over the Sun, has additional partnerships with a number of companies to test novel technologies including spacesuits and mechanical life support systems as well as to train commercial astronauts. We aim to considerably increase the number of such partnerships over the next five years through hosting workshops at B2 on particular challenges relevant to the UN sustainable development goals.

B2 will partner only with organizations whose objectives align with our focus on sustainability and resilience, and with our mission and vision. Given the disproportionate impacts of climate change and other environmental issues on marginalized communities, B2 researchers are committed to working with NGO and community partners in such communities. In addition, B2 will ensure that its commercial partners have an explicit and active commitment to mitigating these inequities as we work with them to implement solutions to increase resilience.

This pillar fits under the UA strategic pillar Grand Challenges: environment.

Chapter 3. OUR REGION (Pillar 3)

Using community expertise and demonstrations to advance resilience of arid lands

Arid lands constitute a substantial portion of the lands on Earth (35%) and are expanding with climate change. We will enhance our efforts on resilience of arid lands by capitalizing on the potential synergies between the main campus of the UA and B2 based on the convergence of our desert southwest location, institutional focus on Earth systems and the environment, and UA strengths: excellence in controlled environment agriculture and cooperative extension in the College of Agriculture and Life Sciences (CALS), excellence in hydrology, and global leadership in water policy and space sciences. We aim to increase our partnership with the UA Arizona Institute for Resilient Environments and Societies and the ASU Wrigley Global Futures Laboratory, as well as forge a partnership with the UA Space Institute.

Pillar 3: OUR REGION

Objective: *Build upon UA and regional strengths through strong partnerships to enhance the quality of life and resiliency locally and in ways relevant to other arid communities. The UA/B2 will be increasingly recognized as an international hub of excellence, providing examples of and solutions for resilience in arid lands.*

Assessment: *Short-term success will be measured by the number, quality, and longevity of partnerships for resilience of arid lands and the number and progress of demonstration projects and case studies. Longer-term, we will measure how our case studies and demonstrations are used to stimulate new projects and their impact inside and outside our region.*

B2 will build on this convergence of our desert southwest location and this vast regional expertise to develop case studies in resilience. For example, planned projects will demonstrate the synergy between controlled environment agriculture and agrivoltaics to reduce energy and water use and intensify production of many crops at the UA Experiment Station in Yuma, and to experiment with crop resilience under expected climate change in the B2 controlled environment including those from native seeds. B2 has a long-term goal to be a demonstration net zero community where the public can observe, and experience implemented solutions.

This pillar fits under the UA strategic pillar Arizona Advantage.

Chapter 4. TOMORROW'S LEADERS (Pillar 4)

Preparing the next generation of leaders in resilience science and solutions

> ***Pillar 4: TOMORROW'S LEADERS***
>
> ***Objective:*** *To increase the educational activities and curricula tied to B2 research, more fully integrate diverse undergraduates in B2 activities, and become a major attractor for UA students and students from across the globe.*
>
> ***Assessment:*** *Short-term, we will collect data on the number of courses taught, the number and demographics of students involved in different programs, student outcomes such as majors and graduation rates, and the quality of visitor experiences. Longer-term assessments in collaboration with educational researchers will investigate the role of B2 in attracting excellent and diverse students to UA and the consequences of B2 engagement for careers and public understanding of science.*

The integration of research and education has long been an essential part of the mission of Biosphere 2, which has had a Director of Education, Dr. Kevin Bonine, since 2013. Adding funding for personnel to manage and implement the education program is critical. Many of the educational programs already underway are well described at the B2 website for K-12 and undergraduate students or in the strategic plans for each of the core research systems (Appendices V-IX). Indeed, undergraduate students are already critical parts of much of the research at Biosphere 2 through grants to individual researchers, partnerships with the UA Honors College, the long-running National Science Foundation (NSF)-funded Research Experiences for Undergraduates (REU) summer program, and, crucially, the UA Vertically Integrated Projects (VIP) Program. The VIP Program is a transformative approach to enhancing higher education by engaging undergraduate and graduate students in ambitious, long-term, large-scale, multidisciplinary project teams that are led by faculty. This approach exactly fits the work at B2 and the Tropical Rain Forest and the Ocean both already have a VIP team in place. We plan that each of the other major research systems will establish a VIP in the next year or two that will eventually have a team of 10-20 undergraduates and graduate students per year. Involving undergraduates in research, especially in their first year or two in college has been found to significantly increase retention in STEM, especially for students belonging to groups historically excluded and therefore under-represented in STEM. Therefore, we will focus recruiting for our VIP teams on first- or second-year students from such demographic groups and ensure that all mentors have had training in leading diverse groups. Leading a VIP is a major effort for a faculty member; B2 will act as an advocate to departments for counting leading a VIP as part of the expected teaching load in the faculty member's home department. Financial Support should also be provided for graduate students and postdocs to help mentor students, perhaps through the Broader Impacts components that are required as part of research grants by the National Science Foundation.

Graduate students have also long been an essential component of research at B2, but we will expand formal training in interdisciplinary and transdisciplinary approaches. For example, the Landscape Evolution Observatory has recently been awarded a large grant on Landscape Terraformation from the Growing Convergence Research Program at NSF–a program designed to create entirely new areas of science by funding interdisciplinary teams to conduct integrative projects that would not be funded under traditional grants programs. Additional funding for students comes from the France-Arizona Institute of Global Grand Challenges at UA. All faculty and students involved in the project attend a weekly seminar. This seminar meets weekly, alternating between project meetings to plan details of the ongoing research across all disciplines involved and journal club-style meetings to learn from each other about the conceptual frameworks and approaches of the different disciplines and help move the group towards convergence among those disciplines. Similar seminars will be established for the other research systems to facilitate greater integration among the students and more senior scientists working in those systems.

K12 students have also been involved in research at B2, most notably in the Agrivoltaics system (see Appendix V-C). We propose to expand this work by integrating high school students into the VIP teams in each research system, where the undergraduate students will help mentor the high school students, enhancing their own experience while also supporting the younger students. As with the undergraduates in the VIPs, we will focus our recruitment and partnership efforts with schools with high populations of students from minoritized groups. Campus regulations will be followed for hosting and mentoring pre-college students.

Since 2007, when UA first took over management of B2, it has been focused on engaging K-12 teachers in an effort to improve STEM learning outcomes for students in southern Arizona and beyond. By providing immersive, hands-on, inquiry-based workshops and professional development for teachers, our investment in the K-12 system is multiplied by the interactions of participating teachers with their peers and by the hundreds or thousands of students that experience a trained teacher's classroom. The Arizona Center for STEM Teachers was a regular staple of summer programming at B2, with participation by 30 or more teachers for up to two weeks; we plan to resurrect this powerful program. Other K-12 Teacher programming includes collaboration, with funding from the NSF Noyce program and from the APS Foundation, for immersive workshops for K-12 teachers led by UA's Borderlands Master Teacher Fellows and in collaboration with the UA College of Education and its Borderlands Education Center. Agrivoltaics is a compelling vehicle into inquiry and STEM for teachers and students. Barron-Gafford has NSF RET (Research Experiences for Teachers) funds to engage Arizona teachers in his work. In addition, Agrivoltaics is a topic that has been picked up by rural partners like the Bisbee Science Center as an experiential teaching and learning tool.

We will ensure funding is available for students at all levels to present their research at conferences, both locally (at the annual B2 symposium and on campus) and at national conferences such as the American Geophysical Union and other professional organizations.

In addition to research engagement, B2 will increase its formal course offerings, taught by faculty associated with B2 recruited from across campus. Ongoing courses and curricular initiatives include a partnership with the Honors college for an interdisciplinary minor in Future Earth Resilience, a MOOC on Biosphere 2 research on the Coursera platform, and a cross-listed UA course (RNR/ENVS/GEOS/ECOL 388) on B2 research. The B2 Innovative Teaching Fellows program works with selected UA faculty from any College or School to include work at Biosphere 2 in their existing courses or to develop new courses, or connections to other student engagement. As part of a multinational consortium, B2 will help develop an International School of Agrivoltaics, targeted to both graduate students and farmers.

We will revive a past partnership with Arizona FORGE and UA Tech Parks to provide UA students entrepreneurship opportunities and internships with B2 partner companies.

The focus of B2 on hands-on experiences, both in research and in internships with industrial partners, is a critical component of workforce development because these real-world experiences develop skills in teamwork and critical thinking. In addition, B2 can take advantage of UA partnerships with community and tribal colleges to add technical workforce development programs, especially in sustainable agriculture.

In addition to expansion of our formal and informal education programs, we will work towards enhancing the experience of other visitors to B2 and, importantly, the impact of the B2 experience on the understanding of and commitment to individual behaviors that increase societal and environmental resilience. As a major regional attraction, B2 is visited by up to one hundred thousand tourists every year. We will closely examine and modify our exhibits, tour scripts, and apps to suggest lessons from B2 research that empower visitors to contribute to resilience themselves–a kind of DIY B2 at Home! For example, exhibits on agrivoltaics research could point out how a few solar panels over a backyard garden could reduce water use, increase food yield, and produce electricity. Exhibits on SAM could incorporate information on composting and reducing garbage.

This pillar fits under the UA strategic pillar of Wildcat Journey.

Chapter 5. NETWORKS (Pillar 5)

Deepening connections to national and global networks of science, innovation, and education

B2's research and innovation will leverage national and global partnerships to maximize impact in science, solutions, and educating the next generation of leaders. Our many existing and planned partnerships with scientists, entrepreneurs, companies and organizations around the globe place B2 as a growing node in a network of similar-minded researchers and innovators focused on local solutions to sustainable development challenges around the globe.

> ***Pillar 5: NETWORKS***
>
> ***Objective:*** *To increase and strengthen long-lasting and impactful partnerships addressing Earth's greatest challenges. B2 will become recognized globally for its collaborative research and educational initiatives and its role in convening thought leaders to impactfully address global grand challenges.*
>
> ***Assessment:*** *Short-term, we will evaluate the number and quality (including outputs) of partnership convenings and conferences at B2 and B2 leadership roles in national and global networks. Longer-term, we will assess the longevity and impact of B2 partnerships on innovation in science, education, and sustainable development.*

Examples of ongoing international partnerships include

- Using agrivoltaics to develop food-energy-water solutions that build resilience in communities in the Americas, Europe, the Middle East, and Africa (Appendix VIII).
- Using the B2 Ocean to investigate mechanisms to create resilience in global coral reef ecosystems. (Appendix VI)
- Converging multiple disciplines across the UA and institutions in France to gain a holistic understanding of terraformation with funding from the National Science Foundation and the recently launched France-Arizona Institute of Global Grand Challenges at UA, in partnership with CNRS (Appendix V)
- Using the B2 tropical rain forest to study whole-ecosystem effects of prolonged drought and rewetting by a large collaboration between European scientists and B2 scientists (the Wald project; see TRF writeup in Appendix IV)

Examples of partnerships in the planning stages include

- Working with several multinational companies to generate solutions for human survivability and resilience in space and on other planets; this is increasingly significant as we prepare for the age of commercial space travel (Appendix IX)
- Engaging more with social scientists in the B2-hosted, CNRS-funded iGLOBES Center.
- Co-hosting a series of workshops on ethics in science by the two newly announced Kavli Centers for Ethics, in partnership with the UK-based Eden Project.

We will further increase the opportunities for starting and enhancing international partnerships by convening international thought leaders from academia, industry, national labs and research institutes and NGOs in strategic workshops on particular challenges related to UN SDGs.

This pillar fits under the UA strategic pillar Arizona Global.

Chapter 6. EXCELLENCE IN OPERATIONS (Foundation)

Objective: *Provide financial and operations support to enable the research, education and innovation plans – our 5 pillars – to flourish at B2.*

Foundational to all the pillars in support of the B2 mission are excellence in operations. B2 already has a world-class staff. However, the current operating budget is insufficient to fully support existing operations, let alone the ambitious objectives described above. During the first year of this five-year strategic plan, we will develop detailed operational plans to fully support the five Pillars; this process will involve all staff to ensure broad agreement on the goals and buy-in as to how they will be achieved and assessed. Plans will cover the following areas:

- Financial
- Communications
- Steps to approach net zero carbon emissions
- Waste and water recycling and reuse
- Hiring and retention of world-class staff
- Excellence in safety, health and security
- Facilities and infrastructure

The number of staff has been declining over the last ten years, with an especially steep drop as a result of the operating budget drop during the pandemic. Thus, it has been difficult to maintain adequate support for even the current level of research effort, let alone the increased level we aspire to with this plan. Increasing operations, research, and education staff are all critical, as well as regularizing support for Research Directors, including the near-term need for assigning a permanent RD for the Tropical Rain Forest. A separate Financial and Staffing Needs document lays out the proposed staffing plan and budget requirements to support the five Pillars of this plan over the next few years.

This foundation fits under the UA strategic pillar of Institutional Excellence.

Chapter 7. JUSTICE, EQUITY, DIVERSITY, AND INCLUSION (Foundation)

Objective: *Biosphere 2 is a place with participants from a wide diversity of groups, where everyone feels welcomed, has equal opportunity and resources, and is encouraged and supported to succeed and to learn.*

As a federally designated Hispanic-serving institution (HSI) and as the home for large numbers of Native American students, the University of Arizona has an especially significant moral responsibility to provide equitable opportunities and inclusive environments for all students, regardless of background. This responsibility extends well beyond students of any level, to the faculty and staff and to the collaborators, partners, and visitors at Biosphere 2. In addition, it is now well-established from social science and the business world that more diverse groups with more diverse perspectives make better decisions. We will move faster towards meeting our strategic objectives, ask more relevant research questions and deliver more just and relevant solutions, and achieve our vision for the Biosphere 2 campus by making it a more diverse, equitable, and inclusive place.

