2015

# The Feasibility of a Terraforming Expedition

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Oct 16, 2014
BIOL 121
Professor Huish

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**Introduction:**

Establishing a colony of humans on another planet has long been a goal of the human race. In this essay I will lay out the feasibility of such a colony, using research and theories generated by astrophysicists, botanists, and planetary scientists.

Terraforming is defined as altering a planet's surface until Earth's life forms can survive without excessive protection. Here I will discuss the basic methods and theories behind terraforming, as well as possible methods of transporting materials, theories of planetary development, the timescale on which the project might take place, and where funding for such a large project might come.

This paper aims to establish the feasibility of a human colony on any off-world body with a range of Earth-like size and gravity. I will often use the examples of Mars, Venus, and Earth's Moon to prove facts or suggest possibilities, but the paper is intended to present a broader view of terraforming.

**Methodology:**

The methods used to change a planet's atmosphere and eventually alter its ecosystem are not perfectly understood by scientists today, even on Earth. (Fogg vii) Yet as the issue of climate change on Earth has shown, humans have a very great impact on the planet they inhabit. It is not a large step beyond this to consider attempting this interference purposefully. For this paper, I will consider planets currently without life or enough atmosphere to sustain life.

Once a planet has been established as acceptable for terraforming (acceptable parameters will be established in a later section), the first addition must be gaseous compounds to increase atmospheric pressure. On cold planets with significant amounts of frozen carbon dioxide and/or water, the introduction of warming compounds such as chloroflurocarbons will trigger a chain reaction. As the frozen gases melt they will sublimate because of low pressure, but will then be trapped by the planet's gravitational field. (Goslee)

This creates an atmosphere rich in carbon dioxide, but once the temperature lies within the range for the hardiest Terran lifeforms the first photosynthesizing organisms can be introduced. (Graham 1285) Lichens and cyanobacteria will add oxygen to the atmosphere as well as break down into the first layers of soil as they decay.

After these first microbes are established on a planet-wide basis, bryophytes such as various mosses and liverworts can be added to the mix. This will lead to the establishment of a true carbon cycle, and as some of the mosses (such as species of the Sphagnum genus) can begin sequestering the carbon from the atmosphere. As atmospheric pressure and surface temperature increases and water becomes more abundant, certain flowering plants that thrive in antarctic and tundra conditions can also be added. (Graham 1286)

It is only after these plants have spread across the surface of the planet that humans may be able to survive without excessive protections. (Graham 1285) This process may take anywhere from decades to centuries, and while the organisms may have started out Terran, they will inevitably adapt to their new home with increasing differences. This is not an attempt at a controlled experiment, but a wholesale alteration of a planet; differences in gravity, light, and native minerals will result in vastly different ecosystems than those we are familiar with. (Robinson 59)

When attempting to terraform a planet (Earth-like or not), one must keep in mind ethical considerations. This paper considers the terraforming of planets without significant atmosphere and life on the basis that humans do not have the right to interfere with an already developing planet. This non-anthropocentric view (a view establishing that life has worth outside of it's value to humans), establishes that harming the life of an individual or species, regardless of intelligence/sentience/stage of evolution, is morally impermissible.

**Parameters for a suitable planet:**

The parameters for a candidate terraforming planet have already been determined, with some uncertainties. (Dole 6) These parameters contain both upper and lower limits, and can be altered depending on how the terraforming has progressed. For example, lichens and algae will be able to survive in conditions that would kill humans. These parameters set out both introductory (upon finding a planet) and end-step (comfortable human survival) limits.

