2024 Mars Terraforming Workshop Proceedings

April 15 and 16th 2024, Pasadena, California
Hosted by The Astera Institute and Pioneer Labs
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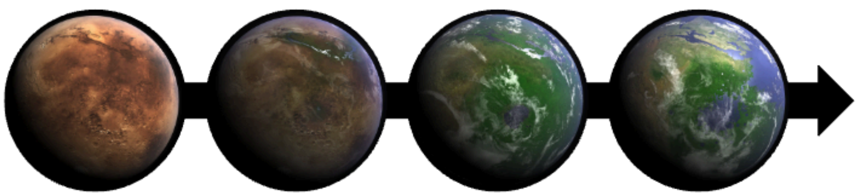
Summary: For most scientists, terraforming still lies solidly in the realm of science fiction. However, recent developments in climate, biotech, and space science demand reassessing its feasibility. To do so, we hosted a two-day workshop to formulate an up-to-date perspective on the feasibility of terraforming Mars. Attendees generally agreed that warming Mars and greening it with a photosynthetic biosphere are feasible and could be accomplished in relatively rapid timescales, perhaps less than a century. A green Mars would be conducive to agriculture and domed human settlements. Over much longer timescales, a green Mars could develop a planet-wide pure oxygen atmosphere, protecting the surface from harmful radiation and enabling human life 'outside' with no need for a magnetic field. These workshop proceedings summarize these discussions, highlight outstanding technical questions, and identify research priorities for the field moving forward.



Workshop #1: is terraforming Mars feasible, how could it be done, and what might change our minds?

INTRODUCTION

Since the early 90's when terraforming Mars was last roadmapped, technology has developed in several fields. Global warming has proven that humans are capable of altering planetary climates and has prompted the development of climate engineering technologies that are nearing deployment on Earth. Improvements in synthetic biology have created possibilities to tailor organisms to thrive in non-Earth environments. Advances in space science, especially from the private space industry like SpaceX' Starship, are dramatically altering the landscape of possible space missions. Meanwhile, recent discoveries have transformed our knowledge of Mars' surface, soil, and ice deposits.

We hosted a two-day workshop to discuss the feasibility of terraforming Mars in light of these developments. During the meeting, attendees identified outstanding technical questions that would inform the feasibility, approach, and cost of terraforming. While this workshop focused primarily on technical analysis, we also identified additional areas in ethics, policy, and economics that would benefit from a dedicated future workshop.

DEFINING TERRAFORMING

The word 'terraforming' means many things to many people. This range of definitions is generated by a huge diversity of frameworks for reasoning about the ultimate goals of humanity's engagement with space. For many, the purpose of terraforming is to enable human life on specific nearby worlds like Mars, especially by creating an Earthlike breathable atmosphere that can be enjoyed without a pressure suit. For others, spreading life throughout the universe — cultivating conditions hospitable enough for non-human life to thrive — is the desired outcome.

For the purposes of this workshop, we used the following definition of terraforming: "planetary-scale climate engineering that makes the planet more amenable to life," and focused specifically on terraforming Mars.This definition is broad and applies to making a planet amenable to any sort of life. Though we adopted a broad definition, we found that the ultimate goal of "enabling humans to walk around outside on Mars without a pressure suit" acted as a well-defined and challenging endpoint that helped to frame technical conversations.

ORGANIZERS

The workshop was co-hosted by the Astera Institute and Pioneer Labs.

The Astera Institute is a nonprofit that empowers visionary, high-leverage science and technology projects with the capacity to create transformative progress for human civilization.

Pioneer Labs is a nonprofit startup engineering microbes for Mars. Short term, these microbes will be used for *in situ* resource utilization (ISRU) biomanufacturing; long term, the properties of these organisms may inform the feasibility of terraforming.

The workshop was organized and moderated by Edwin Kite, Erika DeBenedictis and Natalie Ma.

Dr. Edwin Kite is an Associate Professor at the University of Chicago, where he has most recently studied engineered artificial aerosols that could be used to heat Mars. He is a participating scientist on the Mars *Curiosity* Rover.

[1] Image credit: Kevin Gill via National Space Society

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Dr. Erika DeBenedictis is the CEO of Pioneer Labs, a nonprofit startup engineering a pioneer species for Mars. She is a computational physicist (Caltech), and biological engineer (MIT). She previously ran an academic lab in London at the Francis Crick Institute. She is also the founder of Align to Innovate, also a research nonprofit.