Thus, a diverse workforce, equitable distribution of resources, and an inclusive climate are all essential to achieve the foundational objectives that have been laid out for each of the Pillars. Yet, B2 does not yet have a workforce that is representative of the greater Arizona or US population, nor has the workforce climate and resource distribution been rigorously assessed. In the first year of this strategic plan, we will engage all levels of researchers, staff and administration at B2 to propose specific JEDI goals, develop concrete plans to achieve them and to assess progress towards those goals. Such broad involvement in detailed planning is essential to ensure complete buy-in and commitment by everyone at B2. **The administration of B2 commits to allocating 2% of its operating budget each year towards achieving the JEDI goals that will be thus defined and to acting vigorously on all recommendations arising from that process.**

In addition to working on JEDI issues within B2, our research and partnerships to generate innovative approaches to increase societal and environmental resilience directly address issues of environmental justice, given the well-documented disproportionate impact of climate change on already marginalized communities (see Chapter 2).

This foundation fits under the UA strategic pillar of Institutional Excellence.

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Appendices

Appendix I: Strategic planning process

Appendix II: Brief history and current context at University of Arizona

Appendix III: Description of Biosphere 2 research facilities

Appendix IV: Highlights of research impacts to date

Appendix V: Landscape Evolution Observatory (LEO)

Appendix VI: Ocean (B20)

Appendix VII: Tropical Rain Forest (TRF)

Appendix VIII: Agrivoltaics: Food, Energy, and Water Resilience Solutions (FEWRS)

Appendix IX: Space Analog for Mars (SAM)

Appendix X: Limitations and mitigation approaches for B2 research

Appendix XI: Industrial partnerships

Appendix I. Strategic planning process

The B2 community initiated a major process of strategic planning in fall 2020, taking advantage of the newly established Science Advisory Board (SAB) to help guide the Research Directors and B2 Executive team. The Research planning included education and equity and inclusion as central components.

After an initial SWOT analysis (see below), the first phase of the research strategic planning revolved around defining grand challenge questions for each of the research systems and for B2 as a whole, using an iterative process to ensure integration across systems. The Research Directors of each of the systems worked with their collaborators, staff, and liaisons to the Science Advisory Board (SAB) to derive draft grand challenge questions for their systems and presented these at a virtual workshop in Spring 2021. Discussion of these at the workshop and in subsequent meetings resulted in synthetic grand challenge questions for B2 as a whole, as well as more refined versions of system-specific questions, which were finalized in May 2021. The process of defining what questions could be best addressed at B2 also resulted in clear articulation of the unique opportunities presented by B2 facilities, as well as the potential challenges.

Once the core research questions for B2 as a whole and for each system were defined, each Research Director worked with their collaborators, staff, and liaisons to the SAB to develop both short-term (2-3 years) and medium-term (3-5 or 6 years) research goals and implementation plans. Drafts were presented and discussed by the SAB at a workshop in September 2021, with penultimate versions incorporating insights from the workshop due in February 2022. The Deputy Director for Research and Chair of the SAB drafted additional background material and B2-wide plans, with input from the Research Directors and Executive team. The penultimate B2 Research Strategic Plan was reviewed and discussed by the SAB in April 2022, and subsequently revised by the Deputy Director for Research and Chair of the SAB. Additional comments from the SAB, Research Directors and Executive team were solicited in July and the final version submitted to the full Board in September 2022.

SWOT Analysis

STRENGTHS

1. Unique controllable mesoscale biomes - relevant to current climate change observations and predictions - that can be used to understand and forecast ecosystem/human system dynamics
2. Global recognition of the facility and history; history of visionary bold thinking
3. Original owner excited about, and provided endowment for, UA to utilize for research and education activities
4. University of Arizona upper administration believes B2 is a draw for students and faculty and a strategic resource consistent with UA Strategy of an interdisciplinary focus on the Earth's environment; no other university has its own biosphere
5. Global entities eager to partner to find solutions to vexing sustainable development challenges – CNRS, Arava, Mexico City, …

6. Beautiful architecture and surrounding environment, amazing engineering of the facility and ongoing research that can be used to engage the public about science, climate change, environmental health, and sustainable/resilient development
7. Ambitious and energetic research directors and executive team; dedicated and knowledgeable staff

WEAKNESSES

1. Not enough funding for making full use of the facilities; under endowed and understaffed
2. No strategic plan; lack of clear or consistent articulation of mission and vision that matches key strengths and opportunities
3. Facility is 30 years old and needs maintenance and updating, especially for strategic research
4. External awareness includes historical media blitz in 1990's of scientific 'failure'
5. Research fully utilizing the facilities requires high infrastructure startup costs that are difficult to fund through federal grants.
6. Scientific experiments and results either historical or current not well communicated/known to general public and UA; not yet well-grounded in day-to-day concerns of the broad public
7. Perhaps distrusted by various 'environmental' entities (departments, centers) in UA and beyond
8. Distance from campus and civic centers is a deterrent for faculty, staff, students and visitors/tourists
9. Only about 10% of visitors/tourists are repeat visitors
10. Cost of tourist visit is high compared to other Tucson-area attractions
11. Insufficient knowledge of how to innovate for the developing world.
12. Insufficient connection to industry and not-for-profit corporations as partners
13. Lacking staff, resources, and focus to execute K-16 education mission
14. Unclear what impact B2 has on visitors and their attitudes and behaviors
15. Have not yet articulated metrics of success
16. Lack of focus on diversity, equity and inclusion

OPPORTUNITIES

1. Federal funding for environmental research is likely to increase in the next 4 years (EPA, DOI/NOAA, DOE, NSF); EU has funded developing a circular economy and both US and EU are pledging net zero carbon emissions by 2050, which is known not to have a solution at present - research and demonstration projects are needed for various regions
2. US Department of Agriculture strategic science plan requires twice the productivity of land with the same amount of land by 2030 – current expectations are for more funding of USDA research as well as more USAID money to provide solutions for agricultural productivity increases in the global South
3. UA research and policy strengths including agricultural extension and AZ Experiment Stations in arid lands are ripe for using desert biome and external desert environment to provide solutions for agriculture/food in newly arid lands due to rampant global desertification, as well as understanding how deserts can become carbon sinks
4. US, EU, Russia, China and other nations as well as private companies are planning for human habitation on Moon and Mars in the near future decades – B2 contained environment test station (SAM) and collaborators can quickly provide impact in the first real biological life support research and solutions

5. LEO and SAM together can understand and have the potential to accelerate soil formation required for terraforming off world and efficiently replenishing soils on Earth
6. B2 Ocean, if equipped quickly with lights and turbulence generators, is the only controlled and contained coral reef system big enough to understand ecosystem dynamics of resilient coral and can make a different for ocean reefs worldwide – a new global funding mechanism for reef restoration has just been announced out of G20
7. B2TRF can partner with EU partners and Berkeley Lab to develop more accurate models of chemistry, ecology, and local rain/climate forming ability of tropical rainforests and test hypothesis hard to accurately measure in the field
8. Investment in developing Gaia Circle undergraduate research and capstone opportunities can enhance the connection of donors and undergraduates with Biosphere 2 and its research and solution portfolio
9. Faculty B2 Teaching Fellows, if the program is funded, will connect undergraduate learning experiences and more faculty in all disciplines and across the University with the Biosphere 2 Mission; could develop other globally attractive university-level programs
10. Arizona ranks at bottom among US states for K-12 learning, including in STEM. B2 could make a huge difference in the quality of Arizona education, preparation and retention of teachers, and economic development benefits via workforce development and attraction/retention of education-minded employees (see Southern Arizona Leadership Council https://www.salc.org/ and Making Action Possible https://mapazdashboard.arizona.edu/ for relevant statements and data)
11. Research on informal learning outcomes
12. Staff workplace satisfaction survey and subsequent improvement plan

THREATS

1. UA funding cliff projected after June 2028
2. Delays in finding enough start-up funding to provide needed infrastructure and research and operations personnel has delayed the start of impactful new research plans in Ocean and potentially LEO. This could make the B2O plans irrelevant to global coral restoration efforts and may dampen enthusiasm of all research directors and potential research funders
3. Chinese are eager to build or building currently contained Mars analog facilities that could be in competition to SAM and they seem to have ample funding
4. COVID-19 vaccination campaign is rolled out too slowly across the globe to avoid a mutation that evades current vaccines – which could cause economic disaster in US in UA and in potential partners globally
5. Budget cuts and reallocations
6. Lack of consistent focus and (perceived) drop-in support for many current projects
7. Staff morale

Appendix II. Brief history and current context at University of Arizona

In the late 1800s, the Biosphere 2 property was part of the Samaniego CDO Ranch. After several changes of ownership, it became a conference center in the 1960s and 1970s, first for Motorola, then for UA. Space Biospheres Ventures bought the property in 1984 and began construction of the current facility in 1986 to understand how biospheres work and to research and develop self-sustaining space-colonization technology (Marino and Odum 1999).

Two missions, between 1991 and 1994, sealed volunteer researchers inside the controlled-environment facility to monitor and demonstrate how humans could sustain life in a closed atmosphere, water and food system with only energy and information exchange with the outside. Behind this highly public exercise was useful research that helped further ecological understanding. Several first-person accounts have been published by former crew members that provide different perspectives on the experiment (Poynter 2006, Allen 2009, Nelson 2018).

In 1994, Decisions Investments Corporation assumed control of the property and Columbia University managed it from 1996-2003. Columbia reconfigured the controlled-environment facility for more rigorous scientific research, including some now iconic studies on the effects of carbon dioxide on plants (Lin et al. 1999, Lin et al. 2001) and effects of ocean acidification on coral reef growth (Langdon et al. 2000). Columbia University also built classrooms and housing for college students of earth systems science, now used as a conference center and housing for researchers and conferees.

The property of 1658 acres was sold to CDO Ranching in 2007 who then leased the central part of the property to UA from 2007-2011. The UA assumed ownership of 39.5 acres including the controlled-environment facility and the conference center built by Columbia University in July 2011 and it now serves as a facility to support research by UA faculty and an international community of scientists and engineers. As a laboratory for large-scale projects, such as the Landscape Evolution Observatory, the university's stewardship of Biosphere 2 allows researchers to propose and perform key experiments aimed at quantifying consequences of global climate change and understanding the mechanisms underlying these consequences, as well as to design and demonstrate possible solutions for future resilience of ecosystems and society.

As a research center under the Office of Research Innovation and Impact of the University of Arizona, B2 now employs 36 people with an annual operations budget of roughly $3M. The staff and faculty provided some compensation by Biosphere 2 are comprised of 47% women, 19% Hispanic or Latinx, 6% Asian American, and no African Americans or Native Americans. These proportions are not materially impacted by including the faculty Research Directors and faculty executives whose salaries are not paid directly by Biosphere 2. Over the last ten years, over 77 faculty from more than 20 departments across campus and researchers from over 50 institutions have participated in research and education activities at B2.

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Appendix III. Description of Biosphere 2 research facilities

The core research facility of the Biosphere 2 campus is the 3.14 acres controlled-environment structure encased in a glass and steel space frame. The campus also has numerous experiments and demonstrations outside this core structure, carried out on the combination of owned (39.5 acres) and leased (5 acres) lands of the surrounding Sonoran Desert outside of Oracle, Arizona. The Biosphere 2 campus serves as a 162,000 m^2 model city and urban ecosystem with its own local power substation. Operational for over 30 years, the meso-scale synthetic ecosystems inside the controlled-environment facility include the world's largest controlled systems of tropical rainforest, fog desert, savanna, mangroves, and ocean.

Biosphere 2 is used heavily by UA researchers and is also operated as a research user facility.   Each of the major synthetic ecosystems inside the core facility and the two major experimental systems outside of it has been assigned a UA Research Director, who is responsible for overall research strategy and oversight of activities in that system. The Research Directors also typically lead major research efforts in their particular systems.

Other UA researchers and researchers from around the globe can propose and carry out research in any of the systems inside the controlled-environment facility as well as make use of the expertise of staff and other facilities on the B2 campus for field experiments and demonstrations of 'green' technologies. The process for proposing and accepting research proposals is described here.

The major synthetic ecosystems inside the controlled-environment facility include:

The **Landscape Evolution Observatory (LEO)**, is the world's largest laboratory experiment in the interdisciplinary Earth sciences, begun in 2011. The experiment consists of three artificial landscapes contained within elaborate steel structures that serve as the world's largest lysimeters, located inside three adjacent bays within the glass and steel frame of Biosphere 2. The three 30-m x 11-m sloped landscapes are filled to a uniform depth of 1 m with crushed basalt rock, from more than 1 million pounds extracted from a volcanic crater in northern Arizona. Artificial rainfall from sprinklers is tightly controlled and water in-ground is measured on the slopes by the lysimeters and over 1000 in-ground sensors and controlled sample ports for analysis. Effluent run-off is analyzed, and overhead cameras document the substrate and plant growth. LEO allows an interdisciplinary team of scientists to observe each step in the landscapes' evolution, or terraformation — from purely mineral and abiotic substrate to living, breathing landscapes and soil that support microbial and, ultimately, vascular plant communities. The current Research Director of LEO is Scott Saleska, Professor of Ecology and Evolutionary Biology and of Soil, Water and Environmental Sciences at the University of Arizona.

The **Biosphere 2 Ocean (B2O)** is a state-of-the-art experimental mesocosm for coral reef research. The B2O is the largest research aquarium in the world, with a surface area of 35 m x 20 m and a volume of 2.6 million liters. The 7-meter-deep fore-reef environment slopes up to a shallow lagoon partially separated by a fringing reef crest and channel. Mechanical systems simulate or substitute for natural environmental processes and physical and chemical parameters such as temperature, mixing, gas exchange, nutrient concentrations, and partial pressure of CO_2 can be independently manipulated (Atkinson et al. 1999). The B2O is in the process of being upgraded in order to develop viable solutions for building resilient reefs of the future—reefs which can maintain critical reef structure, function, and diversity in the face of continuing climate change and acidification. The current Research Director of B2O is Diane Thompson, Director of Marine Research, Assistant Professor in the Department of Geosciences, University of Arizona.

