KU LEUVEN GHENT UNIVERSITY

FACULTY OF SCIENCE

Terraforming Mars

The Role of Pioneer Organisms and the Possibility of a Biologically Driven Nitrogen Cycle

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Abstract

The aim of this thesis is to discuss the terraforming of Mars, in particular the role that biology will play in this process. A number of pioneer organisms have been proposed, that will be able to contribute to the development of a habitable Mars. Most of the research done on terraforming has been focussed on the CO_2, temperatures and water aspects. This thesis aims to shed more light on the availability of nitrogen on Mars and the potential to introduce a biologically driven nitrogen cycle. Our estimates show that the present nitrogen is able to support a biomass of over ~$8.5x10^{14}$ kg on an area roughly 30% of the total Martian surface. However not enough nitrogen is present to also act as an atmospheric buffer gas to maintain, humanly breathable, atmospheric conditions. Aside from the technological developments, the societal requirements for such a large project are discussed. Before terraforming projects are undertaken there will be a need for strong international cooperation on a global scale, perhaps in the form of a global space agency. There is also a strong need for more internationally binding space laws in order to ensure such projects are undertaken in an orderly manner.

Summary

Mankind stands at the precipice of spreading its species across the Solar System and eventually the our galaxy. The ambition to send man to Mars and to colonise the planet has re-entered popular culture and both space agencies and private companies are developing the technology needed for such an endeavour. This accompanied with the growing call to make humanity an interplanetary species, there is a possibility that Mars will become a second home-planet. The question is how will mankind live on Mars, will it be in sealed domes with an artificial atmosphere or will we develop Mars into a habitable planet by terraforming?

This thesis discusses the terraforming of Mars, with a focus on the role that pioneer organisms will play in this process. Also the potential to develop a biologically driven nitrogen cycle on Mars is discussed.

However in order to make Mars a habitable planet a number of environmental prerequisites must first be achieved. The global temperatures will need to be raised at least above 273 K, atmospheric pressures will need to be increased as much as possible, the atmospheric composition needs to be adapted, free flowing water must be made available, and the radiation levels will need to be reduced. A number of technological solutions have already been proposed to achieve these goals. Apart from these factors there are more requirements needed to create a truly habitable planet, one such a requirement is the presence of essential components for life such as nitrogen. The focus in most of the terraforming studies however lie in the field of CO_2, water availability and temperatures. Few studies investigate the availability of nitrogen and if these reserves are sufficient for the full terraforming of Mars. Nonetheless the importance of nitrogen should not be forgotten.

We have used current data to calculate the availability of nitrogen on Mars and we have estimated the size of the biosphere that can be supported by it. Although nitrogen is relatively scarce on Mars we have estimated that it will be enough to sustain a biomass of over ~$8.5x10^{14}$ kg, which is roughly 0.02% of Earth's biomass. We suggest to keep the biosphere confined to a relatively small portion of Mars, as our calculations indicate that there is only enough nitrogen to sufficiently fertilise roughly 30% of the Martian surface. A localised biosphere will remain interconnected and will be able to develop into a stable system. Unfortunately there is not enough nitrogen available to also act as an atmospheric buffer gas to raise the atmospheric pressures and to fulfil a humanly breathable atmospheric composition. Therefore other options should be considered to achieve the atmospheric requirements, such as the import of inert buffer gasses from other planets or asteroids.

We have proposed a number of organisms that will be able to pioneer the colonising of Mars after the initial terraforming processes have achieved the most basic requirements. These organisms are able to survive in harsh conditions and possess capabilities that will help in the terraforming of Mars, such as oxygen production, detoxifing the environment or the ability to

fill various nitrogen cycle roles. We have also suggested the use of a sequence of biological waves in order to improve the atmosphere and soil conditions in a gradual way, this will also enable us to establish a biologically driven nitrogen cycle. Biotechnology will likely play an important role in the further development of more suitable organisms.

Apart from the technological and scientific hurdles that need to be overcome, there are also several societal requirements that need to be achieved. These include international cooperation on a global scale, the creation of new international space laws and reaching an ethical justification for terraforming Mars.

It is clear that we will need to create an entire interconnected ecosystem on Mars in order to develop a truly habitable planet. And more research is to be done on Mars' environment, conditions and composition as well as there is a need to further study the various candidate organisms for such a venture. Nonetheless it remains feasible that in 200 years the first pioneer organisms will be able to colonise Mars. Full terraforming however will still require thousands to several hundred thousands of years, depending on the future technological developments. However, terraforming is not necessarily an all-or-nothing scenario and any steps that are taken will increase the habitability of the planet. It is therefore not unlikely that Mars will already be colonised by humans long before full terraforming has been achieved.

List of Abbreviations and Acronyms

Anammox	ANaerobic AMMonium Oxidation
BCE	Before the Common/Current Era
CE	Common Era or Current Era
CERN	Conseil Européen pour la Recherche Nucléaire
CFC	Chlorofluorocarbon gasses
COSPAR	Committee on Space Research
DNA	Deoxyribonucleic acid
ESA	European Space Agency
GWP	Global Warming Potential
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
NPT	Non-Proliferation Treaty or *Treaty on the Non-Proliferation of Nuclear Weapons*
N-wave	Nitrogen cycle establishing wave
OST	Outer Space Treaty or *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*
O-wave	Oxygenic wave
pMMO	membrane bound Methane MonoOxygenase
RNA	Ribonucleic acid
RSL	Recurring Slope Lineae
SAM	‘Sample Analysis at Mars’ investigation by the MSL
UN	United Nations
UV	Ultraviolet

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1. Introduction

From the moment Yuri Gagarin left the Earth's atmosphere, in 1961, as the first man ever to venture into outer space, humanity has been on a course to spread its reach beyond Earth's borders. A mere eight years later, Neil Armstrong set foot on the moon and with it humanity had first set foot on another celestial body. With the development of various space stations mankind has proved its capability to survive, though not yet thrive, beyond its home planet.

Many scientists argue that with the start of the industrial revolution the human impact, on the Earth and on its biodiversity, has reached such proportions that we might have ushered in a new epoch, the Anthropocene (Waters *et al*, 2016). However this human impact will most probably not stay limited to our planet but will spread across our solar system in the coming centuries, as we can already see with the increase of space debris. With the continued growth of the human population on Earth and the consequential effects that mankind has on the planet and its environment, more and more visionaries, scientists, engineers and even politicians are looking towards potential new grounds to colonize beyond our own planet.

The ambition to send man to Mars and to colonise the planet has re-entered popular culture through literature, movies and promises made by prominent visionaries and entrepreneurs such as Elon Musk and Jeff Bezos. The SpaceX's founder's promise to send the first people to Mars in the early 2020's (SpaceX, 2017) is reminiscent of John F. Kennedy's 1962 promise to send the first man to the moon before the end of that decade. These ambitious proposals are not only a continuation of humanities pioneering spirit but according to many also an important step to ensure the survival of the human species (SpaceX, 2017; Hawking, 2017). The reasoning behind this is that if humanity chooses to remain a uniplanetary species, it will always be susceptible to planetary extinction. However if humanity becomes an interplanetary species, the risk of total extinction is significantly reduced.

The question then rises; How will humanity colonize other planets and celestial bodies, beginning with those in our solar system? Will we live in synthetic biospheres which are sealed off from the rest of the planet? Will we have space stations orbiting the planets? Or will we adapt planets to meet our requirements for habitability?

This thesis will discuss the latter option, terraforming. A particular focus will lie on the role that biology will play in the process of terraforming Mars, also the availability of nitrogen and its capacity to support a biologically driven nitrogen cycle will be examined. Although the focus will lie on the scientific, technical and engineering aspects, other issues such as the legal and political prerequisites and ethical considerations will also be discussed as these also play an important role in such large scale projects.

1.1 What is Terraforming?

The term terraforming was first used by the science fiction author Jack Williamson in his 1942 short story, "Collision Orbit" which was published in the "Astounding Science Fiction" magazine under his pseudonym, Will Stewart (Williamson, 1942). However what does this term specifically mean?

Etymologically speaking the term *terraforming* consists of two elements namely the Latin *Terra-* which quite literally means "Earth" and *–form* derived from the Latin *–fōrmis* or *fōrma* meaning "having the form of" or "shape". Terraforming therefore directly translates to "Earth shaping" or "giving the form of Earth". In more direct terms, it is often used to describe the process of planetary engineering with the intention of transforming a certain planet into an Earth-like planet and subsequently making it capable of supporting the human species, ultimately creating a self-sustaining planetary biosphere much like Earth. In 1993 Richard Cathcart succeeded in having the verb "to terraform" formally recognized after which it was first included in the 4th edition of "The New Shorter Oxford English Dictionary" (Brown, 1993).

For the purposes of this thesis the following definition for terraforming, developed by Martyn J. Fogg in his book "Terraforming: Engineering Planetary Environments" (Fogg, 2013a), will be used:

Terraforming is a process of planetary engineering, specifically directed at enhancing the capacity of an extra-terrestrial planetary environment to support life. The ultimate in terraforming would be to create an unconstrained planetary biosphere emulating all the functions of the biosphere of the Earth – one that would be fully habitable for human beings.

Another term that is used alongside and often interchangeably with terraforming, is "ecopoiesis" which was created by Robert Haynes in his paper "Ecce Ecopoiesis: Playing God on Mars" (Haynes, 1990). Ecopoiesis created from the Greek words *oikos*, meaning "house", and *poiesis*, signifying "production" or "making", thereby translating to home-making. The paper describes the term as the "fabrication of a sustainable ecosystem on a currently lifeless, sterile planet", it further elaborates that "terraformation is a specialized form of ecopoiesis, which refers to the development of specifically earth-like conditions culminating in the transfer of suitable Earth organisms to the target planet". It can therefore be a part of the larger process of terraforming. How ecopoiesis fits in the larger terraforming will be described later on.

Humans have already been dabbling in adapting Earth to suit their needs for many thousands of years, whether it has been the redirecting of rivers, draining or creating lakes by building dams, or reclaiming land from the sea by building dykes or by dredging. One example of how humans have managed to create a habitable location in an otherwise hostile environment, is the City of Las Vegas in the United States of America. Located in the middle of the Mojave

Desert, people have had to create an artificial lake, Lake Mead, by building the Hoover Dam to provide the city's water supply. Over the last few decades it has become clear that the Earth's climate is changing and more and more people have come to realise that this is largely the result of various human endeavours, such as our industries and large-scale animal agriculture. Although the current changes might not directly result in the extinction of the human species, it will significantly damage the human species, the environment and the ecosystems currently inhabiting Earth.

As we can see, mankind has already shown its capability to alter certain large planetary processes, however when it comes to manipulating the climate it has largely been an (un)foreseen side effect of many smaller scale activities. It has been estimated that humanity has released 555 Pg of carbon dioxide into the atmosphere since 1750, thereby raising the atmospheric CO_2 to the highest concentrations in at least the last 800000 years (Lewis & Maslin, 2015; Waters *et al*, 2016). One can imagine the potential that could be reached once scientists and engineers start to work on methods with climate manipulation as main goal. In the near future, humanity will increase the scale of such project, which will eventually reach global proportions to halt or reverse climate change for example. Such geoengineering projects will be the frontrunners of the planetary engineering needed for the terraforming of other planets (Fogg, 2013a). Because of such developments, terraforming engineers will most likely find that they do not have to develop all new technologies and machines in order to reach their goals, but will rather have to adapt existing techniques and technologies. However this will be discussed later on.

1.2 The History of Terraforming

In the past century scientist have joined the science fiction writers in their interest for planetary engineering. Though it took several decades before the first data-based proposals were written and thus the concept of terraforming became more credible. Carl Sagan was one of the first to publish such papers, one example is his 1961 paper "The Planet Venus" (Sagan, 1961). Due to a lack of data, Sagan wrongly assumed the clouds surrounding Venus to be water vapour and his estimates of the atmospheric pressure were far off. The premise was that man could send microorganisms into the clouds, which would then use photosynthesis to fixate CO_2 in biomass while producing O_2. The decrease in greenhouse gasses would thereby reduce the temperature enough for the water to precipitate and once the surface temperatures had dropped, microorganisms would be able to transform Venus in a habitable planet. Although the paper has since been disproven on various aspects, it did show that terraforming could be a very realistic possibility. In the following years Sagan continued to publish various papers and in 1971 the discussion turned to Mars.

With his paper “The Long Winter Model of Martian Biology: A Speculation” (Sagan, 1971) the door was opened to scientific speculation on the terraforming of Mars. A number of papers were published over the course of two years by Sagan and his Cornell University colleagues, Joseph Burns and Martin Harwit (Burns & Harwit, 1973). However as often happens in science, new data confuted several of the hypotheses and speculations made in the papers. Nonetheless the fantastic statements and theories formed the basis for the terraforming discussion (Sagan, 1973). The most striking aspect of Sagan’s papers is the fact that he describes large scale planetary engineering projects which would require relatively limited effort. His take on microbiological planetary engineering as a self-amplifying and powerful tool is a theory that still influences its current successors, including this thesis.

In 1976 NASA came with its own study on terraforming, titled “On the Habitability of Mars: An Approach to Planetary Ecosynthesis” (Averner & MacElroy, 1976). The study described similar methods as coined by Sagan a few years earlier, and further elaborated on the use of biological methods for planetary engineering of Mars. In the same year one of the authors hosted the first ever terraforming conference. Although the concept of planetary engineering became a subject of larger papers, it still remained a highly speculative topic and did not reach a fully respected scientific status yet. It therefore continued to be more of a scientific hobby of scientists. At the end of the 1980’s the momentum of terraforming studies had increased to such a degree that entire editions of various scientific journals were published with terraforming as subject, workshops and other conferences were also organised. The interest in terraforming and planetary engineering has risen ever since. And although the terraforming community remains relatively small, it has produced a respectable list of literature. With the increase of interest for space colonisation, in the popular community, the terraforming community will most certainly grow significantly over the coming decade.

2. Mars

Mars is often called Earth’s twin, however one might argue that Venus is more alike in respect of size, mass and surface gravity. Although Mars is a lot smaller, the surface environment is very similar to that of Earth. Also the daily sun cycle is comparable with that of our planet, though slightly longer. A Martian day, often referred to as a “sol”, takes 24 hours, 37 minutes and 23 seconds compared to Earth’s 23 hours, 56 minutes and 4 seconds (NASA, 2015a). However as Mars is located on average at 227.9 million km from the Sun, which is about 78 million km further than Earth, the solar radiation intensity at the Martian surface is only around 43% of that of Earth (S_o = 1361.0 W/m^2) (Averner & MacElroy, 1976) (NASA, 2016a). Its year and seasons are also much longer, taking around twice as long as an Earth year or season respectively.

The atmosphere is however much thinner and only provides around 7 degrees in greenhouse effect which results in a global surface temperature of ~210 K. The atmosphere consists primarily of CO_2 with some N_2, argon and some trace elements. Oxygen concentrations are but ~0.13% and ozone concentrations are down to 0.04 - 0.2 ppm (Fogg, 2013b; NASA, 2016a), which is much too low to provide an ozone layer to shield the surface from UV-radiation like on Earth.

Mars also does not have a significant magnetic field which further reduces the radiation shielding capabilities. The solar wind and cosmic radiation will therefore bombard the surface, only being shielded by the upper atmosphere and the relatively weak remnant magnetic field trapped in the crust (ESA, 2016). The absence of a dipolar magnetic field was originally thought to be an indication that the Martian core had solidified, new studies show however that the core is entirely molten (Stewart *et al*, 2007). Why the dipole ceased to exist still remains unknown (Solomon *et al*, 2005) yet some argue that the return of such a dipole field is a possibility in the future of the planet as crystallisation occurs in the core (Stewart *et al*, 2007).

Although the planet is much smaller than Earth, the Martian surface has a surface area roughly equivalent to the land surface area of Earth (Fogg, 2013b; NASA, 2016a). Other planetary parameters of Mars compared with those of Earth, are listed in table 1.

Table 1: Comparison of Mars' Planetary Parameters with Earth's Planetary Parameters (Fogg, 2013b; Beech, 2009; Averner & MacElroy, 1976; NASA, 2017a, 2016a)

Parameter	Mars	Earth
Mean Distance from the Sun (km)	2.279×10^{8}	1.499×10^{8}
Mean Orbit Velocity (km/s)	24.0769	29.783
Sidereal Orbital Period (days)	686.971	365.25
Eccentricity	0.0933941	0.01671123
Obliquity (°)	25.19	23.44
Perihelion (km)	2.0662×10^{8}	1.4709×10^{8}
Aphelion (km)	2.4923×10^{8}	1.5210×10^{8}
Sidereal Spin Period (hr)	24.623	23.934
Total Mass (kg)	6.4169×10^{23}	5.9722×10^{24}
Mean Radius (km)	3386.2	6367.45
Polar Radius [Equatorial Radius] (km)	3376.2 [3396.2]	6356.8 [6378.1]
Surface Area (km^2)	1.4437×10^{8}	5.1006×10^{8}
Volume (km^3)	16.318×10^{10}	108.321×10^{10}
Mean Density (kg/m^3)	3933	5514
Surface Gravity (m/s^2)	3.71	9.80
Magnetic Dipole Moment (Tesla x m^3)	$< 8 \times 10^{11}$	7.91×10^{15}
Solar Irradiance (W/m^2)	586.2	1361.0 (S_o)
Bond Albedo	0.250	0.306
Surface Temperature Min.–Max. (K)	120-293	185-331
Average Temperature (K)	210	288

As we can see in table 1, the orbit of Mars around the Sun is very elliptical, this results in significant temperature variations on the surface during the various seasons. These seasonal temperature fluctuations are also dependent on its planetary inclination, which is also slightly higher than Earth's. The atmospheric composition, as well as its other atmospheric parameters of Mars compared to those of Earth are listed in table 2 below.

Table 2: Comparison of Mars' Atmospheric Parameters with Earth's Atmospheric Parameters (NASA, 2016b, 2016a)

Parameter	Mars	Earth
Atmospheric Mass (kg)	2.5 x 10^{16}	5.1 x 10^{18}
Atmospheric Pressure (mbar)	6.36 (at mean radius)	1014
Atmospheric Scale Height (km)	11.1	8.5
Mean Temperature (K)	210	288
Atmospheric Composition (by Volume)		
Major Components	CO_2 (95.32%) N_2 (2.7%) Ar (1.6%) O_2 (0.13%) CO (0.08%)	N_2 (78.08%) O_2 (20.95%) H_2O (~1%, highly variable)
Minor Components (ppm)	H_2O (210) NO (100) Ne (2.5) HDO* (0.85) Kr (0.3), Xe (0.08)	Ar (9340) CO_2 (400) Ne (18.18) He (5.24) CH_4 (1.7) Kr (1.14) H_2 (0.55)

*HDO: Hydrogen-Deuterium Oxide

2.1 The Martian Geography

Much like Earth's crust, Mars' surface rocky geology consists of minerals composed of silicon, oxygen, iron, magnesium, aluminium, calcium and potassium. The large amount of oxidised iron in the upper surface gives the planet its reddish hue (Nimmo & Tanaka, 2005). The Martian surface consists primarily of basaltic minerals covered by iron(III) oxide dust which tells its volcanic and tectonic history. However Mars is no longer tectonically or volcanically active .

