

## THE FORMATION OF MARTIAN ECOSYSTEMS: RATIONALE AND DIRECTIONS FOR FUTURE RESEARCH

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Sometime in the future, intentionally or not, humanity will introduce terrestrial life onto Mars. If intentional, the introduction of life may be for the purpose of ecopoeisis and/or terraformation. Ecopoeisis is the introduction of a viable ecosystem on a previously lifeless world [6]. In the case of Mars, ecopoeisis most likely would result in a psychrophilic (cold-adapted), osmophilic (high solute/dessication-adapted) and anaerobic (oxygen-lacking) ecosystem. While ecopoeisis might be an interesting experiment, in and of itself, it would provide little benefit to the people living on Mars. However, many of the processes involved in ecopoeisis provide the first steps toward terraformation—the transformation of Mars into an Earth-like, human-habitable planet. A terraformed Mars would include an oxygen/nitrogen (or oxygen/argon) atmosphere and a relatively warm, wet climate.

Since Mars' present environment is very hostile and not conducive to the growth of terrestrial life [3], both ecopoeisis and terraformation require initial planetary engineering to alter the climate. Several methods of planetary engineering have been suggested, including large numbers of nuclear detonations or nuclear thermal generators, asteroid/comet bombardment, addition of fluorocarbons to the atmosphere, large orbiting mirrors, and carbon dust over the Martian surface [2,4,7,10,11]. Although the initial planetary engineering requirements for ecopoeisis versus terraformation differ somewhat (Table 1), for the purposes of this paper, I assume that they are achievable.

A hypothetical terraformation project might proceed as follows. Initial planetary engineering would release water, carbon dioxide, and possibly some oxygen [8], into the atmosphere. The higher atmospheric pressure (>50 mbar) allows stable bodies of liquid water to form as well as creating a "greenhouse effect" that warms the planet. As Mars' atmospheric temperature increases, more CO<sub>2</sub> and other gases may be released into the atmosphere. Mars can now be seeded with pioneer organisms that start to convert the CO<sub>2</sub> to O<sub>2</sub> and the presumed nitrates (NO<sub>3</sub><sup>-</sup>) to N<sub>2</sub> [10]. Some organisms may also continue the process of increasing the atmospheric pressure by converting carbonates (CO<sub>3</sub><sup>2-</sup>) to CO<sub>2</sub> [5]. As photosynthesis continues the process of O<sub>2</sub> production, and the atmospheric pO<sub>2</sub> level rises above 50 mbar, higher plants can be introduced. Materials from the plants provide building materials as well as reduced carbon that can be kept

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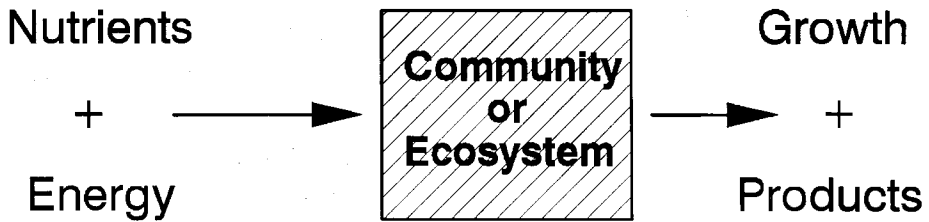
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semi-permanently out of the atmosphere. As the environment becomes more hospitable, a greater variety of organisms may be introduced. Because of Mars apparent lack of tectonic activity, normal terrestrial biogeochemical nutrient cycling cannot occur. Biological communities may have to be designed to recycle nutrients as much as possible. Also, “nutrient mining” for phosphates and sulfates may become necessary. Although this may sound unusual, it is relatively common in modern agriculture—most fertilizers are mined from the earth and applied to crops. The same idea would apply to Mars on a larger scale. Eventually, though, the planet becomes human-habitable over a time scale of hundreds to thousands of years.