The **Tropical Rain Forest (TRF)** mesocosm was created to simulate several tropical rainforest habitats (Leigh et al. 1999). Terraces surround the east, west and north sides of a central "mountain." Small trees including papaya, coffee, cocoa, and palms are in these terrace areas. Larger trees (up to 24 m at the top of the structure) inhabit the lowland area beside the mountain. The TRF currently has about 100 species of plants from Puerto Rico, Belize, Venezuela and Brazil, with a surface area of 47 m x 49 m. The soils in the biome are synthesized from local material with textures ranging from sandy loam to clayey loam. In profile, the soils contain a topsoil layer which is rich in nutrients and usually less than one meter thick and subsoil which consists of gravelly granite material from 1 to 4 meters thick. Like everything inside the glass at Biosphere 2, the inside soil is hermetically sealed by a steel liner from contact with the outside. The temperature of TRF ranges from 20^o to 30^o C and it currently is the Earth's hottest rainforest canopy. Research in the rain forest focuses on the elemental (C, N, and H_2O) fluxes and organismal interactions within the soil-plant-atmosphere continuum. The rainforest is often used to design and calibrate measurement protocols and models of field rainforest systems. The current Interim Research Director of TRF is Joost van Haren, Assistant Research Professor, Environmental Science, W. A. Franke Honors College at the University of Arizona.

In addition to these major mesocosms, Biosphere 2 contains several smaller synthetic ecosystems:

Biosphere 2's 1400 m^2 coastal **fog desert** mesocosm was designed to simulate an arid desert scrub ecosystem in a coastal climate with erratic winter rainfall and summer drought. Soils were constructed to simulate those found in arid places ranging from immature dune sand to profiles with clay, carbonate, and salt accumulations.

The **mangrove** mesocosm, at roughly 900 m^2, is the world's largest indoor controlled mangrove system dedicated to research. It includes both grass-dominated marshes (ca. 20% of area) and forested mangrove swamps that are found naturally along a gradient from freshwater to marine systems (ca. 80% of area; Finn 1996).

The **savanna** mesocosm was designed to provide a hydrological transition zone between the desert and rainforest mesocosms and includes a thorn forest. Vegetation zones within the savanna mesocosm were created primarily from edible species, including acacias, large-seeded grasses, and fruit-bearing trees.

Two additional major experimental systems are underway outside the controlled-environment facility:

By colocating agriculture and photovoltaics (renewable energy from solar panels) within an approach called '**agrivoltaics'** (Barron-Gafford et al. 2019) (www.TheSolarFarm.org), simultaneous synergies can be created including: (*i*) the shade from photovoltaic panels reduces plant stress, (*ii*) renewable energy efficiency is increased because of cooling effects of plant transpiration, and (*iii*) evapotranspiration is reduced such that water resource requirements for food production are reduced. The agrivoltaic garden plots at B2 are used to quantify and model these impacts for a diversity of crops and panel designs, as well as for education and outreach. The Research Director of this effort to design and demonstrate resilience solutions at the nexus of food, energy and water is Greg Barron-Gafford, Professor, School of Geography, Development and Environment, University of Arizona.

A ***Space Analog for the Moon and Mars* (SAM)** is a sealed Mars habitat analog located outside and down the hill from the controlled-environment facility. SAM integrates a controlled environment (greenhouse), workshop, kitchen, common area and crew quarters to support up to four inhabitants from five days to a few months. The space includes the fully refurbished 480 cubic meter Test Module that was built in 1987 as a sealed prototype for Biosphere 2. A commercial CO_2 scrubber provides mechanical life support. A pass-through airlock leads to an adjacent half-acre Mars yard where pressure suits, rovers, and drones can be tested. The Mars yard will be modeled after a crater on Mars as a human landing site. In addition, the SAM Mars yard will include varied terrain and select obstacles, a massive synthetic lava tube with skylight, and a gravity off-set rig to provide the experience of exploring on foot in lower gravitational fields. SAM will operate as a user facility to investigate solutions for providing breathable air, potable water, food production and waste reprocessing for long-duration human space exploration. The Research Director of SAM is Kai Staats, Research Scientist, Biosphere 2.

In addition to these major facilities outside the controlled-environment facility, UA radio and visible astronomy facilities also are situated on land around B2.

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Appendix IV. Highlights of research impacts to date

A. Space Ventures and Decision Investments era (1992 -2003)

Columbia geochemist Wally Broecker was hired as a consultant on the Biosphere 2 atmosphere in 1992, while the volunteer researcher 'Biospherians' were inside, in order to find out why there was a dramatic imbalance in oxygen and carbon dioxide. He discovered that the extremely high organic matter content of the rainforest and farm areas supported high rates of microbial decomposition that rapidly depleted atmospheric oxygen, while atmospheric CO_2 was absorbed by the structure's unsealed concrete (Severinghanus et al. 1994). When Decisions Investment Company took over Biosphere 2 and the Biospherians were removed, they brought in Columbia University to supervise research in the facility, and Wally Broecker became the research director. See Marino and Odum (1999) and Osmond (2005) for more details on research during this period.

B. Columbia University era (2003-2007)

A number of important publications from B2 came out in the Columbia era. For example, in a now classic study using both the tropical and temperate forests of B2, Lin et al. (1998) found that when CO_2 was elevated, plants had higher gross photosynthesis, but their leaves and roots and the soil microbiome also respired more, resulting in a net release of CO_2. This result was a critical step in addressing the then controversial topic of whether increased CO_2 would have a net benefit to plants through fertilization. Experimental droughts revealed the importance of functional diversity in photosynthetic response to drought (Rauscher et al. 2004) and greatly improved estimates of how different atmospheric gasses (e.g., nitrous oxides, isoprenes) respond to drought—a key component of modeling global nitrogen and carbon cycles (Pegoraro et al. 2004, van Haren et al. 2005).

In another iconic study, Chris Langdon, a marine biologist then at Columbia University used the B2 Ocean to provide ecosystem-scale estimates of the declines in coral skeletal calcification due to increased CO_2-induced ocean acidification independent of any changes in coral growth due to warming (Langdon et al. 2000; see also Marubini et al. 2001 and Langdon et al. 2003).

C. University of Arizona era (2007 - current)

Important work on climate change and earth systems science continued and expanded further during the University of Arizona era starting in 2007. Since 2007, Biosphere research has produced more than 160 peer-reviewed journal articles, and over $19 million in research grants. While masters theses and PhD dissertations conducted entirely or partially at B2 have not been consistently tracked, a partial list includes at least 27.

Severe degradation of the B2 Ocean due to algal overgrowth led to a series of workshops focused on restoring the habitat for a major research program on coral reef resilience and restoration, leveraging mesocosm research to solve complex environmental problems (Sagarin et al. 2016). Diane Thompson, UA and Julia Cole, now at the University of Michigan, with a team of over 40 collaborators from 8 countries, have been working on the refurbishment of the reef and planning for future research. The B2O has recently received a major gift from the Haury Foundation, which is being used to enhance the lighting and turbulence over the reef – the last large item needed to install coral on the cleaned-up reef and begin this major research program. In the meantime, a number of studies have been conducted using raceways or portions of the B20. For example, Killam et al. (in review) has demonstrated that giant clams have tremendous biomonitoring potential as sensitive indicators of reef resilience to ocean warming and acidification.

A key advantage of the B2 **TRF** is the ability to control atmospheric humidity independently of air temperatures. Smith et al. (2020) took advantage of this to show that photosynthetic decline at high temperatures in natural rainforests is likely due to concomitant increases in atmospheric humidity deficits rather than high temperatures *per se* since similar declines are much weaker in B2 at even higher temperatures, so long as atmospheric humidity is kept high. Most recently, a very large 5-month international research campaign (WALD) in the TRF was successfully accomplished in early 2020. This effort of over 50 scientists, 13 institutions and 4 countries was coordinated by TRF director and science co-lead Laura Meredith, and funded mostly by a European Research Commission Consolidator grant of co-lead Christiane Werner, University of Freiburg. The goal of this grant was to develop a novel technological and theoretical basis to understand the response of primary versus secondary carbon metabolism in plants subject to drought. The first major papers from the campaign have been published or are in press in high profile journals (Werner et al. 1921) and many additional analyses are in progress; these demonstrate the value of monitoring in real time the soil-plant-atmosphere interactions in a complex ecosystem, with diverse responses to stress, such as distinctive releases of specific volatile hydrocarbons.

An initial publication on **agrivoltaics** in *Nature Sustainability* (Barron-Gafford et al. 2019) confirmed the powerful potential of co-location of solar panels and agriculture by showing that shading by the panels provides multiple additive and synergistic benefits, including reduced plant drought stress, greater food production and reduced PV panel heat stress. This approach has also been a powerful tool for engaging students in research through collaborations between B2 and multiple elementary and high schools in Tucson to study how well different crops grow under solar panels. Ongoing work is expanding the initial demonstration plots at B2 to much larger networks both nationally and internationally (Colorado, Illinois, Kenya, Mexico, Israel).

The goal of the construction of the largest controlled landscape experiment on Earth, **LEO**, by an interdisciplinary team of UA scientists, was to bridge the gap between laboratory and field experiments to meet the challenges of understanding and predicting landscape-scale changes in the Earth system behavior in the critical zone- the interface between the solid Earth and its fluid envelopes, where ongoing coevolution of biota, soils and landforms occur. The first ten years of LEO primarily focused on the physical processes of rock weathering and water transport from the nano-scale to entire landscapes. The high density of sensors for soil moisture has enabled extremely precise calibration of the standard hydrological equations used to model small-scale vertical flow. However, these models appear to be inadequate for scaling up to entire hillslopes; current work is aimed at developing new scaling models to understand flow over landscapes. Hydrology is linked to weathering of rock through water-filling of soil pores and the availability of dissolved CO_2 into those pores; research at LEO has worked out in detail the sequence of weathering products, along with their modes of transport across the landscapes. Ongoing work focuses on how microbial and plant life modifies these physical processes across scales, with the first-ever establishment of vascular plants on LEO hillslopes slated for 2023.

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Appendix V. Landscape Evolution Observatory (LEO)

Research Director: Scott Saleska, Professor of Ecology and Evolutionary Biology and of Soil, Water and Environmental Sciences at the University of Arizona

Introduction and History

The U.S. and the world today face the increasingly urgent question of how to better understand and manage complex physical-biological systems in the face of an array of challenges, including global climate change, loss of biodiversity, increasing drought and water shortages, and degradation of landscapes. At the root of these problems is **the fundamental question of landscape terraformation**: how does life expand and sustain itself, in increasingly complex forms (from simple microbial life, to non-vascular mosses, to vascular plant-microbe associations with complex hydraulic architectures and life-sustaining symbioses), across landscapes at multiple scales to transform bare rock into complex multi-function ecosystems? This question of basic science is directly applicable to a diverse range of societal problems from how to build sustainable life support systems for space travel or on other planets (as investigated in SAM) to how to restore severely degraded landscapes such as mine tailings.

The Landscape Evolution Observatory (LEO) at B2 was constructed during 2010 to 2012, and the first rains were introduced to the LEO hillslopes in 2013, to study the fundamental processes involved in **landscape terraformation**. LEO consists of three replicate sloping landscapes within steel structures inside UA's Biosphere 2. The landscapes are 30-m length, 11-m wide, with an average slope of 10°, filled to 1 m depth with 500 metric tons of basaltic tephra ground to a loamy sand texture, and instrumented with 1900 sensors for high-resolution monitoring of soil climate, conductivity and CO2 mixing ratios (Pangle et al 2015; Volkman et al, 2018).

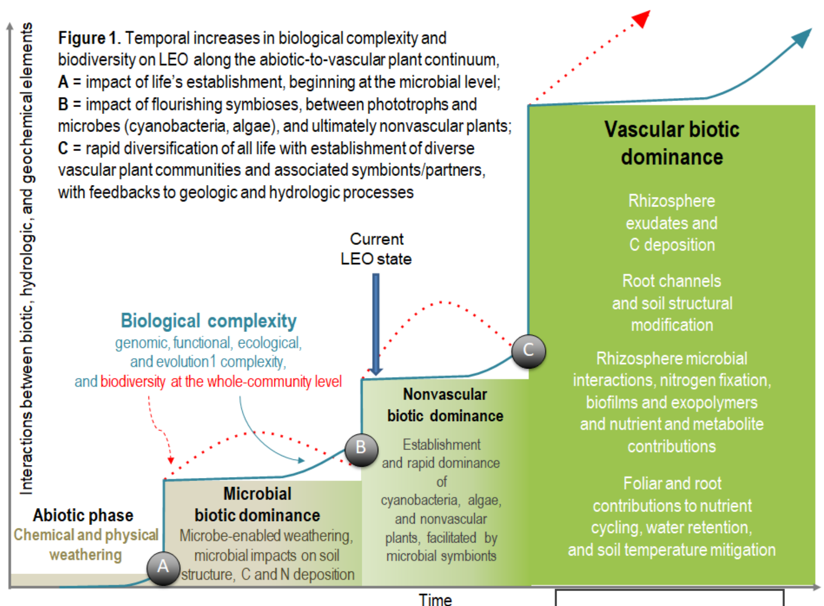


Figure V-1

Since construction, the LEO landscapes have become increasingly complex as diagrammed in Figure V.1. Over the last ten years, the abiotic and microbial dominance phases have revealed much about the physical processes of landscape evolution from bare rock to the development of networks for water flow (the science of hydrology) and the influences of water flow on the weathering of rock and the beginnings of the development of soil (the science of geochemistry) (Dontsova et al. 2014; Pohlmann et al. 2016, van Haren et al. 2017)

Microbes colonized the LEO landscapes very early and much has also been learned about how water flow and weathering processes influence how, where, and which microbes appear on the landscape and, in turn, how these microbes influence further weathering and water flow (Cueva et al. 2019). Only in the last year or two have nonvascular plants (mosses) begun to colonize LEO, setting the stage for study of the evolution of increasingly complex ecosystems. We will experimentally add vascular plants–the last stage in Figure V-1–within the next two years.