2.1.1 The Dichotomy of Mars

The topography of the northern and southern hemispheres are very different from each other. The northern hemisphere is largely covered by relatively flat plains that were flattened by lava flows in the planet's history. Most of the northern hemisphere also has a much lower elevation, about 3-6 km, compared to the rest of the planet (Watters *et al*, 2007). These "lowlands" cover about one-third of the Martian surface and have been named the "Borealis Basin". The southern hemisphere however has a rougher surface which is pitted and cratered by various impacts and is generally more elevated. The sharp contrast between the two hemispheres is known as the Martian dichotomy. The elevation differences can best be compared with the elevation difference between the oceanic floors (Martian "lowlands") and the continents on Earth (southern Martian hemisphere). Figure 1 shows the various elevations of the Martian surface.

At the interface or transition zone between the "lowlands" and the "highlands", the surface shows a very complex topography, that contains knobby and fretted terrain. This rough fretted terrain consists of mesas, extensional troughs, lobate scarp thrust faults and fault-controlled fretted valleys and it is often interpreted as the remnant of highland materials resulting from tectonic activity, widespread erosion, mass wasting and retreat of the dichotomy boundary scarp (Watters, 2005; Watters *et al*, 2007).

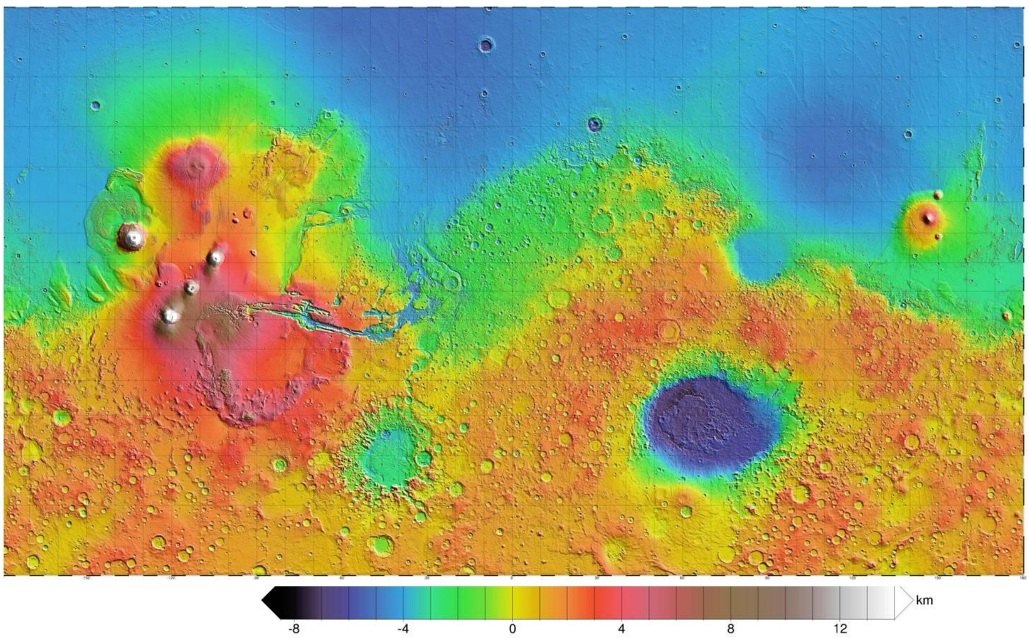

Figure 1: Elevation Map of Mars; Colours signify different elevations as indicated by the legend at the bottom of the figure. (NASA, 2017f)

How this distinct dichotomy came to be is still not entirely known, however there are a number of different hypotheses that would describe such a phenomenon. The dichotomy can also be seen in figure 2, where it is clear that the northern hemisphere is located at much lower elevations than the rest of the planet and that it seemingly divides the planet in two.

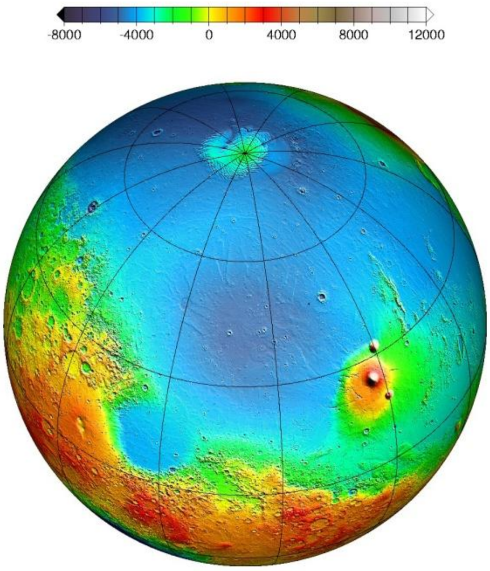

Figure 2: Mars' Surface Elevation Differences Projected on a Globe; Colours signify different elevations as indicated by the legend at the top of the figure. (Lunar and Planetary Institute, 2017)

The most supported three hypotheses are firstly the Endogenic Origin hypothesis, which states that plate tectonics and mantel convections were responsible for the dichotomy. A number of theories exist within this hypothesis. Early on it was postulated that, due to convective upwelling the northern crust was fractured and the crustal material was transported towards the southern hemisphere where it subsided by crustal delamination, thereby forming rises such as the Tharsis rise (Wise *et al*, 1979). The Tharsis Rise can be seen in figure 1 on the left as the region with the highest elevation. More recent models of Martian mantle convections show that crustal extension and volcanism were likely involved in the dichotomy formation. A model of a 1-degree mantle convection, a model in which mantle upwelling dominates in one hemisphere and downwelling in the other hemisphere, could explain the crustal dichotomy (Roberts & Zhong, 2006). If there was a high enough thermal contrast (>1000K) between the core and the mantle at the end of planetary accretion, this could have resulted in a single large plume or superplume. Such a superplume may have produced a melting on planetary scale which would have played an important role in the formation of the current dichotomy (Ke & Solomatov, 2006; Watters *et al*, 2007). However evidence for plate tectonics still remains scarce and therefore this hypothesis still lacks confirmation (Wong & Solomatov, 2015; O'Rourke & Korenaga, 2012).

Secondly there is the hypothesis of a single impact event with a large object. It has been proposed that the Borealis Basin is the resulting impact depression. However the Borealis Basin does not resemble the single circle depression that would be expected from a massive single impact event. Aberrations can be explained by additional processes that occurred after the impact (McGill & Squyres, 1991). The material that was ejected by the impact would have been spread across the "lowlands", apart from that the impact would have generated enough heat to form volcanoes. Absence of evidence for such an ejecta blanket could be explained if the impact occurred early in the Martian history, after which any textural evidence would have been destroyed by later processes such as erosion and smaller impacts (McGill &

Squyres, 1991). If geological evidence were to be found it would provide a very convincing case for this hypothesis. By studying the overall dichotomy boundary of the Borealis Basin, including underneath the Tharsis rise by using gravity and topography measurements, the shape of the basin has been found to be of an elliptical shape. The simplest explanation for the elliptical shape would be that it is the result of a massive impact (Andrews-Hanna *et al*, 2008; Marinova *et al*, 2008).

And thirdly there is the multiple impact hypothesis in which the "lowlands" were formed by connecting impact crates of a number of large impacts. The evidence used for this hypothesis are the remnants of several large impact basins, however much of the northern "lowlands" lie outside the rims of such basins (McGill & Squyres, 1991). Add the fact that many of the rims and inner ejecta are much lower than the "highlands" (Thomson & Head, 2001). This hypothesis therefore lacks evidence for its case. Another argument against this hypothesis is that it is statistically implausible that all those impacts occurred at the northern hemisphere. Both impact models do however agree that such an event would have taken place before the end of the Late Heavy Bombardment.

2.1.2 The Martian Polar Caps

Like Earth, Mars has two permanent polar ice caps, consisting primarily of water ice (Darling, 2016)(Fogg, 2013b). Due to Mars' axial tilt (Mars: 25.19° compared to Earth: 23.44°) (NASA, 2016b, 2016a), the poles lie in continuous darkness during the polar winters. The overall dimensions of the poles do change seasonally as temperatures vary during the Martian year. During the winters the polar caps grow as they accumulate dry ice when the temperatures drop beneath the CO_2 freezing point (148.15 K at Martian atmospheric pressure of 6.36 mbar as can be seen in figure 3) (Faure & Mensing, 2007; NASA, 2012, 2017b).

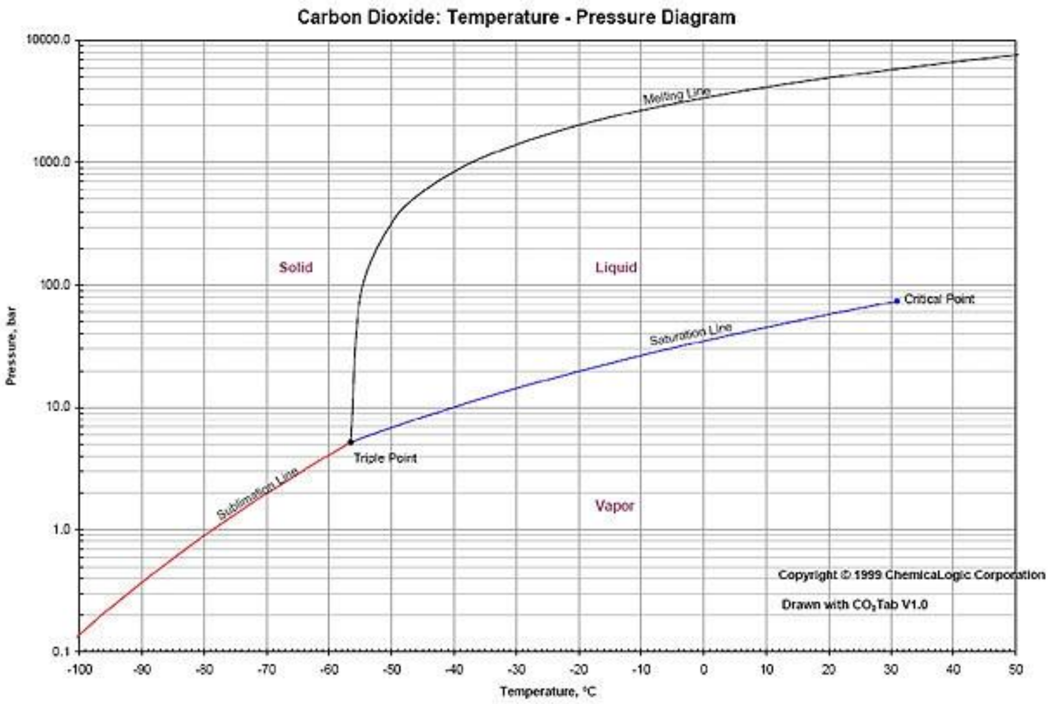

Figure 3: Carbon Dioxide Phase Diagram Pressure over Temperature (Global CCS Institute, 1999)

The condensing of the atmospheric CO_2 (an estimated 3 to 4 x 10^{12} tons, which is roughly equivalent to 12 to 16 percent of the total Martian atmospheric mass) (NASA, 2016c) at the poles during their respective winter influences the atmospheric pressure significantly and even changes in the gravitational density have been measured due to this CO_2 precipitation (Genova *et al*, 2016; NASA, 2016c).

The northern polar cap has the largest surface area of the two poles, with a diameter of roughly 1000 km and has a thickness of up to 3 km (Jaumann & DLR, 2017; NASA, 2010) and contains an estimated 821000 km^3 of water ice (Putzig *et al*, 2009). The ice cap is covered seasonally by a thin layer (±1-2m) of dry ice (Darling, 2016) during which the northern polar cap spreads to a latitude of 68° (Jaumann & DLR, 2017). As explained earlier the northern hemisphere is generally located at a lower elevation than the southern hemisphere and thus the northern polar cap lies at an altitude of -5250 m at its base and -2250 m at its top (Fishbaugh & Head, 2001; Faure & Mensing, 2007) as can be seen in figure 4.

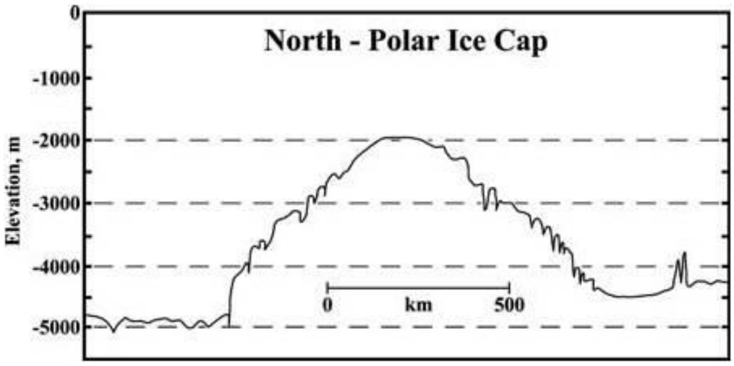

Figure 4: Elevation Range of the Northern Martian Polar Ice Cap (Fishbaugh & Head, 2001)

The southern polar cap's centre is not located perfectly at a latitude of 90°S, but 150 km north of it and the cap has the shape of a dome with a diameter of the permanent cap of roughly 400 km (Barlow, 2008; ESA, 2015) with a thickness of up to 3.7 km (Plaut *et al*, 2007), its top reaching +3500m. However during the southern winter the ice cap grows until it covers the surface up to a latitude of 50°, as the carbon dioxide precipitates on its surface. The southern cap has an estimated 1.6 million cubic kilometres of water (Carr & Head, 2003; Plaut *et al*, 2007) stored combined in its ice cap and the underlying deposits. A comparison of the elevation differences between the two Martian polar regions can be seen in figure 5

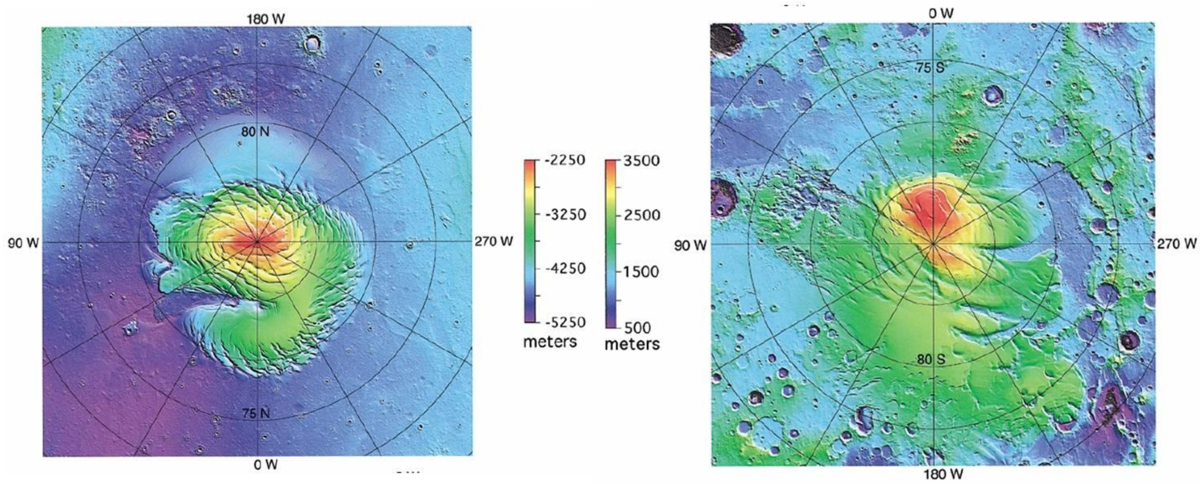

Figure 5: Comparison of the Elevation Differences of the Two Martian Polar Regions; North (left), South (right); Colours signify different elevations as indicated by the legend in the middle of the figure. (Faure & Mensing, 2007)

2.1.3 Hydrology

Much like Antarctica, Mars is very dry due to its low temperatures. Most of the water on Mars is frozen either in the polar caps, ice patches or in underground frozen reservoirs. As described above the estimated amount of water combined in the polar caps is roughly 2.5 million km^3 (Carr & Head, 2003; Plaut *et al*, 2007; Putzig *et al*, 2009) which is equivalent to roughly a quarter of Earth's fresh liquid water (US Geological Survey, 2016). Underground water ice deposits are still being discovered however. In 2016 for example the *Mars Reconnaissance Orbiter* (MRO) discovered a large underground water ice reservoir with an estimated volume of 12100 km^3 in the Utopia Planitia basin, which is located in the northern lowlands (Jet Propulsion Laboratory, 2016). The basin is currently the largest known impact crater in the Solar System with an estimated diameter of 3300 km (Jet Propulsion Laboratory, 2016). More of such periglacial landscapes have given rise to the likely existence of several other regions with a similar permafrost character (Mangold, 2005; Ulrich, 2011; NASA, 2017c). Figure 6 depicts the periglacial landscape found in Canada.

Figure 6: Periglacial Landscape in Canada (Pidwirny, 2006)

A number of craters have already been discovered that contain ice patches and it is likely that more will be discovered in the near future (ESA, 2005). The *Mars Odyssey* mission also mapped the distribution of water on and in the upper surface of Mars and found that certain areas contained as much as 7.5 mass percent of water. The overall measurements resulted in mass percentages between 1.5 and 7.5%, which indicates that there is a reasonable amount of water still trapped in the upper surface layers

(Boynton *et al*, 2007). The MRO also discovered indications for the presence of flowing liquid water. The orbiter studied a phenomenon called recurring slope lineae (RSL), which are seasonally recurring narrow streaks that form on the warm surface (when temperatures reach 250-300 K) of the Martian slopes (Ojha *et al*, 2015). It had already been proposed that these were the result of brine flows, but no direct evidence of liquid water or hydrated salt had yet been discovered. The thought process behind this was the fact that fresh water would sublimate quickly or freeze in most of the surface conditions of Mars. Briny water has a much lower freezing point and a lower evaporation rate and thus will be liquid in more cases than its "pure" water equivalent. However after analysing the data sent by the MRO and comparing with laboratory data, it became clear that these RSL had high concentrations of hydrated salts, magnesium perchlorate, magnesium chlorate and sodium perchlorate, which indicated that they were the result of flows of briny liquid water on a seasonal basis (Ojha *et al*, 2015; NASA, 2015b). This phenomenon was studied at four different locations. Figure 7 shows a picture taken by the MRO of RSL on the slopes of Mars.