Dr. Natalie Ma is a molecular biologist who currently works at Deep Origin, a company building computational tools for biology. She previously advocated for more research on using biotech in space science applications in the article The case for biotech on Mars.

ATTENDEES

Dr. Casey Handmer is the CEO of Terraform Industries, a company producing natural gas from direct carbon capture. He previously worked at NASA's Jet Propulsion Laboratory (JPL) and has written extensively about the possibility of terraforming Mars, including with solar sails.

Dr. Laura Kerber is a Research Scientist at JPL. She is a planetary geologist who has worked on Global Climate Models to investigate early Mars. She has also investigated the possibility of heating Mars with a solid state greenhouse effect.

Dr. Devon Stork is a Founding Scientist at Pioneer Labs. Devon is a chemist (Harvey Mudd) and biological engineer (Harvard). He was previously principal scientist at Tenza engineering probiotics to make drugs in the gut. Devon has recently written about the challenges living organisms would face growing on Mars.

Dr. Una Nattermann is a Founding Scientist at Pioneer Labs. Una is a protein designer (University of Washington) and biological engineer (MIT). She previously engineered non-model bacteria to upcycle plastic degradation at the Voigt lab.

Dr. Woody Fischer is a geobiology group leader at Caltech. He studies coevolution of life and Earth's climate, including the evolution of oxygenic photosynthesis and the rise of atmospheric oxygen.

Dr. Pete Worden is the Chairman of the Breakthrough Prize Foundation. Pete has a PhD in Astronomy from the University of Arizona, and is a former NASA Ames Research Center Director. He leads the Breakthrough Initiatives, a privately funded suite of research programs to find life beyond Earth, with a vision to expand humanity into the Solar System and to the stars.

Dr. Hooman Mohseni is the AT&T Chair Professor of Electrical and Computer Engineering at Northwestern University. His group is currently engineering nanoparticles for Mars terraforming.

Dr. Nils Averesch is an Assistant Professor of Space Biology at the University of Florida. He has worked extensively on the development of microbial cell factories to support space exploration, and has collaborated on experiments investigating the response of microbes to the space environment on the ISS-NL.

Dr. Joe Von Fischer is a biologist at Colorado State University. His group conducts basic and applied research on greenhouse gas emissions.

Hooman Reza Nezhad is the founder of Solcoa, a company focused on cost-effective metal refining. This technology may be applied to Martian ISRU for metal refinement.

Dr. Harry Atwater is the Otis Booth Leadership Chair of the Division of Engineering and Applied Science at Caltech. He is the Chair of the Lightsail Committee for the Breakthrough Starshot program.

Danielle Fong is the CEO of Lightcell, a company building a high efficiency thermophotovoltaic generator.

Dr. Alfonso Davila is a Research Scientist at NASA Ames Research Center. He studies life beyond Earth by conducting theoretical and experimental research on the nature and distribution of life in extreme deserts.

Dr. Jeehyun Yang is a postdoctoral fellow at JPL, where he studies planetary atmospheres.

The following five attendees joined us remotely for a Zoom panel.

Dr. Robin Wordsworth is the Gordon McKay Professor of Environmental Science and Engineering and a Professor of Earth and Planetary Sciences at Harvard University. Recently, he has worked on enabling Martian habitability with solid state-greenhouse effect and defining the minimum physical requirements for life in space.

Dr. Charles Cockell is a professor of astrobiology at the University of Edinburgh with interests in life in extreme environments, the potential habitability of extraterrestrial environments and space microbiology. He has also investigated the possibility of heating Mars with a solid state greenhouse effect.

Dr. John Cumbers is Founder and CEO at SynBioBeta.

Dr. Christopher Mason is Professor of Genomics, Physiology and Biophysics at Weill Cornell Medicine.

Dr. Nina Lanza is a staff scientist at Los Alamos National Laboratory and Principal Investigator of the ChemCam instrument onboard the Curiosity Mars rover.

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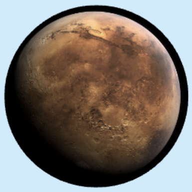
Near-term

Today Mars is too cold and dry for Earth–like life to flourish. The first step is abiotic engineering to heat the planet.

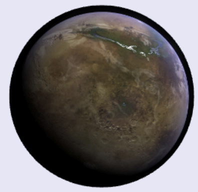
Method: abiotic engineering
GOAL: ⬆ Temperature



Mid-term

A future, warmer Mars would be suitable for non–human life. A planetary ecosystem would begin producing oxygen.