**Table 1**  
**ENVIRONMENTAL AND PLANETARY ENGINEERING REQUIREMENTS**  
**FOR ECOPOEISIS AND TERRAFORMATION**

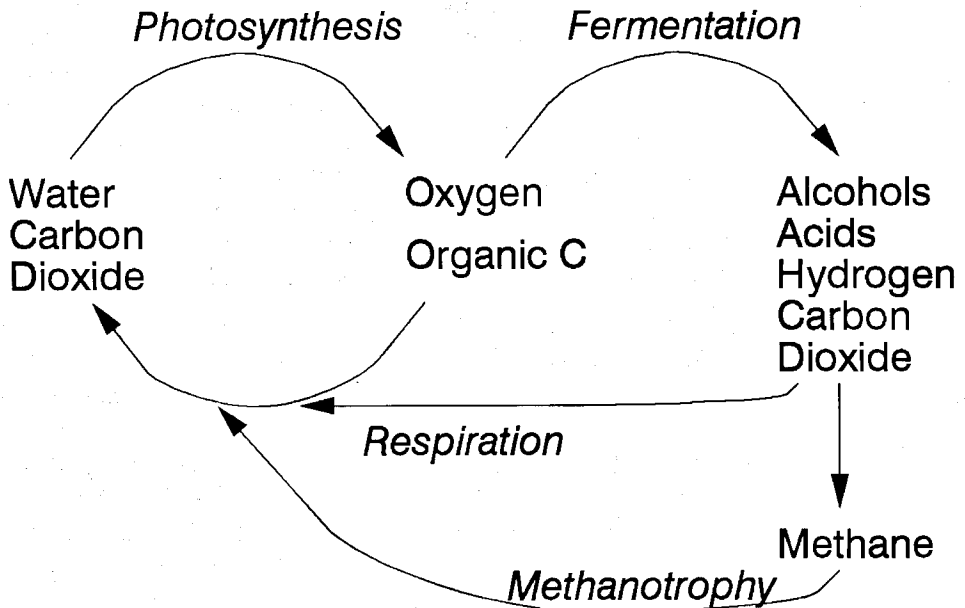
Environmental Conditions	Ecopoeisis Requirements	Terraformation Requirements
Atmospheric Pressure	~25 mbar	~50 mbar initially, 1-2 bar at completion
Atmospheric Composition	Current Mars	Current Mars initially, 20% O <sub>2</sub> with 80% N <sub>2</sub> or other buffer gas at completion
Mean global temperature	>0°C	10-15°C at completion
Inorganic nutrient reserves	Sufficient for ecosystem growth and maintenance	As in ecopoeisis, plus sufficient nitrogen reserves (NO <sub>3</sub> <sup>-</sup> ) to produce N <sub>2</sub> in the atmosphere
Water	Occasional precipitation and small bodies of water (ponds, lakes, creeks)	At least moderate precipitation and large, permanent bodies of water (seas, oceans, rivers)

While this process appears relatively straightforward (most of the technology exists), the details of getting everything to work pose many problems. Most of the previous models for terraformation have treated ecosystems with a “black box” approach [10]. That is, if energy and raw materials are provided to a community or ecosystem, growth and products will result (Figure 1). Microbial ecologists routinely use this approach in studying terrestrial ecosystems, and for isolating microorganisms with a desired trait. For example, nitrates may be added to a soil sample to determine the presence of denitrifying bacteria. The difference between terrestrial ecosystems and proposed Martian ecosystems is the level of diversity. A typical temperate, terrestrial soil may contain hundreds of species of micro- and macroorganisms. Therefore, a reasonably high probability exists of finding a microorganism that utilizes a particular pathway. Since Mars has no known indigenous life, any introduced organisms must be selected and/or designed to perform a particular function. Because virtually all biological reactions are enzyme mediated, they usually have a narrow range of operating parameters (pH, temperature, osmotic potential, etc.). Thus, simply treating Mars as a biological “black box” for terraformation is unrealistic. Instead, detailed understanding of how ecological cycles on Mars would function is required.

