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BIOLOGICAL ASPECTS OF THE ECOPOEISIS AND TERRAFORMATION OF MARS: CURRENT PERSPECTIVES AND RESEARCH

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Several plans for the ecopoeisis and terraformation of Mars have been speculated upon over the past several years. However, most of these proposals tend to treat the biological processes involved as a "black box" without specific detail to organisms and ecosystems. This paper's purpose is to provide a very basic outline of the processes needed for a viable Martian community and to provide direction for further research necessary to predict the compatibility of terrestrial life with Mars' environment, present or modified.

1. INTRODUCTION

The ecopoeisis and/or terraformation of Mars is an idea that is steadily gaining acceptance as a feasible possibility and many papers have been published on the subject in the past several years (reviewed in [1, 23]). However, most propositions for changing Mars focus on either the large-scale engineering of the planet to form suitable biomes, or on possible pioneer organisms that could survive in an altered Martian environment [2, 3]. Between these extremes are the proposed populations and communities that would be responsible for actually changing Mars' environment. Although methods for using non-biological means of changing Mars' environment are conceivable, for the purposes of this paper, I am concentrating on biological means of ecopoeisis and terraformation. I believe that the ultimate goal of terraformation or ecopoeisis should be the establishment of a self-regulating environment and that biological means of terraformation are the most appropriate in attaining this goal. Even though a truly self-regulating environment may not be possible, minimal additional human intervention would be preferable to constant manipulation of environmental factors.

Proposed time scales for biological terraformation of Mars range from 60 years [4] to 10,000 years or more [1]. These time scales are based on very rough estimates obtained by scaling the production of terrestrial ecosystems to Mars. They do not account for factors such as temperature, atmospheric composition, community composition, etc. of individual ecosystems. For example, if Mars was inhabited solely by cyanobacteria, the time required for terraformation could be different than if Mars had more diverse ecosystems. The placement of ecosystems would also have an impact on their productivity. Presently, the equatorial regions of Mars receive more light per unit area and have higher average temperatures than the polar regions. However, the polar regions tend to have more atmospheric pressure and moisture than the equatorial regions. More accurate models of these communities and populations could provide better predictions of the effects of introduced life on the Martian environment and would also show where more Earth-based research is required.

2. MARS' ENVIRONMENT: PRESENT AND FUTURE

Although Mars appears to be a relatively hospitable planet when compared to the other members of the solar system, excluding Earth, it is still virtually incompatible with life as we know it. Mars receives only 43% of the sunlight that Earth receives. While this insolation is sufficient for photosynthesis, Mars' thin atmosphere of only eight mbar retains very little heat. The average surface temperature of Mars is -60°C compared to Earth's 15°C. Mars' low temperature and atmospheric pressure also make the existence of liquid water on the surface almost impossible.

The primary problem for the existence of terrestrial life on Mars is the lack of water. Although Mars may have vast water reserves as permafrost and in the polar caps, liquid water is unavailable. The total atmospheric pressure of Mars would have to exceed 10 mbar in order for liquid water to be stable. Mars' atmosphere does occasionally reach this pressure around the poles but the temperature there is still too cold for liquid water. Conversely, the temperature near Mars' equator rises above 0°C during the Martian summer but the atmospheric pressure there isn't high enough for liquid water to exist. In order to keep useable quantities of water in a liquid state at more hospitable temperatures, the atmospheric pressure would have to be around 50 mbar [5]. Optimistic ideas of highly specialized microbial life in unusual microhabitats (endolithic, endoevaporitic, underground chemosynthetic) surviving in the Martian environment have been proposed [6-8] but even if they do or could exist, their metabolic rates would be too low to cause any noticeable changes in Mars' environment. Other obstacles to life on Mars include high UV radiation, very low pO_2, and a high proportion of CO_2. None of these factors of themselves necessarily preclude terrestrial life but they do contribute to a hostile environment. Papagiannis [9] provides a review of the conditions necessary for a habitable planet.

The most plausible means of making Mars more habitable is to increase the amount of CO_2 in the atmosphere to a pressure of one to two bars. Several ways to do this have been suggested, including extreme numbers of nuclear detonations, asteroid/comet bombardment, large space mirrors, addition of greenhouse gases (*i.e.* halocarbons) and dusting Mars with a layer of carbon [1, 4]. For the purposes of this paper, I will simply assume that Mars can be engineered to produce a thick CO_2 atmosphere and a mean temperature of 10-15°C. From this point, biological processes would be necessary to continue the change in Mars' environment to become suitable for human survival. Also, since Mars has almost no tectonic activity, biological systems and human intervention would have to replace geochemical cycles to prevent the remineralization of Mars' atmospheric and surface volatiles.