Grand Challenges

LEO is currently being used to address the three grand challenges involved in understanding the processes of landscape terraformation:

1. *How can we predict the expansion of increasingly **complex life forms** across landscapes as they interact to transform bare rock, CO_2, and water into multi-function living ecosystems**?***

   Landscape evolution involves the interactions and feedbacks between physical phenomena and biological succession -- from microbial colonization (including cyanobacterial crusts and algae), to the establishment of non-vascular biota (e.g., mosses), to the rise of vascular plants with roots and sophisticated hydraulic architectures (Fig. V-1). As this biological complexity increases, it drives increasing complexity of the physical environment through an accelerating cascade of strengthening interactions among all these components. Real world observations tell us that unexpected phenomena emerge as systems become more complex; developing mathematical models that will predict such phenomena is essential if we are to manage the processes of restoring or creating new landscapes.

2. *How can we predict the **scaling** of phenomena, i.e., how are processes at small spatial scales aggregated to the larger scales of entire landscapes?*

   Phenomena such as water and nutrient flow and vegetation patterns on a landscape ultimately arise from processes occurring at much smaller spatial scales such as geochemical transformations in soil micropores or bacterial consumption of carbon-rich exudates from a plant root. But the outcome of these micro-scale processes cannot simply be summed to understand phenomena at landscape scales because of complex covariances and feedbacks among these processes. Understanding these scaling relationships is critical for developing predictive models of landscape terraformation.

3. *How can we achieve c**onvergence across disciplines** that have historically focused on independent evaluation of different aspects of landscape terraformation separately?*

   Landscapes are influenced by *interacting* processes that are studied by different disciplines, including interactions among organisms, fluid flows of water and CO_2, and other geochemical reactions. These processes *covary* across a landscape, and among landscapes. Such covariances are driven by *feedbacks*: soils foster plants, and plants build soils; fluid flows supply water and CO_2 and nutrients to plants, and plants alter those flows by moving water from soil to atmosphere and CO_2 from atmosphere to soil; geochemical reactions are driven by fluid flow, and geochemical reactions transform the soil properties that govern the flow of fluids.

> We hypothesize that growing 'convergence research' of landscape terraformation (or any other interdisciplinary science) is not only, or even primarily, a technical goal met by teaching a practitioner of one discipline the technical knowledge of another; it is also the adaptive challenge of *understanding and bridging* the cultural differences (the distinct habits, languages, and perspectives through which different disciplines see the world) that separate and define existing traditional disciplines. This is ultimately a training and education challenge, with welcome benefits to broadening participation, that requires **social science insights** into how cultures of natural science work and may be reconstructed into cultures of convergent science practice.

All of these challenges for LEO fit under B2-wide Grand Challenge 2: *improving and better constraining Earth system models, including assessing assumptions about processes, functional forms, and parameters.*

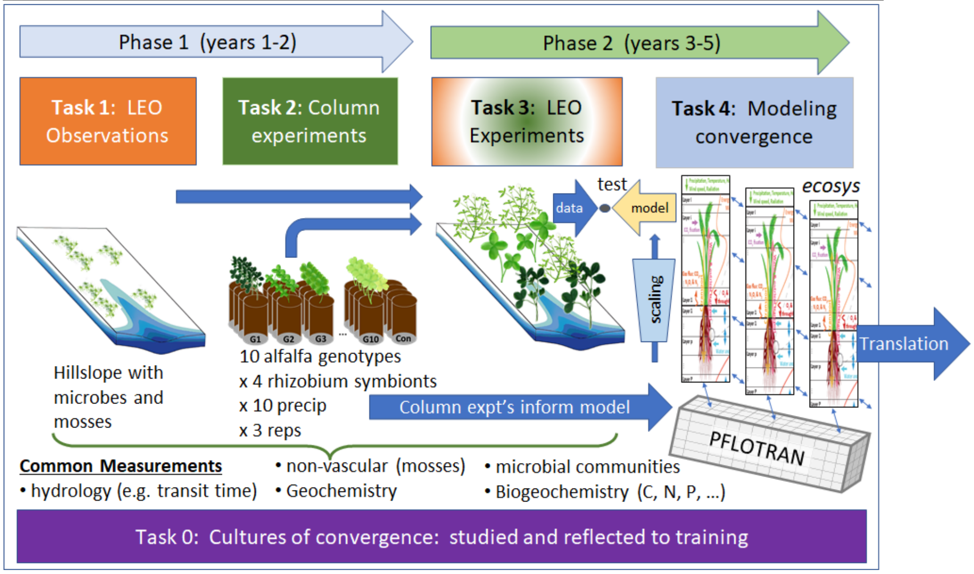
Why B2 is a good place to address these challenges

Addressing these grand challenges for advancing a science of landscape terraformation requires the capacity for study at the scale of individual soil cores or plants, whose implications for larger scales can also be simultaneously measured and tested at these larger scales, under experimental conditions that are complex enough to be realistic, but simple enough so that the mechanisms can be directly manipulated and rigorously probed. The unique strength of the Landscape Evolution Observatory (LEO) is that it provides just such an experimental tool.

Research Goals

With the leadership of LEO Research Director Scott Saleska, the LEO team recently (2021) received a major grant from NSF to address these grand challenges. The near term (5-year) research goals of this project are divided into two phases (Figure V-2). In Phase 1, we will first document the evolving effect of non-vascular spontaneous colonization by mosses and biotic crusts on hydrology and geochemistry in LEO (Task 1 in Figure V.2). We will also characterize the performance of different alfalfa-rhizobium symbiont variants, grown in separate soil columns (with hydrology and geochemistry) (Task 2) -- to provide a basis to predict community assembly of alfalfa variants when grown together across the hillslope in Phase 2. The alfalfa variants represent a range of well-characterized genotypes with different root traits that we expect to have strong impacts on the soil processes essential for landscape evolution. Thus, they represent an ideal model system for studying both ecological and evolutionary processes in a landscape context. In Phase 2, Task 3 seeds LEO hillslopes with a full mix of alfalfa variants, observing relative success in successive experiments. Task 4 is modeling, depicted on a hillslope, with PFLOTRAN (a high-resolution subsurface model of hydrology and geochemistry) underlying the lower resolution full-ecosystem model (*ecosys*, conceptualized as coupled "grid cells", with 3 shown here, spatially arrayed across the hillslope). *Ecosys* model parameters for different alfalfa variants come via soil column experiments of Task 2, and scaling predictions emerge from full *ecosys* model runs that are then tested by the Task 3 hillslope experiment. Underlying all other tasks is Task 0, which studies "Cultures of convergence" in natural science inquiry via social science methods.

Figure V-2. Research tasks for putting life on LEO over the next 5



Education Activities

Graduate students and postdoctoral trainees are a critical part of the LEO Terraformation research project; currently at least 7 PhD students will be funded through our grants from NSF and other sources for their dissertation research, along with 4 Postdoctoral fellows. All trainees, as well as all project faculty, attend the weekly Landscape Terraformation research seminar. This seminar meets weekly, alternating between project meetings to plan details of the ongoing research across all disciplines involved and journal club-style meetings to learn from each other about the conceptual frameworks and approaches of the different disciplines and help move the group towards convergence among those disciplines. Graduate students can take this seminar for academic credit.

We will use several approaches to integrate undergraduates into LEO research.

- All undergraduates, regardless of the mode of affiliation as described below, will be invited and strongly encouraged to attend the Landscape Terraformation seminar and, if possible, take it for credit. Although some of the material and discussion will undoubtedly require more background than most of the undergraduates will have for full comprehension; attending such research meetings is an important part of adjusting to the culture of science, especially in the transdisciplinary context so critical to modern science.
- Undergraduates will be hired to assist with all aspects of the research, from collecting samples from the experimental landscapes to processing samples in the laboratory to helping parameterize and code the models; these students will be expected to participate in both regular laboratory meetings with their research mentor and attend at least some of the Landscape Terraformation Seminar.
- We will establish a Vertically Integrated Project (VIP) team (Chapter 8E) to connect with established UA infrastructure for this kind of long-term, interdisciplinary scholarship. The VIP students will both work within the more task-oriented disciplinary context of a particular research mentor but also be fully involved in the group discussions and work towards convergence across disciplines. We will also investigate connecting to existing VIPs at UArizona, or even at other institutions.

- Students from across the US who are selected for the [Biosphere 2 REU Site](), funded by the National Science Foundation (and hence open only to US citizens) will be offered positions with the LEO Terraformation project for 10 weeks for each of the next 5 summers.
- We are exploring bringing in international teams of students as a complement to the summer REU program, including a group from Mexico City (funded by UNAM and philanthropy) and a group from France as part of the B2 partnership with CNRS.

Justice, equity, diversity, and inclusion

We pay strong attention to recruiting diverse cohorts of students, at all levels, and follow best practices to create an inclusive environment for participants from undergraduates to faculty. The leadership team of LEO is quite diverse and ensures that speakers, leaders of subprojects, etc. are equally diverse, including in stage of career. Respectful listening and attribution of credit for ideas and efforts is a key value in our meetings and activities.

Current Funding

a. NSF Growing Convergence Research: PI: S. Saleska, "Growing a new science of landscape terraformation: The convergence of rock, fluids, and life to form complex ecosystems across scales**". $3.5M at UA & LBNL** (+ 100K at Cal Lutheran) for 5 years (2021-2026)
b. UA-CNRS: (2 students -- one at UA LEO, one in France -- for 3 years)
c. NSF Hydrology: PI: P. Troch, "Hydrologic closure relationships at different levels of hillslope model complexity", **$508K** (2021-2024)
d. NSF Earth Sciences: Druhan, Chorover, Troch, and Derry; Collaborative Research: Concentration - Ratio - Discharge (C-R-Q) relationships of transient water-age distributions (273K to UI, $**466K to UA**, 273K to Cornell) (2022-2024)
e. UA RII Equipment Enhancement Fund (internal): Saleska, Pauli, Arnold, Tuller, Dontsova, A "Local" Remote Sensing capability to enhance the science of Landscape Terraformation at UArizona's Landscape Evolution Observatory (LEO) at Biosphere 2. **$137K** for equipment purchases. (2022)
f. UA RII Production Grant (internal): Bonine, Bugaj, et al., Science in Motion: Scaling Broader Impacts of UArizona Resilience Science Through Student-Engaged Filmmaking, Animation, Data Visualization, and Motion Arts-Science Pedagogy. **$15K** (2022)

LEO as a research platform

LEO welcomes synergistic collaborations related to Landscape Terraformation, especially those that capitalize on the opportunities of this unique experimental mesocosm. Proposed projects related to the grand challenges are particularly welcomed. For example, Prof Jennifer Druhan from University of Illinois is the Principal Investigator of an NSF-funded collaboration, including Lou Derry from Cornell University, with UA Professors Peter Troch and Jon Chorover, that will test new models of hydrological-geochemical evolution on hillslopes with experiments at LEO. The partnership of Biosphere 2 with the Ecotron of France won a grant from the UA-CNRS partnership which is funding a collaboration to conduct paired experiments in LEO and the "ecocells" of the Ecotron. Multiple additional collaborative research opportunities will be generated once plant experiments begin on LEO, slated for 2023.

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Appendix VI. Ocean (B2O)

Research Director: Diane Thompson, Assistant Professor in the Department of Geosciences, University of Arizona.

Introduction

Coral reefs are one of the most biodiverse and socio-economically important ecosystems on Earth, providing coastal protection, habitat for major global fisheries, and other critical goods and services worth over 3 billion dollars every year in the US alone (Brander et al. 2013). However, they are under immense stress globally due to changing ocean conditions–especially increasing temperatures, ocean acidification, increasing hurricanes intensities, overfishing, and diseases. To date, we have lost nearly 50% of the world's reefs (e.g., Selig et al. 2012, NASEM, 2018), and we risk losing them entirely if we do not act to limit climate change and protect coral reefs. Novel, even radical, solutions for creating resilient reefs are imperative to ensure the future of reef ecosystems, coastlines, and fisheries (among other critical goods and services provided by reefs, as recently revised by the NAS coral crisis committee, NASEM, 2018). Such resilient reefs can recover following stressors and withstand changing ocean conditions, while maintaining their critical structure and function.

The coral reef research community has identified a wide array of potential interventions that can improve reef resilience, but urgently needs a way to test these potential solutions before applying them to natural, vulnerable reefs (NASEM, 2018, Thompson et al., 2020). Like other grand challenges under the NSF Big Idea "Understanding the Rules of Life," the coral reef crisis requires collaboration across research areas and inclusive training of next generation solutions-oriented scientists to understand interactions across reef scales (in space, time, and levels of complexity) and improve predictions for reef diversity and function under future warming and acidification. Using this approach, the Biosphere 2 Ocean research program will provide fundamental knowledge of ecosystem dynamics on restored reefs, and practical, applied solutions for reef managers globally to build resilient coral reefs of the future.

Why B2 is a good place to address these challenges

The Biosphere 2 Ocean (B2O)—a state-of-the-art experimental mesocosm for coral reef research—provides a unique opportunity to bridge the gap between controlled small-scale experiments and large-scale studies in natural systems, integrating across disciplines and spatio-temporal scales (Figure 3.3). The B2O research program brings decades of studies to action, capitalizing on the 2.6-million-liter mesocosm to develop viable solutions for building resilient reefs of the future. These resilient reefs can maintain critical reef structure, function, and diversity in the face of continuing climate change.

