The case for Mars terraforming research

Can we understand enough about climate and ecosystems to build them elsewhere?

Erika Alden DeBenedictis[1], Edwin S. Kite[2], Robin D. Wordsworth[3], Nina L. Lanza[4], Charles S. Cockell[5], Pamela A. Silver[6], Ramses M. Ramirez[7], John Cumbers[8], Hooman Mohseni[9], Christopher E. Mason[10], Woodward W. Fischer[11], & Christopher P. McKay[12].

1. Pioneer Research Labs (erika@pioneer-labs.org), 2. University of Chicago, 3. Harvard University, 4. Los Alamos National Laboratory, 5. University of Edinburgh, 6. Harvard - Wyss, 7. University of Central Florida, 8. SynBioBeta, 9. Northwestern University, 10. Weill Cornell Medicine, 11. Caltech, 12. NASA Ames Research Center.

Author summary
Terraforming Mars is widely discussed, yet lacks rigorous study. More research is needed−ranging from warming methods to biological engineering−to clarify feasibility, costs, ethics, and planetary impacts before any ambitious, large-scale attempts.

Abstract
Terraforming Mars has long captured the imagination, but has received surprisingly little rigorous study. Progress in Mars science, climate science, launch capabilities, and bioscience motivates a fresh look at Mars terraforming research. Since Sagan's time it has been understood that terraforming Mars would involve warming to enable oxygenic photosynthesis by engineered microbes, then slow oxygen build-up enabling more complex life. Before we can assess whether warming Mars is worthwhile, relative to the alternative of leaving Mars as a pristine wilderness, we must confront the practical requirements, cost, and possible risks. We discuss what we know about Mars' volatile inventories and soil composition, and possible approaches to warm Mars and raise atmospheric O_2. New techniques have emerged that could raise Mars' average global temperature by tens of degrees within a few decades. Research priorities can focus on understanding fundamental physical, chemical and biological constraints that will shape any future decisions about Mars. Such research would drive advances in Mars exploration, bioscience, and climate modeling.

Main text
Exploration of Mars is motivated by scientific, societal, and engineering goals, and the centuries-old dream (e.g., [1]) that people could one day live there. Missions to date reveal a hostile surface environment, featuring a deadly triple cocktail of extreme cold, the high ultraviolet radiation flux that reaches the surface, and lack of sustained liquid water [2]. Despite this harshness, advocacy for large-scale Mars settlement has continued for decades [3-6].

Proposed motivations for terraforming are diverse. Carl Sagan once wrote, "If we do not destroy ourselves, we will one day venture to the stars." Since Sagan's time we have confirmed that Mars once had rivers and lakes but suffered a global climate catastrophe, so perhaps Mars can be seen as an environmental restoration challenge

[7, 82]. Some argue that a hospitable Mars is essential to achieve self-sufficiency, surpassing the limitations of isolated outposts [5-6]. Others are motivated by the scientific desire to learn about the universe, as the realization of humanity's dreams to explore the universe is assisted by expanded human presence [3]. An alternative view is that Mars should be left as a pristine wilderness, whether or not it contains life today [8]. Indeed, any movement of humans beyond Earth raises ethical issues: it is a trope of science fiction that even though humans have already restructured Earth's land surface, nitrogen cycle, etc, at planetary scale [9], attempts to do the same for other worlds will be seen as dysfunctional.

An important part of the "should we?" question is "can we?" Research can shift ethical discussions from abstract speculation to grounded debates about specific technical possibilities. Before we can assess whether greening Mars is worthwhile, we must confront the practical requirements, cost, and possible risks. Recent advancements and private space capabilities demand that humanity engages with these technical and ethical questions head-on. Remarkably, the feasibility of terraforming Mars has not been comprehensively addressed since 1991 [10]. This Perspective outlines the research agenda necessary to determine whether making Mars hospitable to life is possible. This technical knowledge is a prerequisite for a larger, well-informed democratic dialogue about the possibility of deployment.