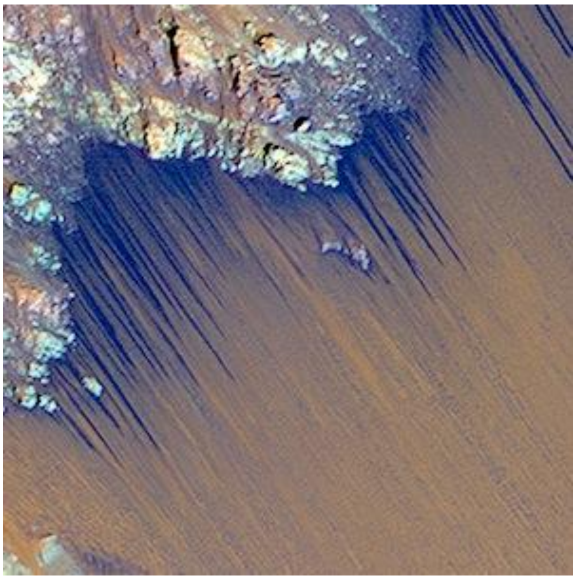

Figure 7: RSL on the Slopes of a Martian Crater; Picture taken by the MRO (Mcewen, 2014)

Not all Mars' water has been discovered yet however we can be fairly certain that more will be found in craters, caves and lava tubes as well as more underground deposits. And although there is not as much water on Mars as there is on Earth, it could be enough to support life on the planet. One can imagine that as the water has been freed from the polar caps and regolith, which will be discussed later, the Martian dichotomy would result in a large northern sea along with several lakes created by the water that will have pooled in the existing craters.

3. Terraforming Mars

3.1 What needs to change?

When taking all of Mars' characteristics into account, Mars does seem to be the most Earth-like planet in our solar system. Though this is indeed the case, Mars is still far from habitable for free living terrestrial life forms and even farther from supporting free living humans. Mars will therefore need to be adapted in a number of different ways, the following five of which being the most essential (Fogg, 2013b):

1. Raise global temperatures
2. Increase atmospheric pressures
3. Change the atmospheric composition
4. Facilitate the presence free flowing water
5. Improve radiation shielding

The first aspect that instantly comes to mind is the temperature that needs to be increased. Due to the low Martian temperatures most of the water reserves are frozen, a significant part of its previous atmosphere is stored in ice caps and the temperatures are largely unsupportive for life at the current moment.

A number of different approaches can be taken to raise the temperatures on the planet, some using the natural presence of energy and others that plan on using manmade energy sources. These methods will be discussed later.

The planet's characteristics that result in these low global temperatures are firstly the fact that Mars is in an orbit located at 78 million kilometres further from the sun, compared to Earth (NASA, 2016a). Secondly the Martian orbit is more elliptical than Earth's and thus the temperature variations during the seasons are more significant, thereby creating large global temperature contrasts. Thirdly, as mentioned earlier the atmosphere of Mars is far less dense than Earth's atmosphere, its greenhouse effect (giving only a 7 K in temperature increase) (Fogg, 2013b) is therefore much lower which further reduces the global temperatures. Lastly as Mars is located further from the sun any incoming sunlight that is reflected back into space will reduce the effectiveness of solar warming. Mars' albedo, even though it is lower than that of Earth (0.250 compared to 0.306 respectively) (NASA, 2016a, 2016b), is still a factor that contributes to the overall global temperatures.

Although all terraforming procedures can be considered to be too advanced at the current moment, changing orbital parameters of a planet will be even more futuristic and will therefore not be discussed in this thesis. The focus will therefore be on increasing temperatures by focussing on the other Martian non-orbital characteristics.

As mankind has learned in the last century, CO_2 is a greenhouse gas that can contribute in raising the global temperatures. Most of the scientific community studying terraforming therefore agree on using the CO_2 trapped in the Martian regolith and in the ice caps, to facilitate temperature increase (Fogg, 2013c). Estimates put the minimum temperature rise needed to free the polar CO_2 reserves at 5 K (Zubrin & McKay, 1993), as will be discussed later.

The current atmosphere of Mars is tenuous compared to Earth's atmosphere. This low pressure can be attributed to a number of reasons, the first one being the low temperatures that affect the atmosphere as described earlier which precipitate the atmospheric CO_2. A second explanation is the fact that at least part of Mars' prior atmosphere has been eroded by the solar wind due to the loss of Mars' magnetic field around 3.9 billion years ago (Stanley *et al*, 2008; NASA, 2017d). Even today Mars is losing its atmosphere at a rate of ~100 grams of gas per second(NASA, 2015c) as a result of solar wind.

In order for humans to survive, the atmospheric pressure needs to be at least above 60 mbar as water will start to boil at body temperature below this limit, which has been dubbed the Armstrong limit (~18-19 km altitude on Earth) (Fogg, 2013c). However more atmospheric pressure requirements are present for the survival of humans and therefore there is a need to further raise atmospheric pressures, as will be discussed later. The overall composition of the atmosphere will also need to be changed to fully support human life. Mars' composition of its atmosphere is currently similar, though with much lower water concentrations, to Earth's early atmosphere (Trail *et al*, 2011)**.** The current atmosphere cannot sustain aerobic life at the moment however it would be able to support anaerobic or facultative anaerobic life. Nonetheless with its high concentration of CO_2 it does provide the potential to be developed into an atmosphere similar to Earth's current atmosphere, at least concerning O_2 concentrations. The requirements for humans to breathe is a lower breathable partial pressure of oxygen of 212,235 mbar. Linked to this the oxygen concentration brings an upper flammability limit of <25% oxygen. Also concentrations of 1% CO_2 (at Earth's atmospheric pressures) will result in health issues in humans over a prolonged period of time (Rice, 2003; Bierwirth, 2017) and will therefore have to be kept preferably below an equivalent of 0.5% at Earth's atmospheric pressures (5.06 mbar partial pressure), to avoid any negative effects. One question that does remain is whether similar nitrogen concentrations to Earths' can be reached with present environmental nitrogen reserves. This will be further discussed later on.

Free flowing water must be made available on the Martian surface to support life. As water is considered to be essential for life, the water reserves on and under the Martian surface will have to be freed. This could be done by "simply" raising the global temperatures and surface pressures above the freezing point of water. However the atmospheric pressures also play an important role in this. The current pressures do not support the presence of pure liquid water, as was mentioned earlier, however it can be assumed that once the temperatures rise, the trapped CO_2 will have evaporated and raised the atmospheric pressures.

Another problem that needs to be dealt with is the high flux of radiation bombarding the surface. Earth is protected from most of the solar and galactic radiation by the shielding provided by its magnetosphere and any radiation that does pass through this shield is neutralised by the upper atmosphere. Mars however, as explained earlier, lost its magnetic field and its atmosphere is much thinner. The current UV flux (200-300 nm) reaching the surface is ~6 W/m^2 which is very high (Fogg, 2013b). To ensure the survival of life and certainly humans and to create possibilities for photosynthesis, this radiation must be reduced.

One aspect that immediately becomes clear is the fact that much of these elements are interconnected. For example as temperatures rise the atmospheric components trapped in the poles will evaporate, thereby increasing atmospheric pressures and changing its composition. As atmospheric pressures rise the melting points of the various elements also change thereby further expediting their thawing subsequently resulting in free flowing water, among other things. The increase of atmospheric gassing will further help in trapping heat, raising the temperatures even more and last but not least the increase of atmospheric density will also increase the amount of radiation shielding. The increased atmospheric density will increase the advective heat transfer to the poles, further pushing the process forward (Fogg, 1998). One sees that as one aspect changes the others will inevitably follow. This feedback-connection (figure 8) is used in most of the terraforming methods described in previous literature.

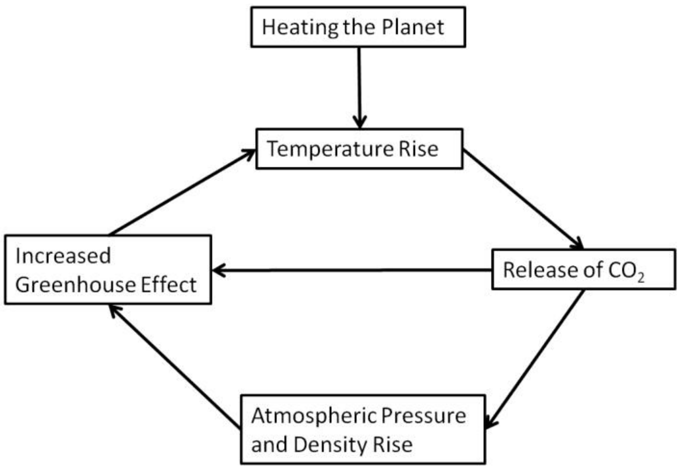

Figure 8: Feedback loop of Warming Mars

However this feedback-loop requires a certain instability of the Martian environment. The positive feedback effect between the surface temperature and atmospheric pressure could then be initiated by a relatively small amount of planetary engineering. The engineered “push”, by raising the temperature or lowering the albedo for example, would then tip over the precarious balance which would lead to a runaway greenhouse effect (Sagan, 1971; Beech, 2009). If the climate is stable, this method will not be practical and terraforming Mars will become a more strenuous process.

It is important to reiterate the fact that ecopoiesis and complete terraforming are different methods that share similarities and which can follow up on each other. The prerequisites for ecopoiesis may be less stringent than for complete terraforming. This is one of the reasons that terraforming experts consider using ecopoiesis as an intermediary step in the process of complete terraforming (Averner & MacElroy, 1976)**.**

The table below (table 3) (Fogg, 2013c) lists the minimum changes that need to be made for ecopoiesis and terraforming. As mentioned earlier the changing of orbital parameters will not be discussed as such an endeavour is still far beyond our capabilities.

Table 3: Requirements for Ecopoiesis and Terraforming (Fogg, 2013c)

Parameter	Present value	Minimum for ecopoiesis	Terraforming
Surface Gravity (m/s^2)	3.71	Not Possible	Not Possible
Bond Albedo	0.250	As low as possible	As low as possible
Mean Surface Temperature (K)	210	At least 273	At least 273
Atmospheric Pressure (mbar)	6.36 (at mean radius)	> 10	380-3700
CO2 Partial Pressure (mbar)	6.06	> 0.1	< 10
O2 Partial Pressure (mbar)	0.01	Not necessary	95-500
N2 Partial Pressure (mbar)	0.17	> 1-10	> 212
Hydrosphere	Frozen	Liquid water available	Liquid and atmospheric water available
UV Flux 190-300 nm	~6 W/m^2	As low as possible	Ideally 0

3.2 Transforming the Planet

As discussed earlier many of the above mentioned needed planetary changes have already been the topic of numerous academic papers since the 1970's. The various methods that have been described in literature will be discussed in this chapter. Many of the methods depend on a runaway greenhouse effect to take over after an initial engineering burst. A runaway greenhouse effect works in the following way.

The initial release of trapped CO_2 reserves will increase the greenhouse effect of the atmosphere. The added amount of heat trapped by the atmosphere will raise the temperatures that will in turn release even more of the CO_2 as well as the frozen water deposits. This further increases the greenhouse effect as well as the atmospheric pressure and this cycle continues until a new stable state has been reached. This runaway greenhouse effect could then take over a large part of the needed terraforming process, without requiring a continuous stimulus. As mentioned earlier such a feedback-loop could significantly minimize the energy needed to be put into the terraforming process.

3.2.1 Albedo

One technique to initiate the warming of Mars' climate is by lowering the mean surface albedo. The solar energy that is constantly reflected back into outer space could be reduced which would subsequently increase the temperatures. An effective way to reduce the mean planetary albedo would be to focus on reducing the albedo of those surfaces with the highest albedos. In this case this would be the polar caps with albedo variations of up to >0.60 (Kieffer *et al*, 1999; Averner & MacElroy, 1976). By lowering the albedo at the polar caps, the frozen CO_2 (a maximum estimated <100 mbar (McKay *et al*, 1991; Fogg, 2013b)) will evaporate and thus further expediting the warming of the planet via greenhouse mechanics. The first method that is described in literature is by darkening the polar caps with a layer of dark dust or material. By covering high albedo parts of the planet with low albedo material, such as dust and rocks from the Syrtis Major region (albedo of ~0.089) (Fogg, 1992), the overall reflected solar energy can be strongly reduced. Sagan originally proposed to cover 6% of the polar caps with a 1 mm layer of carbon black. One issue with this method would be the fact that the total mass of the carbon black material would amount to 10^{11} kg (Sagan, 1973; Fogg, 2013b), which would require many missions to Mars. However the low albedo material of the Syrtis Major region could be a feasible substitute. Nevertheless the surface winds must be held into account, as the seasonal strong winds carry large volumes of dust to and from the polar caps on a yearly basis. The fact that this has not resulted in a shift of the climate stability shows that the winds will prohibit such an event happening effortlessly. It would therefore be more likely to deposit 10 to a 100 times more material to balance out these aeolian processes (Sagan, 1973; Fogg, 1992).

In a similar way covering the entire Martian surface with a low albedo dust of 1 mm would require the transport and dispersion of an estimated 2.6×10^{14} kg of dust. Although this is a large mass that needs to be shifted, when compared to processes on Earth it is ~46% of the total annual deliberate shift of materials during mineral extraction processes (5.7×10^{14} kg) (Douglas & Lawson, 2001; Goudie, 2013). This makes such an endeavour more feasible, though it might not be the most efficient when looking at other terraforming methods.

Another option to reduce the albedo would be to use vegetation or other organisms to darken the poles for example (Sagan, 1973). This option seems to be a more attractive and simpler solution, as this would imply a self renewing and self replicating low albedo layer which can adhere or attach itself to the surface. Such a method would require only a limited amount of transport and maintenance (Fogg, 1992). Unfortunately no terrestrial organism is capable to survive, grow and thrive under the current polar conditions. Nonetheless such a technique might start playing an important part when looking at the rapid progress that is being made in the field of biotechnology (Gibson et al, 2008, 2010; Hutchison III et al, 2016). Moreover a biological albedo reducing layer could be used after certain conditions have changed as a result of other terraforming methods.

One limiting factor of reducing the albedo is the fact that even if the surface is maximally darkened by reducing its albedo to zero, the maximum temperature increase will only be about 10 K (Fogg, 1992). The overall effect of lowering the albedo will therefore be quite modest, a reduction towards an albedo of 0.13 would net in an increase of ~2.5 K and a reduction to 0.089 would result in an estimated increase of ~5 K (Fogg, 1992). A second aspect that has to be kept in mind is the fact that as the temperatures rise the atmosphere will start to develop clouds, which in turn will increase the albedo to an albedo similar to Earth's (~0.3). The development of a thicker atmosphere will also result in more features that further complicate the reduction of the albedo such as flowing water and storms, that will wash and blow away the low albedo top layers (Fogg, 1992).

3.2.2 Space Reflectors

As mentioned earlier Mars is located 78 million km farther from the Sun than the Earth, this results in an average insolation of 0.43 S_o and thus the amount of solar energy is much lower than on Earth (NASA, 2016a). Increasing the insolation would therefore be beneficial for terraforming. There have been a number of proposals to place large mirrors in an orbit around Mars which would focus sunlight on to Mars. Some proposals use a mirror system that would heat the entire planetary surface and others use a system that only focuses on specific areas. There have already been test done with space mirrors in Earth orbit, such as the Znamya project by the Roscosmos State Corporation for Space Activities which successfully launched the Znamya 2 mirror with a radius of 10 m and which produced a 5 km wide orb in the sky, with a luminosity equivalent to a full moon, by reflecting sunlight (Space Frontier, 1999).

Zubrin and McKay proposed using mirrors to specifically warm the southern polar cap. By their estimations a rise of 5 K at the southern polar cap would be sufficient to cause the CO_2 reservoir to evaporate. Using information on the needed solar energy to raise the blackbody temperature of a surface area south of 70° latitude by 5 K above the current 150 K of the polar region, they calculated that this would require a mirror with a radius of 125 km stationed at 214000 km behind Mars (Zubrin & McKay, 1993), see figure 9.

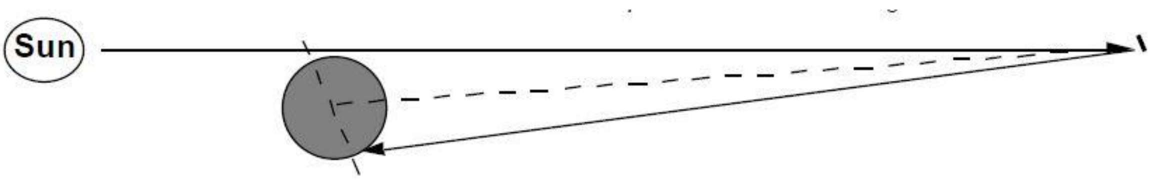

Figure 9: Orbiting mirror located 214000 km behind Mars to reflect the Sunlight back to the Martian surface (Zubrin & McKay, 1993)

The mirror would be able to provide 27 terra Watt (TW), according to Zubrin and McKay, and would be kept in position by balancing the gravitational and light pressure forces. Such a mirror, if constructed out of solar sail type aluminized Mylar material with a density of 4 tonnes/km^2 would give a mass of 2x10^8 kg (Zubrin & McKay, 1993) . This would be too heavy to be launched from Earth, therefore a method of space-based manufacturing would have to be considered. The relationship between the mirror mass, radius and the resulting temperature increase is depicted in figure 10. The aluminium needed for such a construction should not be an issue as it is comparable with 0.17% of the annual global aluminium production (2016 figures for global aluminium production: 1.15x10^{11} kg, (World Aluminium, 2017)), although as said it would not be built on Earth.

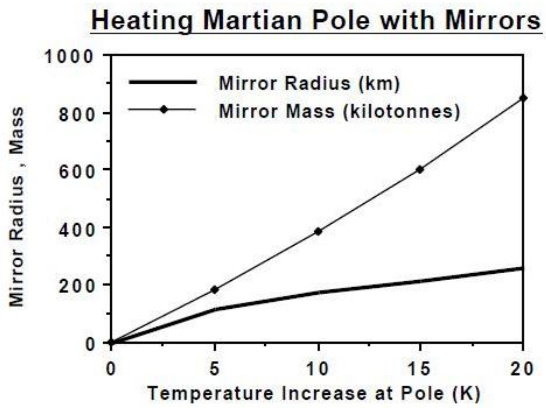

Figure 10: The Relationship between Mirror Mass, Radius and Polar Temperature Increase on Mars (Zubrin & McKay, 1993)

Aside from evaporating the CO_2 ice caps, such mirrors could be used to focus on smaller regions to melt frozen lakes and drive water out of the permafrost (Birch, 1992).

3.2.3 Greenhouse Gasses

Although the CO_2 present on Mars might be able to provide a strong greenhouse effect, adding more greenhouse gasses could prove useful in heating the planet or to initiate a runaway greenhouse effect by melting the CO_2 reserves.

Gasses such as CH_4 and N_2O have a strong greenhouse effect in Earth's atmosphere that are 21 and 206 times stronger than CO_2. However CH_4 only has a lifetime of 10 years and nitrous oxide has a lifetime of 150 years after which it is broken down by photodissociation (Fogg, 2013b). Because of these characteristics, plus the fact that in the current state of Mars there is no biological production of these molecules, these gasses are not ideal to initiate terraforming. They could however contribute to the warming of Mars after ecopoiesis has been achieved, by introducing species that specifically produce such gasses in high concentrations for example, as will be discussed later on.

Although no biological production of CH_4 is yet available, the possibility for a non-biological method of CH_4 synthesis could be considered. A combination of the Sabatier reaction, which is a reaction of hydrogen with CO_2, and the electrolysis of water, which generates hydrogen and oxygen (Carey & Giuliano, 2011) is one such example.

