Planetary Ecosynthesis on Mars: Restoration Ecology and Environmental Ethics

Christopher P. McKay
NASA Ames Research Center
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1. Introduction

There has been a lively discussion recently about the science and ethics of "terraforming" Mars. The high level of interest is a result of spacecraft discoveries about Mars combined with the realization that humans are effectively warming the Earth and wondering if they can, and should, do the same on Mars. I suggest that terraforming is more appropriately called planetary ecosynthesis, and in this Chapter I review the scientific studies of planetary ecosynthesis and the environmental ethics associated with instigating such global change on another planet.

Mars today is a cold, dry, frozen desert world on which not even the most hardy of Earth life could survive. Temperatures average -60^{o}C and the pressure averages 0.6 kPa, over one hundred times less than atmospheric pressure at the surface of the Earth. As a result of the low pressure, and secondarily the low temperature, water is not liquid on the surface of Mars at any location or season. Strong solar ultraviolet radiation reaches the surface of Mars to complete the deadly mix of hostile environmental conditions.

But Mars has not always been this harsh. There is compelling evidence that early in its history Mars had stable liquid water on its surface [1, 2]. Presumably this phase of liquid water was associated with a higher pressure and somewhat warmer atmosphere. This evidence for liquid water on Mars – originally from the Mariner 9 and Viking missions and now confirmed by recent missions – is the central motivation for the search for past life on Mars (e.g.[3, 4]).

The fact that Mars once supported widespread liquid water and possibly life on its' surface opens the question of the feasibility of restoring such conditions on Mars by artificial means. The fundamental challenge of restoring habitable conditions on Mars is to warm up the planet from its current -60^{o}C to over 0^{o}C, and perhaps as warm as $+15^{o}$C – reaching parity with Earth. Humans have demonstrated, and implemented, the technology to warm planets with Earth as our first target. The level of human-induced warming on Earth is debated but is probably on the order of a few degrees. On Mars the warming needed would be tens of degrees – a hundred times larger than on Earth – but the extrapolation from Earth to Mars is conceptually straightforward. Energy balance calculations suggest that warming Mars might be achieved in 100 years or less [5, 6]. Producing an oxygen rich atmosphere would take more than 100,000 years. Thus, warming Mars is within current technology and this fact frames the discussion about Mars in a fundamentally different way than planetary scale environmental alteration on any other world of the Solar System. Because the question of "can we" has been tentatively answered for Mars in the affirmative, the question of "should we" and "will we" warrant consideration.

The scientific issues associated with planetary ecosysnthesis on Mars have been discussed in the scientific literature for decades. Initial discussions were limited [7-10] until "Making Mars Habitable" was featured on the cover of *Nature* magazine and the field was rightly considered to have entered mainstream scientific discussion [5]. There are currently two international science journals, *Astrobiology* and the *International Journal of Astrobiology* that explicitly consider planetary ecosynthesis as part of their content.

2. Conditions needed for habitability

The first step in considering ecosynthesis on Mars is the delineation of the requirements for habitability. We tend to think of the present Earth as the only model for a habitable world. However, there are two alternative possibilities for life supporting states for Mars, one with oxygen and one without. These two alternative states are listed in Table 1, adapted from McKay et al. [5]. Life could survive on Mars in an atmosphere composed of carbon dioxide with moderate levels of nitrogen and low levels of oxygen. Such an atmosphere is thought to have prevailed on Earth before the rise of oxygen 2 Gyr ago. It is also the likely composition of a thick early atmosphere on Mars. Many bacteria, some plants and even a few animals can survive in low oxygen atmospheres. Humans would require a source of oxygen and could not breath the high carbon dioxide.

A second habitable state to consider is an oxygen-rich atmosphere that is essentially the same as on the present Earth. As we discuss below it appears feasible to create a habitable state on Mars based on a carbon dioxide rich atmosphere but it is not feasible to create an oxygen-rich atmosphere.

Table 1. Habitability (adapted from McKay *et al.* [5]).