Contemplating building a climate and ecosystem beyond Earth highlights gaps in our fundamental knowledge of these systems. Ongoing developments in three key areas have returned terraforming to the martian research agenda. First, our understanding of climate modeling and climate engineering, including for Earth, has recently advanced [11]. It is timely to investigate how these techniques might be applied on other planets. Second, progress in synthetic biology has improved our knowledge of extremophilic organisms and our ability to engineer their properties [12-13], opening new possibilities for tailoring life to thrive in the extremes of Mars. Third are numerous developments in space science. The emergence of Mars transport vehicles like Starship will broaden the scope of possible space missions by increasing the mass we can launch from Earth by >100× per Mars landing [14], and independent cost estimates suggest three-orders-of-magnitude improvement in cost to the surface [15]. Our understanding of the basic science of Mars has advanced, including understanding that a warmed Mars would retain volatiles for many millions of years [16]. Finally, new options for warming Mars have emerged, using ultralight materials [17], solar sails [18], or nanoparticles [19]. Thus, a fresh look at the research agenda for greening Mars [10,20] is timely. Restoring a habitable planet is harder than sustaining one, and thus Mars presents the ultimate sustainability challenge.

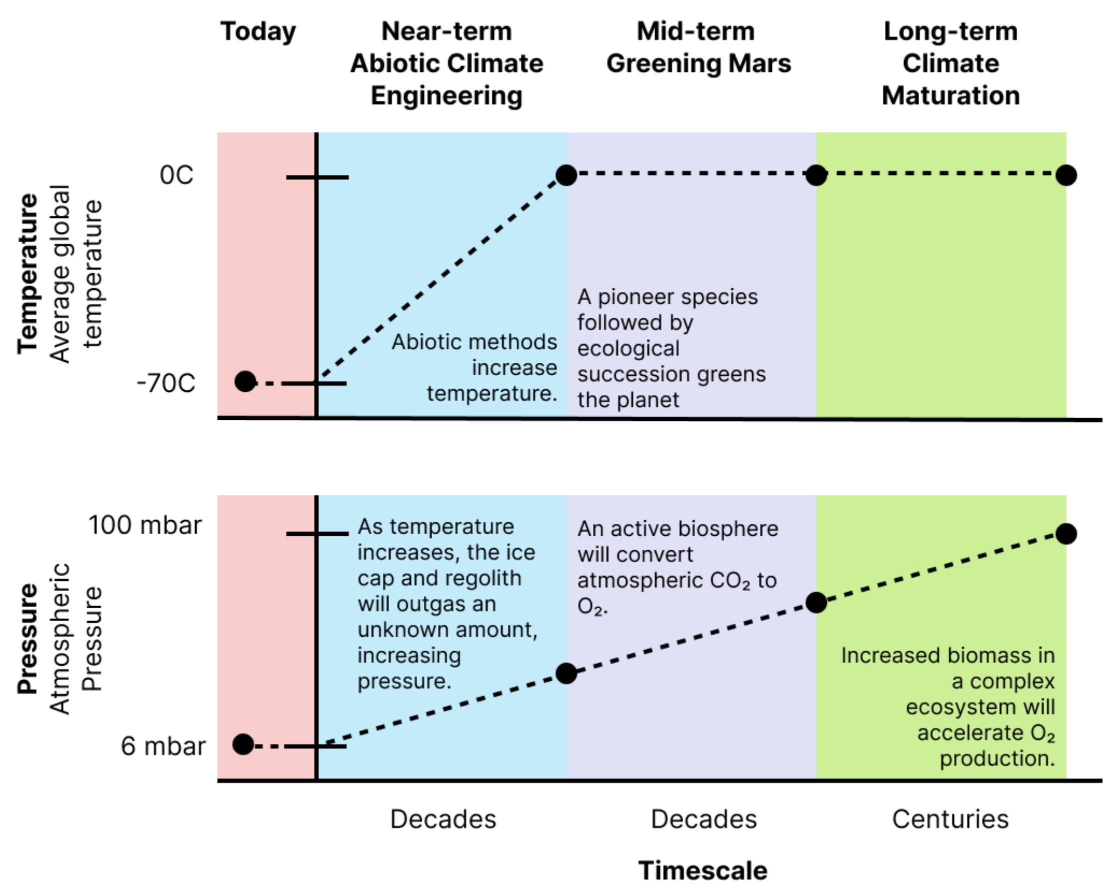

Fig. 1. Thresholds in making Mars suitable for life. A schematic of three phases of terraforming that would change two major planetary climate parameters — pressure and temperature — from their current values to an end state more suitable for complex life.