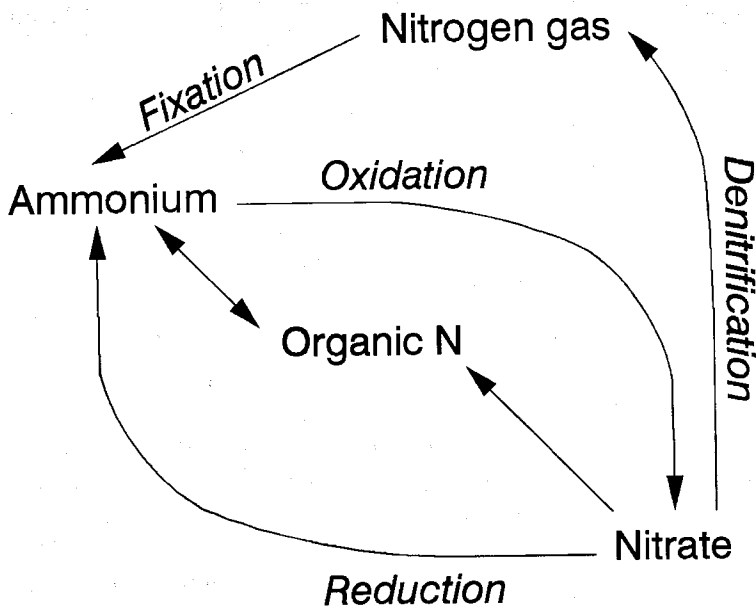


**Figure 1** The “black box” approach to ecosystem research. While this is a common approach in terrestrial microbial ecology, introduced Martian ecosystems would not have the complexity and/or diversity to make this a valid means of research. Communities and ecosystems be have to be designed to function in specific ways.

In the first steps of terraformation, the carbon and nitrogen cycles are the most important (Figures 2 and 3, respectively). Carbon dioxide from the polar caps, soil, and carbonates would be released into the atmosphere during and after initial planetary engineering. Photosynthetic organisms would then convert the CO<sub>2</sub> to O<sub>2</sub>. Herein lies one of the first problems: only one photosynthetic organism (an alga) is known to survive and grow autotrophically in 100% CO<sub>2</sub> [9]. Higher plants require a minimum pO<sub>2</sub> of 50 mbar for proper growth and development. Since current models predict a maximum of 10 mbar pO<sub>2</sub> from planetary engineering, more research into pioneer organisms that can survive in near 100% CO<sub>2</sub> is needed.



**Figure 2** The carbon cycle. One of the main functions of organisms on Mars will be to convert CO<sub>2</sub> to O<sub>2</sub> and usable organic compounds. Methanotrophs may also play a role in the initial warming of Mars. Illustration adapted from [1].



**Figure 3** The nitrogen cycle. Initially, the processes of denitrification will have to dominate in order to produce  $N_2$  for the atmosphere. At the final stages of terraformation, N-fixing organisms will be needed to complete the cycle. Illustration adapted from [1].

If Mars is to become human-habitable, the atmosphere will require a buffer gas ( $N_2$  or Ar) in addition to oxygen. A pure oxygen atmosphere at 1-2 bar pressure would not only have toxic effects on most organisms, but would tend to cause almost spontaneous combustion of most reduced materials. Although humans have routinely used pure  $O_2$  atmospheres in space applications, these are usually at reduced pressures ((300 mbar). Unfortunately, a 300 mbar  $O_2$  atmosphere would not provide enough thermal insulation to keep Mars warm. The most likely candidate for a buffer gas on Mars is the same as that found on Earth—nitrogen. Mars' atmosphere contains minute amounts of  $N_2$ , and nitrogen reserves in the form of nitrates are thought to be present [3].