1. Sabatier Reaction: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O + E$
2. Electrolysis of water: $2H_2O + E \rightarrow O_2 + 2H_2$

Resulting in a combined reaction equation:

$$CO_2 + 2H_2O + E \rightarrow CH_4 + 2O_2 + E$$

The two reaction equations, in which the factor "E" signifies the use or release of energy, show the potential for such a system. Though the Sabatier reaction is an exothermic reaction a certain amount of initial heat is required to trigger the reaction, as well as a catalyst such as nickel or ruthenium on aluminium oxide. In order to make use of this system a power source will therefore be needed. The electrolysis of water is added to provide the needed hydrogen, however other methods can be used to supply the hydrogen. In 2011 a test was run to produce methane in a simulated Martian atmosphere for the sole purpose of producing the CH_4 as a rocket propellant. The setup resulted in a production rate of 1 kg per day and an optimized system, weighing 50 kg, was projected to be able to produce 1 kg per day while consuming 700 W of electrical power (Zubrin *et al*, 2013). A system in which several of these small factories are spread across the Martian surface, would therefore be possible and could counterbalance the breakdown by photodissociation of the methane.

The introduction of ammonia to the Martian atmosphere has also been proposed by Pollack and Sagan (Pollack & Sagan, 1991), which by their estimations could raise the surface temperature above 273 K after providing an NH_3 partial pressure of ~0.1 mbar. The difficulty lies in the generation of the required NH_3, which could be produced either by genetically engineered nitrogen-fixing organisms that could survive in Martian conditions or ecopoiesis conditions or by chemical factories running on nuclear fusion for example. The main issue would be the fact that the nitrogen needed to produce the required amount of NH_3 translates in roughly all the atmospheric nitrogen on Mars. Another option that has been offered is to introduce N_2 from celestial bodies with high nitrogen content such as Venus, Earth or Titan. Alternatively ammonia might be imported by transporting ammonia containing asteroids

(Pollack & Sagan, 1991; Fogg, 1992, 2013b). Another important issue is the fact that ammonia rapidly photodissociates by UV radiation, which is estimated to break down up 0.1 mbar of NH_3 in 30 years making such a method unlikely (Fogg, 1992). Moreover a partial pressure of 0.1 mbar of NH_3 is on the threshold limit of tolerable concentrations for human survival at 1 atmospheric pressure (1013.25 mbar) (Dole, 1964). The use of NH_3 as a large scale greenhouse gas is therefore unlikely and undesirable.

A number of proposals to use artificial greenhouse gasses have been put forward. CFC gasses (Chlorofluorocarbon gasses), for example, have a greenhouse effect more than a 10000 times stronger than that of CO_2. CFC gasses have a long lifetime and are non-toxic and thus are very promising for such an endeavour. On Earth the uses of CFCs have generally been banned as they destroy the ozone layer, however on Mars this would not be a problem, at least not in the beginning stages of the terraforming process. The CFC gasses function as a greenhouse gas by absorption of the outgoing infrared radiation, ideally in the window in which CO_2 and H_2O vapour have little activity. One problem is however that CFCs will be far less stable in the Martian atmosphere than here on Earth and will therefore have a much lower lifetime. This is due to the intensity of 200-300 nm UV radiation which is higher at Mars and which destroys the C-Cl bond, the lifetime of a CFC molecule will therefore be reduced from many years to several hours (McKay *et al*, 1991; Fogg, 1998). Fluorine-based greenhouse gasses are far more stable and will be able to better withstand the UV radiation, thereby increasing their lifetime. Marinova *et al.* have identified a number of such non-toxic promising gasses (Marinova *et al*, 2005) namely; CF_4, C_2F_6, C_3F_8, SF_6. The C_3F_8 molecule produces the most efficient warming: 0.56 K and 33.5 K for partial pressures of 10^{-5} mbar and 0.01 mbar respectively. The group also developed an even more efficient mixture of 15% C_2F_6, 62.5% C_3F_8 and 22.5% SF_6 and computed that by adding ~0.002 mbar of this mixture to the Martian atmosphere it would raise the temperatures enough to initiate a CO_2 runaway process, alternatively the addition of ~0.004 mbar of C_3F_8 could do the same (Marinova *et al*, 2005). One advantage of these non-chloride and non-bromide gasses is the fact that these do not destroy ozone. In Earth's atmosphere the lifetimes of CF_4, C_2F_6, C_3F_8, SF_6 are respectively; 50000, 10000, 2600, and 3200 years and have a global warming potential (GWP, compared to CO_2, with a GWP of 1) of 5700, 11900, 8600, and 22200, respectively (Houghton *et al*, 2001). The reduced solar flux at Mars might increase these lifetimes, however the high UV radiation and other radiation could also reduce them. Making exact estimations of the lifetimes is therefore difficult and complicated.

3.2.4 Regolith Degassing

In order to have a climatic greenhouse runaway process to heat Mars in one fluent process, a large CO_2 reservoir able to deliver over 1 bar of atmospheric pressure will be required. The reservoir should also be in a state of precarious stability which can easily be freed out of its trapped condition (Fogg, 2013c). It is estimated that the largest CO_2 reserve on Mars is trapped in mineral grains in the regolith, with upper estimates of ~300 mbar of CO_2 (McKay *et al*, 1991). The question remains if this CO_2 reserve is labile enough to be freed by relatively modest terraforming techniques. McKay *et al.* studied this problem and developed a model which could approximate the temperature rise needed to liberate the CO_2 from the regolith.

The following expression was developed by McKay *et al.*, where M_a is the total adsorbed CO_2 by the regolith, T is the surface temperature, P is the atmospheric pressure, T_d is the response of adsorption to the temperature and the response of the adsorption to the pressure is expressed by the γ and C is a normalized constant that depends on the specific surface area of the adsorbent and the depth of the regolith (McKay *et al*, 1991):

$$M_a = C\, e^{-T/T_d} P^{\gamma}$$

The T_d is required temperature change to outgas a 1/e fraction of regolith CO_2. A low T_d thus indicates that the CO_2 is weakly bound and a high T_d indicates a strong bond. In their paper a γ of 0.275 was chosen based on experimental data and a C was chosen to simulate a total CO_2 reservoir in the atmosphere and regolith of 1 bar although this is an overestimate.

The study conducted by McKay *et al.* showed a more comprehensive survey of the possibility to degas the regolith in order to initiate a runaway CO_2 greenhouse effect. They ran the model for two different cases, the first one is done under the assumption that the CO_2 is uniformly adsorbed in the planets regolith with the average planetary temperature. And the second one uses a more realistic (due to the lower temperatures) approach in which the CO_2 is concentrated in the regolith of the polar regions and thus the focus is on polar temperatures. The search for a stable high temperature and high pressure state in the two cases resulted in a T_d of 10 K for the first one, although this would be highly unlikely as previous experiments with materials analogous to Mars regolith resulted in T_d's of 35 K to 60 K (Valenzuela & Myers, 1989; Fanale & Jakosky, 1982). The case with the polar CO_2 regolith deposits resulted in a more realistic T_d of ~40 K. The results are depicted in the graphs below in figure 11. As we can see the curve for 10 K in the first case crosses the atmospheric curve three times, the first one indicates the current stable state where almost all of the CO_2 is trapped in the regolith, the second one indicates an unstable transition point and the third one indicates a stable state in which most of the CO_2 has spread into the atmosphere. The graph for the polar case shows the 40 K curve crossing the atmospheric curve three times, again with the same stable and unstable points. The graph shows that the instability point will be located at a CO_2 pressure of >100 mbar, however if artificial heating is provided (by methods described above, for example) this can be lowered as this will have the effect of raising the polar temperature curve. This results then in an instability point at lower pressures (McKay *et al*, 1991; Fogg, 2013b). Once the runaway sequence is complete the artificial heating can be stopped and planet would settle in its new stable state.

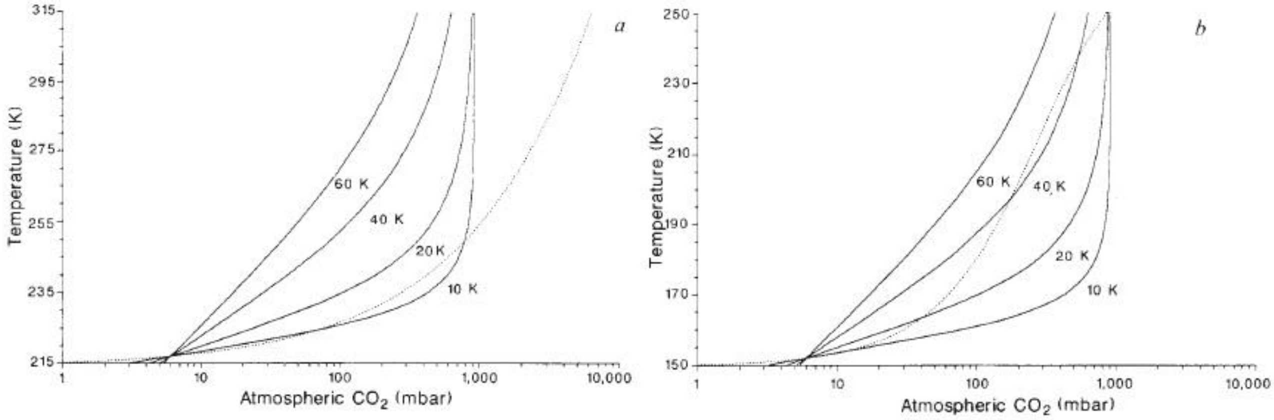

Figure 11: Degassing of the Regolith; **a**, in the case of a global regolith and **b**, in the case of a polar regolith. Both for a total CO_2 equivalent to a partial pressure of 1 bar. The 4 solid curves correspond to T_d values of 10, 20, 40 and 60K. In **a,** the dotted line shows the average Martian temperature that increases due to the degassing. In **b**, this dotted line represents the polar temperature as a result from the degassing. Potential steady states are reached at the intersection of a solid line with the dotted line. (McKay *et al*, 1991)

Other more destructive methods that are able to liberate the trapped CO_2 from the regolith, that have been proposed are the use of buried thermonuclear explosives (Fogg, 1989, 1992) and asteroid impacts (Zubrin & McKay, 1993). The use of thermonuclear explosives has the advantage that much of the raw materials, such as deuterium, can all be found on Mars (Fogg, 1989).

The overall power of the explosives and placement depth would have to be calculated very carefully to minimise the loss of atmospheric gasses to outer space after detonation. It has already been estimated that a 1 megaton (Mt) nuclear explosion could free 10^9 kg of CO_2, though experimental explosions ("Gasbuggy" 26 kt underground nuclear test) have resulted in a yield equivalent to $4.1x10^8$ kg CO_2/Mt (Fogg, 1992).

One factor that severely limits the feasibility of the thermonuclear option is the fact that the number of explosives needed to reach a 1 bar CO_2 will have to be of the order of ten million, depending on the thickness of the Martian carbonate sediments (Fogg, 1989, 1992). The other issue is the present danger of radioactive contamination. Though this might be minimized by using non-fission triggered explosives, which reduces the neutron flux into the direct environment and which burns its fuel as efficiently as possible thereby reducing the radioactive isotopes produced at detonation. The remaining activity is due to the neutron activation products which decay very rapidly and unburned tritium fuel, which has a half life of 12.32 years (Winterberg, 1981; Fogg, 1992). For safety reasons, these methods should not be used while humans are present on the planet. Lastly there are a number of legal issues pertaining to the use of nuclear power in outer space, these will be discussed in the chapter on legal requirements.

In much the same way as using thermonuclear explosives to devolatize the regolith, the use of an asteroid impacts has been proposed. Aside from the impact, if the asteroids contain gasses such as ammonia or methane the added greenhouse gasses will help further heating of the planet (Zubrin & McKay, 1993). However the potential loss of gasses to outer space should not be overlooked.

3.2.5 Recreating a Magnetic Field

An important aspect that needs to be addressed is the fact that Mars will lose its newly created atmosphere by the solar wind, which will continue to strip away the gasses. In order to preserve the terraformed atmosphere a magnetic field will have to be provided. A number of methods have been proposed. The *National Institute for Fusion Science*, Japan, have done a feasibility study on a system which would consist of 12 planet-encircling superconductive rings which carry a maximum current of 6.4 MA (Mega Ampere), with a 1 GW (Giga Watt) power requirement, in order to produce a magnetic field equivalent to 10% of the Earth's geomagnetic field. This approach has been developed by the research group to strengthen the Earth's magnetic field to protect Earth from high-energy radiation, however they also indicated that such a system could be developed in order to protect Mars (Motojima & Yanagi, 2008).

A second method that has been proposed is to create an artificial magnetosphere of 1-2 Tesla generated at the L1 point of Mars (~320 x R_{Mars}) (Green *et al*, 2017; Strizzi *et al*, 2001), Mars would then be protected by the magnetotail. However this is still just a concept and no further studies have been published yet. On the other hand, new research is done at CERN (Conseil Européen pour la Recherche Nucléaire) to develop such an artificial magnetic field, on a smaller scale, in order to protect astronauts (CERN, 2015; SR2S, 2015). It is clear that a magnetic field will have to be provided to ensure that the terraformed atmosphere remains intact.

As we look back on the various techniques have been described, we can see that most of the required Martian adaptations can be fulfilled, at least to a certain extent. The global temperature is raised by a number of processes, which will facilitate the evaporation of volatiles such as CO_2 at the poles and potentially from the regolith**.** The atmospheric pressures will therefore increase and the addition of more CO_2 greenhouse gasses will further enable the temperature rise. The release of the polar and regolith CO_2 would result in a maximum pressure rise of ~400 mbar. Once the temperatures have risen above 273 K water ice will start to melt, thereby fulfilling the required free flowing water. The increased atmospheric pressure along with the proposed methods of creating an artificial magnetic field will reduce the hazardous solar and galactic radiation. Ecopoiesis has hereby been achieved. One aspect that still needs to be addressed is the alteration of the atmospheric composition to suit human requirements. For this particular demand, biology will most likely play an important role.

4. Nitrogen on Mars

Most of the terraforming studies focus on the carbon dioxide, oxygen and water on Mars. Although these are indeed important components to develop Mars into a habitable planet, there are other factors that need to be studied. One such a requirement is the availability of nitrogen, that can be incorporated in a biological nitrogen cycle.

Nitrogen is one of the primary nutrients essential for terrestrial biology, it is a vital component in many biological molecules such as in genetic material DNA/RNA, signalling molecules, hormones, as well as in all proteins and in numerous other aspects. Amino acids, which are the building blocks for proteins, all have nitrogen in their common structure and some in their side chain as can be seen in figure 12.

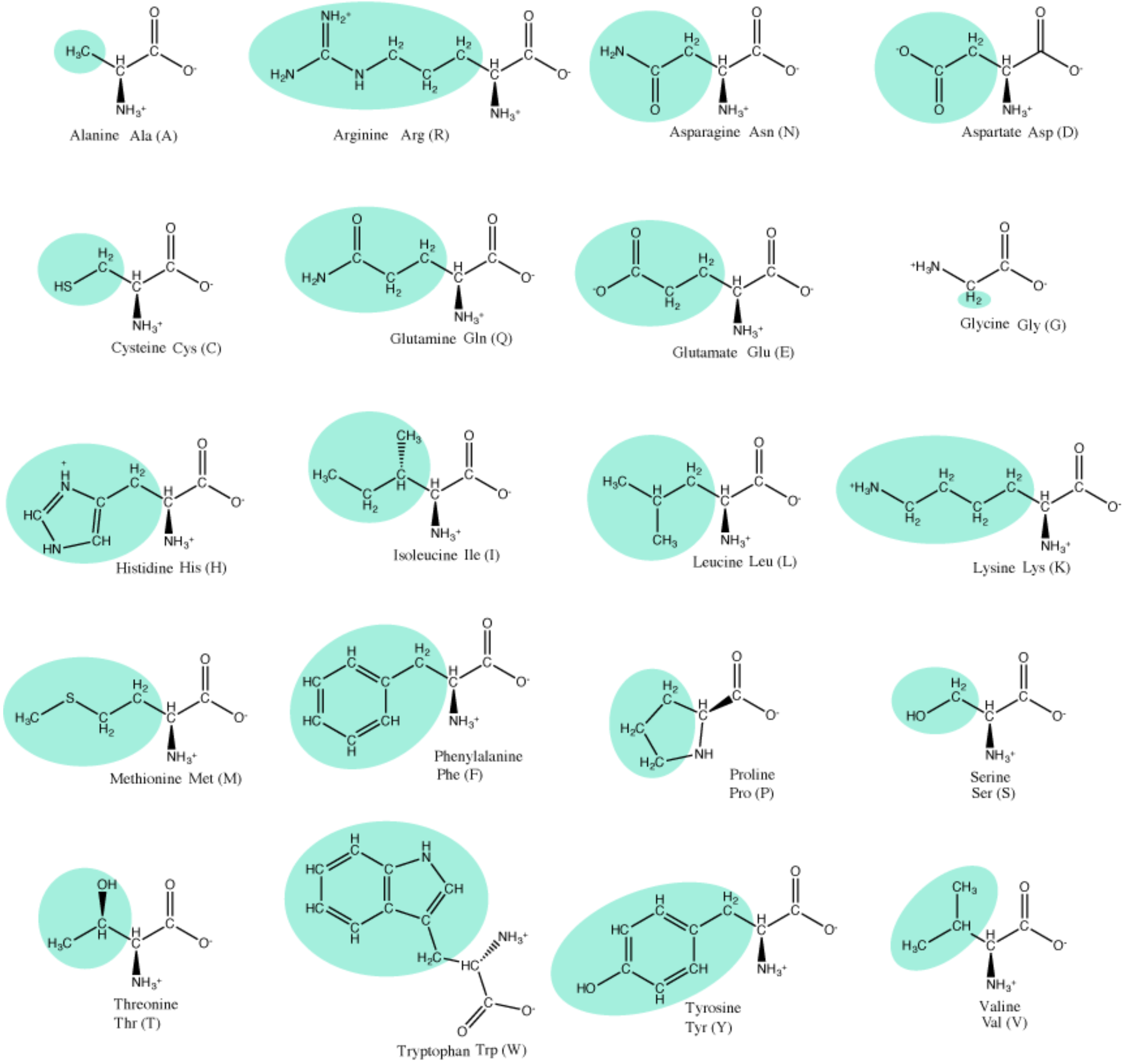

Figure 12: Terrestrial Life's Amino acids, the side chains have been highlighted. (UC Davis, 2017)

Because of this the nitrogen cycle on Earth is an essential component for the continued survival of life. On Earth ~78% of the atmosphere is N_2 however this molecular form of nitrogen is inaccessible for most of the terrestrial organisms. Therefore counter-intuitively (usable) nitrogen is a scarce resource which limits much of ecosystem productivity. For most organisms the N_2 will have to be converted into ammonium (NH_4^+) or nitrates ($-NO_3$) to be accessible. The nitrogen cycle on Earth ensures the continued processing of nitrogen from atmospheric N_2 towards NH_4^+, NO_2, NO_3 for example and vice versa. Nitrogen undergoes various transformations during its time within the ecosystem to both inorganic as organic forms. The main transformation processes in the nitrogen cycle (figure 13) are nitrogen fixation, nitrification, denitrification, anammox, and ammonification, these processes are facilitated by a large and diverse range of microorganisms.