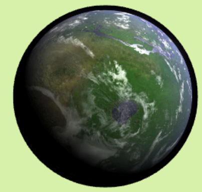
Method: photosynthesis
GOAL: ⬆ O2



Long-term

In the long term, Mars would accumulate more atmosphere and have a stable, favorable climate.

Method: abiotic + biotic
GOAL: ⬆ pressure, stabilize climate



THE THREE PHASES OF TERRAFORMING

We divided discussion of terraforming technologies broadly into three phases that are distinguished by how soon they might become relevant. In the *near-term*, Mars is too cold and dry for life to flourish, and so terraforming is largely restricted to abiotic engineering technologies that make it more life-compatible. In the future *mid-term*, Mars would be compatible with non-human life, opening up new possibilities to use highly scalable biological processes to build a planet-wide biosphere. Some terraforming objectives, like creation of an oxygen-rich atmosphere, would likely happen in the *long-term*, and might require both abiotic and biotic processes.

NEAR TERM

Today, Mars is too cold and dry for Earth-like life to flourish. In the near-term, engineering activities that can make Mars more amenable to life are abiotic strategies designed to increase temperature.

Several techniques have been proposed for heating Mars. For each, we challenged attendees to (a) produce order-of-magnitude estimates for key metrics for these proposed techniques: $/°C (or $/°C/yr), and for regional techniques, also $\$/km^2$, and to (b) specify the environmental conditions (daily temperature swing, pressure, etc.) of the first life-compatible location as a function of dollars spent on abiotic climate engineering.

Heating Mars with gases or aerosols

On Earth, the atmosphere acts as a blanket, retaining heat with a greenhouse effect at global scale. One proposal for heating Mars is to enhance the atmosphere's greenhouse effect using gases or aerosols. Small metallic artificial aerosols that scatter and/or absorb in the infrared range would be >5,000× more effective per kg than the strongest greenhouse gases (e.g., fluorocarbons) at warming Mars (Ansari *et al*., in review). A goal is to further improve the °C/kg, sufficient that it may be feasible to manufacture these aerosols on Earth and transport them to Mars. Workshop attendees debated various strategies for estimating the cost $/°C of this approach, with some estimates as low as $1B/1°C/yr for materials and shipping costs, or even lower if materials are made on Mars. Outstanding questions about this approach include experimental measurement of predicted aerosol properties, additional research into cost-effective ways to manufacture and transport aerosols, and biocompatibility for both microbes and humans.

Heating Mars with space-based geosolar engineering

In space-based geosolar engineering, reflective surfaces are placed in orbit around a planet to either reduce (with a sunshade) or increase (with a sun reflector) the amount of light a planet receives. Positioning sun reflectors at the Mars-Sun Lagrange point 2 point to heat Mars is one of the first proposed terraforming techniques and dates back to the 1970s. Workshop attendees discussed various strategies for estimating the cost $/°C of this approach, with some estimates as low as $1B/1°C/yr for materials and shipping costs, similar to heating Mars with aerosols. Outstanding questions include obtaining an estimate of the technology development cost for this approach, which would require improving the surface area/kg and manufacturing cost/kg of sun reflectors.

Heating Mars with nuclear explosives: not necessary

Using nuclear explosions to heat Mars is a frequently-discussed, and almost as frequently criticized, strategy for heating the planet. While nuclear bombs could be used to heat Mars, this approach would require exploding the equivalent of the entire U.S. arsenal every two minutes to sustain a warm Mars. This poses a range of challenges including probably lower effectiveness per dollar than other alternatives.

MID TERM

A future, warmer Mars would be suitable for extreme life. In ecology, the term *pioneer species* refers to hardy species that are the first to colonize barren environments, or to repopulate areas disrupted by forest fires, volcanoes, and other disturbances. On Mars, the first pioneer species would be able to grow exponentially within the life-compatible area. Ecological succession subsequently diversifies and stabilizes the ecosystem. The resulting biomass would produce oxygen via photosynthesis and this would increase atmospheric pressure.

We challenged attendees to create order of magnitude estimates for how soon mid-term engineering could begin, especially in terms of doubling time of microbes under environmental conditions that range from Mars-today to a future Mars that has been heated. We note that a dominant factor in the cost of terraforming is how much abiotic heating is required before scalable biological processes can begin to contribute. For this reason, it is extremely valuable to obtain good estimates for how close Earth-based life can get to living on Mars.