**i. temperature**

The first step in terraforming any planet would be to regulate the temperature enough that Terran organisms could survive. In the first stages of establishing life on another planet, temperatures at which the smallest cyanobacteria and algae can survive is the first step. Certain species can survive up to 110 degrees Celsius (for extreme thermophile bacteria) and down to -10 degrees Celsius, for antarctic cryophile algae. (terraforming: engineering planetary environments) There are many other examples in nature of plants and animals surviving at 'extreme' temperatures, but for the final stages of terraforming, when human beings are able to walk freely on the surface, the annual mean temperature range should lie between zero and thirty degrees Celsius. (Dole 9) Within this average there may be days of much colder or much warmer temperatures, as long as the periods of greater heat and/or chill do not extend for more than a month. (Dole 8)

**ii. light**

The amount of light a planet receives will not vary, and humans investigating candidate planets must be wary of the amount of radiation the planet's surface receives.The creed that one must adopt is that of 'less is better'. The more changes one must make to a planet, the greater the cost of the operation.

The approximate limits for (useful) photosynthesis of plants are 0.02 to 30 lumens per square centimeter. (Dole 10) Below 0.02 the light is too diffuse for photosynthesis to proceed at a useful rate, and above 30 lumens photosynthesis is actually impeded by a process termed 'solarization'. Humans can see enough to walk around cautiously if the light is as low as $10^{-9}$ lumens per square centimeter, and find light painfully bright if it goes above 50 lumens (This is a simplification, not factoring in such variables as the so called 'snow blindness' or the presence of shade-creating plants or buildings). Thus, one must select a candidate planet receive daytime illumination somewhere between the levels of .02 and 30 lumens per square centimeter.

**iii. radiation**

It is estimated that humans absorb .003 rem of background radiation per week in normal Terran environments. The acceptable levels for workers at atomic energy plants is 0.1 rem per week. There have not been studies conducted to determine the effects of constant exposure to differing doses of radioactivity, but the 'mutation doubling rate' is considered to be 30-50 rem. Thus, as long as levels of radiation were determined carefully by planetary scientists, there would not be adverse affects to allowing relatively high levels of radiation. Especially since these levels would be determined at the planet's surface before the creation of a sheltering atmosphere. (Dole 20)

**iv. gravity**

Gravity is an unalterable facet of a planet, depending on the mass, speed of rotation, and vicinity of other stellar bodies. Studies using large centrifuges on Earth's surface to simulate heavier gravities have shown that humans can function comfortably in gravities up to 1.5 times the force of Earth's gravitational pull. While humans can continue to function for small amounts of time in gravities up to five times the pull of Earth, the corresponding 'weight' makes any activity impossible. (Dole 12)

Gravity is unlikely to alter the processes of microorganisms, and since any attempts to alter the gravity of a planet would require moving masses that would fundamentally alter too many of the planet's properties, it is best to consider only planets with up to 1.5 the pull of Earth. Planets much smaller can also be considered, as the lower limits of human survival in gravities less than that of Earth have not been determined. (Fogg 109)

**v. pressure**

Currently Earth's atmosphere stands at 1013 millibar at sea level. (Fogg 105) By measuring the effect of different mixtures of gases, several basic limits for survivable pressures have been established.

On the lowest possible end of the scale, various bacteria and algae have been tested under laboratory conditions to survive in pressures as low as 6 mbar of pure carbon dioxide, depending on species. While this would be sufficient to begin terraforming, higher plant forms will need greater amounts of $CO_2$ as well as essential oxygen and nitrogen compounds. Since bacteria will be decomposing on the planet at this point, the beginnings of establishing a carbon cycle will be evident and can be used to introduce more complex plants. (Fogg 101)

Oxygen, too, is linked to the life and health of more complex plants. The majority of flowering plants require oxygen to be at levels of at least 20 mbar. Most plants require at least this much oxygen to support aerobic respiration, whereas the bacteria and lichen introduced before now would be using a combination of aerobic and anaerobic respiration. Studies suggest that many bryophytes thrive at levels as low as 30 mbar of oxygen, and that rice (a plant used to having roots in anoxic conditions) can exist indefinitely at levels from 20-25 mbar. (Graham 1286)

The only other gas critical to the growth of plants is nitrogen. As ammonium and nitrate salts it is available to plants for growth. As a gaseous compound it acts as a buffer, stopping the extremely flammable oxygen from catching fire repeatedly. Since any oxygen concentration greater than 25% runs the risk of even damp vegetation catching fire a concentration of nitrogen or other inert gases of at least 75% is required (Fogg 105). As nitrogen is the only reasonable candidate for such bulk buffering, the minimum presence of nitrogen is defined at 60 mbar, provided 20 mbar of $O_2$ (the limit for plant survival), 10 mbar of $H_2O$, and a fraction of an mbar $CO_2$.