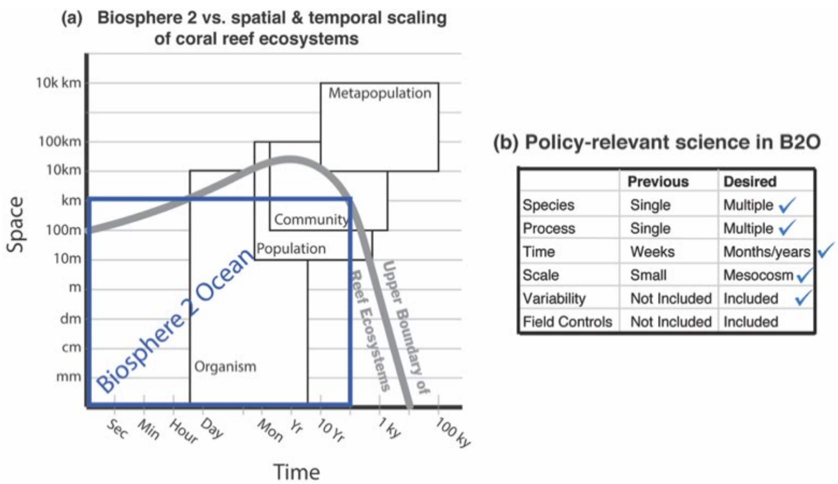

Figure VI-1 (a) Typical spatial and temporal scaling of *coral reef ecosystems* with respect to the B2O experiment (recognizing within ecosystem scaling, e.g., microbial communities, may occur at shorter space / time scales). Scaling from microns to 600 m^2 & mins to decades, the B2O can capture reef processes from the molecular to ecological scale (modified from Hatcher 1997). (b) Recommendation of how to make reef science more policy relevant (relative to existing studies); blue checks indicate those captured by the B2O experiment (modified from Pendleton et al. 2016).

The controlled environment of the B2O is a perfect test bed for novel, even radical, techniques of reef restoration, selective breeding, and assisted evolution that are too difficult or risky to test in the wild. These activities cannot be undertaken on a natural reef, as the risks for the existing vulnerable reef ecosystem are too great. Nor can they be done in small aquaria or meter-scale mesocosms, which lack the requisite scale and complexity. Further, in the B2O, processes can be controlled and measured across spatial scales and specific control components can be engaged or disengaged. This kind of science is required to effectively support decision-making relevant to climate change (Pendleton et al. 2016; see also Figure VI-1).

With a cohort of international collaborators and the unique controlled environment of the Biosphere 2, we can test reef solutions before they are implemented in the natural setting. Further, the algae-dominated reef state of the current B2O–resulting from the gap in administrative oversight between Columbia and University of Arizona ownership– is similar to a degraded reef and presents a unique opportunity to investigate recovery and restoration processes and explore solutions for rebuilding resilient coral reefs. Finally, and critically, the Biosphere 2 experiments are not bound by existing ecological associations or biogeographical constraints among species, allowing us to explore whether combining species differently can enhance resilience.

The scale, control, and accessibility of B2O enable us to tackle big ideas and new frontiers in coral reef science (Sagarin et al. 2016). First, state-of-the-art engineering upgrades will facilitate precise abiotic control and simulations of realistic future environmental conditions (e.g., extreme thermal stress and elevated carbon dioxide). For example, the ability to simulate high background temperature variability (of up to 2°C per day) is essential for stress-hardening and future-resilience experiments: several studies have demonstrated that reefs are less susceptible to extreme events if they are frequently exposed to temperature extremes (e.g., Brown et al. 2002, Thompson and van Woesik 2009, Donner 2011). Further, the quantity and wavelength of light reaching the B2O reef–which is lower and more selective than typically found in nature–can be modified within an array of LED and halide lights. Carbon dioxide levels can be manipulated to simulate current and projected future ocean acidification and its effects on ecosystem-scale calcification. This precise control of the B2 mesocosm will allow us to test—for the first time—the resilience of restored species, genotypes, symbiotic algae, and their associated microbiome in the face of continued warming and acidification. Second, the large experimental reef in the 2.6-million-liter mesocosm (with realistic fringing reef structure—from fore-reef to reef crest to back-reef lagoon) will allow us to capture intrinsic processes and study interactions among species, functional groups, and trophic levels. Further, the biogeochemical succession from a degraded to healthy reef system will provide new insights into recovery and patch dynamics at an unprecedented scale. Finally, this closed system allows us to test the role of microbes in mediating critical processes on resilient reefs (a big open question that we are uniquely poised to address, leveraging advances in genomics and state-of-the-art facilities at UA and our partner organizations; see Thompson et al. 2020). In sum, using this ecosystem approach in a controlled mesocosm, we can simulate realistic stress, variability, and functional interactions as we "engineer" a resilient reef that will be tolerant of current and predicted future ocean conditions.

Finally, in parallel to the engineering of the main B2O mesocosm, we have built experimental flow-thru tanks (raceways) in a newly renovated space. These raceways support satellite experiments, which recirculate with their own local dedicated life support systems. We have worked with Aqualogic (a leading company in ocean raceway tanks) to design a B2O raceway prototype for our experiments; to date we have 2 operational raceway systems funded by private philanthropy, with plans to establish up to 5 identical systems to enable experimental replication. Each system has its own heat exchanger and will ultimately have its own pCO_2 control system (developed by SAB liaison Chris Langdon). In collaboration with our partners at Mote Marine Laboratory and Hawai'i Institute of Marine Biology (HIMB), these raceways will be used to grow corals that are more resistant to warming and ocean acidification, through interventions such as stress hardening, probiotic treatment, phage therapy, and assisted evolution. Critically, these raceway systems can be utilized to achieve replication and address this major limitation of the B2O, particularly when paired with field experiments. For example, a repeated measures experimental design with temporal replication can be used to test the recovery and persistence of thermal tolerance following stress hardening in the experimental raceway systems.

Grand challenges

Numerous "Big Ideas" or questions in coral reef research can be uniquely addressed in the Biosphere 2 Ocean, which tie into the B2-wide grand challenges [indicated by B2 GC in brackets below]:

1. *How do novel interactions among species on pan-global, restored coral reefs dictate ecosystem health, structure, and function in a changing environment? [B2 GC1]*

    Entirely novel ecosystems are developing as species distributions shift under a changing climate. These novel ecosystems create challenges for reef conservation and management, as novel interactions re-define functional roles, ecological niches, and ecosystem services. On the other hand, novel ecosystems also provide new opportunities for coral-reef species and transplanting resilient species may become a key component of global restoration efforts (NASEM, 2018).

2. *Can reef organisms acclimatize and/or adapt rapidly to ocean change? How long does resistance persist, and can it be passed between generations? [B2 GC1]*

   Innovative initiatives have yielded major advances in techniques for reef restoration and increasing resilience through interventions such as stress hardening (via warming and ocean acidification), probiotic treatment, phage therapy, feeding, and assisted evolution (see review by NASEM, 2018). These approaches offer great potential for (re)building resilient reefs that can better withstand warming and acidification. We identify a growing need to test these solutions in controlled environments before they are applied in the wild, to ensure their efficacy and reduce potential impacts (see also NASEM, 2018). In particular, the control of the B2O facilitates research on the resistance and resilience of restored genotypes to future stress, and on the persistence of engineered resistance (i.e., how long do these interventions increase resistance?). Addressing these questions in a controlled fashion will improve the survival of out-planted corals and improve the efficacy of critical, yet costly, restoration efforts worldwide.

3. *How are compounding stressors (e.g., warming, acidification) impacting reef growth (i.e., calcification) at the ecosystem scale? [B2 GC2]*

   Numerous small-scale laboratory experiments have identified physiological, developmental, growth, and behavioral impacts of ocean acidification on a diversity of reef organisms (see review by Albright et al. 2016). However, it is extremely difficult to scale these impacts up to the reef level to determine the consequences for coral reef ecosystems as a whole (Gaylord et al. 2015), particularly as the impact of ocean acidification and warming may interact in complex ways across reef communities (e.g., Kroeker et al. 2013). The cumulative impacts of warming, acidification, eutrophication, and local stressors have led many studies to conclude that we may cross a critical tipping point from coral- to fleshy algae-dominated reefs if we do not take rapid action to combat climate change and protect reefs (e.g. Pandolfi et al. 2005, Hoegh-Guldberg et al. 2007, Hoegh-Guldberg et al. 2011, Knowlton et al. 2021). We can use B2O to quantify the impacts of different degrees of temperature and acidification change on calcifying reef organisms, and in turn, their impact on the climate records generated from carbonate skeletons (e.g., corals, coralline algae, bivalves, and foraminifera).

4. *What technologies and cyber infrastructure are required to successfully restore and monitor coral-reef ecosystems and disseminate data? [B2 GC3]*

   Each of these "Big Ideas" will also benefit from the unique opportunity to test technological solutions and methodologies. The scale of the B2O facilitates testing of new sensors, floats, restoration materials, etc. before they are applied in the natural environment.

Research goals

Phase 1: Bioremediation & Reef Restoration

During the bioremediation and restoration phase, we have been closely monitoring all physical, chemical, and biological conditions of the B2O in its current "degraded state" to establish a baseline for the system and determine the timescales across which key parameters change (or cycle) on the reef. The physical conditions (light, temperature, salinity, pH, chlorophyll, blue-green algae, and dissolved oxygen) of the B2O are monitored continuously. Twice weekly, we also collect water and sediment samples from the B2O to measure the key chemical (e.g., nutrients, alkalinity / acid buffering capacity, cations, anions) and microbial (bacterial, viral) constituents of the B2O. In parallel, the macro-biome (e.g., algae, invertebrates, fish) are monitored ~monthly using conventional reef survey techniques and state-of-the-art 3D photo mosaic technology (in collaboration with Stuart Sandin at Scripps Institution of Oceanography). During this phase, we have also remediated the reef substantially – pulling over 10,000 pounds of macroalgae in preparation for coral experiments in Phase 2. We expect to complete the engineering and remediation of the reef and begin Phase 2 in mid-late 2023. Finally, and critically, we are leveraging this sampling routine to expand both our citizen science and undergraduate programs at the Biosphere 2.

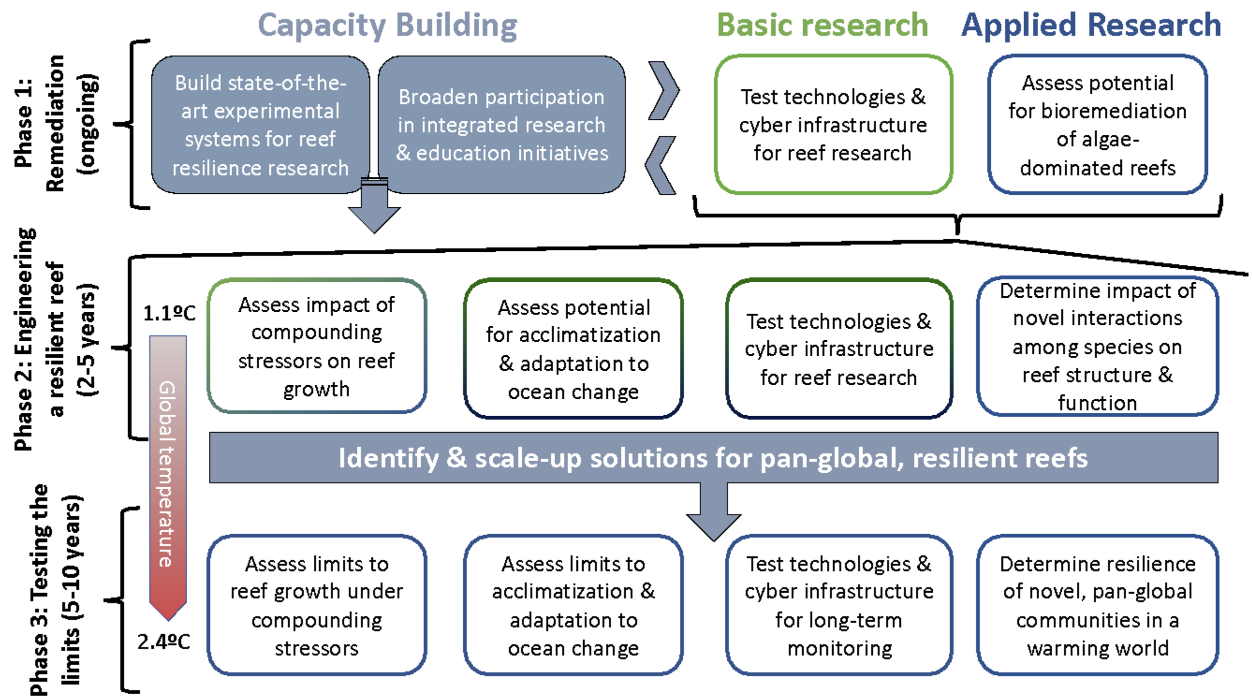

Figure VI-2: Three-phase research plan for the Biosphere 2 Ocean to tackle grand challenges at the interface of basic and applied research, aiming to identify & scale-up solutions for pan-global, resilient reefs.

Phase 2: Bold experiments–engineering a resilient reef

During phase 2, we will test recent advances in materials and techniques for coral restoration. Capitalizing on the range of controlled environments in the B2O and adjacent experimental raceways, we will also conduct experiments to explore novel ways to increase corals' resilience to stress (e.g. through selective breeding and/or by manipulating depth, feeding, symbionts, or stress exposure). Some examples of projects include:

1. *<u>Tropicalization of temperate reefs [GC1]</u>:* The B2O provides a unique opportunity to determine the impact of novel species interactions from climate-change induced range expansions on socio-ecological function (e.g., coastal protection, habitat complexity, etc.). First, we can bring together species from across regions with minimal cost and risk compared to such efforts on natural reefs (NASEM,

2018). Second, the unparalleled scale of the B2O system is crucial for replicating inter-species interactions needed to properly quantify these impacts on an ecosystem scale.