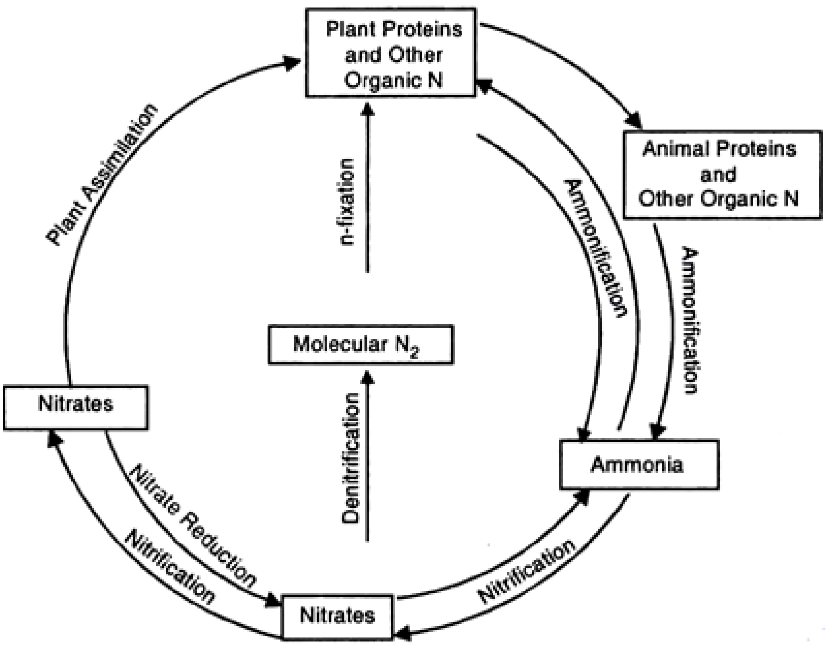

Figure 13: Nitrogen cycle within an ecosystem (Nikita, 2016)

On Mars however the atmosphere only has 2.7% N_2 (~0.15 mbar partial pressure) and thus the feasibility of creating a nitrogen cycle on Mars should be investigated. This amount is only a small fraction of the initial nitrogen that Mars had during is accretion (Mancinelli & Banin, 2003). Estimates of the nitrogen concentrations in the early Martian atmosphere range from 3 to 300 mbar N_2 (Mckay & Stoker, 1989). These estimations are based on the assumption that Mars formed from an equal fraction of volatiles as the Earth did (Fogg, 2013b).

The question that needs to be asked is "where did all the nitrogen go?". There are two processes that could describe the removal of the nitrogen from the atmosphere (Mancinelli & Banin, 2003; Jakosky & Phillips, 2001);

1. Escape of N-atoms into outer space by impact erosion or hydrodynamic escape.

2. Capture and burial of nitrogen in the form of nitrates and ammonium salts within the Martian regolith.

The first process would could be problematic for the required nitrogen cycle as this would encompass the loss of most of Mars' nitrogen to space and thus no possibility of retrieving it. The second process however could prove very beneficial for the initial development of a bio-driven nitrogen cycle. The presence of nitrates and ammonium in the Martian ground could potentially indicate that the ground is fertile enough, working much like a fertilizer, at least for hardy microorganisms and perhaps even hardy plants (Hand, 2015).

By studying the isotope ratios in the atmosphere the enrichment could indicate a loss of 50-90% of the atmospheric species to outer space and from the $^{15}N/^{14}N$ ratios a loss of ~90% of the nitrogen is calculated (Jakosky & Phillips, 2001). However these data only indicate enrichment and not necessarily its loss to outer space.

Evidence of fixed nitrogen in the form of nitrates has already been discovered, in aeolian sediments and drilled sedimentary deposits from the Gale crater, by the *Curiosity* rover (Hand, 2015; Stern *et al*, 2015). The existence of such nitrate salts had already been suggested by Mancinelli and Banin. The thesis behind this is the fact that much of Mars is dryer than the Atacama desert in Chili, which is the driest non-polar desert on Earth (nitrate salts are highly soluble in water) and also the only place where larger deposits of nitrate salts have been found, apart from in the Antarctic desert (Mancinelli & Banin, 2003). The fact that nitrates have been found in the aeolian sediments hint at the possibility that nitrates occur globally and not only in certain Martian mudstones. The results from the Sample Analysis at Mars (SAM) investigation by the Mars Science Laboratory (MSL) *Curiosity* rover indicate a presence of 110-300 ppm of nitrate in aeolian samples and 70-260 and 330-1100 ppm of nitrate in two different drilled mudstone samples (Stern *et al*, 2015).

Another fixed form of nitrogen that could be present on Mars would be ammonia, which would be stored in the mineralogy, however the current Martian missions have not yet uncovered any indications of its presence. At the moment data from *Curiosity* is being analysed to see if ammonia could be identified in the samples (Wray *et al*, 2013).

4.1 Nitrogen Availability

We can make a rough estimation of the nitrogen availability on Mars by using the current data. The total mass of the Martian atmosphere is ~2.5×10^{16} kg and 2.7% of the Martian atmosphere is made up of N_2 (NASA, 2016a) which leads to a total atmospheric N_2 mass of roughly 6.75×10^{14} kg.

If we take an average of the measured nitrate concentrations within the drilled and aeolian samples, which is a very rough estimate and which will not accurately represent reality, we can at least estimate the amount of nitrates trapped in the Martian ground. The overall amount of nitrate (~100-1100 ppm) in the samples result in ~0.01 to ~0.11 wt % of the ground. *Curiosity* drilled to a depth of 5 cm to collect the samples and thus we do not have information on the underlying sediment.

However if we take these results and calculate this for the entire Martian surface, using the average bulk "soil" density of the Martian ground measured by the Mars pathfinder (Hviid *et al*, 1997; Allen *et al*, 1997); 1.52 g/cm^3, we can provide a rough estimation of the nitrate in the Martian ground.

> The total surface area of Mars is 144 371 391 km^2 (NASA, 2017a), using a depth of 5 cm this gives:
>
> 1.44×10^{18} cm^2 x 5 cm = 7.22×10^{18} cm^3
>
> Which gives a total weight of 1.52 g/cm^3 x 7.22×10^{18} cm^3 = 1.10×10^{19} g

Giving us an estimated 1.10×10^{15} g to 1.21×10^{16} g of nitrates in the upper 5 cm of surface of Mars. If we assume that these concentrations are constant for the uppermost 50 cm of the surface layer this would give us nitrate amounts of ~1.1×10^{16} g to ~1.2×10^{17} g.

Recalculating this to the potential N_2 amount:

> Molecular mass of nitrate (NO_3^-): 62.0049 g/mol
>
> Molecular mass of dinitrogen (N_2): 28.01340 g/mol

In the top 5 cm surface layer:

> Lower limit: 1.10×10^{15} g /62.0049 g/mol = 1.77×10^{13} mol NO_3^- = 1.77×10^{13} mol N = 8.85×10^{12} mol N_2
>
> 8.85×10^{12} mol N_2 * 28.01340 g/mol = 2.48×10^{14} g N_2 = 2.48×10^{11} kg N_2
>
> Upper limit: 2.73×10^{12} kg N_2 (calculated in the same way)

In the top 50 cm surface layer:

> Lower limit: 2.48×10^{12} kg N_2
>
> Upper limit: 2.71×10^{13} kg N_2

This would result in a maximum estimated total potential N_2 mass on Mars of 6.75×10^{14} atmospheric N_2 + 2.71×10^{13} kg N_2 (trapped in nitrate) = ~7.02×10^{14} kg N_2

Compared with the nitrogen abundance here on Earth, 78% of the total atmospheric mass 5.1×10^{18} kg or 3.98×10^{18} kg of N_2 in the atmosphere alone and an unknown amount in the biosphere, ground and mineralogy, the nitrogen content on Mars is severely lacking.

Nonetheless at least part of the Martian ground can be enriched with nitrogen and thus increasing its fertility. The present dinitrogen, 7.02×10^{14} kg, can be transformed into nitrates or ammonium resulting in a potential ~31.1×10^{14} kg of NO_3^- or ~9×10^{14} kg of NH_4^+. However this would require the transformation of the entire nitrogen content, which is unlikely.

If we take the terrestrial soil nitrogen content figures that range from 1 to 5 % of biologically active nitrogen compounds within arable soil (Sądej & Przekwas, 2008; Plant & Soil Sciences, 2017). We can then estimate the enriched soil that can be made with the present nitrogen. This would give us a potential 6.22×10^{16} kg of soil enriched with nitrates. Further calculating would give us 6.22×10^{16} kg/1.52 g/cm^3 = ~4.09×10^{13} m^3 of soil, which gives us a surface area of 4.09×10^7 km^2 enriched to 1 meter that can be produced. This would be roughly 30% of the total Martian surface that could be used for the biosphere. However this does not take into account the biospheric nitrogen, nor the fact that it will be unlikely that all the nitrogen can be captured in the ground and that no atmospheric nitrogen will be available in this scenario. As mentioned earlier ammonia concentrations have not been studied yet and the nitrate concentrations have only been measured to a certain depth at a limited number of locations. It is therefore possible that more (or less) nitrogen is present on Mars than we have estimated.

Further calculations with the average nitrogen concentrations within terrestrial organisms, which range from 0.1 wt% to 9 wt% (~3 wt% in humans) (Emsley, 1998; Basu, 2010), we can estimate the size of the potential biomass that is able to live on a terraformed Mars.

Studies have estimated that the total mass of Earth's biosphere is an approximate 0.00008 wt% of the Earth's mass (Mickey *et al*, 2017). Which gives us roughly

$0.0000008 \times 5.97 \times 10^{24}$ kg = ~4.8×10^{18} kg (0.00008% of total mass of Earth, (NASA, 2016b)).

Up to 9% of this mass is nitrogen which gives a biospheric nitrogen mass as high as 4.3×10^{17} kg. The ratio bio-nitrogen over atmospheric nitrogen (mentioned above) is ~0.10. If we use this ratio as a guideline for the Martian biosphere this would give us a potential biospheric nitrogen mass of ~7.6×10^{13} kg, or a respectable ~8.5×10^{14} kg of total biomass this is roughly 0.02% of Earth's biosphere. We can also calculate the biomass per square meter and compare that with Earth's. We can see that Mars has a biomass over square meter ratio of ~5.9 kg biomass/m^2 (surface area of Mars: 144,371,391 km^2 (NASA, 2017a)) and if confined to only 30% of its surface ~196 kg/m^2, which is still much lower than when compared to Earth's ratio of 9410 kg biomass/m^2 (Earth's surface area: 510100000 km^2). However as we have mentioned several times, these calculations are very rough approximations.

These numbers do not bode well for our ultimate goal of transforming Mars into a planet where humans can live freely. Here on Earth nitrogen plays the role of inert buffer gas, which keeps the atmospheric pressure high enough without harmful interaction with the biology.

Apart from that, as explained earlier, nitrogen is one of the most important elements in almost all biological products. On Mars the present nitrogen will not be able to play both roles. As the replacement of nitrogen within biology is near impossible, nor would it be desirable as this is effectively change life at its very basis and it is unlikely that humans would do this to their own species. The only remaining options would then be to find a replacement for nitrogen as an inert buffer gas or importing nitrogen from off-planet reserves, such as asteroids or other celestial bodies.

The requirements for humans is a lower breathable partial pressure of oxygen of 212,235 mbar and an upper flammability limit of <25% oxygen. Also concentrations of 1% CO_2 (at atmospheric pressures) will result in health issues in humans over a prolonged period of time (Rice, 2003; Bierwirth, 2017) and will therefore have to be kept preferably below 0.5% at atmospheric pressures (5.06 mbar partial pressure), to minimize any negative effects. In the lower atmospheric pressure of a potential 400 mbar, which is equivalent to the atmospheric pressure at ~7000 meters above sea level here on Earth, the O_2 percentage will then have to be ~53% and the CO_2 partial pressure will have to be <5.06 mbar. The rest of the pressure, a partial pressure of ~182.7 mbar, needs to be build up by an inert buffer gas. However we should not forget the flammability of such an atmosphere, and thus pressure will likely need to be raised even further to reduce this. In Mars' current atmosphere a partial pressure of ~0.10 mbar is provided by argon which is far too low for our needs. The introduction of safe greenhouse gasses as well as other inert gasses has also been mentioned earlier and such additions will likely be useful to raise the atmospheric pressures. Nonetheless it the estimations show that there will be enough nitrogen available to be able to set up a biologically driven nitrogen cycle, once suitable organisms have been found.

4.2 Setting up a Biologically Driven Nitrogen Cycle

In order to set up a nitrogen cycle, we propose to first denitrify the Martian ground. Although this is counter intuitive, the reason behind it is the fact that the nitrogen content is so low on Mars. Therefore there will not be enough to support a large global biosphere and thus it will only be able to sustain a localised biosphere of moderate size. By denitrifying the entire Martian ground and releasing it into the atmosphere as N_2, it becomes available for localised use. It also helps in raising the atmospheric pressures, however this would not its primary goal as it will be recaptured in the biosphere.

A simplified representation of denitrification is the following redox equation:

$$2\ NO_3^- + 10\ e^- + 12\ H^+ \rightarrow N_2 + 6\ H_2O$$

In which the nitrate functions as an electron acceptor during the bacterial respiration, this normally takes place when other more efficient electron acceptors, such as oxygen, have been depleted.

In a first wave (1st N-wave), denitrifying (mostly anammox) hardy microorganisms would be spread across the planet which would initiate the release of N_2 into the atmosphere. Simultaneously, nitrogen fixating ($N_2 \rightarrow NH_3$) as well as nitrifying ($NH_3 \rightarrow NO_x^-$) microorganisms will capture the dinitrogen from the atmosphere and store them in nitrogen species (ammonia and nitrates) that can be used by a large variety of organisms. However these nitrogen fixing organisms will be kept localised in order to enrich the soil of predefined areas where the envisioned biosphere is to exist (~20-30% of the Martian surface). Simultaneously, though we propose a certain initiation period for the 1st N-wave, an oxygen producing wave (O-wave) can be sent in order to prepare the atmosphere. However this O-wave should also be kept confined to the planned biosphere areas to minimize its spread over the globe, as this would be counterproductive with respect to the 1st N-wave.

Once these two nitrogen cycle groups have settled and a certain balance and sufficient soil enrichment has been achieved in the biosphere regions, a second wave with a large variety of organisms can be introduced. From the nitrogen cycle perspective, this second wave (2nd N-wave) would contain various species that will close the nitrogen loop. Organisms that are able to perform ammonification, and thus break down the organic material to make the nitrogen available again in the form of ammonia for example, and those able to perform anammox, thus freeing the nitrogen from nitrates and ammonia in anaerobic environments. However anammox species will most likely already be a part of the 1st wave in the denitrifying group.

The other 2nd wave species (those not nitrogen cycle specific) will use the biologically active nitrogen species, such as ammonia and nitrates, to grow and fulfil their processes, oxygen production for example. Thus fulfilling the assimilation part of the nitrogen loop and thereby closing the nitrogen cycle. Within this second N-wave there will most likely also be a number of plants thereby coupling the nitrogen waves with the oxygen producing waves, though in reality every organism is part of the nitrogen cycle.

In much the same way, the oxygenation of the atmosphere can be done by a similar wave sequence. In the first wave mostly anoxic (or microaerobic) oxygenic photosynthetic bacteria will develop the atmosphere until the oxygen concentrations are sufficiently high for aerobic oxygenic photosynthetic species, such as plants. After which a second wave of oxygen producing organisms will be introduced. However more will be discussed later on. As mentioned these O-waves should be kept confined to the biosphere zones as they will constitute one of the first parts of the future biosphere. Depending on the status of the planetary conditions as a result of other biological waves, such as the oxygen content, a choice of species is to be made per wave. The suggested composition of the various waves will be discussed later on, after we have discussed a number of potential pioneer organism.

5. Ecopoiesis and Pioneer Organisms

As mentioned earlier biology will play an important role in the process of terraforming Mars after ecopoiesis has been achieved. Microorganisms and other hardy organisms will help develop Mars into a more habitable environment.

Firstly as already mentioned the growth of biological matter on the Martian surface will affect the albedo, which will be significantly reduced in certain areas thereby contributing to the warming of the planet. Secondly certain organisms can help in the freeing of adsorbed atmospheric gasses (nitrogen, oxygen, carbon dioxide) from the mineralogy by (chemo)lithotrophy, which will in turn help raise the atmospheric pressure, change its composition and again further expedite the increase of temperature. And thirdly by selectively using certain (micro)organisms, the atmospheric composition can be changed by oxygenic photosynthesis, methanogenesis, chemosynthesis etc.

We therefore propose the use of certain pioneer organisms that are found on Earth in extreme and Mars-like environments, to fulfil the remaining requirements to fully terraform Mars ready for human habitation.

The pioneer organisms will have to survive the early post-ecopoiesis conditions present on Mars. For the remainder of this chapter the following conditions are assumed to exist after initial terraforming steps have been undertaken.

The atmospheric CO_2 concentrations will be very high, similar to the present conditions (~95%) and oxygen concentrations will be negligible. The atmospheric pressure will still be low (max. ~400 mbar) compared to Earth conditions. The average temperatures will be low but above the freezing point of water, however they might seasonally dip below 273 K. Lastly the radiation fluence will still be high (unless an artificial magnetic field has been made possible), though significantly lower than the current Martian surface radiation, which will also restrict biological habitability.

The current ground (not soil as this implies the presence of biological material) conditions are not ideal for plant growth even when temperatures have risen above the freezing point of water. The ground does have a number of usable minerals for plant growth, however this might not be the case for nitrogen compounds. Such a limited availability of nitrogen is similar to what can be seen in volcanic soils here on Earth (Sigurdsson *et al*, 2000). It is therefore interesting to see how such volcanic soils are made fertile by pioneer organisms which fixate nitrogen from the atmosphere into useable compounds for plants. This relationship between plants, microorganisms and the environment will likely play an important role in the choice of pioneer organisms to terraform Mars. We have found a number of potential pioneer organisms, which we will discuss in the following sections.

5.1 Candidate Pioneer Organisms

5.1.1 Microorganisms

A source of useful pioneer organisms can be found in studying the most primitive microorganisms on Earth and those that are able to survive in various extreme environments, or extremophiles.