We consider three thresholds in making Mars suitable for life (Fig 1). Each threshold motivates complementary research programs that should start now. Even though the later phases are further away in time, research on all three phases will illuminate the overall costs and overall benefits of terraforming Mars and thus contribute usefully to the "should we?" discussion. The first phase in greening Mars would involve abiotic environmental engineering to heat the planet, locally and/or globally. A future, warmer Mars would pass the threshold of creating conditions over large regional scales suitable for extreme life. In the second phase, some extreme species will be able to grow within the life-compatible area. As the first step, an autotrophic, (likely) anaerobic primary producer is needed, followed by ecological succession to diversify and stabilize the ecosystem [21]. A green planet with a flourishing biosphere including algae and plants would constitute a second threshold. The third phase aims at developing a biosphere with complex plant life and perhaps trees (but not necessarily animal life), with increased O_2 content and atmospheric pressure. We now consider each phase in turn.

Short term. Thirty years ago, ref. [10] wrote "We suggest that a key goal for future exploration of Mars should be to determine the feasibility of terraforming that planet." Since then, humanity has sent dozens of missions to Mars. What have we learned?

Mars' thin atmosphere (~6 mbar CO_2) results in a global average temperature of -70° C (despite local highs exceeding 20°C). This T and P precludes pure, stable surface liquid water across much of the planet, limiting biological potential. As Mars' soil has the nutrients and volatiles needed for life [23-28], increasing liquid water availability would enable scalable biological techniques for agriculture and ecological succession, improving Mars's habitability for humans.

Mars has less H_2O than Earth, but still has at least enough ice to form a >300 m deep ocean over 10^7 km^2 of the planet [29]. However, known H_2O reserves are in the colder parts of Mars's surface [12, 30-31], with minimal confirmed water in warmer regions (2±1 wt% water-equivalent hydrogen in minerals, largely releasable at <350 °C [32]). Thus, for Mars to be livable, temperature must rise to the point where melting starts at relatively cold locations. These H_2O-ice-bearing locations are high priorities for human missions as H_2O can be processed for propellant [33], and their temperature likely needs to increase by at least 30°C to start to melt the ice. An added challenge for melting is that evaporitic cooling (where heat is absorbed as ice transforms from condensed phase to vapor) hinders ice melting on Mars, because of the large amount of energy required to transform ice into vapor [34].

Warming Mars could be achieved by increasing insolation (currently 130 W/m^2, much less than for Earth) using solar sails as mirrors to collect and reflect additional light onto the planet [5], or by enhancing the greenhouse effect. Local enhancement methods include tiling the surface with silica aerogels (solid-state greenhouse effect) or nanocellulose [17,35], while regional/global approaches include engineered aerosols [19]. These techniques appear much more mass-effective than earlier proposals based on anthropogenic atmospheric warming on Earth (using fluorocarbon gases [36]). Mars' low atmospheric thermal heat capacity ensures faster (global or local) warming responses to radiative balance changes compared to Earth.

Further research is crucial to model warming's effects on Mars's climate. Recent advances in Earth's climate models can be applied to Mars (e.g., [37]); similarly, the challenge of expanding these models to a new planet could improve predictions for both. Many effects must be carefully modeled to generate realistic predictions. Warming will perturb water, CO_2, and dust cycles [22, 38], reactivating feedbacks from wetter periods in Mars history and that could help or hinder near-future warming efforts. Atmospheric thickness will at least double as buried CO_2 ice is released [39]. While H_2O-vapor feedback is positive and cloud feedback likely positive (but of uncertain magnitude) [40], dust cycle intensification may warm the planet overall but lower peak temperatures [41]. Research is needed to track ground ice redistribution (toward the equator, or onto high ground?) as the water cycle intensifies [42-43] and to simulate dust cycle changes under warmer conditions [44]. Model intercomparisons are also needed [45].

