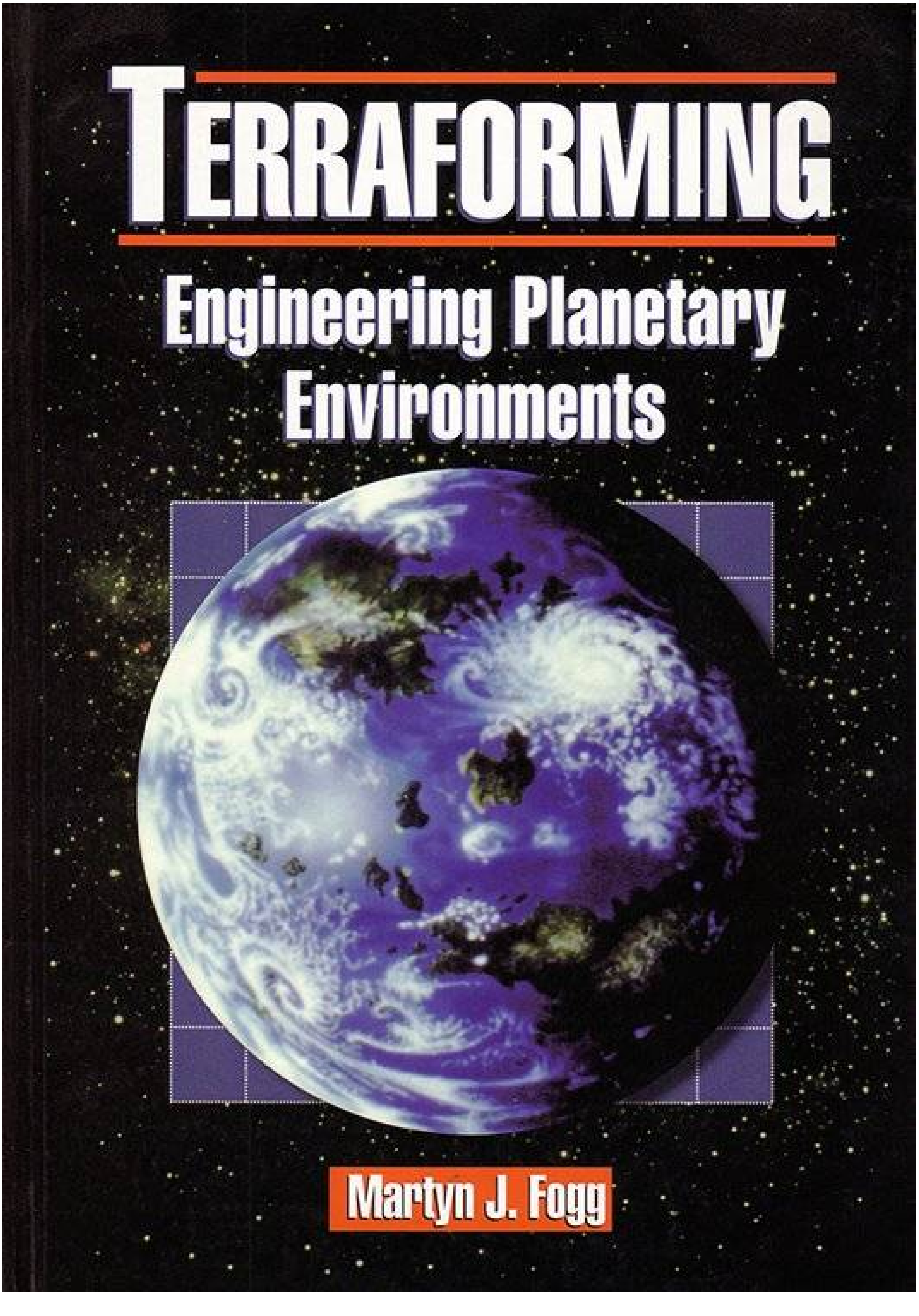
TERRAFORMING
Engineering Planetary Environments
Martyn J. Fogg

Terraforming

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Cover illustration by Ronald Brocklehurst (see Plate 7.8)

To the Engineers

Alfred James Adams

and

Bertram Hartle Fogg

Foreword

What I cannot create I do not understand

Richard P. Feynman,
Written on his office blackboard
as he left it for the last time
in January 1988

Welcome to the practicalities of orchestrated planetary change. In this fascinating work of scientific synthesis, Martyn Fogg describes how it might become possible to implant life on other planets, and to ameliorate, through ecological engineering techniques, the currently corrosive processes of global change on Earth.