Chroococcidiopsis is one such species. *Chroococcidiopsis* is one of the most primitive cyanobacteria on Earth and it could be a good candidate to spread life on Mars. The characteristics that are most appealing are its oxygenic photosynthetic capability, its strong desiccation-resistance, radiation tolerance and its capacity to live under low temperature conditions. On Earth *Chroococcidiopsis* is able to withstand low moisture contents partly by growing on the underside of translucent rocks which filter through enough sunlight to support photosynthesis. The rocks trap enough moisture by condensation on the underside of the rock, thus provide a habitable environment for the cyanobacterium. The cyanobacteria are not limited to growing under such translucent rocks as they have also been found to grow under the edges of opaque rocks, using the little scattered sunlight that reaches this region for their photosynthesis (Smith *et al*, 2014; Billi *et al*, 2013). Another aspect that makes this species even more suitable is the fact that it has nitrogen fixating capabilities (Banerjee & Verma, 2009), which it uses to survive in the Antarctic regions where biologically usable nitrogen species are not in abundance. The ability to use oxygenic photosynthesis as well as nitrogen fixation is extremely rare and it is thought that the nitrogen fixation occurs during the night, while using the energy built up during the day (Billi & Caiola, 1996; Banerjee & Verma, 2009). This characteristic would enable *Chroococcidiopsis* to fertilize the Martian ground for other organisms. *Chroococcidiopsis* is also found in salt deposits in the Atacama Desert (Republic of Chile) (Billi *et al*, 2013) which indicates a strong osmotic stress tolerance and that the microorganisms might also be able to survive in the briny water flows currently on Mars (Cumbers & Rothschild, 2014). The radiation resistance of *Chroococcidiopsis* has already been tested and it was shown that the cyanobacterium was able to withstand 2.5 kGy, and higher, of X-ray irradiation depending on the strain. It is thought that its radiation resistance comes from its ability to survive prolonged periods of desiccation, as this also requires efficient DNA repair mechanisms to overcome the increased DNA damage that the severe dehydration can cause (Billi *et al*, 2000). One problem is the fact that no studies have been done on the CO_2 tolerance of *Chroococcidiopsis* and thus its ability to survive in the CO_2-rich atmosphere and is still uncertain, however it has already been shown that *Chroococcidiopsis* is able to survive in extreme pH conditions which might be the result of

CO_2 dissolves in the water (AlgaeBase, 2017; Magana-Arachchi & Wanigatunge, 2013). It was also shown that *Chroococcidiopsis* is able to grow in microaerobic conditions, unfortunately its nitrogen fixating capacity is reduced by rising O_2 concentrations (Banerjee & Verma, 2009; Bothe *et al*, 2010). *Chroococcidiopsis* possesses many of the needed characteristics to survive on Mars in the early post-ecopoiesis stages and the following phases, thus making it a suitable candidate for one of the first biological waves.

Other cyanobacteria can be considered to join *Chroococcidiopsis* in the first oxygen generating waves. Several other cyanobacteria are also able to facilitate nitrogen fixation, certain cyanobacteria also produce neurotoxins which are extremely dangerous for wildlife. *Chroococcidiopsis* however does not produce such toxins. When choosing other cyanobacteria this toxicity must be kept in mind.

Algae are another useful source of oxygen producers, in particular the algae growing in the arctic environments are of interest to us. One such a candidate is *Chlamydomonas nivalis*, which is a green algae that grows in the snow of the Alps as well as in Siberia among other regions (Duval *et al*, 1999). Its growing conditions range from several degrees below 0 °C to 20°C with an optimum photosynthesis between 1.5°C and 20°C (Remias *et al*, 2005). The algae is able to survive below freezing temperatures by producing a kind of 'anti-freeze' solution consisting of various alcohols, glycerine, sugars and lipids. Research has also shown that it is able to withstand high levels of UV radiation by producing flavonoids which act as antioxidants (Duval *et al*, 2000; Hoham *et al*, 2000). Although the algae is termed a green algae, it has bright red coloured astaxanthins surrounding its chloroplasts which protects them from the high UV radiation (Williams *et al*, 2003). Its colour turns the snow red which it uses to lower the albedo of the snow, as can be seen in figure 14. It thereby increases the amount of absorbed sunlight which in turn raises the temperature and melts the snow around the cells. This extra characteristic can be of great value to us to lower the albedo of the polar and other snowy regions. On Earth the snow contains a nutrients that have been deposited by the wind or by the weathering of rock. The presence nitrates, sulphates and phosphorus is required for the survival of the algae (Jones *et al*, 2001), these components are available on Mars (Bishop *et al*, 2004; Jet Propulsion Laboratory, 2011; Ojha *et al*, 2015). Its tolerance for high CO_2 concentrations however are not yet known. And unfortunately *C. nivalis* is only able to grow in aerobic conditions.

Figure 14: *Chhlamydomonas nivalis* turns the snow red resulting in a phenomenon called "Watermelon Snow" (Quesnel, 2013).

A potential microorganism that might be able to play the role in the denitrifying group, is the free living bacterium *Paracoccus denitrificans*. This bacterium is able to denitrify soils in anaerobic as well as in aerobic conditions. Apart from that *P. denitrificans* is a chemolithoautotroph but is also able to get its energy from organic compounds. Experiments have shown that the bacterium is able to grow between 10 °C and 40 °C with an optimum at 37 °C, at pH values between 6 and 10 with an optimum of 7.6 and several strains showed a salt tolerance of up to 7% sodium chloride (Nokhal & Schlegel, 1983). Apart from that its capability to tolerate and even thrive under hypergravity (~400 000 g) (Deguchi *et al*, 2011), proves itself as a hardy organism. One aspect that is remarkable is the fact that the ancestors of this bacterium are held as the predecessors of eukaryotic mitochondria (John & Whatley, 1975). The use of this microorganism would therefore almost be poetical, in the way that it helped our ancestral eukaryotes and thus multicellular life evolve and now it can help terrestrial life evolve into multiplanetary life.

Another denitrifying candidate is *Candidatus Methylomirabilis oxyfera* (Wu *et al*, 2012), this bacterium has a unique capability to couple anaerobic oxidation of methane with the reduction of nitrite to dinitrogen in a “intra-aerobic pathway”. *Ca.M. oxyfera* is able to oxidise methane in anaerobic conditions in order to gain energy. This pathway is being considered as a new method used by early life on Earth, when the atmospheric oxygen levels were extremely low and the methane concentrations were significantly higher (Ettwig *et al*, 2010). Another useful trait is its ability to grow at temperatures as low as 10 °C (Kampman *et al*, 2014). Its ability to generate oxygen, although only for internal use, can be of interest for future synthetic biological purposes as will be explained later.

Deinococcus radiodurans is known as one of the most radiation resistant organisms on Earth. It has been shown to survive radiation doses of 5000 Sv, which is 1000x the lethal dose for humans (5 Sv). The bacterium’s radiation tolerance is highly dependent on manganese complexes, which help in the protection of its DNA repair proteins (Slade & Radman, 2011; Sun *et al*, 2010). The availability of manganese is therefore vital for its survival. Manganese has already been discovered on Mars, as Mn-rich coatings on several rocks in the *Gale crater*, by the *Curiosity* rover in 2014 (Lanza *et al*, 2014). The presence of Mn in relatively high concentrations significantly increases the chances of survival by *D. radiodurans*. Further extremophilic characteristics are its ability to survive desiccation, vacuum, low temperatures (as low as -35°C for over 10 days) and acidic environments (Diaz & Schulze-makuch, 2006). Because of its polyextremophilic nature it is often put forward as the candidate to colonize other celestial bodies. However even this bacterium has its limitations, for instance *D. radiodurans* is obligate aerobic and chemoorganoheterotrophic. It therefore requires oxygen and organic compounds as a source for energy, two components that are not in great abundance on Mars. Nonetheless *D. radiodurans* might still play a role in the biological transformation of Mars, this will be discussed later on in the chapter on synthetic biology.

5.1.2 Plants

In the later stages of the development of a new atmosphere, plants will be able to be used. Although plants generate oxygen by photosynthesis, plants also respire oxygen. During the day there is a net increase of oxygen, however during dark periods no photosynthesis is active and thus there is a net oxygen consumption. Therefore oxygen should already be present in the atmosphere. The exact concentrations needed are not yet known.

One potential pioneer plant could be a member from the *Lupinus* genus. This plant genus has a very strong nitrogen fixating capability due to its rhizobium-root nodule symbiosis. This capacity enables lupins to grow on infertile soils and thus pioneering barren terrain, while fertilizing the soil for other plants. Various lupins are therefore also often one of the first plants to grow on fresh volcanic soil (Sigurdsson *et al*, 2000). Its nitrogen fixating capability comes from its mutualistic symbiosis, or endosymbiosis, with the *Bradyrhizobium* bacillus. In this symbiosis the bacillus provides the nitrogen fixating capability in exchange for nutrients in the form of carbohydrates from the plant.

The *Lupinus* genus is also very sturdy against various other environmental conditions. The *Lupinus arboreus* (figure 15), or tree lupin, for example is able to survive and tolerate temperatures down to -12 °C (261.15 K), *L. albus* -6°C, *L. luteus* -8°C, *L. angustifolius* -9°C and *L. polyphyllus* was shown to be able to withstand periods of extreme frost as low as -25 °C (248.15 K) (Australian Government Department of Health and Ageing, 2013; Botanical Society of Britain & Ireland, 2017).

Figure 15: *Lupinus arboreus* (The Watershed Nursery, 2017)

However one aspect that still needs to be studied is *Lupinus*' ability to tolerate high CO_2 concentrations as well as the rhizobium's ability to absorb the atmospheric nitrogen in the high CO_2 atmosphere. As Mars' atmosphere consists for ~95% out of CO_2, the plant's ability to survive and grow in such conditions is vital. If the plant is able to survive such an environment, its photosynthetic capacity will start to fixate the carbon of the atmospheric CO_2 in order to grow and as a by-product it will release O_2 into the atmosphere. Although as said, plants also need oxygen during the night time and thus a certain amount of oxygen will already have to be present in the atmosphere. One aspect that has not yet been mentioned, which is very important for the continued survival of the pioneer species, is the reproductive cycle. *Lupinus* is capable of sexual and asexual reproduction. In the asexual reproduction *Lupinus* propagates by root fragmentation and root sprouts. For its sexual reproduction however it requires insects, such as bees, to pollinate its flowers (Australian Government Department of Health and Ageing, 2013). Fortunately the species can propagate asexually, the limitation created by the need of insects will be discussed later on. Soil requirements for *Lupinus* are the availability of Mn, iron, phosphorus and for its root nodule bacteria cobalt (Australian Government Department of Health and Ageing, 2013). Fortunately all the elements can be found on Mars in sufficient amounts (Greenwood *et al*, 2013).

Another group of plants that should be studied is the group of the xerophytes. Xerophytes are plants that have adapted to arid condition, such as the deserts or the arctic/Antarctic and tundra regions. In our case those that reside in arctic and other cold environments will provide us with potential candidates. Characteristic for most of the plants growing in the tundra regions is their small size and shallow root systems. By growing close to the ground they are able to resist many of the cold weather effects and damage caused by eolian processes, such as wind-blown ice crystals that can have an abrasive effect (Pielou, 2012). The shallow root system is used as only a thin layer of soil normally thaws in the summer season and refreezes during the colder seasons. Plants growing in the permafrost regions are predominantly hardy mosses and liverworts, also grouped under the name bryophytes (Losos *et al*, 2008). All mosses and liverworts possess the photosynthetic capacity which further helps our cause. In fact it has been proposed that the oxygen levels in the Earth's atmosphere are, for a significant part, thanks to the spread of bryophytes around 470 million years ago (Lenton *et al*, 2016). Bryophytes can either reproduce sexually, in which the wind or insects usually transport the pollen from one flower to another, or they can use vegetative reproduction, in which new plants grow from intentionally fragmented pieces which have been spread by the wind (Losos *et al*, 2008).

Calliergon giganteum, or arctic moss, is a slow growing moss which grows at the bottom of tundra lakes as well as on certain parts of the tundra ground (Sand-Jensen *et al*, 1999). Temperatures in the tundra environment range from -25°C during the winters to 10°C in the summer and the temperatures of the tundra lakes hardly ever reach temperatures over 6°C (UCMP, 2004). In order to survive the dry and harsh environment of the tundra, *C. giganteum* has developed methods to protect itself from desiccation as well as to the short growing season by storing nutrients in order to grow new leaves more rapidly in the following spring. Another aspect that will be extremely useful for the low nitrogen content on Mars, is the fact that arctic freshwater lakes are also lacking nutrients, in particular nitrogen and phosphorus containing nutrients. After studying *C. giganteum* it was found that the nitrogen content within its tissues was much lower than what was previously considered essential for life (Sand-Jensen *et al*, 1999; Ueno *et al*, 2009). Its ability to grow in cold, low nutrient, low sunlight, short growth seasons and dry locations are the cause for its slow growth. Other studies have shown that the growth of aquatic bryophytes is promoted by high concentrations of dissolved CO_2 (Bain & Proctor, 1980). More studies done on the effect of CO_2 concentrations on bryophytes have found that high CO_2 concentrations led to an increase in the photosynthetic rates (in some cases) (Coe *et al*, 2012; Tuba *et al*, 1998), higher stress tolerance towards heavy metals (Takács *et al*, 2004) and stressful temperatures (Coe *et al*,

2012) and an increase in reproduction (Coe & Sparks, 2014; Tuba *et al*, 2011). As such, these characteristics make psychrophylic (and later on mesophylic) bryophytes very strong candidates to assist in the terraforming of Mars.

5.2 (Per)chlorates

One issue that must not be overlooked is the fact that certain regions of Mars have high perchlorate and chlorate concentrations. Perchlorates, $-ClO_4$, are known to contaminate the environment on Earth as a result of herbicides, bleaching agent, explosives and solid rocket propellants for example. Certain sources of agricultural fertiliser also contain perchlorate which will leak into the groundwater due to its high water solubility (Urbansky *et al*, 2001). Perchlorates can also build up in plants where it will damage the photosynthesis process. Perchlorates can result in significant health problems in humans and animals as it affects the function of the thyroid gland of mammals for example, so the high concentrations on Mars form another health risk.

Chlorates, $-ClO_3$, such as sodium chlorate are used as non-selective herbicides which is also problematic for any future plant growth during the terraforming of Mars. It is also highly toxic for humans and animals. Fortunately there are a number of microorganisms that are capable of growing in such regions by (per)chlorate reduction which provides the microorganism with energy. Most of the organisms able to facilitate such (per)chlorate reduction use the enzymes perchlorate reductase and chlorite dismutase. The reactions catalyzed by these enzymes are described below, in which E_a is an electron acceptor located on the enzyme:

By perchlorate reductase:

1. $ClO_4^- + 2\ E_a.H_2 \rightarrow ClO_2^- + 2\ E_a + 2\ H_2O$
2. $ClO_3^- + E_a.H_2 \rightarrow ClO_2^- + E_a + H_2O$

   (Bender *et al*, 2005)

   By chlorite dismutase:

3. $ClO_2^- \rightarrow Cl^- + O_2$

   (Schaffner *et al*, 2015)

As we can see, these reactions will result in the generation of O_2, another aspect that could prove useful in the development of a human-compatible atmosphere.

There is a large list of microorganisms that are able to breakdown (per)chlorates, however not all organisms will be suitable for our goal of spreading life on Mars. One characteristic that all of those microorganisms have in common is that they are facultative anaerobic or microaerophilic. The highly soluble perchlorates result in the briny water of which the *Mars Reconnaissance Orbiter* found evidence, organisms that will have to live in these perchlorate environments will also have to be halophilic or at the very least halotolerant.

One potential organism would be the hyperthermophilic archaeon *Archaeoglobus fulgidus* which reduces (per)chlorates to chlorites by using molybdo-enzymes, which are similar to perchlorate reductase. However *A. fulgidus* does not reduce chlorite in a biotic way but relies on sulphur compounds to abiotically react with the chlorite (Liebensteiner *et al*, 2013). *A. fulgidus* is a chemolithoautotroph which uses energy gained from the reduction of sulphates to sulphides. As the results of the Mars rover *Opportunity* as well as other rovers has shown, sulphates are abundant on the Martian surface (Bishop *et al*, 2004; Jet Propulsion Laboratory, 2011). Its anaerobic capabilities make it a suitable candidate, unfortunately it only grows at high temperatures between 60-95°C, with an optimum at 83°C (Klenk *et al*, 1997).

Dechloromonas aromatica, a bacteria that is found in river sludge is able to grow in anaerobic conditions. Apart from that *D. aromatica* can reduce (per)chlorates to harmless chloride and also has the potential to degrade various aromatic contaminants in the sludge, such as benzene (Salinero *et al*, 2009). The precise pathway is still being researched. Although its optimum growth temperature is at 30°C, it has been shown that it can remove perchlorate at temperatures as low as 10°C (Dugan *et al*, 2009; Bardiya & Bae, 2011). These characteristics make it a suitable candidate as a pioneer organism.

Another promising candidate would be the *Pseudomonas stutzeri* strain PDA which is able to reduce (per)chlorates in aerobic as well as anaerobic conditions (Clark *et al*, 2016). The overall growth conditions that have been found suitable for the *P. stutzeri* species are a wide range between 4°C and 45°C (Lalucat *et al*, 2006), however not every strain was able to grow at each temperature and thus studies still have to be done on the survivability of strain PDA under the lower temperature conditions. Aside from the temperature tolerance, the species' tolerance for high CO_2 atmospheric concentrations will need to be investigated. Another point of interest might be the fact that other strains of *P. stutzeri* are capable of either nitrogen fixation, denitrifying and some can do both (Deng *et al*, 2014; Lalucat *et al*, 2006). Unfortunately the bacterium is not able to grow without the energy supplied by organic molecules and no strain is able to grow at acidic conditions lower than pH 4.5 (Lalucat *et al*, 2006). Nonetheless this species is of interest either as (per)chlorate reducer, for the nitrogen cycle or as a genetic donor for a synthetic biology solution.

As mentioned earlier the terrestrial environment that we should look at for inspiration and hardy organisms are the arctic and permafrost regions. *Methanobacterium arcticum* is one such a microorganism, this methanogenic archaea grows in permafrost regions of the Russian arctic and is able to use the perchlorate as an electron acceptor during periods of anaerobic methane oxidation (Shcherbakova *et al*, 2015). Its ability to grow autotrophically at low temperatures, in perchlorate enriched environments and under anaerobic circumstances makes this halophilic archaea *M. arcticum* a suitable candidate. Its production of methane using the atmospheric CO_2 also helps in the creation of a stronger greenhouse effect and thus would help in the warming of the planet and its reduction of perchlorates will lead to lower perchlorate concentrations.

Other members of the *Methanobacterium* genus, such as *M. veterum* and *M. bryantii* (Krivushin *et al*, 2010; Shcherbakova *et al*, 2011), have similar characteristics such as psychrophilic, halotolerant and anaerobic capabilities as well as the ability to grow under high perchlorate concentrations. Several of the *Methanobacterium* genus have also been shown to be able to grow under low pressures (6-143 mbar) (Mickol & Kral, 2016). However they lack the ability to degrade perchlorates and thus these organisms will only be able to help terraforming by generating CH_4 as a strong greenhouse gas.

5.3 Synthetic Biology

As we have seen there are a number of existing species that can be used as pioneer organisms to make Mars more habitable. However as we have also seen each of them has a weakness which could potentially limit its survival capacity on Mars. It would therefore be useful to turn towards the field of synthetic biology to create an organism that suits the needs. The rapid progress in biotechnology indicates that it would certainly possible in the (near) future, to create entirely synthetic organisms with only suitable characteristics. In 2008 the first synthetic bacterial genome was created (Gibson *et al*, 2008) only two years later the first self-replicating synthetic cell was constructed (Gibson *et al*, 2010) and in June of 2016 the first minimal cell was created (Hutchison III *et al*, 2016), which has the smallest genome for a cell that is still able to autonomously replicate. Existing organisms have already been modified to provide useful services. *D. radiodurans* for example has already been modified to degrade, digest and sequester various pollutants, such as heavy metals, in radioactive environments (Brim *et al*, 2000). Its radiation tolerance is an interesting characteristic that might be used in the creation of novel life forms.