Workshop attendees discussed the question of how much Mars must be warmed before pioneer species could grow in ‘outdoor’ conditions. On Earth, pioneer species and cold-loving organisms often thrive where others cannot by growing very slowly. It is desirable for the planetary ecosystem to be complex and have substantial metabolic activity that can be deployed toward producing food and oxygen and remediating waste, as the biosphere does on Earth. For this reason, workshop attendees expect that it may be beneficial to heat the planet beyond the minimum temperature necessary for the very first pioneer species in order to improve growth rates and metabolic activity of the biosphere.

Stressors on Mars

The most challenging conditions for life on the Martian surface are UV radiation and low abundance of liquid water. While certain terrestrial organisms already exist on Earth that can grow at -12°C and under Martian atmospheric pressures (7 mbar), even the most radiation-resistant forms of life as we know it would only be able to survive for minutes under UV radiation-levels of Mars’ surface. Nevertheless, a small amount of regolith could be enough to mitigate UV radiation effects substantially. Equally problematically, all known forms of life require liquid water for metabolism and growth, and the low pressure and temperature mean there is no liquid water on Mars that is usable by known biology: any liquid water that may currently be present on Mars is likely a eutectic brine that has a prohibitively low water activity.

Note that Martian regolith has 110–300 ppm of nitrate (at the Rocknest aeolian samples site) in fixed nitrogen species, making it effectively ‘pre-fertilized’. However, the low atmospheric pressure means that it is important not to volatilize this nitrogen. Once in gaseous form, it would be difficult to re-fix any N_2 due to low partial pressure.

Pioneer species

The first pioneer species would need to be facultatively anaerobic autotrophs – beyond these initial properties there is considerable speculation about the identity and specific properties/characteristics of the first organisms that would be capable of proliferating unprotected on the surface of Mars. Promising organisms could be identified by bioprospecting extreme environments on Earth, conducting growth tests under simulated Martian conditions, and then testing promising candidate organisms on Mars in contained areas.

Testing pioneer species in greenhouses.

Testing organisms in greenhouses on Mars prior to outside deployment offers several advantages, including the opportunity to drive evolution in a relevant environment albeit under partially relaxed Martian conditions to alleviate potentially prohibitive selection pressure. This could facilitate identification of the most pertinent fitness-improving adaptations on genome-level as they are acquired.

A primary stressor on Mars is that average surface pressure (7 mbar) is just below the triple point of water, meaning that its liquid form is not stable across most of Mars’ surface. Greenhouses could relatively easily mitigate this issue by partial pressurization of the atmosphere, possibly in combination with temperature control. A sophisticated greenhouse might have complex temperature and pressure control, while a minimal greenhouse could be as simple as an enclosed plastic bag. Pioneer species could be prepared for outside growth as they graduate to increasingly more minimal greenhouses. The degree of environmental control required to allow sufficient metabolic activity throughout the Martian day for organisms to not only proliferate but also thrive was a major point of discussion among participants of the workshop.

Could the ‘greenhouses’ be self-growing?

Attendees discussed the possibility that shelters could be self-growing. Many organisms on Earth form protective biofilms that enable them to grow in environments that would otherwise be too extreme. Some self-growing protection may inevitably happen naturally, for example, microbes on the top layer of a community will die when exposed to UV, forming a protective layer that could shield microbes below them. Attendees also discussed adaptations on the cellular level, such as the calcium carbonate shells of coccolithophores, and the possibility that analogous cellular systems could be engineered to withstand Martian conditions. We expect it will be valuable to further investigate biomaterials that can be uniquely beneficial on Mars or uniquely generated under Mars atmospheric conditions.

Target habitats for first outdoor organisms

Growth in ice covered lakes is a plausible first near-surface environment that could be a habitat for life as Mars warms. Water substantially attenuates ionizing and UV-radiation while remaining translucent to light of the photosynthetically relevant spectrum. The surface ice and heat capacity of liquid water stabilize the temperature of this niche, reducing the extent to which organisms need to tolerate daily freeze-thaw cycles that expend energy required for repair of the resulting damage.

Ice-covered lakes will emerge when there is sufficient seasonal melt to feed lakes. A precise number for how much heating is required will have to be informed and substantiated by thorough climate simulations, but it is likely to be around 30°C of heating. Organisms in similar lakes on Earth have a doubling time on the order of years but an average water temperature as low as -2°C can support faster-growing species with doubling times as low as one week.

