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A Search for Life in the Universe Advances Life on Earth

Catherine G. Fontana[1,2*], Sabrina Elkassas[3,4*], Tristan A. Caro[5*], Srishti Kashyap[1*], Alta E. G. Howells[1,6,7*,†]

1. University of Colorado Boulder, Department of Geological Sciences, Boulder, CO, USA
2. Interdisciplinary Quantitative Biology Program, BioFrontiers Institute, University of Colorado Boulder, Boulder, CO, USA
3. Massachusetts Institute of Technology, Department of Earth, Atmospheric, and Planetary Sciences, Cambridge, MA, USA
4. Woods Hole Oceanographic Institution, Department of Marine Chemistry and Geochemistry, Woods Hole, MA, USA
5. California Institute of Technology, Division of Geological and Planetary Sciences, Pasadena, CA, USA
6. NASA Ames Research Center, Moffett Field, CA, USA
7. Blue Marble Space Institute of Sciences, Seattle, WA, USA

† Corresponding author: alta.howells@colorado.edu

* Authors contributed equally to this publication

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Abstract

Astrobiology, while traditionally focused on understanding the origin of life on Earth and the potential for life elsewhere, offers powerful tools and insights for addressing urgent challenges on our planet. This perspective, written by early career researchers, calls for a deliberate integration of astrobiological research with applied sciences in environmental engineering, biotechnology, and resource management. We highlight how knowledge from Earth analogs for other planetary bodies can inform strategies for carbon capture, low-carbon energy production, waste remediation, and biotechnology. Examples include engineering serpentinizing systems for hydrogen and carbon sequestration, harnessing extremophile and cyanobacterial metabolisms for sustainable industrial processes, and applying microbial bioremediation to mitigate environmental contaminants and pollutants. As technologies developed for space exploration begin to find terrestrial relevance, we argue that astrobiology must evolve to become a bidirectional science that not only explores the cosmos but also supports sustainable life on Earth. This dual approach strengthens our ability to design and implement astrobiological missions to other solar system bodies while simultaneously supporting improved stewardship of our own Earth.

Introduction

As early career researchers, we recognize an increasing tension between fundamental questions in science, such as “Where did life come from?” and “Does it exist elsewhere in our solar system and universe?” and pressing questions of environmental sustainability on Earth. We contend that these questions are not contradictory; instead, we among others[1,2,3] increasingly observe investigations in fundamental, astrobiological questions intersecting with applied scientific fields, particularly in the realms of climate sustainability, biotechnology, and resource management. Here, we propose a path that fosters synergy between Earth analog research and the application of biology and geochemistry of these natural systems to applied science. Given that astrobiology intersects heavily with multiple Earth-facing fields of study, **this early career perspective argues that an Earth-centric approach to astrobiology can benefit both the field of astrobiology and the only planet known to harbor life: Earth.**

Over the next two decades, we urge the astrobiology community, which conducts fundamental research on Earth in the search for life elsewhere, to advocate for and engage in translating our research in the aid of our own planet. We contend that there is significant motivation to reexamine and harness the extensive capabilities of microorganisms, and the analog environments they inhabit, to address the growing energy and resource demands of human life on Earth and potentially beyond. In this perspective, we highlight several illustrative, but non-exhaustive examples of processes and themes that represent the convergence between astrobiology and applied science, including:

1. **Astrobiology and Environmental Science and Engineering**: Investigating the interactions between biological and geological processes in analog environments to develop innovative solutions for energy production and carbon capture.
2. **Astrobiology and Biotechnology**: Harnessing the unique capabilities of extremophiles and other environmentally relevant microorganisms to develop biotechnological applications that can address issues such as waste management, bioenergy production, and bioremediation.
3. **Astrobiology and Resource Management**: Applying knowledge gained from studying microorganisms in analog environments to improve resource management practices on Earth, ensuring sustainable acquisition and use of natural resources.