2. *Novel host-symbiont interactions [GC1]:* In building a 'pan-global' reef assemblage in the B2O, we also have a unique opportunity to test the stability of the symbiont community (dinoflagellates within the family Symbiodiniaceae, LaJeunesse et al. 2018, Quigley et al. 2018) within coral hosts when new species converge, as well as assess the role of the microbiome in the specificity and flexibility of the symbiosis. In future work, the B2O may also test more radical interventions, such as genetically engineered host-symbiont combinations (one of the interventions reviewed by NASEM, 2018).
3. *Acclimatization and adaptation [GC2]:* Leveraging the coral raceways to create a factorial experimental design, a novel assemblage of corals (across ocean basins, life history strategies & presumed genotypic resistance to stress) will be subjected to a series of interventions (including stress hardening, probiotic treatments, and/or feeding) to increase resistance to warming and acidification. These "hardened" corals will be out-planted on the B2O reef in phases (under "modern" stable conditions and under acute stress) to study the acclimatization response and its persistence.
4. *Reef calcification under a changing climate [GC3]:* This project will leverage the unique mesocosm offered by the B2O to address the impacts of temperature and acidification on calcifying reef organisms, and in turn, their impact on the climate records generated from carbonate skeletons (e.g., corals, coralline algae, bivalves, and foraminifera). The B2O also provides a unique opportunity to test Coastal Enhanced Weathering and related solutions to accelerate Earth's natural long-term carbon sequestration process.

Phase 3: Testing the limits

In the final phase of this five-year plan, this resilient reef will be exposed to environmental conditions of future reefs (i.e., high temperature, low pH, frequent extreme events) to examine the adaptive potential of coral reef ecosystems to projected climate change.

Education activities

We have created additional interactive, hands-on learning experiences for marine science courses and community outreach, leveraging the unique opportunities afforded by the B2O mesocosm. First, we have developed virtual reality experiences, which bring the wonder of the Biosphere 2 Ocean and our innovative research projects to thousands of people each year at exhibitions and conferences. Second, when COVID-19 forced the cancellation of the formative field trip for Ocean Sciences (412B) students, instructor Diane Thompson created a virtual field trip at the Biosphere 2. In the virtual field trip, she demonstrated many of the oceanographic sampling methods that they would have observed on the trip. For example, she collected a zooplankton tow and viewed ciliates, hermit crab larvae, copepods, and amphipods under the microscope. Leveraging Martin Pepper's videography expertise and equipment, they even gave students a "fisheye" view of the zooplankton net as they collected the plankton sample, and the van Dorn sampler as they collected water from the subsurface. Finally, Professor Thompson also introduced the students to the innovative research on coral reef resilience at the Biosphere 2.

During Spring 2019, Kevin Bonine and Diane Thompson also developed content for a new connected series of undergraduate research and learning experiences centered on ocean science, anchored at Biosphere 2 (B2). The course "Reef systems under threat: Novel solutions-based ocean science at Biosphere 2 & Mote Marine Laboratory," will be a three-week, three-part intensive field course for 15 students (6 UA credits; summer session). These immersive student experiences will link the challenges facing marine coral ecosystems to potential solutions and mitigation strategies. By partnering with national and international colleagues, meeting with local stakeholders, and visiting coral reefs in crisis, we will also provide real-world context for cutting-edge science and personalize the need for bold solutions. This novel and ambitious undergraduate research course experience will offer an in-depth understanding of ocean science and conservation, and the hands-on methods required for both, all at ecosystem scale and in an appropriate socio-cultural context. Although our Keck Undergraduate Education Program proposal to support students in this course was not funded, we will continue to seek funding opportunities to offer this course without financial barriers to inclusion.

Finally, the Biosphere 2 Ocean hosts a vibrant group of undergraduate interns and summer REU students, most of whom complete independent research projects under the direction of Dr. Diane Thompson. Starting in the Fall 2021, Drs. Hackett (Ecology and Evolutionary Biology), Thompson (Geoscience), and Miller (Math) scaled up this program through a new "Vertically Integrated Project" (VIP) focused on coral reef resilience (https://uavip.arizona.edu/teams/environment-and-resilience-teams/coral-reef-resilience-biosphere-2-science-scale).

Justice, equity, diversity, and inclusion

We work closely with the Honors College, ASEMS program, and individual departments to broaden participation in the Biosphere Ocean education and research programs. Nearly 100% of the interns in the program have been from underrepresented groups in oceanography (including women, LGBTQ+, minority, and first-generation students). We strive to increase the number of underrepresented minorities participating in these programs and have applied for a number of grants (see below) to reduce barriers to participation in these activities. We will continue working with our partners to achieve these goals over the coming years.

Current Funding

a. Loan from UA Foundation preceding sale of property gift of Haury Foundation - $500K.
b. Remainder of proceeds from sale of property – up to $2M.
c. Philanthropy - $122,604
d. NSF Division of Ocean Sciences; PI Diane Thompson; "CAREER: Climate-change vulnerability in the Marshall Islands: learning from the past & inspiring a new future." (Total award: $1,015,000) This award builds new partnerships with the Biosphere 2 (B2), Tucson Unified School District (TUSD), and the Marshall Islands Marine Resource Authority (MIMRA). Through progressive and cooperative solutions-oriented learning activities, this program will bring together Arizona &

Marshallese communities to develop and evaluate new K-12 educational modules, train a diverse group of next generation marine scientists, and share powerful Marshallese stories to promote urgency for solutions.

System as research platform

The Biosphere 2 Ocean welcomes synergistic collaborations related to coral reef resilience and ocean solutions that capitalize on the unique opportunities of this controlled mesocosm. Proposed projects related to the grand challenges are particularly welcomed, though there are many other complementary projects that may leverage this system alongside the broader aims of the B2O research outlined above. For example, PIs Winslow Burleson and Michael Lombardi are leveraging the scale of the B2O in the design and development phase of their "Ocean Space Habitat SM," alongside active *Phase 1* research on the reef restoration and biogeochemical cycling. Future research (*Phase 2* & *Phase 3*) would particularly benefit from additional expertise in macroalgae, Symbiodiniaceae, and herbivore dynamics, and application of genomic and epigenetic tools.

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Appendix VII. Tropical Rain Forest (TRF)

Interim Research Director: Joost van Haren, Assistant Research Professor, Environmental Science, W. A. Franke Honors College at the University of Arizona.

Introduction

A full strategic research plan for the TRF is on hold until a permanent Research Director is appointed. Ideally, a new faculty member would be recruited specifically for this role in partnership with a UA academic department; such a position does not currently exist and would require substantial startup research costs from B2. Alternatively, an existing UA faculty member could fill this role but even then, funding is needed to support at a minimum a laboratory manager or postdoctoral fellow to support work in B2. In the interim, we are grateful to Dr. Joost van Haren for his leadership.

Despite the lack of a permanent director, substantial activity in the TRF is occurring, both to improve infrastructure and in research. The ongoing research addresses the first three of the B2-wide Grand Challenge questions, i.e., response to global environmental change, constraining Earth system models, and improving technology for environmental research and monitoring.

Specific ongoing activities include:

- Understory replanting to increase species replication and capabilities for species-level studies of climate change responses and fill in the depauperate mid-canopy component of the rain forest.
- Vegetation growth assessment and monitoring of carbon cycling to continue to generate a solid baseline dataset that supports future experiments.
- Environmental instrumentation (tower sensors) and data collection overhaul. We are planning to recalibrate all the instrumentation in the rainforest to start in April and to migrate all the data collection to the National Instruments (NI) systems also used in the LEO space. As part of that process, we will also install sensor cable boxes at each tower height to allow for easier removal of the sensors from the profiles.
- Measurement of methane emissions from trees in flooded and upland forest ecosystems. One of the biggest challenges in measuring this important greenhouse gas is how to measure concentrations at local interfaces (stem/soil/water) in a seasonally flooded forest. To solve this problem, we enlisted a group of five engineering undergraduates to work on this problem as their capstone project during the winter term 2022. The system will be installed in March 2022 in an area that can be flooded and drained with multiple cycles within a single month. Once tested and refined, the system template will then be used to manufacture similar systems for studies in Brazil, as part of a DOE grant to Scott Saleska, Laura Meredith, and Joost van Haren with other collaborators from both US and Brazil.
- Water balance in tropical forest trees. Hannah Johnson's Honors Thesis is comparing variability in water content, sap flux and plant growth (point dendrometer) over a range of light and temperature values to understand the role of leaf and wood traits in controlling response to the environment.

- Coffee plant response to light and temperature. As part of her Honors thesis, Jeri Wilcox has identified important health traits of coffee plants and then measured those across the rainforest to assess the plant health in relation to growing temperature and light status.
- Ozone measurements inside Biosphere 2. This will provide supplemental data to address concerns from reviewers regarding a paper submitted to Nature on production of chiral mono-terpene compounds during the WALD campaign.

Education

As noted above, many of the projects in the TRF involve undergraduate Honors Theses and engineering capstone projects. In 2021, the TRF started Vertically Integrated Project with a team of 3 undergraduate students; this will grow in subsequent years. The presence of coffee and fruit trees in the TRF also presents numerous opportunities for community partnerships. For example, preliminary work for a study on the effect of growing conditions on coffee flavor is being conducted with Burc Maruflu, coffee sommelier at Savaya Coffee. Discussions are ongoing with Tucson Community Supported Agriculture (CSA) group to generate a cohort of volunteers to help harvest fruit crops to share with the Tucson CSA community.

Justice, equity, diversity, and inclusion

All tropical forests are outside the first world boundaries and have been devastated by imperialism. Global tropical rainforests are some of the most diverse landscapes on Earth and as such rainforest research requires a diverse workforce. To foster input from diverse backgrounds the rainforest replanting board includes researchers from Brazil, Colombia, Mexico and Puerto Rico (two men and two women). REU and Honors Intern students have included many students from underrepresented groups and minorities. We will work with the UA HSI office (using Handshake as part of the Faculty Challenge grant, see below) to hire students from diverse backgrounds. Since science sets out to better understand the world around us, diversity of background and thought are a prerequisite to achieve that goal.

Current Funding

a) UA AIRES Resilience grant ($99,790) to Joost van Haren and co-PIs to research tropical forest and globally important crop (coffee and chocolate) resilience to climate change in the hottest rainforest on Earth and Biosphere 2.
b) UA Faculty Challenge grant ($7,500) to Joost van Haren for enhancing undergraduate participation in the Biosphere 2 rainforest research.
c) Department of Energy; Terrestrial Ecosystem Science grant (~$1M; PI Saleska, Co-Pis van Haren and Meredith; Trees as conduits for connecting belowground microbial processes to aboveground CH_4 emissions at the Terrestrial-Aquatic Interface.) that will fund testing of the continuous, discrete flux measurements on tree stem and soil/water interfaces in flooded forests.
d) UA Engineering Capstone project support; ($4,000) to fund the initial development of the flooding adapted automated flux systems with a group of five engineering students.

Appendix VIII. Agrivoltaics: Food, Energy, and Water Resilience Solutions (FEWRS)

Research Director: Greg Barron-Gafford, Professor, School of Geography, Development and Environment, University of Arizona.

Introduction

Growing climate pressures are exacerbating vulnerabilities and injustices across our food, energy, and water systems and are at odds with our sustainable development goals of increasing resilience, expanding food and renewable energy systems, and bolstering human well-being. Many regions are facing increasing water scarcity that places conventional agriculture and farmland at risk. Projected climate change has been estimated to reduce food production by between 8-45% globally, and Arizona will lose nearly 1/3 of irrigated agriculture because of water restrictions. Transitions to renewable energy will reduce the severity of projected climatic change, but we are finding that the impacts can be more immediate if deployed creatively. By colocating agriculture and photovoltaics (PV; renewable energy from solar panels) within the approach we call 'agrivoltaics', we are finding simultaneous synergies including: (i) the shade from PV panels reduces plant stress, (ii) PV renewable energy efficiency can be increased, and (iii) reduced evaporation - such that water resource requirements for food production are reduced. Below, we detail a plan for building beyond our ground-breaking research and educational work at Biosphere 2 to (i) create national and international networks of agrivoltaic research systems, (ii) determine the physical science and production impacts of agrivoltaics across wide climatic regions, (iii) adopt and optimize our "B2 model" of agrivoltaics to include water purification and treatment systems, and (iv) ultimately link 'basic' and 'applied' research, socio-political science, and experiential education to truly effect change and build food, energy, and water resilience (Figure 3.5).

Grand challenges

Globally, communities increasingly seek resilience strategies to manage expanding populations and demands for energy and food, especially in light of a changing climate that threatens our reliance on dwindling water resources. Today, the western US provides a substantial proportion of food production for the US, including vegetables and forage crops. Water shortages in the region increasingly lead to crop yield declines due to irrigation interruptions. At the same time, energy production from PV has increased exponentially, signifying an increase in its cost-effectiveness and grid suitability. By 2030, solar installation in the US could reach 330 GW, which would require approximately 8,000 km2 of land. With two-thirds expected to be ground-mounted solar, land-use conflicts will arise. Unfortunately, PV-based renewable energy production is vulnerable to the same warming trends that threaten food systems, in that average panel efficiencies decrease by ~0.6% per ^{o}C. Additionally, siting restrictions of PV installations due to land availability, technical, and socio-political policies have become a major challenge for wide-scale deployment. An either-or discourse between food and PV energy production unnecessarily compounds issues related to allocating space, water, and capital for development of resilience strategies. Bridging the knowledge gap between the theoretical potential of agrivoltaics and the slow pace of adoption requires a systems perspective with robust biophysical modeling of crop types and PV array designs that yields high prediction capacity combined with a rigorous socio-political assessment of barriers and how to overcome them. A major science challenge is merging research from biophysical and societal domains into a framework that leads to pathways for deployment of agriculture-compatible solar technologies.