Parameter	Limits	Note
Global temperature	0°C - 30°C	Earth = 15°C
Composition for plants, algae, microorganisms		
Total pressure	> 1 kPa	Water vapor pressure plus O_2, N_2, CO_2
CO_2	>0.015 kPa	Lower limit set by photosynthesis
		No clear upper limit
N_2	>0.1 - 1 kPa	Nitrogen fixation
O_2	>0.1 kPa	Plant respiration
Composition for breathable air		
Total pressure:		
Pure O_2	> 25 kPa	Lung water vapor plus CO_2, O_2
Air mixture	> 50 kPa	Based upon high elevation
	< 500 kPa	Buffer gas narcosis
CO_2	< 1 kPa	Set by toxicity
N_2	> 30 kPa	Buffer gas
O_2	> 13 kPa	Lower limit set by hypoxia
	< 30 kPa	Upper limit set by flammability

Figure 1. Liquid water in the past on Mars. Mars Global Surveyor image showing Nanedi vallis in the Xanthe Terra region of Mars. Image covers an area 9.8 km by 18.5 km; the canyon is about 2.5 km wide. This image is the best evidence we have that some of the fluvial features on Mars were carved by liquid water in stable flow on the surface for an extended interval. Photo from NASA/Malin Space Sciences.

3. What went wrong with Mars?

There is compelling evidence that Mars had more habitable conditions in the past. However, it is not clear what happened to the atmosphere and hydrosphere of early Mars. It is generally thought that Mars lost its carbon dioxide atmosphere through a combination of processes all related to its small size (Mars is 1/10 the mass of the Earth, Mars and Earth are compared in Table 2). These processes include the formation of carbonates, loss to space due to solar wind sputtering, and atmospheric erosion due to impacts of comets and asteroids. The relative importance of these processes is debated (see, e.g. [11]) but these processes all occur on Earth as well. They are more pronounced on Mars because it is so much smaller than the Earth.

Earth is large enough that its internal heat flow can drive plate tectonics. Mars has a single thick plate. As a result Mars does not have the recycling of material that results from the subduction of one plate under another and the ejection of gases in the resulting arc volcanoes. The gases emitted from arc volcanoes such as Mt. St. Helens in the Cascade Range represent the recycling of material into the atmosphere by plate tectonics. Mars is too small to have plate tectonics and hence has no way to recycle materials such as carbonates. The lack of recycling and high loss rates due to lower gravity and no magnetic field are thought to be responsible for the loss of most of the carbon dioxide of the early martian atmosphere. The amount of CO_2 still present on Mars is unknown.

Table 2. Comparison of Mars and Earth.

Parameter	Mars	Earth
Mass	0.107	1
Surface pressure	0.5 to 1 kPa	101.3 kPa
Average temperature	-60ºC	+15ºC
Temperature range	-120ºC to +25ºC	-80ºC to +50ºC
Atmosphere composition	95% CO_2 2.7% N_2 1.6% Ar	78% N_2 21% O_2 1% Ar
Incident sunlight	149 W m^{-2}	344 W m^{-2}
Surface gravity	3.73 m s^{-2}	9.80 m s^{-2}
Solar day	24h 39m 35.238s ("sol")	24 h
Sidereal year	687 days, 668.6 sols	365.26 days
Obliquity of axis	25 deg	23.5 deg
Eccentricity	0.0934	0.0167
Mean distance to sun	1.52 AU	1 AU (1.49×10^8 km)

Figure 2. Warming of Mars due to simple fluorine-based gas independently and the best gases combination (dashed line) for the given total greenhouse gas amounts ($PCO_2 = 0.6$ kPa) from Marinova et al. (2005).

There may have also been some loss of the initial water on Mars but a large part of it is still present on Mars --- frozen into the ground in the polar regions. Based on the morphology of the craters in the polar regions of Mars, it was deduced that the ground there is rich in ice [12]. Direct confirmation came from the gamma ray and neutron detectors on the Mars Odyssey mission which indicated the presence of ice-rich ground in the upper two meters for latitudes poleward of about 60° in both hemispheres [13].

Radar results indicate that this ice-rich ground extends down to 2 km or more in the northern hemisphere [14]. A veritable frozen ocean of water is still present on Mars.