In order to convert the nitrates to  $N_2$ , denitrifying bacteria could be introduced (Figure 3). These bacteria utilize nitrate in place of oxygen as the final electron acceptor during cellular respiration. During the process, the bacteria convert nitrate to nitrite, nitrous oxide and/or molecular nitrogen. An initial screen process would be used to select microorganisms that perform the complete reduction of  $NO_3^-$  to  $N_2$ . Also, because nitrate respiration is relatively efficient (second only to aerobic respiration), the growth rates of the denitrifying organisms would be fairly rapid, assuming that all other conditions are favorable. Denitrification has its problems, though. On Earth, this is an anaerobic process. Most organisms that possess the denitrification pathway are either killed by oxygen, or turn off the pathway in the presence of oxygen (in favor of aerobic respiration). Also, denitrifying organisms are heterotrophic, and require organic materials for food. Thus, a substantial population of autotrophs is required to nourish the denitrifiers, but the autotrophs also produce oxygen, which inhibits denitrification. This

situation might be overcome in one of two ways: find microorganisms that naturally denitrify under aerobic conditions, and/or genetically alter microorganisms to denitrify under aerobic conditions.

Nitrogen fixation is the opposite of denitrification. Some terrestrial microbes reduce  $N_2$  to ammonia or ammonium ( $NH_3/NH_4^+$ ) when nitrogen sources are limited. The ammonium is then incorporated into amino acids and other biomolecules. Some microorganisms can fix  $N_2$  even at the miniscule  $pN_2$  of 0.2 mbar on Mars [10]. Although nitrogen fixation will be needed in the final stages of terraformation to complete the nitrogen cycle, it would be detrimental to the earlier stages when  $N_2$  production occurs. Since several genera of cyanobacteria also fix  $N_2$ , the organisms used for  $O_2$  production would have to be selected or modified so that they do not interfere with  $N_2$  production at the same time.

The last two major nutrient cycles, sulfur and phosphorus, probably will not cause concern until the final stages of terraformation. Most plants and microorganisms readily assimilate sulfur in the form of sulfate ( $SO_4^{2-}$ ) (Figure 4). Sulfates are generally not volatile (although sulfur oxides are), and they are not as soluble and mobile as nitrates. Some bacteria convert sulfates to sulfur or sulfides ( $S^{2-}$ ), but in an oxidizing environment, these two species are quickly converted back to sulfur oxides and sulfates. Sulfur oxides are usually converted back to sulfates when they react with water (acid rain) and are returned to the soil. Because of their lower solubility in water, sulfates may eventually sediment out in bodies of water and be lost from the ecosystems. Since Mars does not appear to undergo geological cycling as on Earth, dredging or mining for sulfates may eventually become necessary in order to maintain the cycle.