In addition, we must determine through laboratory and numerical experiments whether proposed warming approaches can (or cannot) work. The path to deployment is long, and requires forethought. For example, engineered aerosols require laboratory validation of key microphysical parameters, and wind-tunnel studies. A small-scale field test at Mars would be needed to validate models, in turn requiring greenhouse-agent plume dispersal calculations and also monitoring instruments (which can also be used to enhance Mars weather/climate science). The need for small-scale field tests can be seen by considering the alternative: full scale deployment based on computer models only, which would be unwise. If all goes well, the next risk-aware step could be a temporary, moderate, and responsive global warming (still below the habitability threshold), to validate models of climate feedbacks. Any warming method (local or global) must be controllable, reversible within years, and biocompatible, factors that will shape deployment strategies [46].

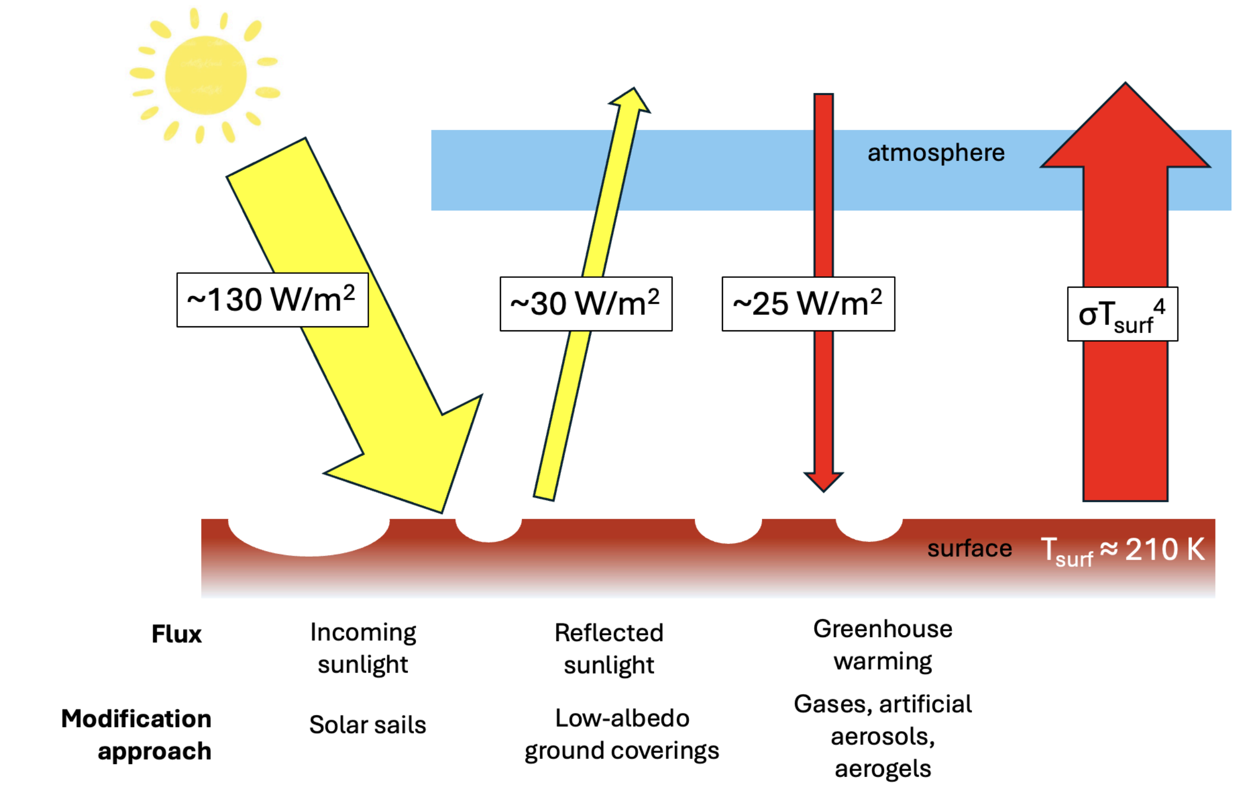

Fig. 2. Energy sources and sinks on Mars. Major shortwave (yellow) and thermal infrared (red) fluxes are depicted as arrows. The thickness of the arrows is proportional to the flux. The climate of Mars is determined by the balance between incoming and outgoing sources of energy. Presently, the net absorbed energy is E = 125 W/m^2, resulting in a surface temperature of T ≈ 210K. Adjustment of the energy sources and sinks thus alters average surface temperature.

Together, advances in Earth's launch capacity, combined with proposed new warming techniques, could potentially raise Mars' temperature by 30°C well within the century, permitting liquid H_2O for the first living organisms to grow on the surface.