3. NUTRIENT AND ENERGY FLOW IN MARTIAN COMMUNITIES

Figure 1 depicts the nutrient and energy flow in a Martian community designed for ecopoeisis. Although there are more nutrient cycles in a community than fig. 1 shows (principally phosphorus and sulfur), carbon, nitrogen and oxygen are the elements of most concern. Mars' atmosphere is predominantly CO_2 with very little O_2 or N_2. Humans cannot tolerate high levels of CO_2. In order for Mars to be habitable by humans, instead of just bacteria, algae and plants, most of the CO_2 must be removed and replaced with O_2 and N_2, or another buffer gas. Table I summarizes the problems to be overcome for ecopoeisis and terraformation of Mars after initial planetary engineering raises the temperature and atmospheric pressure.

The energy for biogenic terraformation, like in terrestrial ecosystems, would come from the Sun. While Mars receives only 43% of the solar radiation that Earth does, it is still sufficient for photosynthesis. However, with the high CO_2 content of Mars' engineered atmosphere, available sunlight might be a limiting factor in achieving maximum photosynthetic rates. Since some proposed methods of planetary engineering include the use of large orbiting mirrors, these same mirrors could provide additional light for photosynthesis and might even eliminate night time on Mars altogether. This assumes that planetary and biological engineering have provided warm temperatures and ample water and nitrogen supplies.

The primary purpose of photosynthetic organisms on Mars would be the removal of CO_2 from the atmosphere. Simultaneously, these organisms would be increasing the amount of O_2 in the atmosphere. The rate at which this process occurs is of prime importance to any model of terraformation and data for this process is lacking. The rate of photosynthesis and plant growth, which are not quite the same, depends on such factors as: temperature, pCO_2, pO_2, sunlight, water activity, and nutrient availability (especially nitrogen). Each of these parameters has been tested under terrestrial conditions, but very few tests have been performed under conditions similar to those proposed for an engineered Mars. Photosynthesis may be more efficient on Mars because of the high pCO_2 and low pO_2. Terrestrial plants are partially inhibited by the amount of oxygen in air, even down to only 2% (20 mbar) O_2 [10].

Though photosynthesis is more efficient at low pO_2, most plants require oxygen for proper growth and development [11]. Although the effects of low oxygen on plant growth vary according to species, few plants grow well at oxygen concentrations of less than 50 mbar [12-15]. Many more studies similar to those cited have been performed but most of them are related to flooding and terrestrial agriculture and their applicability to Mars may be limited. Siegel *et al.* [16] germinated winter rye seeds in a simulated Martian atmosphere of 0.09% O_2, 0.24% CO_2, 1.39% Ar and the balance of N_2 (total experimental pressures: 0.1, 0.5 and 1.0 bar), but the seedlings grew slowly and leaves had not emerged after 21 days. Although this experiment was deliberately designed to test a Martian environment, as it was thought to be at the time, it does not reflect present or future (*i.e.* engineered) Martian conditions. It seems very likely that few, if any higher plants could survive in an atmosphere with an oxygen concentration as low as that on Mars. Planetary engineering may increase the amount of oxygen to around 10 mbar [17] but this is still far below the needed 50 mbar required for proper metabolism. Still, at least one