1. Astrobiology for Environmental Science and Engineering

Many of the environments studied for decades within astrobiological frameworks are gaining interest in realms of environmental science and engineering. For example, astrobiologists have long recognized that water-rock interactions are crucial targets for life detection, outlining the fundamental "follow the water" and "follow the energy" life detection strategies.[4,5] Serpentinization, the hydration of ultramafic planetary crust is of special interest due to its production of molecular H_2 that fuels microbial ecosystems in the subsurface,[6] thus motivating the recent "follow the serpentine" strategy (see **Figure 1**).[7] Serpentinizing/serpentinized systems are widespread on the Martian surface, underscored by the discovery of aqueously altered igneous rocks in Jezero crater[8] and the existence of liquid water deep into the Martian crust[9]. The moons Europa and Enceladus (moons of Jupiter and Saturn, respectively) are thought to host active serpentinization processes beneath their icy exteriors[10]. Because of its H_2 generation and its potential to form steep redox gradients that can support microbial life in the absence of sunlight, active or previously active serpentinizing environments are considered to be of great interest for life detection missions on these other planetary bodies. In recent years, investigation of serpentinization has expanded beyond astrobiology into the industrial sector, which recognizes the capacity of geological systems to produce significant quantities of H_2 naturally. Both private and public groups have begun investing in pilot projects to identify, stimulate, and capture low-carbon hydrogen that can be produced via geological processes ($GeoH_2$) in the Earth's subsurface.[11,12]

In addition to energy generation, serpentinizing as well as other analog environments are being recognized as promising sites for carbon capture and sequestration (CCS). In some strategies, CO_2 directly captured from the atmosphere is concentrated and injected into alkaline subsurface aquifers to stimulate the precipitation of $CaCO_3$.[13] However, serpentinizing systems are just one system hosting "extreme" geochemistry that is becoming increasingly relevant to CCS. Deep-sea sediments, often hosting life under extreme pressures and nutrient limitation, are being leveraged for the enhancement of oceanic biomass burial. For example, enhancement of oceanic biomass burial is utilized to stimulate the natural marine "biological pump" where organic carbon is transported to sediments and as particulate organic matter.[14,15] Hypersaline brines, often investigated in the context of extremophilic/halotolerant organisms that may persist in subsurface brines on Mars, are also being considered for carbon sequestration. Current proposals for these systems include landfilling harvested agricultural biomass in hypersaline enclosures below the water activity limits of life to sequester organic carbon underground.[16]

Subsurface life that relies on inorganic carbon in active CCS and $GeoH_2$ sites may confound efforts to sequester carbon and generate H_2 stably. Injections of CO_2 may stimulate subsurface microbial activity, destabilizing sequestered CO_2 and releasing CH_4–a more potent greenhouse gas–through a microbial process called methanogenesis ($4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$).[12] As H_2 is a potent microbial electron donor, H_2 stimulation may subsequently stimulate subsurface autotrophy, which may reduce industrial capture and lower economic viability. Similarly, sequestering carbon as buried biomass in hypersaline environments may be complicated by organisms' ability to persist even at high salt concentrations.[17]

Many of the geochemical and microbiological advances in our understanding of serpentinization, hypersaline systems, the Earth's deep marine subsurface, and other analog environments have been the direct result of fundamental astrobiology and geomicrobiology research supported by NASA and other funding agencies. *This kind of knowledge is proving essential for the successful assessment and deployment of these technologies*. How will industrial perturbation affect local geochemistry? How will microorganisms interact with engineering efforts? These questions are directly relevant to environmental engineering challenges and are addressed by cutting-edge geochemical and microbiological tools that astrobiologists have honed for decades. Long-considered "extreme" or "astrobiology-focused" microbiology and geochemistry are proving to be *rapidly* and *crucially* relevant to environmental engineering problems–a prime example of how fundamental science translates to unanticipated applied questions.