Mid-term. A warmer Mars could support extreme life, initiating ecological succession towards a diverse ecosystem that begins producing an oxygen-rich atmosphere [47-48].

Engineering pioneer species capable of growth despite Mars' unique mixture of five primary stressors - low pressure, oxychlorine species, low temperature, radiation (including ionizing radiation and ultraviolet light), and low water activity (caused, for example, by high ionic concentrations in many locations) (Figure 3) - may be achievable. 1) The pioneer species would need to be anaerobic and tolerate low atmospheric pressures. Microbes can grow at Mars-like pressures of 7 mbar [12]. 2) Oxychlorine salts like perchlorate and chlorate are widespread on Mars. Fortunately, some O_2-generating microbes can use perchlorate reduction for metabolism [49, 50]. 3) The pioneer species will need to grow at cold temperatures, with large day-night temperature swings. Organisms exist that can grow at -12° C [51] and tolerate daily freeze-thaw [52]. 4) Mars radiation (while a problem for humans) is not a problem for microbes. UV-C levels on Mars are high (~3 W/m^2 of UV-C), but can be screened sufficiently while still allowing phototrophy [53-54]. 5) As Mars is heated, the first liquid water will be salty brines including mixtures of chloride and sulfate anions, potentially requiring halophilic microbes, which are plentiful on Earth.

Mars gravity has been shown to be consistent with microbial growth [55]. Other Martian conditions are potentially suitable for microbial growth (Box 1).

Box 1. Mars soil composition. Martian regolith is basaltic soil, composed primarily of silicate minerals. The pioneer organism's home - whether a surface pond, or ground water - will gain nutrients from Mars soil, whose major-element concentration is well constrained and globally uniform, and which has high concentrations of S and Cl relative to Earth soil [24-25]. Although the atmosphere lacks significant N_2, the soil contains fixed nitrogen phases, principally nitrate/nitrite (110–300 ppmw) [23]. The soil at lander sites can (by Earth standards) have high ionic concentrations but be quite nutrient-rich, and ½ kg/m^3 of organic carbon is reported from some Mars sediments [26]. Soil pH is 7.7±0.3 at 68°N [27]. Phosphate release rates during water–rock interactions on Mars are thought to be much higher than on Earth [28]. On Earth, Mars-like rocks (volcanic basalt) support diverse pioneering microbial communities [56].

Mars-adapted organisms may be developed through genetic engineering, directed evolution [57], and Mars-chamber experiments with extremophiles. This research has much overlap with existing science priorities. For example, soil sample return would refine the target habitat by allowing quantification of biocritical trace elements and possible toxins [58]. This research overlaps with Earth green biomanufacturing priorities [59].

Candidate patchy water deposits at Mars' equator (e.g., [60]) could be watering holes well-suited to attract photosynthetic organisms and (inside protective membranes) people. At this stage, we envisage microbes supporting the food and oxygen needs for 10^4 people per site [61], but with automation assisting with gardening/farming (the outside atmosphere will not be breathable). Life would only be possible within the warmest and wettest parts of the planet surface, at least initially. O_2 from perchlorate reduction and photosynthesis could be initially confined within production environments. Once O_2 is sufficient to support respiration in plants (and/or humans) within local membrane-bound environments, excess can be gradually released to the global atmosphere.

By the end of the second phase of terraforming, extremophiles could be at work to transform planetary chemistry. A warmed Mars with an oxygen- and food-producing ecosystem could allow many more people to live on Mars, and would lead the way for a more complex ecosystem and thicker atmosphere.