The factors that resulted in Mars' loss of habitability are related to its small size and resulting lack of plate tectonics. These are not factors that can be changed with foreseeable technologies. Therefore, one possible objection to ecosynthesis on Mars is that it would be doomed to fail over geological time due to the same factors that doomed an initial habitable environment on Mars. The logic of this argument is correct: Mars' newly restored to habitability would only have a finite lifetime. This lifetime would be approximately given by the timescale of the removal of the atmosphere due to carbonate formation, about 10 to 100 million years. This is a short time compared to the age of Mars – 4.5 billion years – but a long time compared to human timescales. It is relevant here to note that Earth will not remain habitable much longer than this timescale. Current estimates suggest that Earth will become uninhabitable in 500 million years or less as it becomes become Venus-like due to the progressive brightening of the Sun [15]. Thus, a habitable Mars that persists for 10 to 100 million years is "Earth-like" in terms of its life expectancy. No solutions for infinite lifetime exist for Mars or Earth. Nothing lasts forever, not even the Earth and sky [16].

As discussed above, it appears certain that Mars still has a vast amount of water, albeit frozen in the ground. The total CO_2 amount on Mars, as carbonate, absorbed gas in the soil, or frozen in the polar caps is unknown. There is only about 0.6 kPa of CO_2 in the atmosphere at the present time but estimates of the total CO_2 in the soil, atmosphere and cap range from as low as a few kPa to as high as 100 kPa [17].

A biosphere requires large amounts of CO_2 and H_2O but also N_2. Nitrogen gas is essential for a breathable atmosphere (see Table 1) and nitrogen is needed by life as an essential macronutrient. The only known supply of nitrogen on Mars is in the atmosphere at a level of 0.016 kPa, a tiny amount compared to the 80 kPa of N_2 in Earth's atmosphere. If this nitrogen were entirely converted to biological material it would only form a layer only 1 cm thick. Mars cannot support a biosphere if the current atmospheric N_2 is the total nitrogen available on the planet. Unfortunately, there is no data on the amount of nitrogen in the soil of Mars as nitrate. Theoretical arguments suggest that lightning and meteorites should have produced nitrates on Mars and there may be up to 30 kPa present [17,18]. The question of the nitrogen supply is probably the key question in terms of the feasibility of ecosynthesis on Mars using near-term technologies.

Mars does not have a planetary magnetic field but probably does not need one to be habitable. There are two primary reasons that a magnetic field is sometimes proposed as required for habitability 1) to provide shielding against radiation and 2) to prevent solar wind erosion of a thick martian atmosphere.

4. Radiation protection

The Earth's magnetic field does not deflect galactic cosmic rays because these particles are much too energetic. These particles are primarily stopped by the mass of the Earth's atmosphere which is equivalent to 1 kg cm^{-2}. The Earth's magnetic field does deflect solar protons, channeling these particles to the polar regions creating the aurora. However, even without the magnetic field these particles would not penetrate the Earth's atmosphere and would not reach the surface.

If Mars had an Earth-like surface pressure of 1 atm, its atmospheric mass would be 2.6 kg cm^{-2} due to the lower gravity (to reach the same surface pressure with a lower gravity, 0.38 g, requires a more massive atmosphere). Thus, the radiation shielding effects of the martian atmosphere would exceed those for the Earth and a magnetic field is not essential for radiation protection. Furthermore, Earth occasionally loses its strong dipole field during field reversals. These events are not correlated with any increases in extinctions in the fossil record.

5. Atmospheric erosion

Because Mars (and Venus) do not have magnetic fields, the solar wind impacts directly on the upper atmospheres of these planets. This does result in a small rate of atmospheric loss at the present time. However, the loss rate would not increase if we increased the surface pressure of the martian atmosphere. This is due to the fact that conditions at the top of a thicker atmosphere would be similar to the conditions at the top of the present atmosphere only raised by a small elevation. For example, if the surface pressure on Mars were to increase to one atmosphere, the low pressure regions of the atmosphere would be raised in altitude. We can estimate the height change by computing the scale height in a warm Earth-like martian atmosphere (Because scale height is inverse with gravity and Mars' gravity is 0.38 times Earth, and inverse with mean molecular weight; Mars 44, Earth 29, the scale height on Mars would be 14 km, compared to 8 km on Earth). To increase the pressure on Mars from 0.6 kPa to 100 kPa requires a pressure increase of 166 or 5.1 scale heights ($e^{5.1} = 164$) resulting in an altitude gain of 71 km for the upper atmosphere. This is a tiny increment compared to the radius of the planet. Thus, the top of the atmosphere would feel essentially the same gravity as it does today and would feel the solar wind at the same intensity. The net result is that the erosion of gases from the martian atmosphere by the solar wind would remain unchanged. The current loss rate is not significant; for example the loss rate of water on Mars today corresponds to the loss of a layer of water two meters thick over 4 billion years (e.g. [19]).