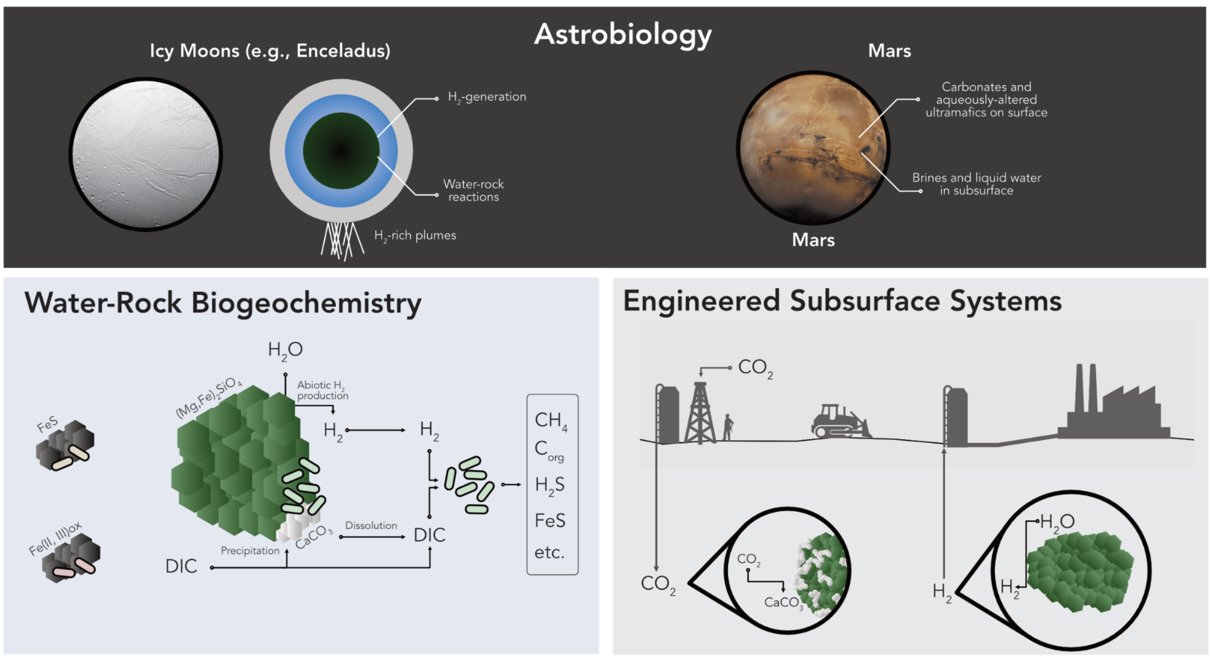

Figure 1. Serpentinizing systems as an example of the intersection of astrobiology and environmental engineering. Serpentinizing processes are inferred to have occurred, or are currently occurring, on Mars and the icy moon of Enceladus. On Earth, these environments are currently the target of industrial technology development in engineered water-rock interactions.

2. Astrobiology and Biotechnology

Astrobiology research, including studies of organisms in analog environments, in situ resource utilization (ISRU), and biosignature discovery, has led to significant biological discoveries that can be applied to technological innovation on Earth. Exemplary organisms of interest include cyanobacteria, alkaliphilic microorganisms, and methanogenic archaea.

Ancient cyanobacteria are credited with oxygenating Earth's atmosphere, which is considered to be a key step in the evolution of multicellularity.[18,19] Because of this, oxygen is also considered a potential biosignature in exoplanet discovery[20]. Over the last 3.5 billion years, cyanobacteria have colonized a diverse range of habitats and continue to play an important role in the global carbon cycle by sequestering roughly 30% of carbon dioxide each year.[21] Because of their prominence as drivers of planetary scale processes, their legacy as organisms that have co-evolved with our planet, and their establishment as well-understood genetic model systems, cyanobacteria hold immense promise for future studies at the intersection of astrobiology and carbon capture technologies (see **Figure 2**). Further research on cyanobacteria's carbon concentrating mechanism, the carboxysome, can provide both insights into organismal evolution in response to environmental pressures and critical information that can be used to bioengineer increased carbon fixation. Cyanobacteria are also master controllers of carbon sequestration via induced mineral precipitation of carbonates. In astrobiology, these induced carbonate precipitates contain indirect but telling biosignatures of microbial activity.[22] However, the ability to further harness the induction of mineral precipitation can lead to new carbon sinks, such as carbonate-based building materials.[23]

Studies of Enceladus and Europa's oceans drive research into organisms adapted to predicted chemical conditions on these ocean worlds. Enceladus's subglacial ocean, for instance, may undergo ongoing serpentinization, resulting in alkaline pH ~9-11[24] and reducing conditions. Alkaliphilic microorganisms, uniquely suited to high-pH environments, are promising candidates for study. They produce organic acids to maintain intracellular homeostasis, secrete siderophores for metal acquisition, and generate exopolysaccharides, biosurfactants, alkaline-stable enzymes, and novel antibiotics.[25,26] Given ongoing astrobiological research on the molecular and genetic bases of alkaliphily,[27-30,] these organisms hold significant biotechnological potential, particularly in industries reliant on inefficient or environmentally harmful processes. For example, the conventional alkali treatment of wood pulp in paper production requires harsh chlorine bleaching. However, thermostable, alkaline-active xylanases from microorganisms offer a more sustainable alternative, requiring fewer chemicals and causing less environmental damage.[26]