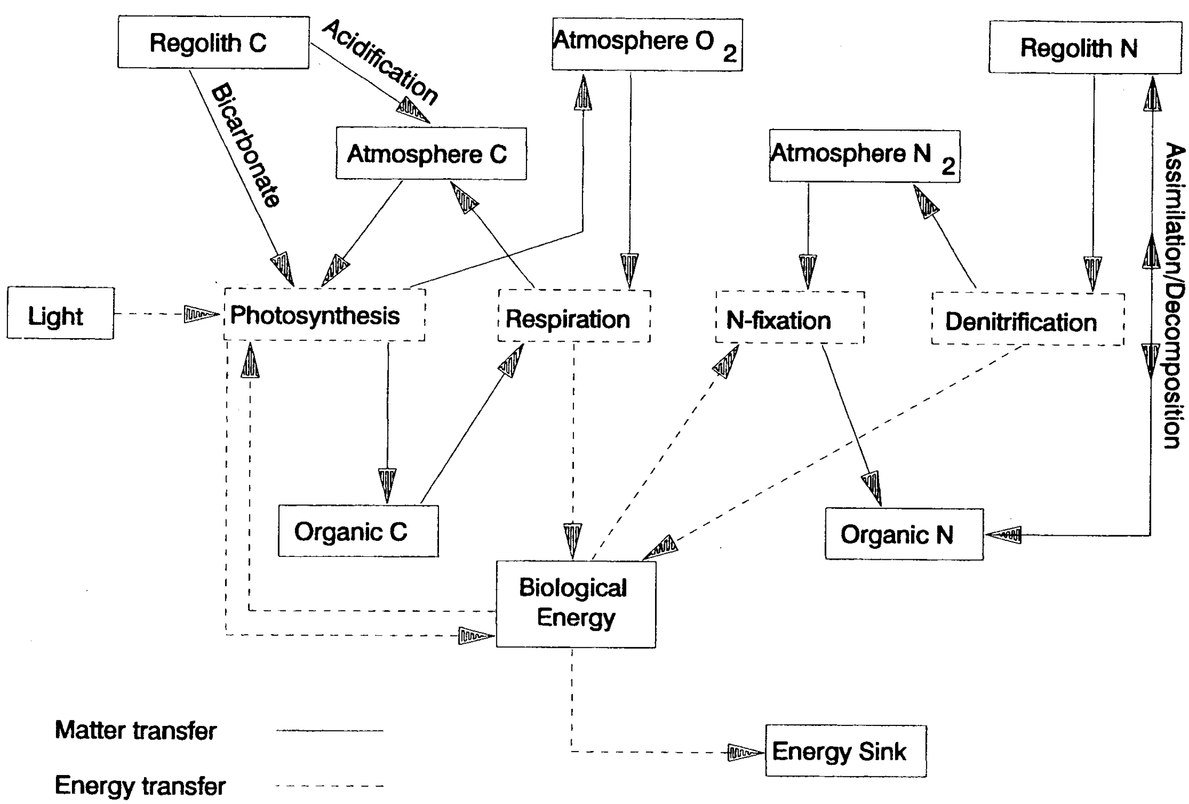

Fig. 1. Proposed carbon and nitrogen cycles for the terraformation of Mars.

TABLE I. *Obstacles to the ecopoeisis and terraformation of Mars.*

Problem	Possible solutions
For plant, algal and bacterial life (ecopoeisis):	
Lack of tectonic activity precludes geochemical cycling.	Design biological cycling systems to replace geochemical cycling; supplement with direct nutrient cycling (*e.g.* burial of fixed carbon).
Initial pO_2 is too low for the normal metabolism of higher plants.	Use cyanobacteria and algae to increase pO_2 to >50 mbar.
Initial pN_2 is too low for most N-fixing bacteria.	Select colonizing organisms that are capable of fixing N at low pN_2; consider genetic engineering to improve terrestrial bacteria.
High UV radiation.	Increase pO_2; select colonizing organisms that are resistant to UV damage.
Additional problems for human habitability (terraformation):	
Engineered Martian atmosphere pCO_2 is too high.	Initial colonization with photosynthetic organisms; burial of fixed carbon to prevent remineralization.
pO_2 is too low for human habitation.	See previous.
Lack of sufficient buffer gas (N_2).	Denitrification of possible nitrate reserves by bacteria.

species of algae can survive with little or no oxygen. Seckbach *et al.* [18] successfully grew the unicellular alga *Cyanidium caldarium* in an atmosphere of pure CO_2 (1 bar pressure). Presumably, other species of algae and cyanobacteria could grow without atmospheric O_2 provided that they had usable light for adenosine triphosphate (ATP) synthesis. This is another area that requires more research with applicability to terraformation.

Besides CO_2 and O_2, some form of nitrogen is necessary for photosynthesis and for life in general. Mars has little nitrogen in its atmosphere and the nitrogen content of the regolith is uncertain, though assumed to be present as nitrate. Although nitrogen as ammonium is preferential, a variety of microbial and plant life can use nitrate, reducing it to ammonium or amines. Under anaerobic conditions, many heterotrophic bacteria use nitrate as an oxidant, yielding N_2 in the process. This is the only biological process capable of increasing the amount of molecular nitrogen in Mars' atmosphere, although industrial means might also be used to convert nitrate to N_2. When regolith nitrogen is limited, many cyanobacteria and a few anaerobic heterotrophic bacteria can reduce atmospheric N_2 to ammonia. This process has a high cost in biological energy (ATP) and would actually be detrimental to the initial stages of the terraformation of Mars, since a large proportion of N_2 is desirable for terraformation. Although extensive research on nitrogen cycling in the context of terrestrial biology has been performed, relatively little research has been undertaken to examine nitrogen cycling under Martian conditions. Of note is research by Klingler *et al.* [19] that showed growth of the nitrogen-fixing bacteria *Azotobacter* and *Azomonas* at pN_2 of 5 mbar. Additional unpublished research [20] revealed nitrogen-fixation by variety of microorganisms at pN_2 of 0.2 mbar—the current partial pressure of nitrogen in the Martian atmosphere.