This gives a minimum atmospheric pressure for a 'plant world' of around 90 mbar.

Humans, adaptable creatures that we are, can acclimate to pressures and concentrations of oxygen very different from what the majority of us experience today. Today in the Andes mountain ranges there are permanent human settlements as high as 5,000 meters above sea level, with total pressures of only 560 mbar and $pO_2$ only 118 mbar, and there is evidence that humans can exist indefinitely at 7,000 meters, with a pressure of 440 mbar and $pO_2$ at only 92 mbar. The lowest pressure atmosphere that humans can survive (breathe) in is one of almost pure oxygen, consisting of only 140 mbar pressure. But oxygen is an extremely flammable gas, and requires a large bulk of inert gases to buffer it. Realistically we can say that the lowest a planet's pressure can be for human habitation is 380 total barometric pressure, with 285 mbar of that being buffer gases (mostly made up of nitrogen). (Fogg 106)

On the other side of the scale, higher pressure atmospheres must be watched for toxicity. Choosing oxygen as a limiting factor, the highest pressures that can be tolerated by humans are around 2600 mbar. Beyond this level oxygen poisoning becomes apparent. But if nitrogen was used as the limiting factor, decreasing the concentration of oxygen, pressures up to 3700 mbar could be tolerated. There is no apparent upper limit for carbon dioxide absorption in plants. (Fogg 106)

**vi. water**

Though largely a function limited by the other parameters here, water is an essential ingredient for terraforming. It is agreed that while no distinct limits have been found, only very few bacteria and plants can survive desiccation repeatedly. Open bodies of water would allow for salt-free soils (as minerals were washed to new seas) and a true hydrological cycle must be formed. (Fogg 111) Where substantial amounts of $H_2O$ are not present either in vapor or frozen form, water can be added by redirecting asteroids and other celestial bodies formed mostly of ice. This form of redirection, already possible today, can certainly be carried out by a civilization advanced enough to begin serious terraforming work. (Dole 19)

**Technology:**

Moving away from the theory of terraforming, in which there is much to be said and little to be done, we now discuss the physical technology that might be used to transport and establish terraforming colonies. No matter the planetary body considered or its distance from Earth, these are questions that must be answered before any verdict of true feasibility can be considered.

**i. transportation**

There are several proposed theories of interstellar travel in scientific literature today. The theory given the most attention is that of anti-matter propulsion. While we can produce small quantities of anti-matter with today's technology, it is extremely cost prohibitive. Producing it on a scale to fuel a terraforming project is currently unfeasible, but because the science for it already exists and has been proven to work research into this field is extremely promising. (Fannin 38)

Another hopeful field of research is that of solar sails. Powered by photons bouncing off of their reflective surfaces, these sails are currently being tested by a small group of scientists in Russia. Theoretically, though the sails will start of with almost minuscule speeds of around 160 kilometers per hour, they will continue to accelerate without the need for fuel. After 100 days, the sail should be traveling at 16,000 km/h. (Reichhardt 678) Some problems with the technology right now include a lack of field studies and an uncertainty as to the stability of the sails. The problem of stability, while it should and will be tested on small rocket missions first, could be fixed by establishing a larger ship that would deploy the sails after it had reached orbit. A larger ship would provide more stability and more possibility of data processing. Again this technology may only be in experimental stages now, but there are current tests being done, and the theory alone is highly encouraging.