Research in the Food, Energy, and Water Resilience Solutions (FEWRS) system focuses on the following Grand Challenge questions (linkages to B2-wide Grand Challenges [B2 GC] are in brackets):

1. How can the co-location of food and renewable energy through photovoltaics (agrivoltaics) create resilient solutions across the food, water, and energy nexus of systems across various climatic zones? [B2 GC 1]
2. How do novel agrivoltaic systems dictate ecosystem health, structure, and function under a changing climate? [B2 GC 1]
3. How can we most efficiently merge lessons from our spatially diffuse field trials into an integrated and scalable model of this novel socio-environmental system? [B2 GC 2]
4. How might plant breeding (to create more shade-tolerant species) or engineering (to link with desalination or water purification) enable wider adoption of agrivoltaics as a resilient FEW system? [B2 GC 3]
5. How can agrivoltaic systems provide resilience against compounding (global change, land use demands, etc.) stressors? [B2 GC 3]

Why B2 is a good place to address these challenges

Our FEWRS Resilience Solutions System sits outside the core controlled-environment facility of Biosphere 2 but resides deep within the core mission of the facility and campus. Beyond a clear connection between our Grand Challenge questions, our system links the issues that our visitors hear about to resilient solutions that they can see and support. By locating our research and education at Biosphere 2, industry partners, school groups, UA students, and policy makers see the bridge between science and experiential learning, and the solutions in practice.

Research goals

Figure 3.5 describes our research goals and plans for the next five years. Addressing our FEWRS 1 question of “How can the co-location of food and renewable energy production through photovoltaics (agrivoltaics) create resilient solutions across the food, water, and energy nexus of systems across various climatic zones?” requires measurements across climatic spaces and through time. Despite initiating our agrivoltaics research 10 years ago and establishing Biosphere 2 as a leader in this field, we are still at a stage of determining which crops across, spring, summer, and fall/winter seasons are appropriate for an agrivoltaics approach.

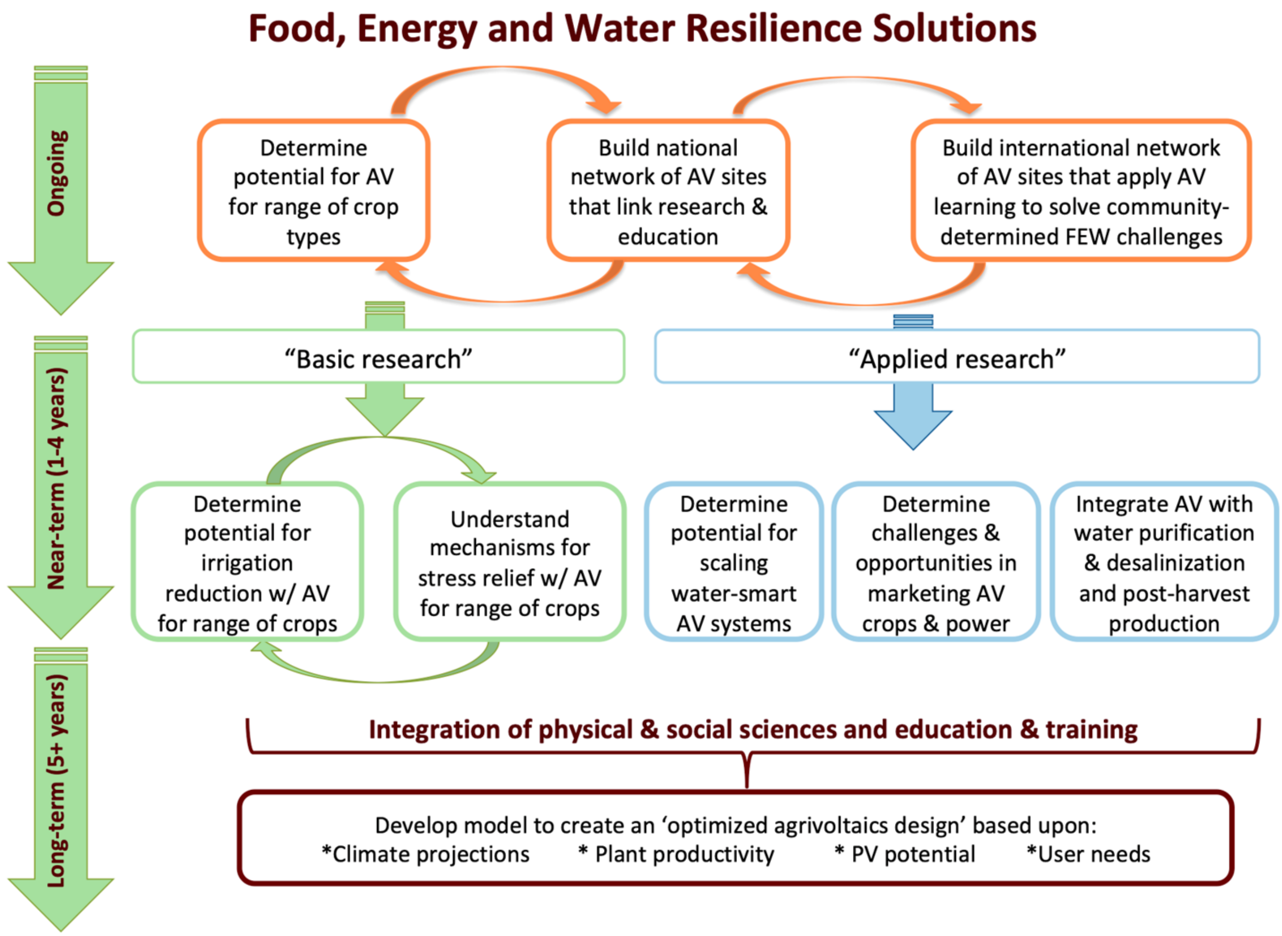

Figure VIII-1. Research goals and plans for the next five years for the Food, Energy, and Water Resilience Solutions research system.

With previous and current support, we have created best practices for ecosystem and vegetative monitoring and deployed the necessary sensor arrays. We are actively working on building out a national (Colorado, Oregon, Texas, Illinois, etc.) and international (Kenya, Israel, Tanzania) network modeled after and improving upon our 'Biosphere 2 Agrivoltaics Learning Lab' system of research and experiential learning across K-12, college-aged, and communities through citizen science. These research areas are iterative and feed upon one another because each new site represents a new climatic and / or socio-political system in which to explore the agricultural and renewable energy production potential and also potential roadblock or incentives for deployment.

Funding from the UA Arizona Institutes for Resilience, NSF (Grant A), and the DOE National Renewable Energy Lab (NREL) have supported our creation of an AZ and national network, and support from the Jewish National Fund (Grant F) and partnerships with the University of Sheffield have supported the creation on an international network in Kenya, Israel, Tanzania. Pending support from the DOE (Grant G) will replicate our efforts in Texas and USDA support (Grant H) will create a large installation in Illinois and Northern Colorado and may support installations at UA Agricultural Extension Centers' UA Campus Farm.

Near-term (1-4 years) Research Plan

Having begun a burgeoning network of research sites and partners, we are focused on a suite of basic research (more attractive to federal funders) and applied research (often more attractive to foundations and industry support). Answering our FEWRS 2 question of "How do novel agrivoltaic systems dictate ecosystem health, structure, and function under a changing climate?" requires a mechanistic understanding of the drivers of the patterns we are finding. Across our sites, which represent different climate zones, we will determine the primary mechanisms that allow an agrivoltaics approach to relieve plants of their climatic stressors (typically associated with temperature, soil moisture, atmospheric drought, and/or light stress) for different crop types. Because of projections of prolonged drought and the pending water restrictions coming to AZ, we are replicating these experiments under typical and significantly reduced irrigation rates. We will repeat measurements multiple years to capture interannual variability in weather.

Answering our FEWRS 3 question of "How can we most efficiently merge lessons from our spatially diffuse field trials into an integrated and scalable model of this novel socio-environmental system?" requires (i) a 'systems' approach that integrates across interested industries and research disciplines and (ii) finding proactive industry partners willing to contribute to upscaling research. For part i, we have begun integrating plant productivity and transpiration, solar capture and light diffusion models into a singular novel framework. None of these modeling systems were designed to be linked to the other, and our early efforts have revolved around linking inputs and outputs among the models so that the interdependence inherent in agrivoltaics can be represented numerically. However, this is a long and iterative process, and creating a working model is a longer-term goal. Still, we anticipate early model iterations will tell us about basic agrivoltaic functions across different climatic spaces, and we can use these outputs to drive our response to our FEWRS 4 question of "How might plant breeding (to create more shade-tolerant species) or engineering (to link with desalination or water purification) enable wider adoption of agrivoltaics as a resilient food, energy, and water system?" As we better understand crop and PV panel function across climatic zones, we will explore how benefits of agrivoltaics (i) scale up in size across larger farms or PV installations, (ii) can be merged with efforts to utilize the power generated for water purification or desalinization or (iii) linked with plant genomics efforts to create lines of crops better suited to reduced light environments characteristic of agrivoltaic systems. Research with the Dead Sea & Arava Science Center (Grant F) plans to make these connections around water purification and treatment in Israel, and a recently awarded NSF Alliance award for working with Native American Communities (Grant B) will enable this work across Arizona and the western US.

Longer-term (4-6 years) Research Plan

Our ultimate goal is to link 'basic' and 'applied' research, socio-political science, and experiential education to truly affect change and build food, energy, and water resilience. Answering our FEWRS 5 question of "How can agrivoltaic systems provide resilience against compounding (global change, land use demands, etc.) stressors?" requires an integration of all of the learning laid out above into blueprints for action. We will use recent grants to build out agrivoltaic research and learning among Native Nations communities (Grant B), teachers (Grant C) and policy makers (Grant D) to broaden the reach of our work. Further, we are working with DOE's NREL to build a numerical model that can allow us to optimize solar sharing among food and energy production and match land use needs and desires of the local communities.

Education activities

Our educational activities are embedded within our research and overall mission. We link research across K-12 grade levels with our agrivoltaics projects through direct engagement at local schools and through teacher research experiences and curriculum co-development (Research Experiences for Teachers; Grant C). Each of the past 8 summers, we have supported engaged learning through the B2 Research Experiences for Undergraduates programs, and we regularly support 1-2 undergraduate research thesis projects on agrivoltaics projects. Most recently, we began the Agrivoltaics: Food, Energy, and Water Solutions Vertically Integrated Projects (VIP) Program with the Honors College at UA, and we are supporting experiential learning of two students.

Justice, equity, diversity, and inclusion

Our efforts to promote justice, equity, diversity, and inclusion are embedded within our research and educational activities. We regularly intentionally recruit from groups underrepresented across STEM. Most recently, we partnered with Diné Research and Extension leader Karletta Chief to secure NSF funding through their Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science (INCLUDES) program to create the Native FEWS Alliance (Grant B). This Alliance is focused on innovative research and community partnerships linking two interconnected challenges: a crisis in access to food, energy, and water in Indigenous communities; and limited educational and career pathways available to Indigenous populations to address these needs.

Current Funding

1. NSF: Solar Sharing: Assessing the potential for co-locating agriculture and renewable energy production in drylands (Barron-Gafford Sole PI). $299,918.
2. NSF: Collaborative Research: NSF INCLUDES Alliance: Broadening Career Pathways in Food, Energy, and Water Systems with and within Native American Communities (Native FEWS Alliance) (Barron-Gafford CoPI); $2,928,085. PI: Karletta Chief.
3. NSF: RET Site: Collaborative Research: Sonoran Photovoltaics Laboratory: Energizing the STEM Pipeline through Citizen Science (Barron-Gafford CoPI); $207,000. PI: Kelly Potter; RET = Research Experiences for Teachers (like the REU is for undergrads).
4. NSF: Planning Grant: Engineering Research Center for Beneficial Energy System Transformations for Climate Change, Adaptation, and Societal Equity (BEST-CCASE) (Barron-Gafford CoPI); $99,982; PI: Christiana Honsberg from ASU
5. NextEra Energy: PV solar panels required to cover ~1.5 acres of land, with the goal of creating a larger-scale, industry-sponsored agrivoltaics system (~$500,000).
6. JNF: UofA-Arava Joint Institute for agrivoltaics as a food, energy, and water resilience solution. (Barron-Gafford CoPI, with Joaquin Ruiz); $43,200 – but Joaquin is working on getting more!

7. DOE: Innovative Site Preparation and Impact Reductions on the Environment (InSPIRE 3.0). (Barron-Gafford Sole PI). $270,000.
8. USDA: Designing Agrivoltaics For Sustainably Intensifying Food And Energy Production. (Barron-Gafford Lead PI; CoPI :Moses Thompson). $1,724,366.

System as research platform

We see our Agrivoltaics Learning Laboratories as an open ‘collaboratory’ for the advancement of use-inspired research. In fact, our Biosphere 2 agrivoltaics research site is used as a ‘dryland’ endpoint for three cross-country experiments (Grants A, G, and H) and an international partnership (Grant F) to understand food, energy, and water trade-offs. Because the Biosphere 2 site is part of the University of Arizona and receives over 100,000 visitors a year, it is an ideal location for trials in research and education. We see the existing Biosphere 2 Agrivoltaics Learning Laboratory and the upcoming dryland crop Agrivoltaics Learning Laboratory at Biosphere 2 as exciting testing grounds for new technologies, metrics, and experiments.

Appendix IX. Space Analog for Mars (SAM)

Research Director: Kai Staats, Research Scientist, UA Biosphere 2

Introduction

We are on the verge of becoming an interplanetary species. Fifty years after the Apollo era, with the Space Shuttle retired and NASA counting the years until the International Space Station is no longer maintained, an entirely new, bold wave of human space exploration is building. Now both private and public endeavors are working together, across the United States and around the world to motivate the dream of three generations into reality – our return to the Moon and establishing a human presence on Mars.