6. Energy and time requirements

The discussion above shows that the necessary materials to construct a biosphere are likely to be present on Mars and that in addition the fundamental physical aspects of Mars that would be virtually impossible to alter such as axial tilt, rotation rate, and eccentricity, are similar to the corresponding values for Earth (see Table 2). The one exception is the surface gravity, which is 0.38 of the Earth value. It is typically assumed that life from Earth can accommodate this lower gravity but this has not yet been tested.

If the physical materials are present, the next question in determining the feasibility of planetary ecosynthesis on Mars is to compute the energy and time required to affect the desired change. The problem naturally divides into two phases [5, 6]. Phase 1 is warming Mars from the present cold state and restoring the thick atmosphere of CO_2. Phase 2 is the production of O_2 in sufficient quantities to be breathable by humans. The energy requirements of each phase are listed in Table 3 and are also expressed in terms of the sunlight incident on Mars. Trapping and using sunlight is the only plausible energy source for changing the environment on a global scale. From Table 3 we can see that if the sunlight incident on Mars could be utilized with 100% efficiency it would take only ~10 years to warm Mars and restore the thick CO_2 atmosphere. Clearly 100% efficiency is an overestimate but atmospheric supergreenhouse gases, as discussed in the next section, can effectively alter the energy balance of a planet and efficiencies of 10% are plausible. Thus, the timescale for warming Mars is ~100 years.

Table 3. Energy Requirements for Terraforming Mars

Initial State	Final State	Amount	Energy [J m^{-2}]	Solar Energy[a] [years]	Time [years]
		Surface Warming			
CO_2(s) at 125°C	CO_2(g) at 15°C	200 kPa; 5.4×10^4 kg m^{-2}	3.7×10^{10}	7.9	
Dirt at -60°C	Dirt at 15°C	~10 m; 2×10^4 kg m^{-2}	1.2×10^9	0.3	
H_2O(s) at -60°C	H_2O(l) at 15°C	10 m; 1×10^4 kg m^{-2}	5.5×10^9	1.2	
H_2O(s) at -60°C	H_2O(g) at 15°C	2 kPa; 5.4×10^2 kg m^{-2}	1.6×10^9	0.33	
			Total:	10	100
		Deep Warming			
H_2O(s) at -60°C	H_2O(l) at 15°C	500 m; 5×10^5 kg m^{-2}	2.8×10^{11}	56	500
		Making O_2			
$CO_2(g) + H_2O$	$CH_2O + O_2(g)$	20 kPa; 5.4×10^3 kg m^{-2}	8×10^{10}	17	100000

[a] Energy divided by the total solar energy reaching Mars in a year, 4.68×10^9 J m^{-2} yr^{-1}
Adapted from McKay et al. [5].

To produce a level of breathable O_2 from CO_2 on Mars would require the energy equivalent of 17 years of Martian sunlight. While the energy level here is comparable to the energy to warm Mars, the efficiency is much lower. Because of basic thermodynamic constraints, the efficiencies for warming are much higher than the efficiencies for causing chemical reactions. Sunlight will not spontaneously produce O_2 from CO_2: a mechanism to drive the reaction is required. The only known mechanism that can operate on a global scale and use sunlight to convert CO_2 to O_2 is a biosphere. This conversion is precisely the reaction that produces biomass in the Earth's biosphere. Given that the Earth has an extensive biosphere that has been utilizing this reaction for billions of years, the efficiency of the Earth's biosphere is a plausible upper limit to the efficiency of a Martian biosphere. The production of biomass on Earth corresponds to the energy equivalent of 0.01% of the energy incident on the Earth as sunlight. Assuming this optimistic efficiency it would take over 100,000 years to produce the minimal breathable O_2 levels on Mars as defined in Table 1. Clearly this efficiency for Earth is an average over all of the Earth's biomes with widely different individual efficiencies, from dry deserts to lush rain forests. If a planet could be entirely covered with rain forests then clearly the efficiency would go up, maybe as much as a factor of 10. However, a global biosphere on Mars is likely to have a range of ecosystems just as does the Earth. The long timescale indicated by this calculation is not a precise prediction but it is a robust indicator that producing a breathable O_2 atmosphere on Mars will take many thousands, or hundreds of thousands, of years.