Ecological succession

The initial pioneer species will have a very slow metabolism, and thus cannot produce substantial biomass in a timeframe that suits human needs. Instead, it could kickstart ecological succession by decreasing albedo and thus increasing temperature, building biological structures like biofilms that shelter other organisms, and leveraging its metabolism to manipulate which compounds are available in the ecosystem, thus enabling succession.

Future, more complex, ecosystems would include a wider diversity of species, comprising multicellular organisms to accelerate biomass formation and the creation of an atmosphere. Such an initial biosphere could be capable of building out microbial soil communities that facilitate agriculture.

LONG TERM

A future Mars would be warmer, with large lakes and seas, home to a planet-wide photosynthetic ecosystem. However, Mars would likely continue to have a thin atmosphere, making it unsuitable for humans to enjoy 'outside.' Creation of an atmosphere would be a final step towards enabling more complex life to thrive on Mars.

Atmospheric composition

Workshop attendees discussed the constraints placed on a possible future Martian atmosphere:

Available sources of *in situ* volatiles. In principle, it might be possible to import volatiles to Mars from other places in the solar system. In practice, doing so may be impractical due to the sheer quantities of material required to create an atmosphere (on the order of 10^{17} kg). For the purposes of our discussion, we restricted ourselves to identifying a target atmospheric composition that is composed entirely of *in situ* volatiles. Mars likely has abundant H_2O, which could be converted into O_2 using photosynthesis or electrolysis. However, the fate of the co-produced H_2 is a major concern, as it must be physically separated (stored or chemically bound) in order to prevent reversal of the reaction. Further, Mars lacks significant known sources for N_2, or other options for inert gases.

Breathability. An ideal atmosphere would enable humans to walk on the surface without a pressure suit or gas mask. This requires a low concentration of toxic gases (i.e., at 1 atm pressure, CO_2 must be <1% by volume), high concentration of O_2 (at least 100 mbar), and above the Armstrong limit (60 mbar) for total pressure.

Ozone. On Earth, oxygen in the upper atmosphere generates ozone, which protects the planet's surface from harmful ultraviolet radiation. A similar effect observed at the poles of Mars today is insufficient to provide significant protection. Improving the ozone layer on Mars would be desirable. In addition, attendees estimated that ~100 mbar of atmospheric O_2 at Mars gravity would likely be sufficient to protect the surface from radiation, even without a planetary magnetic field.

Flammability. Atmospheres that are too high in O_2 will result in rampant forest fires because biomass will readily oxidize.

Overall, a target atmosphere of ~100 mbar pure O_2 could satisfy all the above requirements while being composed entirely of *in situ* atoms. Although different from what we are accustomed to on Earth, such an environment would mean the 'outside' is not lethal to humans while simultaneously remaining below a level that would be highly flammable.

Timescale estimates for atmosphere creation

A "green" planet covered in photosynthetic organisms would naturally generate an oxygen-rich atmosphere over time. Attendees estimated that the accumulation of a planet-wide atmosphere that is composed of 100 mbar O_2 would take on the order of 10,000 years if photosynthetic life covered approximately 10% of Mars' surface. In contrast, accumulation of atmosphere in contained areas could be accomplished much faster. For example, given the same basic assumptions, it would take approximately two years to fill a 100-meter-tall domed structure if its ground-surface area were covered with plants.

OUTSTANDING TECHNICAL QUESTIONS

Throughout the workshop, attendees were encouraged to identify and define outstanding technical questions that might substantially alter the feasibility, approach, cost, or ethics of terraforming. We highlight three of the most pressing technical questions below:

Question #1: Is there currently life on Mars?

For many people, including many scientists, the ethics of terraforming are strongly influenced by whether or not there is currently life on Mars. To date, there is substantial evidence that Mars was *previously* amenable to life. Nevertheless, there is (also to date) no evidence that life *currently* exists on Mars: the surface appears sterile.

The question of whether Mars hosts extant life remains one of the most intriguing yet unresolved questions in astrobiology. As it is impossible to prove that something does not exist, a major point of discussion amongst attendees was interest in creating criteria for reasoning about the level of certainty about the existence or non-existence of life on another planet. Recommendations were put forward regarding where life is most likely to exist on Mars and the difficulties of accessing these areas with robotic landers. Investigating these sites could significantly increase confidence and change the course of discussions around terraforming.