4. NUTRIENT CYCLES ON A TERRAFORMED MARS

Mars lacks tectonic activity: therefore, earthlike biogeochemical cycling of nutrients cannot occur. Yet most of the nutrient cycles might occur with strictly biological and photochemical processes. Friedmann *et al.* [3] suggested using the cyanobacterium, *Matteia*, to release CO_2 from carbonate rocks. *Matteia* can dissolve and utilize carbonates and it could be used in the initial stages of ecopoeisis to release CO_2 into the atmosphere. In later stages of terraformation, some fixed carbon may have to be buried to bring atmospheric CO_2 levels down to human-tolerable levels and to prevent it from being oxidized by the increasing amount of oxygen in the atmosphere [21]. As large bodies of water form, some CO_2 will form new carbonates. Eventually, some form of carbon cycling must occur in order for the Martian ecosystem to remain stable. *Matteia* could play a role in that process as well. *Chroococcidiopsis*, another cyanobacterium, has also been suggested as a pioneer species for Mars [2]. Like *Matteia*, it can survive in arid environments, although it is not known to solubilize carbonate. These organisms, and perhaps others, could be part of the initial steps to increase the amount of O_2 in Mars' atmosphere. As the pO_2 increases, higher plants could be introduced. Eventually, the levels of CO_2 and O_2 could reach levels acceptable for human and other animal existence.

Besides high pO_2 and low pCO_2, some sort of buffer gas will be needed for humans to survive in a Martian atmosphere [1]. N_2 is the most likely candidate. If there are ample nitrate reserves in Mars' regolith, anaerobic denitrifying bacteria (or industrial methods) could convert the nitrate to N_2 and N_2O. Species in the genera *Pseudomonas* and *Alcaligenes* may be well-suited for this task [22]. However, these could not be introduced until after photosynthetic populations had fixed enough carbohydrate for the growth of heterotrophic organisms, but before appreciable increases in atmospheric pO_2. Other nitrate-reducing bacteria could provide ammonium for those organisms incapable of using nitrate. As the nitrate reserves become depleted, some atmospheric N_2 must be fixed to maintain biological communities. The previously mentioned cyanobacterial species, as well as other autotrophic and heterotrophic bacteria are capable of fixing N_2. As atmospheric levels of oxygen increase, the activities of denitrifying bacteria would decrease unless the bacteria occupied an anaerobic habitat.

Sulfur cycling on Mars probably would not be seriously affected by the lack of tectonic activity. Most microorganisms and plants readily assimilate oxidized sulfur as sulfate to form amino-acids and proteins. Under anaerobic conditions, some organisms reduce sulfate to molecular sulfur or hydrogen sulfide. When oxygen is present, H_2S and S_8 may be chemically oxidized or used as an energy source by some bacteria. Some photosynthetic microorganisms can use H_2S in place of H_2O.

The cycling of phosphorus could present a problem on a terraformed Mars. Usually, phosphorus exists as phosphates, most of which are not very soluble in water. Since they are also not volatile, phosphorus is usually well-conserved in stable communities. Still, some loss will occur, and over long periods of time, phosphates would eventually be lost in deep water sediments. In order for a terraformed Mars to continue, periodic dredging and/or mining for phosphate and fertilization of ecosystems might be necessary. The same may be required for other non-volatile, relatively insoluble minerals (*i.e.*, iron, manganese, magnesium, etc.).

5. RECOMMENDATIONS AND CONCLUSIONS

A vast amount of research has been performed to understand the biological processes on Earth. Unfortunately, most of it is not applicable to the ecopoeisis and terraformation of Mars. Much more research concerning the effects of terrestrial organisms on the Martian environment and vice-versa must be done with the expressed purpose, primary or otherwise, to provide usable data for the modeling of ecopoeisis.

Can terrestrial cyanobacteria and heterotrophic bacteria survive in an engineered Martian atmosphere consisting mainly of CO_2? What are the effects of low pO_2 on these microorganisms? What are the limits for the survival of higher plants (pO_2, pCO_2, etc.)? What are the actual mineral and volatile reserves of Mars? Can the various mineral cycling activities (photosynthesis, respiration, nitrification, nitrogen fixation, assimilation, denitrification, etc.) occur in an engineered Martian environment? If not, what are the limits? If life can be introduced on Mars, how will communities and ecosystems change as the Martian environment changes?

All too often, the biological processes involved in terraformation are treated as an engineering problem. That is, the addition of more energy will result in faster transformation of the planet (more carbon fixation, more oxygen, etc.). While this is true to a point, it isn't that simple. The biological processes are ultimately limited by the enzyme systems of individual cells. These systems generally only operate over a somewhat narrow range of parameters. This range is often specific to individual species or even individual cells. Biological systems cannot simply be treated as a "black box" in which energy and raw materials are put and products are received, especially in a largely unknown environment. Only with detailed information about the Martian environment and proposed terraforming organisms coupled with reliable models of the communities that they form will accurate predictions of terraformation be possible. At present, this information is not available.

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