Energetic considerations indicate that warming Mars and restoring a thick CO_2 atmosphere could be accomplished over human timescales (~100 years). Altering the atmosphere to make it breathable to humans (~20% O_2) is not possible with present technologies for all intents and purposes.

7. Warming Mars

There have been many proposed methods for warming Mars (see [20]) but the only one that is clearly rooted in demonstrated technology is based on supergreenhouse gases. Originally suggested by Lovelock and Allaby [21] and worked out in detail by Marinova et al. [22] the basic idea is to use supergreenhouse gases to increase the greenhouse effect on Mars. Marinova et al [22] considered the production on Mars of supergreenhouse gases composed only of F, S, C and H. Supergreenhouse gases containing Cl and Br were specifically excluded from consideration because of the deleterious effect these chemical species have on ozone. Climate calculations have shown that if there is CO_2 ice present in the polar regions of Mars, then a warming of 20°C will cause the complete evaporation of that ice through a positive feedback mechanism [5, 21]. The results of the atmospheric energy balance calculations of Marinonva et al. [22] indicate that the production of fluorine-based gases at levels of 0.1 to 1 Pa is a possible way to increase the mean Mars temperature to the levels necessary to cause the outgassing and evaporation of all available CO_2 ice on Mars. Figure 2 shows the temperature increase for the present Mars for several gases. Of the gases considered, C_3F_8 was the most potent artificial greenhouse gas for use on the present Mars. Less than 1 Pa of C_3F_8 (a few ppm in an Earth-like atmosphere) would result in sufficient warming of Mars to cause complete CO_2 outgassing.

Releasing CO_2 is a key step in warming Mars because CO_2 contributes to the greenhouse effect and thus a positive feedback on further CO_2 release. Furthermore, CO_2 is the most readily available gas on Mars to bring the pressure up high enough that liquid water can be stable.

8. Ethics

In the previous sections I have briefly summarized the state of our scientific understanding of the possibilities of planetary ecosynthesis on Mars. More detailed reviews can be found in McKay et al. [5], Fogg [20], Marinova et al. [22] and Graham [23]. I suggest the following conclusions based on the scientific literature:

1. It is likely that Mars has adequate amounts of CO_2, H_2O, and N_2 for the construction of a biosphere.

2. The timescale for warming Mars and restoring a thick CO_2 atmosphere is relatively short (~100 years). However, it is not practical to create a breathable (~20% O_2) atmosphere on Mars.

3. If restored to habitability Mars would maintain its habitable state for 10 to 100 million years.

4. Supergreenhouse gases based on F, S, C and H could be produced on Mars and used to warm the planet. Human-produced supergreenhouse gases are currently

warming the Earth. Concentrations 100 to 1000 times higher than the anthropogenic levels in Earth's atmosphere are needed on Mars.

5. The scientific community considers planetary ecosynthesis on Mars as a serious topic in space research.

The fact that we are altering the Earth's global climate and the possibility that using the same methods we "can" alter the habitability of Mars implies that the question of "should" we conduct planetary ecosynthesis is a timely and relevant one. The environmental ethics of planetary ecosynthesis on Mars is therefore a subject for consideration and in the rest of the chapter I provide some preliminary observations.