If terraforming activities were to be implemented on Mars, ongoing discussion would still be required. For example, some participants noted that terraforming Mars might restore its climate to a life-compatible state, thawing or rehydrating dormant endogenous life that might merit study or protection. Broadly, attendees called for more discussion and open-mindedness towards revising our conclusions in light of new data.

Question #2: What are the possible fates of water as Mars warms?

Water availability is a critical barrier to life on Mars. This raises a critical question: if Mars is heated, where will the water go? The answer to this question will have important implications for the location of future Martian habitats, the characteristics of the first pioneer species, and the long-term stability of a terraformed Mars. There are two possible undesirable destinations for water when it is melted:

Aquifers rather than oceans? So long as annual average temperatures are below freezing, ground ice forms a seal that would trap any liquid water on Mars's surface. However, if Mars is heated enough to melt the ground ice (or "permafrost"), it is possible that surface water will seep into Mars's subsurface and form aquifers rather than oceans. Liquid water can only contribute to a productive biosphere if it is co-located with sunlight, making water loss to aquifers undesirable. Sufficient subsurface space to accommodate all of Mars' water cannot be entirely ruled out due to our limited knowledge of Mars' subsurface. Resolving this question will require further in depth investigation of the planet's subsurface.

Icy mountains rather than oceans? As the planet warms, the rate of ice sublimation will increase, making water more mobile. A second undesired destination for this water vapor is ice on high-elevation mountains, which act as 'cold traps.' Historically, Mars has cycled between a 'warmer wetter' climate and a 'cooler drier' climate, with its generous high-elevation surfaces that trap water as high albedo ice caps being a major factor. More sophisticated climate models are needed to predict the movement of water as the planet heats, and modeling must include effects such as movement of water toward surface cold traps, deliquescence, and runoff and ponding in ice-covered bodies of water. In general, managing cold traps may be a key feature of stabilizing Mars' climate long-term.

Question #3: How much CO_2 will outgas from the regolith as Mars warms?
We discussed a target atmosphere of ~100 mbar O_2 as a potential long-term endpoint for Mars terraforming (see Long Term Atmospheric composition section). There remain many questions about the speed of building up this atmosphere.

When Mars is heated, it is expected that CO_2 will outgas from the ice caps, resulting in a minimum of 7 mbar and perhaps as much as 50 mbar of CO_2 being added to the present atmosphere. In addition, an unknown amount of CO_2 will outgas from the regolith itself. There are a wide range of estimates for how much will outgas from the regolith. The specifics of regolith outgassing will likely have a substantial impact on the course of terraforming. Specifically, if the total CO_2 outgassed (including from the regolith) was to add 100 mbar (at the high end of the uncertainty range), the increased pressure would enable pioneer species to grow more rapidly and increase the amount of total carbon available to formation of biomass. If the total CO_2 outgassed was only ~10 mbar, more heating would be necessary to sustain surface liquid water, and less carbon would be available for a biosphere to develop.

OPPORTUNITIES TO ADVANCE THE FIELD

Throughout the workshop, attendees discussed technical studies that could be done today, and that would move the terraforming community forward. Four of the most requested studies are highlighted below:

Better climate models for terraforming.
Better climate models are needed to determine the most attractive sites for growth of pioneer species. These models need to account for light, temperature, water availability, etc, and their results will provide biologists with a more accurate specifications for the desired pioneer species. Both local (mesoscale) and global models are needed. Photochemical models are needed to determine the dependence of ozone shielding on atmospheric oxygen levels. More sophisticated climate modeling is needed for both the transient (warming) and steady-state (warmed) climates.

Experimentally validate the properties of engineered aerosols.
Radiative and microphysical (e.g. clumping) properties of warming aerosols should be validated experimentally, for example using flow-tube approaches. Scalable methods for manufacturing, screening, and dispersing warming aerosols should be demonstrated.

Identify or engineer a pioneer species for Mars.
Prospecting as well as engineering of autotrophic polyextremophilic organisms towards growth in Mars-like environments would narrow down the extent of abiotic terraforming that is necessary *a priori*. These approaches should focus on conditions with combinations of high UV radiation, low water, high salt and perchlorate, low pressure, and low temperature.

Establish an up-to-date Terraforming Primer.
Mars terraforming draws on many fields of science and engineering. A primer accessible to beginners in the field is needed to establish a common set of facts about Mars soil, Mars climate (and warming methods), and terraforming-relevant microbial biotechnology. A successful example is the Astrobiology Primer, now in its third edition, which helped establish that similarly-interdisciplinary field.