Methanogens, among the earliest known life forms on Earth, thrive on hydrogen (H_2) and carbon dioxide (CO_2) and produce methane (CH_4). Geochemical models of dissolved H_2 and carbonate species in Enceladus's plumes originating from its subsurface ocean, suggest conditions are energetically favorable for microbial methanogenesis[24,31]. Especially relevant in serpentinizing systems is the hydrogenation of CO_2 by methanogenic microorganisms and the subsequent conversion of biological CH_4 into solid functional carbon materials, including carbon nanotubes, fibers, and graphite, through an industrial process called CO_2 valorization. In addition to sequestering large quantities of CO_2, these materials could be applied to large-scale industrial processes to replace metal utilization.[32]

Astrobiology-inspired spin-off technologies are potentially of great value. The list of NASA "spin-off" technologies, tools, or ideas translated to commercial practice is well documented (https://spinoff.nasa.gov/)[33]. Most famously, taq polymerase, which made possible the polymerase chain reaction and subsequently enabled modern biology, biotechnology, and bioinformatics, was isolated from *Thermus aquaticus*, a thermophilic bacteria first isolated from Mushroom Spring in Yellowstone National Park[34,35]. Recently, NASA-funded geomicrobiology research describing Fusarium fungi in Yellowstone hot springs led to the development of “Fy protein”, a nutritionally complete, sustainable protein source[36] that is now marketed for human consumption. At the macroeconomic scale, it is estimated that space science R&D leads to substantial return-on-investment through technological development and technology transfer. For example, NASA spin-off technologies added upwards of $1.5 billion in value to 15 life science R&D companies alone[37]. Section 21 of NASEM's Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032 identifies cold/cryogenic sample return technologies as a top priority.[38] Applied to Earth-based research, these developments could enhance our ability to preserve biological samples in remote or analog environments—such as deep-sea or high-altitude locations—while maintaining contamination control and planetary protection standards, where the risk of biological contamination is high.