Environmental ethics has developed on Earth and mostly in response to environmental crises. It is perhaps not surprising that extrapolating environmental ethics to an apparently lifeless world is not straightforward. The universal yet unexamined assumption of environmental ethics is that nature is equivalent to life. On Earth this equivalence is obviously true. No aspect of the environment on Earth can be considered separate from biological effects. Most systems of environmental ethics have not attempted to make any meaningful distinction between nature and life. Consider as an example the "Land Ethic" articulated by Aldo Leopold [24]. "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise." As I have discussed before [25]) it is unclear how to apply this to Mars. Indeed as we leave the Earth we see that the equivalence of life and nature is, as far as we now know, only applicable to Earth. Everywhere else in our Solar System we encounter nature that is profoundly devoid of life. The fundamental challenge in applying environmental ethics beyond the Earth is to delve one level deeper than has been necessary on Earth and examine the difference between the environmental ethics of nature and the environmental ethics of life.

I have argued ([25]) that to understand the difference between nature and life in a system of environmental ethics requires a clarification of the fundamental assumptions – the normative axioms – on which the system is based. Systems of environmental ethics are based on varying combinations of three normative axioms which I identify as

1. Preservationism. The fundamental principle that nature is not to be altered by human beings.

2. Wise stewardship. The fundamental principle that the measure of all things is utility to humans, in the broadest and wisest sense of utility.

3. Intrinsic worth. The fundamental principle that there exist sets of objects which have intrinsic worth regardless of their instrumental value to humans.

These are principles on which systems of environmental ethics are based and not categories into which systems of environmental ethics are grouped. Furthermore, they are not mutually exclusive. Indeed, virtually all systems of environmental ethics are based on some combination of these principles in varying degrees. Anti-humanism as expressed by Ehrenfeld [26] is an extreme form of preservationism in which all human actions are to be suppressed. Anti-humanism was the original label used by McKay [25]. Rolston [27] and Hargrove [28] provide a more balanced view of preservationism and suggest the term now used here.

Wise stewardship is certainly the most common and influential fundamental principle in environmental ethics. It is so pervasive that it is often assumed without statement. The most common argument in environmental ethics is that we humans jeopardize our own interests when we degrade the environment.

The third fundamental principle listed above is relatively recent and not fully developed in the environmental ethics literature. The principle of intrinsic worth posits that there are sets of objects which have value of themselves independent of any instrumental or intellectual utility to other beings. The principle itself has wide adherence if the set of intrinsic objects is restricted to human beings. Historically the restrictions were more severe, but over time the sphere of consideration has expanded along the dimensions of race, gender, disability, and ethnicity so that now virtually everyone would agree that all humans are in the set of objects with intrinsic worth. There have been serious arguments presented to expand the sphere of consideration to non-human animals [29] to ecosystems [30] and to all life itself [31, 32]. In all cases the discussion has been in the context of life forms of intrinsic worth pre-existing within the state of nature. No choice between nature and life forms of intrinsic worth has been considered. However, this is just the choice we face on Mars. The state of nature is lifeless and we have before us a choice to replace that state with a state with life forms of intrinsic worth. If richness and diversity in life forms is a value in itself, then planetary ecosynthesis on Mars is a good thing.

9. Utilitarian motivations for planetary ecosynthesis on Mars

Given the importance of the utilitarian principle in environmental ethics it is instructive to consider how planetary ecosynthesis on Mars is – or is not useful – to humans.

Mars is not useful as a “lifeboat” to which humanity flees after having destroyed the Earth. This is a common idea in science fiction but has no technical basis. Past migrations of people have occurred in which a significant fraction of the population relocates over a great distance. An example is the Irish migration to North America. However, this example does not hold for space travel. Any foreseeable technology for space travel involves only a very small number of travelers.

The advantages of a small number of humans and assorted life forms from Earth present on Mars as a genetic “Noah’s ark” are dubious as well. There are certainly possible scenarios, such as a large asteroid strike or unchecked plague, in which large fractions of the human population on Earth are killed, but even if the survival rate on Earth was one in a million the residual population would be huge compared to any plausible population on Mars. Events that could literally sterilize the Earth – such as a nearby supernova and the sun entering the red giant stage – would also sterilize Mars.

Finally the idea that a human colony present on Mars or the prospect of making Mars habitable would allow us, or cause us, to disregard environmental principles on Earth is absurd.