**ii. on-planet growth**

Since each planet will have wildly different requirements and environments, describing in detail the process of terraforming would be difficult, if not impossible. It is here that I use examples from our own solar system to describe in specifics what might otherwise be determined in generalities. Since Mars, a planet with little to no warming and Venus, a planet occupied with a runaway greenhouse effect, are so different, between them we shall cover many avenues of approach to terraforming. (Drake 26)

Regulation of temperature must come first in any terraforming project. (Boyle 60) On Mars, the average temperature would need to be raised from it's current -56 degrees Celsius (Tierney 30). Inject compounds such as chloroflurocarbons, and the subsequent rise in temperature would result in a release of carbon dioxide and even water vapor from the frozen polar regions of the Red Planet. This release would eventually stabilize as enough pressure was formed to sustain liquid water and the last of the planet's reserves were unleashed. This stabilization could take anywhere from decades to centuries (Robinson 59).

For Venus, the opposite problem is presented. Our 'twin' planet has average temperatures of around 482 degrees Celsius (Drake 26), requiring that we find a way to cool it before any colonizing organisms can be introduced. In addition, the surface pressure on Venus with an atmosphere made almost entirely of $CO_2$ is that of 1,500 mbar. Not only would the mix of gases have to change, but huge amounts of atmosphere would have to be removed (Beech 188). On top of this, bacteria that would potentially be able to do a lot of this work removing carbon dioxide would need huge amounts of water that simply is not present on Venus.

Suggestions have been made to construct an enormous sun-shade to be placed between Venus and the Sun, to import massive amounts of carbon and magnesium to create carbonates, or to import equally large amounts of $H_2$ to create water vapor and feed the bacteria. Because of the intense heat and pressure at the planet's surface, the bacteria would be engineered to live in the dense cloud layer of Venus, between 40 and 60 kilometers above the surface. The pressure and temperature in this layer more closely resembles Earth norms, and in fact it has been postulated that there are microbial life forms currently living in this region of the Venusian atmosphere. (Beech 195)

Because of the myriad of problems presented in the terraforming of Venus, it is estimated to take perhaps 15,000 years before the planet would become habitable. (Beech 198) So although Venus is the closest body to Earth besides the moon, the effort needed to terraform it seems prohibitive to the benefit gained from the creation of a habitat that will only be livable so far into the future.

The main obstacle in terraforming Venus is the lack of water, but on Mars there is water ice already available. And any addition of outside gasses or liquids adds costs that are literally astronomical to a terraforming plan. According to Kenneth Roy, writing an article entitled: "Shell Worlds: An Approach to Making Large Moons and Small Planets Habitable.", the force needed to accumulate the nitrogen needed for establishing an Earth-like atmosphere on the Moon would require power equal to a 200-megaton bomb. This includes the energy needed to transport the nitrogen (in liquid from) from another planetary source, such as (in the example above) Saturn's moon Titan. Another option to collecting the water, frozen or vapor, would be to redirect asteroids composed mostly of ice to an impact on the planet's surface. (Schwartz 7) This would have the benefit of costing much less, assuming we can significantly alter the orbit of such objects.

But adding ingredients may not be necessary, if the correct organisms are chosen for the right planet. Once the bare semblance of an atmosphere has been formed on the candidate planet, Terran bacteria and protists and other microorganism can be introduced. (Graham 1285) They have already evolved to withstand various extremes on Earth, and may survive even in the earliest stages of terraforming on a planet without significant atmosphere. (Boston, Todd, and McMillen 977) The goal of establishing these colonies would manyfold, including a net increase in biomass on the planet's surface, an accretion of oxygen as a result of respiration, and a slow establishment of a true water cycle on the candidate planet. Once these microbes have established themselves, bryophytes and more complex lichens may be introduced. Once the mosses, liverworts, and lichens have spread across the planet's surface, increasingly more 'complex' plants may be added. Beginning with flowering plants commonly found in the Arctic and at high elevations, these plants continue to add oxygen to the atmosphere and make the planet more habitable. Animal pollinators may be added at later stages of the flowering plant phase. Again, invertebrate life forms will be introduced first, followed by increasing complex animals. (Graham 1284) It is at the end of this stage that humans may be introduced to the candidate planet, now able to walk around in shirt-sleeves and without any sort of breathing apparatus.