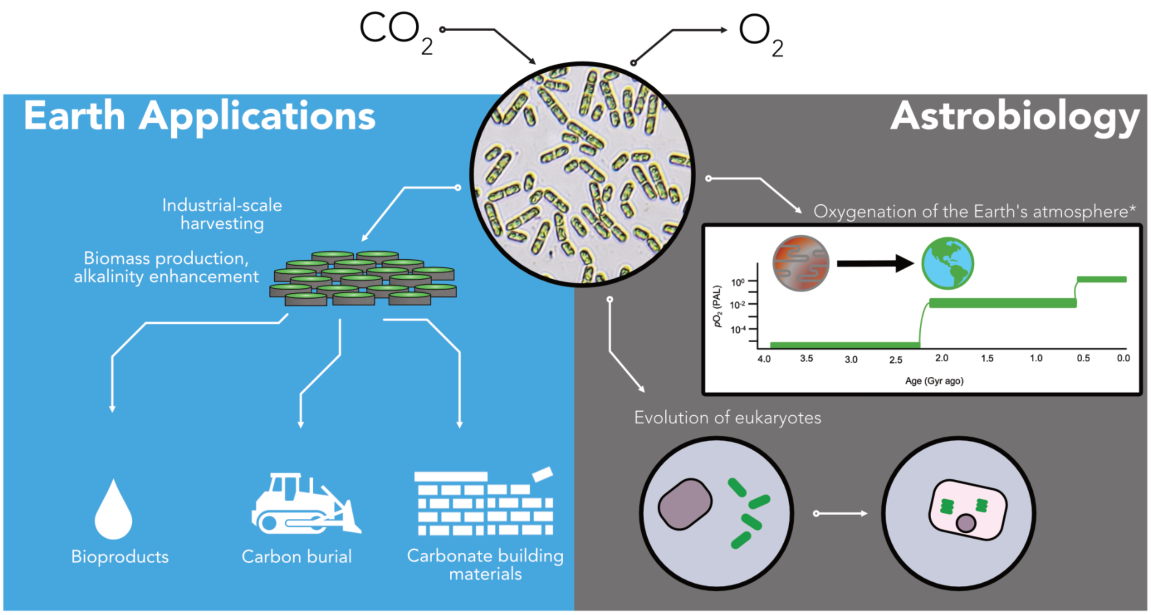

Figure 2. Cyanobacteria as an example of astrobiology and biotechnology. Cyanobacteria fulfill two important roles in Earth habitability: the production of oxygen (right) and the fixation of carbon (from atmospheric carbon dioxide, left). Cyanobacteria are credited with significantly increasing global oxygen levels around 2.4 billion years ago, which shifted our planet's redox conditions and could have spurred the evolution of eukaryotes and complex life. In the modern day, their voracious consumption of atmospheric carbon dioxide can be harnessed to again shift planetary-scale processes by sequestering carbon as biomass, carbonate, or biofuel products.

3. Astrobiology and Resource Management

In recent years, research in analog microbiology, astrobiology, and exobiology has gained relevance for global change and resource management. Microorganisms examined within these research areas could hold significant potential in waste management, rare-metal mining, and bioremediation yet remain underutilized.

In 2016, 44.7 million metric tons of e-waste were produced, a figure that continues to rise with the increasing consumption of electronics.[39] Given the reliance on rare Earth elements in electronic products, recycling and reusing these metals are crucial for future electronics production. Researchers have leveraged the microorganism *Gluconobacter oxydans*, which produces gluconic acid to bind rare earth elements, as well as species such as *Cupriavidus* *metallidurans*, *Delftia acidovorans*, and *Chromobacterium violaceum* to biomine gold. *C. metallidurans*, a heavy metal-tolerant chemoautotroph and one of the organisms used to mine e-waste, has been studied on the ISS for bioleaching rare earth elements from basalt under microgravity and simulated Mars and Earth conditions.[40] The dual relevance of this study exemplifies how future astrobiology research should consider the applications between energy and resource conservation to forward our study of sustainable practice on Earth and beyond (see **Figure 3**).

Astrobiology research has increasingly explored in situ resource utilization (ISRU) to support potential human activities on the Moon and Mars. One major challenge to human presence on Mars is the high concentration of perchlorate (ClO_4^-) in the Martian regolith (0.5–1%), which poses risks to human health, particularly through thyroid disruption[41,42]. Multiple studies[43-47] have investigated the use of rhizosphere-derived and extremophilic microorganisms for perchlorate bioremediation and resource extraction on Mars. Lynch et al. (2019)[45] demonstrated that microorganisms, such as *Azospira, Haloarcula, Acinetobacter, Sporomusa, and Marinobacter*, in perchlorate-rich sediments in the Pilot Valley Basin (a hyperarid environment with high perchlorate loadings) could reduce perchlorate under naturally enriched conditions—highlighting a promising avenue for Martian soil detoxification. In parallel, *Shewanella oneidensis*, a perchlorate-tolerant microorganism, has been shown to efficiently extract iron from synthetic Martian regolith at perchlorate concentrations comparable to those found *in situ*[44]. While perchlorate bioremediation and phytodegradation have been widely studied on Earth, they have yet to be implemented at scale. These studies not only inform future planetary engineering efforts but also hold untapped potential for advancing large-scale terrestrial bioremediation, which remains underutilized even as perchlorate contamination continues to rise[48].