What makes this new space arena unique is that no longer is an astronaut defined by years of service in the military, and NASA is not the only game in town. While the technology to take humans to space has advanced with lower cost rockets, improved telecommunications and flight automation, many facets and functions of deep space travel remain unexplored–knowledge gaps that need to be filled, as noted by NASA's Human Research Program. Professional and analog astronauts can contribute to the next phase of this human exploration journey.

For more than five decades experiments in closed ecosystems have been conducted to various degrees and scales by governments, universities, and private organizations. The intent—to learn the minimum complexity required to sustain human life for long-duration, off-world missions. Each of these studies, whether mostly biological as with the Biosphere 2 or mostly mechanical as with the International Space Station (ISS), has been met with the challenge of real-world complexity.

A hybrid of biological and mechanical approaches must be integrated if we are to become an interplanetary species. Mechanical carbon dioxide scrubbers, oxygen concentrators, water purifiers, and waste management systems are an effective, proven means for keeping humans alive, as implemented on-board military submarines and human space flight systems. But, every submarine can surface in a matter of minutes and ISS astronauts can return to Earth in hours. Once we are living on the Moon, Mars, or a distant moon of Jupiter we will no longer be able to conduct immediate rescue. Therefore, sustainable, mostly self-contained ecosystems must be realized to a certain degree of perfection, with mechanical life support systems as backup only. We are four or five years from again walking on the Moon, a decade to setting boots on Mars, yet NASA has not conducted a closed ecosystem experiment since the mid 1990s.

The sum of all human-in-the-loop, closed Bioregenerative Life Support System (BLSS) experiments is less than a dozen, including those before the Apollo era. According to Dr. Donald Henninger, a closed ecosystem expert at NASA JSC, this lack of experience will make it difficult to construct a functioning, long-stay human facility outside of the cislunar neighborhood. With the incredible pace at which both public and private sector organizations are developing modern vehicles and associated technologies to take humans beyond low Earth orbit, it is imperative that both mechanical and bioregenerative systems are studied not every few years but on a continual basis such that new technologies, improved techniques, and a deeper understanding of the complex systems required to sustain human life are incorporated into near-future missions.

A Space Analog for the Moon and Mars (SAM)
SAM is a hi-fidelity Mars habitat analog being constructed at the renowned University of Arizona Biosphere 2. Research teams visiting SAM can perform missions for as brief as 5 days, or as long as several weeks. They choose their level of fidelity, from a quantified pass-through air flow to a full hermetic seal. External communications can be unregulated or can simulate the light travel time from Earth to Mars with up to 20-minute email delays and no direct web functions.
Built upon the 1987 Test Module, the prototype for the Biosphere 2, SAM integrates a greenhouse (the Test Module), workshop, kitchen, bath, common area and sleeping quarters. A CO2 scrubber provides mechanical life support. A pass-through airlock leads to an adjacent half acre Mars yard where rovers, pressure suits, and tools can be tested over varied terrain, obstacles, and within a synthetic lava tube. A gravity off-set rig will provide the experience of exploring on foot in lower gravitational fields. Living on the Moon, Mars, and in deep space will demand constant improvements in our systems as humans move to new homes among the stars.

These photo essays capture the construction of SAM each week since January 2021.

SIMOC
SIMOC is a Scalable, Interactive Model of an Off-world Community, a research-grade computer model that includes an engaging, educational web interface coupled with Next Generation Science Standards (NGSS) aligned curriculum for grades 5-8 and 9-14.

SIMOC enables citizen scientists to experience the scientific process from hypothesis to experiment to results, and the chance to then go back and try again. A user of SIMOC designs a habitat using the web-based Configuration Wizard, selecting the number of astronauts, duration of mission, food rations, size of crew quarters and greenhouse, food cultivars, mechanical life support, solar panels and batteries. They set the model in motion and see how their astronauts fare.

Are there enough solar panels to provide power? Are there enough plants to remove the carbon dioxide and provide food? Or perhaps, are there enough humans to produce the carbon dioxide for the plants in return?

Supporting human life in a harsh, other-world environment is no easy task. The variables are many. But even a fifth grader can develop an original solution and in real-time learn if it is a success. What's more, students come away with a greater sense of their own human interaction with the ecosystem in which they live now, on planet Earth.

SIMOC is built upon 30 years of authentic NASA data and guidance by the Paragon Space Development Corporation and University of Arizona Controlled Environment Agricultural Center.
Grand Challenges

The SAM development team asks four fundamental questions that help guide our science objectives, all of which are related to B2-wide Grand Challenge question 4: How do we make human-designed ecosystems more resilient to climate change and extreme environments? Their relationship to the UN Sustainable Development Goals (SDGs) are given in brackets.

1. *What is the most efficient, sustainable means to produce nutrition and calories for human consumption?*

   Fundamental to any space craft life support system is the ability to provide adequate food for its human inhabitants. If we cannot bring all of our food with us, for the mass and space is too great, then we must find ways to efficiently, effectively produce high quality foods en route and for the long-duration stay given relatively low power and a very confined space. SAM is working with world-renowned experts in controlled environment agriculture and food cultivar production to define the optimal use of the SAM greenhouse. [SDG goals 3, 11, 12, 13]

2. *How can we reduce total water consumption through integrated systems of reuse and recycling?*

   At SAM all water must be fully recycled. Humidity is condensed and turned back into drinking water. The water used by plants is moved through the system repeatedly, filtered, and reused. Eventually, human urine will also be recycled and maintained within the system as happens on the International Space Station. Over the course of several seasons, the SAM team anticipates developing improvements in these technologies that can be applied to larger scaled deployments. [SDG 6, 11, 12, 13]

3. *How deeply is our existence interwoven with the otherwise invisible microbiome? How are we co-affected over time?*

   The relatively recent scientific study of the microbiome demonstrates how integral the invisible world is to our human existence—from nutrient transport to the roots of plants to the digestive systems and emotions of humans. As with Biosphere 2, the International Space Station, and SAM too, the microbiome plays a significant role in the success and failure of mechanical and biological systems. SAM will employ intensive studies of the microbiome of a hermetically sealed built environment. [SDG 3]

4. *How can we improve our understanding of our personal connection to both local and global systems?*

   As noted in the prior three questions, when we restrict the space in which we live to something significantly smaller, all components and our interactions are amplified. With reduced buffer systems break down faster and therefore must be maintained more regularly. As with the sealed Biosphere 2 experiments, SAM is a mirror for the complex Earth ecosystems in miniature. While preparing our species to become interplanetary, SAM immediately grants us a greater understanding of our role in discovering an improved balance on our first home, planet Earth. [SDG 4, 12]

Why B2 is a good place to address these challenges
SAM is bringing B2 research back to its origins as an experiment to investigate sustaining human life in a sealed environment. It leverages the world class expertise and facilities at the University of Arizona Biosphere 2 and Controlled Environment Agriculture Center (CEAC).

Research Goals
The first goal for SAM is to complete construction, which will happen in four phases.

Phase I – Jan-Jun 2021 – *Complete*. This involved refurbishment of the 1987 prototype Test Module and lung. $52,000 funding was provided by UA Tech Launch Arizona. From January 20 through the close of June 2021 the SAM development team consisting of Kai Staats, Trent Tresch, John Adams, the Biosphere 2 maintenance staff, and a dozen volunteers completed an array of arduous tasks to bring this 34 year-old building back to life as a fully functional, hermetically sealed research facility. The entire process was captured in photo essays posted at https://samb2.space/blog/ and concluded in a four-hour, human-in-the-loop sealed run.

Phase II – Oct 2021 - Apr 2022 – *Complete*. This involved completing the Test Module and lung, adding a workshop and Crew Quarters, and placing a roof over the future 6400 sq-ft indoor Mars yard. $50,000 funding was provided by UA Biosphere 2 – an additional $200,000 is needed. Starting in October 2021, we worked to restore the Test Module with a final coat of paint, new wiring and plumbing, and installation of six hydroponics racks. The 20' and 40' shipping containers are in place with the airlock attached. The 20' provides a workshop and corridor from the Test Module to the 40' Crew Quarters that houses the toilet, kitchen, sleeping lofts and common area for visiting researchers. The original, late '80s greenhouse will be given a new roof to cover the indoor Mars yard, offering basalt and varied terrain for rover, EVA, and tool use research and demonstrations. A dynamic sensor array will be integrated into a local and global SIMOC server for real time data feeds to internal team members, Mission Control, and the SIMOC website hosted by the National Geographic Society.

Phase III – May - Dec 2022 – *Current* Initiated following the Analog Astronaut Conference at Biosphere 2 we have insulated the workshop (20' container), installed an A/C unit in the crew quarters (40' container), installed a new steel roof over the 6400 sq-ft indoor Mars yard (largest of its kind in North America), of 2022 into 2023. Work to complete the workshop and crew quarters begins again in October and includes workbench, 3D printer, electronics workstation and soldering bench, sewing machine, functioning toilet and shower, kitchen, and sleeping pods. With the close of 2022 we will have completed several internal team tests of the pressurized seal and life support system. Installation of the simulated Martian terrain and fabrication of a gravity off-set rig along with a functioning Operations Center and Mission Control are desired.

Phase IV - 2023-24. Develop Mars carts and mobile inflatables; welcome aerospace partners; continue innovation with Crew Quarters, Mars yard, Neutral Buoyancy Lab, and Mission Control.

Once Phase III is complete, research can begin built upon but not limited to five cornerstone science endeavors:

1. The transition from physicochemical (mechanical) to bioregenerative (plant-based) environmental control and life support systems (ECLSS), and the continuously shifting balance of these two as humans enter and exit, and crops are planted, consumed, and harvested.

2. Learn how to close air, food, and water cycles for other-world exploration, and to become better custodians of our home planet Earth.

3. Crew arrival, departure, and EVA evaluation of tools, construction and repair, data collection, and communication while encumbered by pressure suits and the testing of rovers and autonomous vehicles in a simulated terrain Mars yard.

4. A study of the evolution of the microbial community of a transitional, hermetically sealed space occupied by both humans and plants.

5. Computer models that accurately describe a functional, sustainable, long-duration hybrid ECLSS. In particular, SIMOC will be programmed to model SAM and eventually, learn to manage SAM's life support systems through the application of machine learning.

SAM as a research platform

Academic and commercial research teams in the sciences, engineering, and arts from around the world propose experiments and projects to be conducted within and around SAM. Researchers can work on-site to conduct experiments or install equipment to be operated remotely or by SAM staff. Examples of possible projects include:

- Soil, hydroponic, and aquaponic agricultural systems
- Food production and food consumption studies
- Plant-based CO2 sequestration and bioregeneration
- Converting regolith to soil, and soil health studies
- Transition from mechanical to sustainable, hybrid ECLSS solutions
- Seasonal radiation and artificial lighting studies
- AI and robotics automation and cohabitation
- Human factors, tool use, and haptics
- Use of fully functional pressure suits in the Mars yard and terrain park
- Crew health, social, and psychology studies
- To name a few …

Education activities

The SIMOC team has been working with an ASU undergraduate Computer Science Capstone team to integrate SIMOC into SAM and develop a baseline educational package that supports citizen science. This mini-SAM + SIMOC consists of a low cost air quality sensor array coupled with a Raspberry Pi computer and SIMOC, such that students can use the modeling side of SIMOC to predict the outcome of an experiment, and then use the sensors to monitor their own effect on the air they breathe, in real-time, using the same SIMOC interface. As such, students can simulate their own spacecraft or a small habitat on the Moon or Mars while we will use the same system in SAM, for real-time data monitoring by the crew and delivery to the Nat Geo sponsored SIMOC interface. As SAM itself, once the facility is fully operational, we will develop educational curricula around the Mars yard and experiential learning activities. In addition, PhD students will be involved in research, including one already engaged with SIMOC and another starting in the fall of 2022.

Appendix X. Limitations and mitigation approaches for B2 research

The valuable capabilities of the controlled-environment facility of Biosphere 2 for large-scale, yet highly controlled manipulations and measurements in ecosystems necessarily involve tradeoffs. Most obviously, some components of real ecosystems in the field may still be lacking. For the terrestrial synthetic biomes, although diverse suites of microorganisms and other soil organisms are present, insects and vertebrates native to those biomes are largely lacking. In the B2 Ocean, multiple trophic levels are present, although it lacks carnivorous fish. Thus, studies of, for example, the top-down effects of predators on plants or algae through trophic cascades would not be possible in B2. On the other hand, B2 provides an excellent opportunity to examine how primary producers respond to environmental factors, the mechanisms driving those responses, and feedbacks to the environment, which are the key components of Earth system models at regional to global scales.

A second significant challenge of work in B2 is that the large spatial scale means that replicates of the whole system are lacking. However, B2 researchers have implemented a number of approaches to mitigate this limitation. The simplest approach is to implement treatments over time, with pre- and post-treatments responses acting as reference conditions. For example, recent work in the B2 Rainforest examined the effect of drought on ecosystem fluxes by first monitoring the rainforest under a standard precipitation regime for 4 weeks, then through a 9.5-week drought and then a further 3 weeks of recovery. Using this experiment, Werner et al. (2021) were able to identify the role of distinct plant functional types in determining whole-system consequences of drought, as well as signals of stress response in atmospheric chemistry, with important implications for feedbacks to climate change. Another potentially useful approach is the use of time series models to analyze processes, using model selection and parameter estimation in a Maximum Likelihood or Bayesian framework (e.g., Zhang et al. 2014). Finally, the development of small-scale, replicated experiments *within* biomes can be used to elucidate mechanisms in whole-system experiments conducted in the same location/time frame.

Appendix XI. Partnerships with industry

Current partnerships with industry are listed below, including those that are startups with the University of Arizona Center for Innovation (UACI).

- Red Sea Farms - member of UACI
- Solar Space - member of UACI
- Over the Sun (MOU in place) - member of UACI
- Solar Rivers/Techtronics Constructs - member of UACI
- Heliae
- NanoRacks (NDA in place)
- Uplift Aero Space (MOU in place)
- Sierra Space (NDA in place)
- SeedLabs