The following aspects will have to be covered, in the early post-ecopoiesis phases of Mars, and preferably by a minimum of different species:

- Psychrophilic, psychrotrophic and mesophilic
- Autotrophic
- Radiation resistant
- Able to grow at low pressures (60 - ~400 mbar)
- Preferably desiccant resistant and drought tolerant

- CO_2 tolerant/anaerobic
- (Per)chlorate resistant/(per)chlorate reducing (for certain environments)
- Halophilic/halotolerant (for certain environments)
- Ability to be part of the nitrogen cycle (nitrogen fixating, ammonification, nitrification, denitrification)
- Oxygenic

After the first waves of biological transformation of Mars, the environment will have changed and become more hospitable and thus the requirements change:

- Mesophilic and/or psychrophylic
- Autotrophic as well as auxotrophic
- Low pressure (~400 mbar)
- Facultative aerobic/aerobic
- Able to survive in high CO_2 atmospheres
- Radiation resistant

One interesting development is the research that is being done on the creation of hypoxia and anoxia tolerant plants. As mentioned earlier, plants are obligate aerobic organisms which significantly reduces their use in the anoxic initial stages of ecopoiesis. The development of anaerobic or facultative aerobic plants could result in an additional pool of first wave candidates. Vartapetian *et al.* are one of the research groups developing truly anaerobic and hypoxic transgenic plant lines. They have already had success with selecting and creating highly tolerant plant lines of sugarcane (*Saccharum officinarum*) and wheat (*Triticum aestivum*) (Vartapetian *et al*, 2014). Rice (*Oryza sativa*) is one of the many plants being studied, as rice already has a strong natural tolerance of low oxygen levels as it grows in flooded rice fields. Unfortunately even tolerant plants lose a significant part (and often the totality) of their photosynthetic capacity in low oxygen environments. Rice (*O. sativa* cv. Cigalon) however was shown to be very resistant and still maintained a 50% activity of its photosynthesis (Mustroph & Albrecht, 2003). As said this research can provide us with new organisms that can be used to develop an oxygen rich atmosphere.

The earlier mentioned bacterium *Ca.M. oxyfera* uses methane as a substrate and is able to use the oxygen of nitrites to drive its inta-aerobic methane oxidation to generate energy. In this process it will not release any oxygen, only N_2 and thus its usefulness depends on its denitrification. The enzyme responsible for the methane oxidation is the membrane bound methane monooxygenase (pMMO), which is able to oxidise methane as well as other alkanes and thus the bacterium is able to grow on other alkanes (up to a certain extent). The pMMO enzyme uses a tri-copper, a di-copper and a di-iron complex for its activity, both metals are readily available on Mars (Popa *et al*, 2014). When the bacterium was grown in a propylene environment the bacterium did release O_2 and this could be explained by the fact that pMMO has a lower activity with propylene than with methane, thus allowing some oxygen to escape (Ettwig *et al*, 2010). The enzyme responsible for the production of O_2 and N_2 from NO_2^- is not yet known, however it is clear that such an enzyme could prove useful in the development of new species for the terraforming process. A novel organism that is able to breakdown nitrites and release N_2 and O_2, would couple two goals namely the initial denitrification of the ground and the oxygenation of the atmosphere.

As mentioned earlier, synthetic organisms could help increase the greenhouse effect on Mars by producing large amounts of greenhouse gasses, such as methane. By designing a high yield methane producing organism, the photodissociation of the atmospheric CH_4 can be counter balanced to maintain a stronger greenhouse effect. *Methanobacterium,* for example, can be used as a basis such productivity.

By studying various organisms that show promising characteristics, we will be able to compile a library of useful traits along with their responsible pathways and enzymes. Once such a list has been created we will be able to look for viable combinations and we will be able to create such Mars-specific synthetic organisms.

Another aspect that might be interesting to study for synthetic biology is the current research that is being done on xeno-nucleic acids (XNA). Synthetic life forms that use a different genetic “alphabet”, XNA, than our DNA/RNA based life, can have several advantages over DNA/RNA-based life (Steele & Gold, 2012; Laanen, 2015; Herdewijn & Marliere, 2009). For example XNA can be made more stable and resistant to damage, such as radiation damage, which will in turn increase the radiation tolerance of the organism.

5.4 Combining the Pioneer Organisms

The above described pioneer organisms can be fit in earlier proposed wave structure. In the 1^{st} N-wave we suggest a combination of the following denitrifying bacteria:

- *Paracoccus denitrificans*
- *Candidatus Methylomirabilis oxyfera* (genetically modified)
- *P. stutzeri*
- Synthetic organisms that are able to live, preferably autotrophically or chemolithotrophically, in anoxic/microaerobic, cold and high radiation conditions with high CO_2 concentrations and that are capable of dentrification.

Which will be spread over the entire surface to free the trapped nitrogen. In the same wave we propose to add the following nitrogen fixating organisms:

- *P. stutzeri*
- *Chroococcidiopsis*
- Synthetic organisms that are able to live, preferably autotrophically or chemolithotrophically, in anoxic/microaerobic, cold and high radiation conditions with high CO_2 concentrations and that are capable of nitrogen fixation.

However these microorganisms are to be confined to the predefined biosphere locations, where they will enrich the soil with biologically active nitrogen species ahead of the rest of the future biosphere. Along with these nitrogen fixating organisms we could add the 1st O-wave containing the following oxygenic organisms, however we propose to first have an initiation period for the 1st N-wave:

- *Chroococcidiopsis*
- Synthetic organisms that are able to live, preferably autotrophically or chemolithotrophically, in anoxic/microaerobic, cold and high radiation conditions with high CO_2 concentrations and that are capable of oxygenic photosynthesis. Preferably also capable of living in nitrogen poor environments.

These are also to be kept localised in the future biosphere zones as they will constitute the first photosynthetic component of the biosphere.

The biosphere zones will also need to be detoxified by removing the (per)chlorates. A number of the proposed (per)chlorate degrading bacteria will be able to be part of these first waves. Their ability to grow in anaerobic and cold conditions will enable them to work alongside the nitrogen fixating organisms, denitrifying bacteria and oxygenic organism in the biosphere zones. We can also choose to spread those (per)chlorate degrading bacteria over the entire surface in order to detoxify the entire planet, however we feel that this would be an unnecessary cost and unfruitful process which would increase the cost of the seeding missions as well as the cost of environmental nitrogen needed for the survival of these organisms in the more remote locations. This would take away part of the nitrogen that would have been usable in the envisioned biosphere. However it can help in the production of oxygen. The proposed organisms for this group would be:

- *Pseudomonas stutzeri* strain PDA
- *Methanobacterium arcticum*
- *Methanobacterium veterum*
- *Methanobacterium bryantii*

- Other *Methanobacterium* strains
- *Dechloromonas aromatic*
- *Archaeoglobus fulgidus*
- Synthetic organisms that are able to live, preferably autotrophically or chemolithotrophically, in anoxic/microaerobic, cold and high radiation conditions with high CO_2 concentrations and that are capable of (per)chlorate (and other toxic material) degrading. Preferably also capable of living in nitrogen poor environments.

Once the soil has been sufficiently enriched in the biosphere zones and when the atmosphere has been oxygenated up to the point where aerobic photosynthetic organisms can survive. The second N-wave as explained earlier will provide organisms that are able to fill the remaining nitrogen cycle roles. The 2nd O-wave organisms are those that are not able to grow in anaerobic conditions, such as plants. As explained earlier the second waves will start to overlap and go over into each other as every species is part of the larger nitrogen cycle. These organisms will therefore likely be a combination of 2nd N-wave and 2nd O-wave members. We propose to combine the following organisms in the second wave:

- *Calliergon giganteum*
- *Lupinus*
- *Chlamydomonas nivalis*
- Synthetic organisms with a various "ecosystem-relevant" traits and that are able to live in anaerobic or aerobic, cold to moderate temperatures with high CO_2 concentrations.

As the conditions on Mars improve, more and more non-extremophilic organisms will be able to be used in the new biosphere. However these organisms are beyond the scope of this thesis.

5.5 Concluding Remarks on Biological Terraforming

As we can see there are still a number of hurdles that need to be overcome before terrestrial or even synthetic species can contribute to the terraforming of Mars. Unfortunately plants are obligate aerobic and thus they will not be able to contribute in the oxygenation of the atmosphere in the first stages of ecopoiesis. However it can be imaged that artificial biodomes (or greenhouses) can be placed on the Martian surface with an atmosphere similar to that of Earth. Within these domes high oxygenic plants can grow, CO_2 from the outside atmosphere is filtered into the domes and excess oxygen will be ventilated out into the Martian atmosphere. One of the main issues that still remains is the adaptation of the atmosphere to a human-breathable mixture.

It is also quite possible that unless more atmospheric gasses, such as dinitrogen are imported, the Martian atmosphere will never be fully breathable for humans. Pressures can be raised to safe levels and thus humans would be able to walk outside without pressurised suites though still wearing simple breathing equipment.

Another aspect that must not be forgotten is the fact that some plants cannot reproduce without the assistance of an insect such as bees, butterflies, flies etc. Before such plants can be used we would also need to introduce such species, however their ability to survive the post-ecopoiesis conditions will have to be studied first. Some studies have been done on the effects of high carbon dioxide concentrations on honeybees, they showed that it had anaesthetic effects from concentrations >25% CO_2 (Klopfer & Quist, 1955). Unfortunately the number of studies are still limited and the same can be said for research done on the effects of low atmospheric pressures on those organisms. Therefore plants that are able to reproduce without the assistance of another organism will be the preferred plants to use in the beginning stages.

Although not specifically relevant to the terraforming of Mars it might be interesting for the terraforming discussion, to look at other life spreading projects, such as the Genesis project proposed by Claudius Gros (Gros, 2016). This project aims to develop ecospheres on transiently habitable planets. It would involve finding transiently habitable exoplanets, sending robotic spacecrafts to provide a detailed analysis of those planets and then seeding those planets by sending nano-sized spacecrafts carrying microorganisms to the surface. By sending life to planets, that do not have the habitability timeframes needed to develop life on their own, this project aims to jumpstart evolution. Things that we learn from terraforming, especially the knowledge gained from the study of the extremophilic organisms, can also be used for the development of such life-seeding projects in the future.

5.6 Feasibility of Terraforming Mars

If we analyse the feasibility of the process of terraforming Mars, we see that there are a number of factors that need to be studied.

Firstly there is the question on how likely we will be able to warm the planet. The earlier described techniques all have in common the factor of large scale transportation. At the current moment transporting material into space is still very expensive and the cost to send material to Mars is even more expensive. Nonetheless, we are already able to send spacecraft to the surface of Mars with our current technology. The proposed methods of introducing greenhouse gasses, albedo reducing material or the use of orbiting mirrors seem to be the most likely candidates, however this would require launching large amounts of material into space and towards Mars. Even with the strongest super greenhouse gasses, this would still require the transport of several hundred million kilograms of the gasses, with a continual resupply need. If we are able to produce the gasses on Mars itself it would significantly reduce this cost, however this would add the need for large scale infrastructure and factories to be build on Mars. The same can be said for the albedo reduction with Martian low albedo dust. Our current technology cannot facilitate such a large scale operation, however in the next 50-100 years it is feasible to have been developed. For the orbiting mirror method, this would require launching large structures estimated to be in the region of $2x10^8$ kg into space. More likely will be that such structures will be constructed in space with material mined from asteroids for example. Again our current technology, for "in space construction" as well as for asteroid mining, is not yet sufficient to enable us to undertake such a project. However with the increased interest from both government as private industry in space mining, we estimate that this technology will have developed in the coming 50 years.

Secondly there is the issue of building a magnetic field around Mars. Just like the discussed methods for warming the planet, this would require either the launch of very heavy structures and large amounts of material or the creation of a large surface infrastructure. Again this exceeds our technological capability and would likely be done with "in space construction" methods.

Thirdly we have the issue that it is very likely that Mars does not have enough gasses to raise the atmospheric pressures to levels similar to Earth's. As mentioned we could either accept this outcome and live on Mars with simple breathing equipment but no pressurised suits, or we could import gasses from other celestial bodies and asteroids. The first option would be the cheapest and easiest solution. In order to import gasses, such as nitrogen, we would need to be able to travel to other nitrogen rich celestial bodies, such as Saturn's moon Titan, collect the gas and send it back to Mars. The current technology to efficiently travel such distances and the technology to enable this to be autonomous has not yet been developed. However with the development of new propulsion systems as well as the rapid progress made in robotics, such gas harvesting spacecraft are not unlikely. If the option of asteroids is chosen, we would need to be able to divert asteroids to new paths. At the moment there is already research being done on such operations (NASA, 2017e) for the purpose of Earth's protection against asteroid impacts as well as for the purpose of future asteroid mining and for scientific research on their origin. This technology is therefore likely to be ready in the next 20-50 years. However diverting such an asteroid would also require a lot of energy and thus the cost of such a maneuver will likely be high, unless new propulsion systems are developed. The added benefit of sending an asteroid to Mars to burn up in its atmosphere would be the extra heat that will be created and given off to the atmosphere.

Lastly we have the question on the habitability of the Martian environment. In this thesis we have proposed the use of biology to help create a habitable atmosphere and environment. As we have shown, once the temperatures have risen above 273 K and the atmospheric pressures have risen enough, a number of the discussed pioneer organisms will be able to live in the

Martian environment. These organisms are existing simple terrestrial life forms which do not require any extra adaptation. Nonetheless the rapid developments in the field of biotechnology indicate that fully synthetic cells will likely be created in the near future (has already been done to a certain extent). It is therefore conceivable that such synthetic organisms will be engineered specifically to be able to survive on Mars. Seeding life on Mars will not be difficult once the above mentioned prerequisites have been met. It would likely constitute small pods filled with microorganisms that will be sent to the surface by an orbiting spacecraft. The microorganisms will initially be kept frozen during the journey to Mars, this ensures that no extinction (or evolution, though this is highly unlikely on such a short journey) happens onboard. The mass of such pods will be very low as the cells themselves will only weigh in the order of 10^{-13} g, one gram in each pod would give over a trillion cells. As the cells will then reproduce by cell division while using the nutrients available on Mars, the population will be able to grow without any added cost to us. Such a seeding mission would therefore be very cheap, compared to the other terraforming techniques. All the technology needed for the seeding phase is already existent.

Judging on the current technology and the progress that is being made in the relevant fields, it seems fair to assume that the first phases of terraforming could be started in the next 50 to 100 years. How long such a terraforming project would take depends on various factors on which we have very limited data. The ecopoiesis of Mars would depend on the choice of heating technology. It has already been estimated that the lowering of the polar albedo could result in a stable and warmer atmosphere in as little as a 100 years (Sagan, 1973; Fogg, 2013c). Similar timeframes are estimated for the use of orbiting mirrors, if enough sunlight can be reflected to the surface (~10% of incoming sunlight on Mars) (Fogg, 2013b). It is therefore feasible that in 200 years time ecopoiesis, for hardy pioneer organisms can be achieved.

If we look at the timeframe that was needed to develop Earth's current oxygen rich atmosphere, ~2 billion years, we can see that oxygenation of an atmosphere will be a long process. However as we will be consciously oxygenating the atmosphere, we will be able to significantly speed up the process. Nonetheless estimations still range from thousands to 100000s of years to fully terraform Mars if we use all engineering options, such as oxygen producing factories and importing atmospheric gasses, alongside the biological methods (Averner & MacElroy, 1976; Fogg, 2013c; McKay *et al*, 1991). As mentioned in the very beginning, terraforming is not necessarily an all-or-nothing scenario and any steps that are taken will increase the habitability of the planet. It is therefore not unlikely that Mars will already be colonised by humans long before full terraforming has been achieved.

6. Societal Requirements

Apart from the scientific and technical issues, societal issues will also play an important part in such an endeavour. First of all as terraforming Mars will likely take hundreds to many thousands of years, the mission duration will be much longer than mankind has ever undertaken. How would such a multigenerational project be planned and managed? The second problem that needs to be tackled is the legality of a terraforming project. The last issue is the ethical consideration of launching such a mission, should mankind change other planets simply to suit our needs?

6.1 Management

How does one plan and manage a multigenerational mission? How would such a project be funded? These are just a few questions that come up when planning and organising such a terraforming project. As will be discussed in the following legal chapter of this paper, the possibility of one actor or one state initiating such a mission is highly unlikely as this could have far reaching political consequences. An international cooperation should therefore be constructed to discuss the various elements of terraforming Mars, such a project should be a joint human endeavour. At the current moment the only strong international organisation in which such a program could be discussed would be the United Nations (UN), as most of the world's nations are members of this organisation and it has dealt with many international cooperation in the past. Depending on how the mission would be planned and what the technical requirements would be, the cost would be spread over the members. How such a mission would continue after its initial launch is also very important.

Terraforming Mars will take multiple generations and such a venture cannot be compared to any one endeavour that mankind has undertaken in its history. A terraforming project is not something that can be accomplished by intermittent and unorganised productivity such as the construction of the Great Wall of China (~771 BCE to ~1640 CE) which was built over more than 2 millennia, however with moments of inactivity (Encyclopaedia Britannica, 2017)**.** The process of terraforming will be very unstable and fragile and thus precise actions will have to be taken at the correct time. To ensure the success of the program a step-by-step plan covering the entire terraforming process will have to be developed and followed over the course of many generations. Some sort of intergovernmental and multigenerational organisation would have to be created and maintained, again this would most likely be developed as a part of the UN as no global space agency exists that could perform this task.

One other option might be to build a global space agency, with the organisational structure of the European Space Agency (ESA) as a guideline. ESA is currently an intergovernmental organisation with 22 member states all located in Europe and Canada is special associate member of the organisation. The organisation is based on the *Convention of the European*

Space Agency (European Space Agency, 2005), which is a binding treaty to the states party to the convention. This convention dictates the overall workings and diplomacy within the organisation and its cooperation with non-member states/organisations. In the 42 years of its existence, the organisation has managed to provide a strong framework for international cooperation between its member states and it has resulted in truly international space missions. One of its unique strong points is its “Industrial Policy and Geographical Distribution” or “fair return policy”, which ensures that each member states receives an industrial return equal to its investment. This policy gives member states the opportunity to work together in an equal and unbiased manner, while maintaining a strong competitive position in the international market. The framework does however not allow non-European countries to become full member states and thus ESA itself does not have the capability, nor does it have the ambition, to evolve into a global space agency.

In the future ESA’s framework, with the fair return policy in particular, can potentially be used as a guideline for the development of a framework for a global space agency.