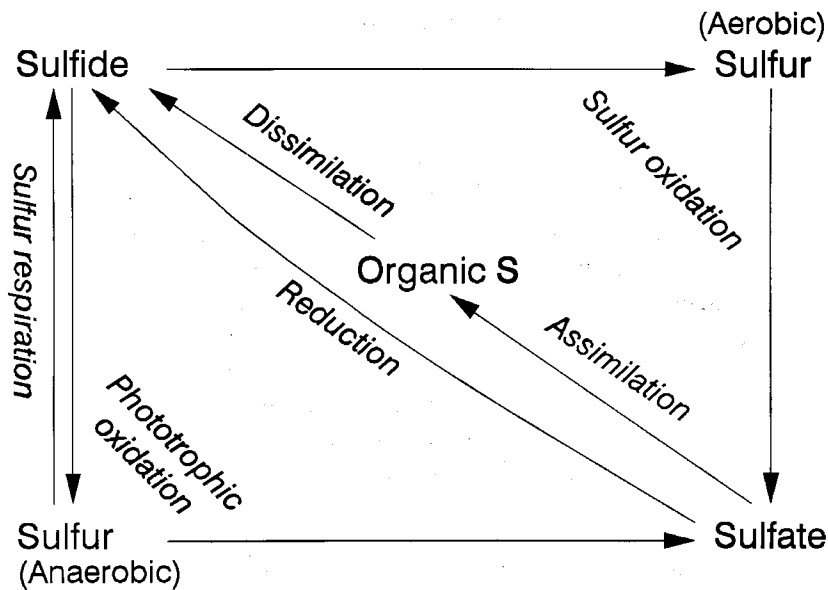


Figure 4 The sulfur cycle. During the initial phases of terraformation, the sulfur cycle will be of little consequence. Most of Mars' sulfur is thought to be in the form of sulfate, which most plants and microorganisms readily utilize. Illustration adapted from [1].

Phosphorus is the most stable of the major nutrients. Phosphorus occurs mainly as phosphate, which is highly conserved and recycled within communities, is not volatile, and is easily precipitated from aqueous solutions (Figure 5). Because of its insolubility, phosphate eventually is lost from ecosystems by sedimentation—even more so than sulfates. As with the sulfates, human intervention in the form of dredging and mining may be necessary to complete the phosphorus cycle. At first, this may seem rather extreme, but it occurs in modern agriculture on a daily basis. Virtually all sulfur and phosphorus, and some nitrogen, used in fertilizers are obtained from inorganic minerals—“fertilizer mines.”

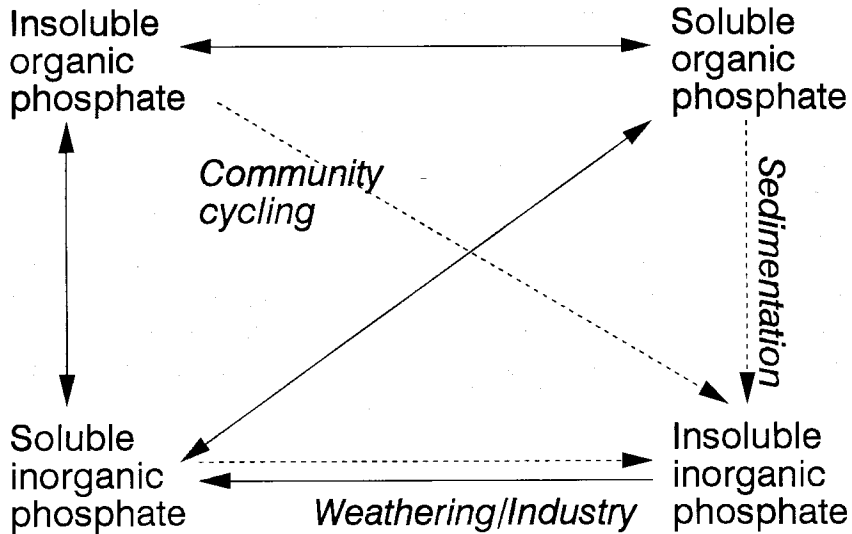


Figure 5 The phosphorus cycle. Most of the problems with the phosphorus cycle will not become evident until late in the process of terraformation. Since Mars does not appear to have tectonic activity, human intervention may be needed to cycle phosphates from sediments, and return them to the ecosystems. Illustration adapted from [1].

The proposals for the terraformation of Mars are essentially applied microbial ecology. While the overall workings of nutrient cycling within ecosystems are understood, the details of the functions of individual organisms and populations are still a matter for investigation—even on Earth. Research into the basic processes involved in ecosystem formation on Mars could easily require 50 to 100 years or more. This research should start with the selection and/or modification of microorganisms to survive under the conditions found immediately after planetary engineering. Later research should include small-scale attempts at forming and directing artificial communities that would continue to modify Mars’ environment. The theory behind the biological engineering of Mars is relatively simple in the general sense. The problems lie in making everything work together toward the goal of creating and maintaining a second Earth.

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