A more plausible utilitarian value that can be obtained from planetary ecosynthesis on Mars is the knowledge that we, human society, would derive from such activities. Humans have global effect on the environment of Earth and our effects are growing as our population and technology increase. It is therefore inevitable that humans will assume some management responsibility for the Earth's environment. The view that the environment is self regulating and does not require human intervention is not tenable if humans continue to have such a growing impact. Understanding the Earth well enough to manage it is a daunting task. Clearly the knowledge needed for this task will primarily be obtained from studies of the Earth itself. However, studies of other planets can provide important comparison points and context for the Earth. Along these lines, studies of planetary ecosynthesis on Mars could provide important lessons as to how a biosphere can work. The words left on Richard Feynman's blackboard on his last day of work "What I cannot create I do not understand" expresses this point. An essential task in understanding, and managing the biosphere on Earth, may be the creation of a biosphere on Mars.

The potential knowledge to be gained by studying ecology on Mars is greatly increased if Mars has indigenous life that represents a separate origin from life on Earth [33]. Throughout this discussion I have assumed that Mars is a lifeless planet. However, it is possible that Mars has life either in secluded habitable zones or frozen dormant in the polar ices. If there is life on Mars, or was life, it may share a common origin with life on Earth or it may represent an independent origin of life. As recently as a decade ago it was assumed that if there was life on Mars it would have to represent an independent origin since it was present on a different planet. However, we now know that rocks from Mars have reached Earth intact and furthermore that the temperatures in these rocks would not reach sterilizing levels during the trip [34]. These rocks are the result of impacts on Mars ejecting material into space. Early in the history of the Solar System the impact, and hence transfer rate, would have been much higher. Thus, life from Mars could have been carried to Earth inside one of these rocks. Presumably the converse is also true – rocks from Earth could have carried life from Earth to Mars. Because of this interplanetary rock transfer it is no longer assumed that life on Mars would necessarily be of a separate origin. Indeed most researchers would consider that the most likely case would be a common origin for life on Earth and Mars and convincing evidence to the contrary would be required before it was concluded that Mars had an independent origin of life.

If there has never been life on Mars then there are minimal implications for planetary ecosynthesis. If there was life on Mars and it is now extinct beyond recovery, then planetary ecosynthesis can be viewed as a type of "restoration ecology". If there is life on Mars, or recoverable life, but it shares a common ancestor with life on Earth then it seems plausible that planetary ecosynthesis can proceed using Earth life forms as needed.

Perhaps the most interesting and challenging case is that in which Mars has, or had, life and this life represents a distinct and second genesis [35, 36]. The discovery of a second genesis of life has profound scientific, as well as philosophical and ethical importance. Philosophically, the discovery would directly address the question of life in the universe, and would strongly support the idea that life is a naturally emergent phenomenon and is widespread and diverse in the universe. Scientifically, having another example of life expands the scope of biology from one to two. There may well be significant advances in medicine, agriculture, pest control, and many other fields of biological inquiry, from having a second type of life to study. I would argue that if there is a second genesis of life on Mars, its enormous potential for practical benefit to humans in terms of knowledge should motivate us to preserve it and to enhance conditions for its growth. Observations of Mars show that currently there is no global biosphere on that planet and if life is present it is in isolated refugia or dormant. It is possible that life present on Mars today is at risk of extinction if we do not alter the Martian environment so as to enhance its global habitability.

An appreciation for the potential utility and value of the restoration of a Martian biota does not depend on the assignment of intrinsic value to alternative lifeforms. The creation of a second biosphere using a second genesis of life could be of great utilitarian value for humans in terms of the knowledge derived ranging from basic biology to global ecology. And a case can be made [35] that its' value exceeds the opportunity cost of not establishing human settlements on Mars.

The utilitarian arguments presented above indicate that we should alter Mars to allow any indigenous life to expand and form a global biosphere even if the resulting biosphere is never a natural home for life from Earth or humans. If there is no indigenous life, these utilitarian arguments indicate that we should alter Mars to support life from Earth even if this never results in a biosphere that can be a natural home for humans. The point is only a theoretical one since our current understanding of Mars and planetary physics suggests that it is not possible using foreseeable technology to make Mars into a world that can be an Earth-like home for humans. Humans would require some sort of O_2 source to move around the planet – a significant improvement in habitability compared to the current state.