6.2 Legal

Not many legally binding laws exist in the current legal framework of international space law and the last of these binding treaties was written in 1979. Since then no new binding laws have been constructed and only non-binding agreements and resolutions have been made by the international community. As one can well imagine no laws directly concerning terraforming have been written. However a couple of laws in the binding treaties can be applied to this concept, at least to a certain extent.

The first treaty that mentions laws indirectly related to terraforming, is the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies* or Outer Space Treaty (OST). The OST states in its second article, art. II, that “*Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means*”(United Nation Office for Outer Space Affairs, 2008). One might argue, when interpreting this article, that once a state or party initiates a terraforming project of a celestial body, it essentially claims the celestial body in question by using it for its project.

Art. IX of the OST is the second law that can be interpreted as being relevant to the subject of terraforming other planets. This article declares that “*States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose*”(United Nation Office for Outer Space Affairs, 2008), the important part in this is the statement on the harmful contamination of the Moon and other celestial bodies. It would be difficult, if not impossible to prove the positive or harmful contamination introduced by terraforming. Introducing life to another planet for example cannot be irrefutably proven to have a positive effect on the planet. It has been shown that the introduction of alien species can have detrimental effects to the environment (the introduction of *Oryctolagus cuniculus*, the European rabbit in Australia for example). As of 2016, 104 states are member to the OST and another 25 have signed the treaty and are in the process of ratification (Committee on the Peaceful Uses of Outer Space, 2016).

The last binding law that can be used for terraforming is part of the *Agreement Governing the Activities of States on the Moon and Other Celestial Bodies* more often referred to as the Moon Agreement. This treaty however only has 16 states as members and 4 signatures of states in the process of ratification (Committee on the Peaceful Uses of Outer Space, 2016). This implies that not many states are bound by the laws defined in this treaty. Nonetheless art. 7 paragraph 1 of the Moon Agreement delivers a expansion on art. IX of the OST, there by stating that "*In exploring and using the Moon, States Parties shall take measures to prevent the disruption of the existing balance of its environment, whether by introducing adverse changes in that environment, by its harmful contamination through the introduction of extra-environmental matter or otherwise.....*", in which "*The provisions of this Agreement relating to the Moon shall also apply to other celestial bodies within the solar system, other than the Earth, except insofar as specific legal norms enter into force with respect to any of these celestial bodies.*" (art. 1, para. 1, Moon Agreement) (United Nation Office for Outer Space Affairs, 2008). This treaty therefore delivers a similar law as the OST, however it further elaborates and adds that measures should be taken to prevent the disruption of the existing balance in the environment. Terraforming is designed to change the existing balance of the environment and such a project would therefore be in direct violation of this law. Though the addition of art.1 of this treaty makes this only applicable to celestial bodies within our solar system and therefore other planets would be open to such a seeding project, at least within the means of the Moon Agreement. However as this thesis discusses the terraforming of Mars and thus this treaty prohibits such an endeavour from taking place, at least at the moment. Apart from that such a project would also fall under the overall guidelines of planetary protection (COSPAR, 2002) and would therefore illegal.

If the option of using thermonuclear explosives to devolatilize the regolith is considered, other treaties and guidelines will have to be consulted. Article IV of the OST directly applies to the use of nuclear explosives in outer space and on celestial bodies. The article states that "*States Parties to the Treaty undertake not to place in orbit around the Earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner.*" (United Nation

Office for Outer Space Affairs, 2008). This clearly states that the use of any kind of nuclear weapon on Mars is illegal, however an important point that has to be discussed is the interpretation of the term “weapon”. The definition of the term “weapon” is, according to the Oxford dictionary (Oxford University Press, 2017);

1. *A thing designed or used for inflicting bodily harm or physical damage.*

    1.1. *A means of gaining an advantage or defending oneself in a conflict or contest.*

As the thermonuclear explosives will not be used to inflict harm or damage to any organism, state or otherwise relevant actor, nor will it be used to defend in a conflict, and thus only to terraform Mars, which can be seen as a laudable objective, the term weapon is not entirely applicable to the explosives.

The second part of the article; “*The Moon and other celestial bodies shall be used by all States Parties to the Treaty exclusively for peaceful purposes. The establishment of military bases, installations and fortifications, the testing of any type of weapons and the conduct of military manoeuvres on celestial bodies shall be forbidden. The use of military personnel for scientific research or for any other peaceful purposes shall not be prohibited. The use of any equipment or facility necessary for peaceful exploration of the Moon and other celestial bodies shall also not be prohibited.*” (United Nation Office for Outer Space Affairs, 2008). This second part of the article provides a further imprimatur, as the entire project is a peaceful endeavour. Though this should not be seen as an approval of using such a technique. This article is also restated in a similar words in article 3.3 of the Moon Agreement; “*States Parties shall not place in orbit around or other trajectory to or around the Moon objects carrying nuclear weapons or any other kinds of weapons of mass destruction or place or use such weapons on or in the Moon.*” (United Nation Office for Outer Space Affairs, 2008), again as stated earlier this article also applies to all the other celestial bodies within our solar system.

On a side note, one might argue that the use and production of such large numbers of thermonuclear explosives undermine the intended goal of the *Treaty on the Non-Proliferation of Nuclear Weapons* (Non-Proliferation Treaty, NPT). As article VI of the NPT states; “*Each of the Parties to the Treaty undertakes to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a treaty on general and complete disarmament under strict and effective international control.*” (United Nations Office for Disarmament Affairs, 1970), the large scale production of nuclear explosives would therefore not contribute to this specific non-proliferation goal.

Apart from these treaties according to principle 3.1a of the *Principles Relevant to the Use of Nuclear Power Sources in Outer Space*, which was adopted by the UN General Assembly in 1992 in its resolution 47/68, any use of space objects with nuclear power source should “....

also ensure with high reliability that radioactive material does not cause a significant contamination of outer space" during its normal operations (United Nation Office for Outer Space Affairs, 2008). Though not a binding treaty, this resolution does set a precedent for the use of mechanisms using nuclear materials. The use of nuclear explosives will most certainly cause contamination of the Martian environment and thus it would be in violation of this resolution.

Before any terraforming project is undertaken, new laws or at least guidelines should be created to ensure that such projects will be executed in a organised and controlled manner which holds the benefit of humanity as its goal.

6.3 Ethical

An important question that needs to be asked, is "should we terraform other planets, such as Mars?". As all law has its fundamental basics in ethics, the proposal for terraforming should also be discussed based on ethics arguments. Therefore some of the arguments for and against such a project are discussed below.

6.3.1 Pro

Robert Zubrin is a strong advocate for terraforming and supports what can be described as a moderately anthropocentric view on the ethics of terraforming. Zubrin, along with other terraforming experts, see terraforming as a moral obligation of humanity to spread terrestrial life to other planets. Robert Zubrin even states "*that failure to terraform Mars constitutes failure to live up to our human nature and a betrayal of our responsibility as members of the community of life itself.*". Human intellect tool that life has developed to spread across the solar system, he even goes so far as to say that; "*Countless beings have lived and died to transform the Earth into a place that could create and allow human existence. Now it's our turn to do our part*." (Zubrin, 1996). He further argues that if Mars is inhabited by microbes, the fact that Martian life has not yet evolved beyond the microbial stage indicates that it will never will in the lifetime of our solar system. Apart from that Zubrin hypothesizes that any Martian life will have risen from the same origin as terrestrial life spread by panspermia. The survival of the fittest scenario between Martian life and alien life introduced by mankind, that would ensue after terraforming would therefore not be fundamentally different from the competition on Earth (Zubrin, 1996). Martyn Fogg further adds to this argument by stating that complete preservationism is simply untenable, as this seems to imply that human consciousness and its ability to develop technology stand entirely outside nature, instead of being a product of natural selection. "*If Homo sapiens is the first spacefaring species to have evolved on Earth, space settlement would not involve acting 'outside nature', but legitimately 'with our nature'.*" (Fogg, 2000). In his book *The Case for Mars: The Plan to Settle the Red*

Planet and Why We Must, Zubrin gives another strong motivation to terraform and colonize Mars:

"*Mars may someday provide a home for a dynamic new branch of human civilization, a new frontier, whose settlement and growth will provide an engine of progress for all of humanity for generations to come.*" (Zubrin, 1996)

Overall the biotic ethics has, as its name implies, at its centre the value of life itself. The principles of biotic ethics are related to bioethics, however biotic ethics values the self-propagating qualities/systems universal to our terrestrial life and whereas bioethics or biocentrism and environmental ethics will value the conservation of existing species.

The first argument that can be made is the fact that by spreading life on Mars, mankind is doing not much more that promoting the evolutionary trend of life's conquest of new environments (Mautner, 1979). Based in biotic ethics the focus lies in the goal to expand the existence of the common gene/protein life that is shared by all terrestrial organisms. By seeding representatives of our terrestrial life on other planets, mankind will help spread "our" (DNA/RNA-protein based) system of life in the universe. It may be argued that the human consciousness and capability gives us a moral obligation to use our technology to assist in this expansion of terrestrial life.

The second argument, which is closely related to the first one, is that by the expansion of terrestrial life over several planets/solar systems will ensure that terrestrial life does not become extinct once Earth becomes no longer habitable (Mautner, 1979). The genetic heritage will be preserved in these new habitats. Though the current man-made environmental or nuclear threats will not sterilize our planet, the Sun's slow evolution towards a red giant will in the future render the Earth no longer habitable. This would of course also affect Mars and would potentially also reduce Mars' habitability. This reasoning is therefore **more of** an argument for terraforming and spreading of life in general and not necessarily for the terraforming of Mars in itself.

6.3.2 Contra

One very strong ethical consideration against terraforming would be the fact that terraforming steps would interfere with any existing biosystems indigenous to the target planet. This could lead to a potential genocide of an entire planetary biosphere. In order to be certain that no biosphere exists on the planet, a detailed survey would have to be done very precisely to detect microorganisms. This is certainly true and before such a project would be started, it has to be made sure that no such event can take place. COSPAR has already defined several "special regions" on Mars, which have been recognised as regions that have the capability to sustain life (Kminek *et al*, 2010). These regions are thereby protected from, at least manned missions, until these regions have been sufficiently studied for - and found free of any presence of life. Any mission that is to enter those regions will have to be sterilised completely to ensure no terrestrial life is able to lift along on the spacecraft in order to colonise the special regions. However there are others that do not entirely agree with this, for example Mautner argues that the spreading of terrestrial life to other planets, would constitute nothing more than the evolutionary struggle for the survival of the fittest (Mautner, 1979) and thus he states that this would not be considered more “evil” than what happens in nature. Nonetheless Mautner does agree that such an event should be avoided as much as possible. He does however argue that mankind should not wait too long and potentially endanger the continued existence of life by waiting to see if there is life on Mars. Mautner states that we cannot be certain that our technology will still exist when we receive proof of extraterrestrial life and that waiting can sentence life to become extinct when our Sun renders Earth no longer habitable (Mautner, 2010). However this argument again is not specifically relevant for the terraforming of Mars but more for terraforming in general. If made specifically for the terraforming of Mars, it can be said that several scenarios can render the Earth less habitable or dangerous for human habitation. To have a “backup” planet would certainly ensure the continued survival of the human species.

A form of weak anthropocentrism can incorporate such biocentric ethics, which would allow certain degrees of terraforming. Christopher McKay is one expert who supports such a form of ethics, his views can however be better described as weak ecocentrism. McKay states that if life is discover on Mars, for example, that that life is more valuable than simply looking at it as individual microorganisms. Such life forms should not be interfered with by terrestrial organisms, however mankind can alter the Martian environment in order to further expand Martian life. “*If we terraformed Mars to allow the expansion of that life we would then reap the maximum benefits from the scientific study of that life form and its development into a full scale global biosphere. We would also enjoy the educational and [aesthetic] benefits of life in a biologically richer solar system.*” (Mckay & Zubrin, 2002). This method would however still be seen as objectionable by strict ecocentrists, who argue that life should be allowed to evolve at its own pace.

A strong argument against terraforming Mars in order to have a spare or backup planet has been delivered in a very succinct way by Paul York (York, 2002). He tackles three common scenarios put forward by those pro-terraforming in the following way;

1. Humanity will ruin or pollute Earth up until the point in which it is no longer habitable.

   York’s response is that “any species that wrecks its home environment would also be a very poor long-term proposition for any new home planet.” He argues that if humanity colonizes Mars soon, two scenarios can occur. The first one being the fact that if humanity has a second home, it will remove or at least diminish our drive to solve the Earth’s problems and thus keep polluting Earth with the safe knowledge of a backup planet. The second scenario states that if humanity has not yet learned how to manage its current planet, there is a significant possibility that mankind will also ruin Mars.

2. The Earth is destroyed or rendered no longer (or less) habitable by an event not of our doing, such as a large meteor impact much like the one that led to the extinction of the dinosaurs ~65-66 million years ago (Pope *et al*, 1998).

   This is indeed a strong impetus to provide humanity with a second planet, however York also explains that there are a number of other measures that can be taken to ensure mankind's survival which are less expensive and more practical. The Near-Earth Asteroid Tracking program of NASA is an example of detecting threats, yet a method of dealing with such threats still needs to be developed. He also proposes the construction of self-sustaining underground Earth colonies to protect at least part of humanity.

3. The Sun continues its evolution towards a red giant thereby increasing the temperatures on Earth until no terrestrial life is possible and even burning up Earth.

   Such an evolution will still take ~5 billion years (Schröder & Smith, 2008), however Earth will become no longer habitable long before that. The current models indicate that this will begin in ~1 billion years and after another 0.8-1.2 billion years no plant life will be able to survive (Caldeira & Kasting, 1992). Only certain microorganisms will be able to survive until Earth is possibly swallowed up by the growing Sun. Nonetheless this still gives mankind enough time and thus there is no need to rush towards Mars.

Of course many other arguments can be made pro and against a terraforming project, however not all of them can be supported by arguments of reason and only by emotion. Nonetheless these arguments should also be considered before attempting such a project.

7. Conclusion

Mankind stands at the precipice of spreading its species across the Solar System and eventually the our galaxy. The ambition to send man to Mars and to colonise the planet has re-entered popular culture and both space agencies and private companies are developing the technology needed for such an endeavour. This accompanied with the growing call to make humanity an interplanetary species, there is a possibility that Mars will become a second home-planet.

However in order to make Mars a habitable planet a number of environmental prerequisites must first be achieved. The global temperatures will need to be raised at least above 273 K, atmospheric pressures will need to be increased as much as possible, the atmospheric composition needs to be adapted, free flowing water must be made available, and the radiation levels will need to be reduced. A number of technological solutions have already been proposed to achieve these goals. Apart from these factors there are more requirements needed to create a truly habitable planet, one such a requirement is the presence of essential components for life such as nitrogen. The focus in most of the terraforming studies however lie in the field of CO_2, water availability and temperatures. Few studies investigate the availability of nitrogen and if these reserves are sufficient for the full terraforming of Mars. Nonetheless the importance of nitrogen should not be forgotten.

The data analysed along with the calculations and estimations made in this thesis show that the current nitrogen content on Mars is very limited and that it lacks the volumes needed to fully terraform the planet, in which humans can live freely without breathing equipment for example. Nonetheless there is enough to establish a small biosphere on Mars. It has been estimated that a biomass of at least ~8.5×10^{14} kg can be supported by the present nitrogen reserves. Unfortunately the nitrogen inventory is not sufficient to also play the role of atmospheric buffer gas, as it does on Earth, and therefore it will only be enough to be part of the biomass and to fertilise the newly generated Martian soil.

We have proposed the use of a number of pioneer organisms that will be able to contribute to the process of making Mars habitable. By introducing a variety of these candidate species, in a number of waves, the Martian soil can be made fertile by enriching it with nitrogen species and the atmosphere will be enriched with oxygen by oxygenic photosynthetic organisms. In the first phases Mars' atmosphere will be near anoxic and will consist mainly of CO_2. The first organisms will therefore need to be able to survive and even thrive with these conditions.

As one of the first steps a biologically driven nitrogen cycle will need to be set up. Firstly the nitrogen trapped in the ground will need to be freed on a global scale and reintroduced into the atmosphere by a first wave of denitrifying organisms. After which the nitrogen will be recaptured in preselected locations for soil fertilisation by nitrogen fixating organisms. Our calculations, based on current data, show that there is only enough nitrogen available to sufficiently fertilise roughly 30% of the Martian surface and thus the fertilisation process will have to be kept localised. By keeping the fertilised soil confined to a relatively small area we can keep the biosphere contained to a limited area, which will ensure that the biosphere stays interconnected instead of spread thin over the entire planet. After the first wave has sufficiently enriched the soil, the following waves will fill the remaining roles of the nitrogen cycle, thus closing the nitrogen loop and establishing a biologically driven nitrogen cycle. We have found several nitrogen cycle organisms that are able to survive the early post-ecopoiesis conditions and which will establish the Martian nitrogen cycle.

Another aspect that needs to be dealt with are the high (per)chlorate concentrations in certain parts of the Martian surface. A number of organisms have been proposed that are able to breakdown these toxic (per)chlorates and that possess traits which would enable them to survive in the post-ecopoiesis conditions.

As discussed, biotechnology will likely play an important role in the biologically driven adaptation of Mars. By using biotechnology we will be able to develop organisms adapted specifically to the Martian environment for each stage of terraforming. It will also enable us to develop more efficient or higher yield organisms to speed up processes such as the oxygenation of the atmosphere or the fertilisation of the soil.

Apart from the technological and scientific hurdles that need to be overcome, there are also several societal requirements that need to be achieved. Firstly as this is such a large project, the costs will be very high and thus it will be highly unlikely that one actor will undertake such a project. Secondly if one actor would undertake such a venture on its own, there will be far reaching political consequences as it could be interpreted as a claim on the planet. A terraforming project will therefore require global international cooperation, quite possibly in the form of a global space agency.

The legality of such a project would also need to be studied. Very few internationally binding space laws exist at the moment and as one can well imagine, none exist on the process of terraforming. Several treaties are applicable, at least to a certain extent, but it is clear that there is a need for more international space laws to ensure future space projects, such as terraforming, are undertaken in an orderly fashion.

Lastly before launching such a project the ethics of terraforming should be considered. Mankind has now reached a point in which it can make decisions that can have an effect on a global scale and in the future on an interplanetary scale. It should therefore also consider each of its actions wisely before such large scale ventures are engaged.

It is clear that there needs to be more research done on; firstly the current conditions and present resources of Mars and secondly on organisms that will be able to survive the early post-ecopoiesis conditions and which are able to provide the required activities, such as oxygenic photosynthesis. Research also needs to be done on other organisms, such as bees and other insects which will assist oxygen producing plants in their reproduction. It is clear that we will need to create an entire interconnected ecosystem on Mars in order to develop it into a truly habitable planet. It remains feasible that in a 100 years time the first stages of terraforming can be initiated and in another 100 years, ecopoiesis for hardy pioneer organisms can then be achieved. Full terraforming however will still require thousands to several hundred thousands of years, depending on the future technological developments. Nonetheless, as mentioned in the very beginning, terraforming is not necessarily an all-or-nothing scenario and any steps that are taken will increase the habitability of the planet. It is therefore not unlikely that Mars will already be colonised by humans long before full terraforming has been achieved.

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