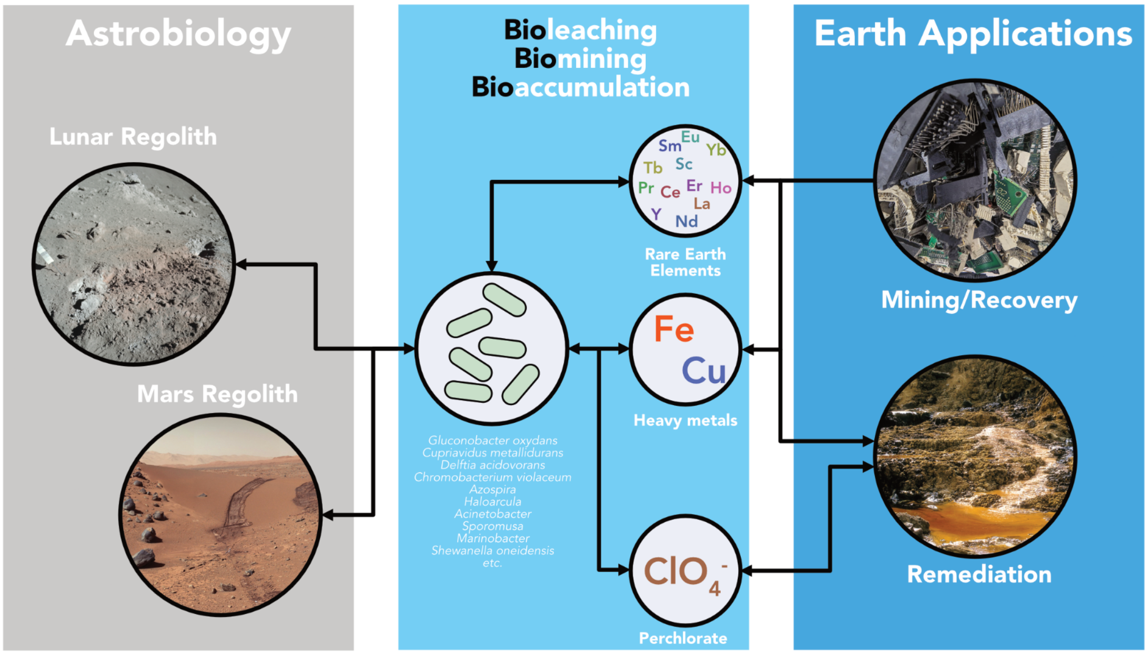

Figure 3. **Microbial strategies for biomining and bioremediation across space and Earth applications.** Microorganisms capable of bioleaching, biomining, and bioaccumulation are being explored for their potential to extract and remediate metals and contaminants in both extraterrestrial and terrestrial environments. In astrobiology, microbes may be used to process lunar and Martian regolith for in-situ resource utilization. On Earth, similar microbial strategies target rare earth elements (REEs), heavy metals (e.g., Fe, Cu), and contaminants like perchlorate (ClO_4^-) for applications in mining/recovery and environmental remediation. Representative microbes include *Gluconobacter oxydans*, *Cupriavidus metallidurans*, *Shewanella oneidensis*, and others. This conceptual framework highlights the overlap between astrobiology and biotechnology.

Conclusions

To meet the ever-increasing energy and resource needs of human life on Earth and possibly elsewhere in the universe, there is significant motivation to examine with a new lens the extensive capabilities of microorganisms and the diverse environments they are from. While staying true to its core mission of understanding the origin, evolution, distribution, and future of life in the universe, astrobiology can increasingly frame its findings through an Earth-focused framework, contributing to efforts in bioenergy production, natural resource recycling, and sustainable energy development.

Astrobiological research has made significant strides since the publication of the 2015 *NASA Astrobiology Strategy*[49], advancing both technologies and the search for life elsewhere in the universe. Chapter 5 of the *Astrobiology Strategy for the Search for Life in the Universe* (2019) emphasizes that instrument technologies for *in situ* life detection have rapidly advanced over the past decade, driven by investments made by companies in the biomedical, food security, and defense sectors.[50]

We argue that these great strides are also applicable to our planet: astrobiology has produced innovative tools and methods to detect life and access analog environments on Earth. We specifically outlined three areas where this is true: (1) The characterization of Earth's environments through an astrobiological lens has empowered our ability to understand Earth's geochemistry and how it may interact with industrial technologies; (2) Extremophilic or specialist organisms that are studied for their relevance to astrobiology research are a robust source of biotechnological potential; (3) Studying organisms with unique capacities for survival and metabolism enhances our ability to remediate Earth environments and prepare non-Earth environments for human exploration. In short, we argue that astrobiology is a key science for its relevance to fundamental scientific questions of our place in the universe and our ability to, more practically, steward the only [known] planet to harbor life.

Author Contributions

Catherine G. Fontana and Sabrina Elkassas co-wrote the sections *Astrobiology and Biotechnology* and *Astrobiology and Resource Management*. Tristan A. Caro and Srishti Kashyap co-wrote the section *Astrobiology for Environmental Science and Engineering*. Tristan A. Caro drafted summary figures with guidance from co-authors. Alta E. G. Howells wrote the *Introduction* and coordinated the production of this perspective piece.

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