**Timescale:**

As stated above in the section on planet growth, timescales will be radically different depending on the body selected. Terraforming naturally expands the possible planets that man could inhabit; instead of searching for that perfect Earth copy, we could begin searching for a planet just within that range of livable circumstances.

The terraforming of Mars, for example, is calculated to take at best 300 years. (Robinson 59) The terraforming of Venus may take up to 15,000. (Beech 198) Because we have so little data on planets even within our own solar system, it is difficult to determine with any sort of accuracy the time needed to terraform a planet. The sheer scale of the project itself it will most definitely take longer than the span of a human life. Three hundred years on Earth has resulted in quite a few changes to the world.

**Funding:**

Perhaps the most limiting factor of all in a terraforming project is our ability to fund it. An undertaking on such a huge scale has never before been considered, and will likely alter the very nature of the economy that attempts it. Moving from an economy constrained by the material resources of one planet to one suddenly in the possession of two or more livable habitats will alter how we view resources and livable space.

However, there are precedents for the effort and money needed to colonize a place so hostile and far away. Consider the first expeditions to North America, the continuous attempt to reach the North and South Poles, or the unenviable search for the Northwest Passage.

NASA, when asked to plan a mission to Mars, responded with a proposal that would have cost 400 billion dollars. Some of it's main costs included having to carry all the fuel for the return trip and having to be assembled in space, as it was too large to be launched from the ground. Other engineers, when designing plans for a private expedition, estimated costs to be closer to 10 billion, or up to 20 billion. (Martian chronicle) Alternative ideas for funding could be lotteries, held weekly or biweekly and siphoning some of the profits to fund the expedition. Some scientists postulate that this scheme could pay for an expedition in as little as three to five years. There have often been prizes awarded by a government or a private official for establishing some new record of travel. There were prizes offered for the first person to reach the South Pole, for being the first to fly across America in less than thirty days, etc. (Tierney 25) These prizes would allow companies and/or governments to pledge their support of extra-planetary research without having to immediately give out money for that research. Media has always been a popular form of funding, and several ideas have already been put out across the internet of making a Mars expedition television series. This would require significant backing from the media companies wishing to film the series, but it would be an investment just like any other.

We must, of course, keep in mind that these are designed as manned expeditions, perhaps better defined as sight-seeing trips. Considered in that light, some of these plans do not strike as true (the television series, for example, would mostly involve watching algae grow for several hundred years). However, these plans show several options that we can look at for funding a terraforming project, some of which do not depend on the independently wealthy 1% for money.

**Conclusion:**

The science and technology needed for basic terraforming exists today. It may not be usable on the scale needed to change the atmospheric make-up of an entire planet, but it does exist. The most logical plans involve sending unmanned robots to begin the process of terraforming on a planet that meets (or is capable of meeting) all the basic requirements for sustainable human life. These robots would do the work of injecting the necessary gases into the atmosphere and seeding bacterial life throughout the surface of the planet. Even if humans arrived not long after their automated companions, it is possible to have sent robots that could construct safe living quarters for the colonists while the terraforming process was taking place. This limits the possibility of computer error proceeding unchecked while the controllers of the terraforming are too far away to change it. Human colonists could then establish themselves within robot-constructed colonies while waiting for the planet to become truly habitable.

The main shortcoming of this plan is money. The cost to terraform even a body as close as Mars is so huge that no one company or government can even consider it today. Add to that the uncertainty behind interstellar travel (should any other likely terraforming candidates be discovered) and it seems that terraforming still lies more in the realm of science fiction than of science fact.

Nevertheless, this paper set out to prove the feasibility of establishing a colony on another planet, and having taken these limits into consideration, I believe that it is feasible. The science exists. All that is left is mustering the resources to put it into play.

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