This discussion has implications for near-term exploration of Mars by robots and humans. Until we know the nature life on Mars and its relationship – if any – to life on Earth, we must explore Mars in a way that keeps our options open with respect to future life. I have argued elsewhere [36] that this means that we must explore Mars in a way that is biologically reversible. Exploration is biologically reversible if it is possible and practical to remove all life forms carried to Mars by that exploration. Because of the high UV and oxidizing conditions on Mars, biological reversibility is achievable. Previous missions to Mars, such as the Pathfinder mission and the two MER rovers, have carried microorganisms to the martian surface where they remain dormant as long as shielded from ultraviolet radiation. To reverse this contamination already present on Mars, it would be necessary to collect all metal objects within which microbes could remain viable. Furthermore, the soil at crash sites and in the vicinity of landers that had come into contact with the spacecraft would have to be thrown up into the atmosphere where it would be exposed to sterilizing ultraviolet radiation. A similar approach can be used to reverse the contamination from human bases.

10. Summary

Planetary ecosynthesis on Mars is being seriously discussed within the field of planetary science. It appears that restoring a thick atmosphere on Mars and the recreation of an environment habitable to many forms of life is possible. It is important now to consider if it “should” be done. To do this takes us into new and interesting territory in environmental ethics but both utilitarian and intrinsic worth arguments support the notion of planetary ecosynthesis. Strict preservationism arguments do not. It is important to have the long-term view of life on Mars and the possibilities of planetary ecosynthesis. This affects how we explore Mars now. Mars may well be our first step out into the biological universe, it is a step we should take carefully.

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Figure 1. Liquid water in the past on Mars. Mars Global Surveyor image showing Nanedi vallis in the Xanthe Terra region of Mars. Image covers an area 9.8 km by 18.5 km; the canyon is about 2.5 km wide. This image is the best evidence we have that some of the fluvial features on Mars were carved by liquid water in stable flow on the surface for an extended interval. Photo from NASA/Malin Space Sciences.

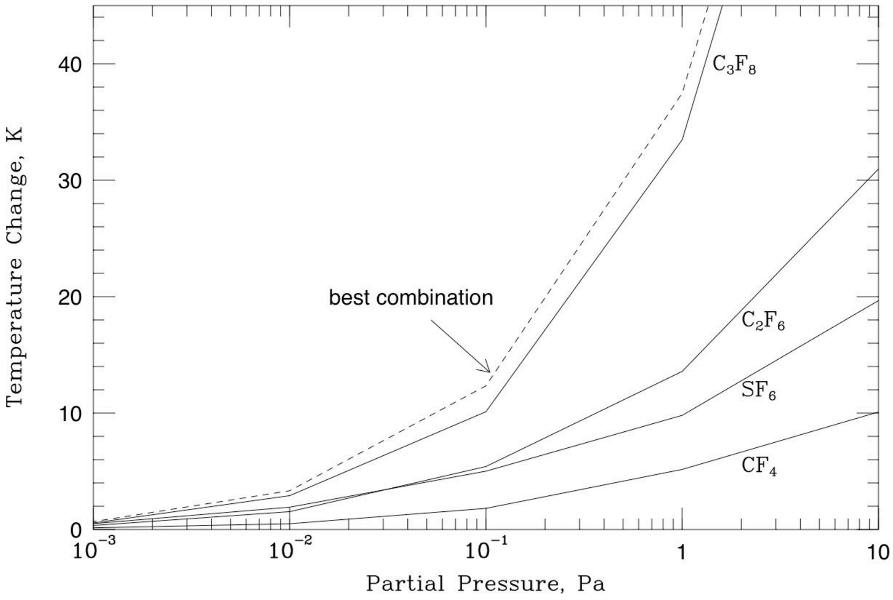

Figure 2. Warming of Mars due to simple fluorine-based gas independently and the best gases combination (dashed line) for the given total greenhouse gas amounts ($PCO_2 = 0.6$ kPa) from Marinova et al. (2005).