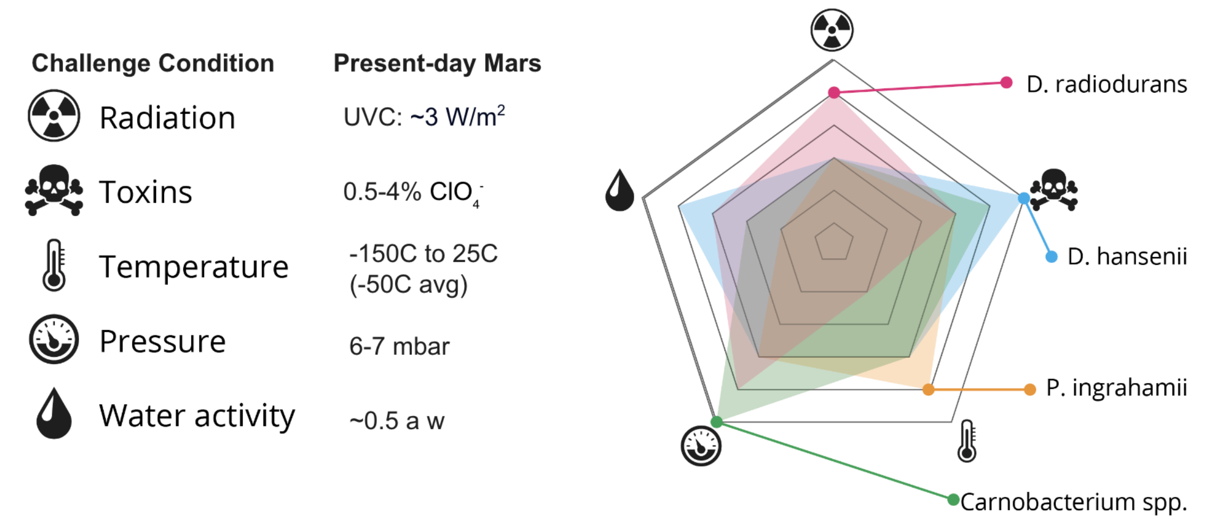

Fig. 3. Present-day extremophiles in Mars-like conditions. A spider plot of known extremophiles and their properties, with higher tolerance farther from the center. Known extremophiles can tolerate conditions approaching or exceeding those found on Mars, including survival of Mars-like UV-C doses [80], *Debaryomyces hansenii* growth in 23% perchlorate salt [81], *Psychromonas ingrahamii* at -12°C [29], and *Carnobacterium sp* growth at 7 mbar [27].

Terraforming and the search for extant Martian life. The idea of terraforming Mars emphasizes the motivation to support people living beyond Earth. There is some reluctance among planetary scientists to contemplate adding more Earth-derived life to Mars (beyond what is already added by landed spacecraft [62]), because Earth microbes might be confused for (or supplant) Mars-derived life, if it exists. This is mitigated by the recognition that landing humans on Mars will introduce orders of magnitude more Earth microbes to the Mars environment (a major finding of the 2019 NASA Planetary Protection Independent Review Board; [62]). Therefore, with humans living on Mars in the near future, a concerted effort is needed to determine if Mars has life. This could be greatly aided by human outposts, and should include soil sample return, and sounding for deep aquifers [63]. If life is detected, then its scientific importance could warrant robust protections for its habitat.

Long term. Once Mars possesses a planetary ecosystem, it would continue to develop over the long-term. One of us (McKay) has argued that the long-term goal for astrobiology should be to enhance the richness and diversity of life in the Universe [64]. What would a target atmosphere for Mars look like? Key *in situ* sources of volatiles include H_2O and CO_2. H_2O can be used to create O_2. CO_2 will be released naturally as the planet warms, and can also be extracted from carbonates - but high levels of CO_2

are toxic to humans [65]. Notably, Mars lacks an obvious source of *in situ* inert gas that might take the role of N_2 in Earth's atmosphere. A 0.1 bar O_2 atmosphere could satisfy human habitability requirements, including breathability and reducing Mars surface radiation to Earth-airliner levels. O_2 levels cannot rise too high however due to the growing risks of uncontrolled combustion. Together, a target atmosphere containing 100 mbar O_2 satisfies all these requirements: feasible to achieve entirely with *in situ* atoms and suitable for human habitation. This atmosphere could be generated within 1-2 years in 100-meter tall domes using photosynthesis or water electrolysis [66].

In addition to domed habitats suitable for humans without pressure suits, more species could inhabit the surface, albeit at lower pressure. As O_2 builds up, more species could live on the surface, and the fraction of (potentially tented/domed) Mars surface area where humans could breathe would increase. An intriguing possibility is self-extending (similar to coral reefs) O_2-impermeable membranes produced by life [17,67]. Organisms or their biofilms might also modulate planetary energy balance through albedo effects and solid-state greenhouse warming [17,68].

While rapid greening of Mars may be possible, establishing a global 0.1 bar O_2 atmosphere through photosynthesis alone would take millennia. Oxygenation via photosynthesis would involve complex biogeochemical cycles [69,70], including O_3 shield formation and organic matter sequestration.

Historically, Mars has experienced relatively wetter and drier periods, at least regionally, with its extensive high-elevation surfaces that trap water as high albedo ice caps being a major factor [42]. Climate stabilization would require understanding water movement between oceans, high-elevation ice, and subsurface aquifers (and its impact on albedo and thus temperature), as well as potential water loss to the deep subsurface through taliks (layers of unfrozen water in permafrost, or permanently frozen ground).

Thus, research needs include improved climate models and more spacecraft data to assess long-term climate possibilities. Future missions [63] to determine what lies beneath the ground ice that is known to exist over at least one-third of Mars's surface - liquid water, or empty pore space, or more water ice - will be important for setting how large Martian lakes and seas can be. After the use of light to split water is well-established, oxygen build-up will require electron acceptors. Quantifying reservoirs of electron acceptors - including sulfates/Fe-oxides, and CO_2 from various sources ($\lesssim$100 mbar [71-72]) or carbonate - is essential, as if electron acceptors are in short supply then it will not be possible for humans to breathe unaided on the surface without expensive importation of volatiles from beyond Mars. It has long been recognized that currently unknown surface and subsurface reservoirs of CO_2, H_2O and nitrate are key to enabling a global biosphere on Mars [10,71]. Discoveries are ongoing: in 2023, the *Curiosity* rover discovered abundant carbonate not seen from orbit [73].

If this stage succeeds, the planet would have a stable, favorable climate, and support a diverse planetary biosphere. The outcome would be something new and different - not a replacement for Earth, but an addition.

The futures of Mars. New ideas for Mars' future have emerged that are sustainable, resilient, and ecologically minded [74]. Technologies developed for Mars habitation, such as desiccation-resistant crops, efficiently remediating soil, and improved ecosystem modeling [21], will likely benefit Earth. Rather than distracting from Earth's problems, Mars terraforming research could provide insights for maintaining oasis Earth, expanding rather than diminishing our environmental responsibility. Mars terraforming research offers a vital testbed for planetary science, potentially validating theories or exposing knowledge gaps. Continued research promises significant scientific progress, regardless of whether full-scale terraforming occurs.

While the possibilities are exciting, anything as big as modification of a planetary climate has major consequences, and would require careful thought once we reached the point where it was feasible. But until we do more research, we don't even know what's physically or biologically possible. Therefore, further Mars exploration is crucial. Priorities include quantifying H_2O, N_2, and CO_2 reserves (e.g., searching for deep aquifers [63]), soil sample return, test missions for proof-of-concept of warming methods, and climate feedback studies. These align with existing mission priorities [75,58]: for example, ice deposit investigations [76] constrain the extent of resources whose abundance could fuel (or restrict) terraforming, and geologically-recent warm climates [40,77] are a natural analog for a near-future warmed Mars. Current Mars Exploration Program Analysis Group goals already support human exploration [75]. No abrupt change of course is needed: indeed, support for people living on Mars provides fresh rationale for many existing mission priorities, alongside precursor/test missions.

Beyond our Solar System, rocky planets are common [78], but worlds that are ready for life will be rare. If people can learn how to terraform a world such as Mars, this may be the first step to destinations beyond. More speculatively, the technologies eventually determined to best enable terraforming will refine our ability to search for technosignatures [79].

Fully terraforming Mars would be (at least) a multi-century project. This is a vast timescale during which Earth's politics will change. What will not change are the physical, chemical and biological constraints - the science - that can be uncovered only through more research.

When people start to live on Mars, "they will inevitably introduce orders of magnitude more terrestrial microorganisms to Mars than robotic missions have done or will do" [62]. The open question is whether we engage with Mars in an informed way, or an uninformed way. As large corporations and governments contemplate Mars terraforming, we suggest that science must have an important role to play. This is only possible if research accelerates appropriately to keep pace with Mars-access capabilities.

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E.D. and E.S.K. conceived the initial idea. E.S.K. wrote the first draft with substantial input from E.D. All authors discussed the topics in the paper, contributed to the writing and commented on the evolving drafts.