Two important technical terms occur throughout this book: *ecopoiesis* and *terraforming.* The first refers to the establishment of evolving microbial ecosystems in initially barren environments; the second to the transformation of a hostile planetary surface and atmosphere into an aerobic environment in which humans might live and work outdoors much as they do on Earth. No one knows whether ecopoiesis and terraforming are scientifically possible or technologically achievable on Mars or any other lifeless planet in the Solar System. The research program to assess their feasibility, at least on Mars, would provide a challenging yet peaceful objective for human activities in space during the next century. Much of the knowledge gained, especially on the interrelations between planets and life, would be relevant to environmental problems on Earth. For example, there is intense debate over the long-term consequences of large-scale environmental perturbations such as global warming, atmospheric ozone depletion, and nuclear winter. These debates arise in the scientific community because we have very limited knowledge of how Earth's global ecosystem was formed, and how it's further evolution has been maintained through interactions with the atmosphere, oceans, and the planetary crust.

In the spirit of Feynman's remark quoted above, I have argued elsewhere that we may never adequately understand Earth's biosphere until we have learned, at least theoretically, how it might be possible to build another one. A feasibility study of ecopoiesis and terraforming would entail not only further exploration of Mars and other planets, but also studies at the comparative climate history of Earth Mars and Venus the nature of Earth's earliest biosphere, analysis of the origin and operation of Earth's biogeochemical cycles, study of the factors which promote stability in ecosystems, and research on the mechanisms of biochemical adaptation used by organisms living in harsh environments. It is ironic to think that humans ultimately might learn how to preserve life on Earth is studying how to start life on Mars.

Until rather recently, terraforming was more often mentioned in science-fiction stories in the popular media than in the technical literature. Fogg's book is the first major study, within the constraints of available knowledge, of the science and technology of ecopoiesis and terraforming. It is a nascent classic, a textbook for the future. Even though the subject matter ranges widely over the physical and biological sciences, the ideas are clearly and logically presented at a level that should be accessible to readers with a basic knowledge of science and mathematics. This is a new field in which there can be, he as yet, no elderly experts to gainsay enthusiastic youth. Those with restless yet controlled imaginations, who would escape the confines of narrowly specialized fields, and who would stretch their minds over new, wide-ranging questions, will surely enjoy this book.

The author is a leader of an informal group of scientists, engineers, philosophers, and writers who are studying the manifold aspects of ecopoiesis and terraforming. He shows in this book how simple order of magnitude calculations (and some computer modeling) may be used to assess the plausibility various planetary engineering scenarios that have been suggested.

People can live in inhospitable places in two distinct ways: by changing the local environment, or by carrying a suitable "environment" with them. Desert irrigation for agricultural development is an example of the first, while the life-support systems of lunar landing modules or orbiting space stations exemplify the second mode of survival. The latter devices cannot be inhabited indefinitely; for lengthy stays the crews sooner or later become dependent on resupply missions from Earth. The first human outposts in space will, of necessity, be of the second kind, even though their occupants may exploit some local resources. Human settlements on other planets may become fully and permanently independent only if these distant environments are transformed to provide Earth-like living conditions and a local agriculture.

Life is a planetary phenomenon, though Earth is the only presently habitable planet in the Solar System. Plants and animals are mutually dependent products of a global ecosystem - the biosphere. All are intricately coupled with each other, and with land, oceans and air by the recycling of water, carbon, oxygen, nitrogen, and other inorganic materials required to maintain life. People also are part and product of this complex biogeochemical life-support system, exotic produce of a planetary engine originally set in motion and continuously fueled by energy from the Sun.

On other planets in the solar system, high and low extremes of atmospheric temperatures and pressures, lack of free oxygen and liquid water, high concentrations of toxic gases, and deadly radiation levels variously preclude the existence of life. Closest to Earth in its astrophysical characteristics is Mars, which, while presently devoid of life, may possess the chemical resources appropriate for its development.

Despite Mars' toxic environment, and the fact that no life exists there now, many geological features of its surface indicate that this world may have once possessed a great Northern Ocean and substantial quantities of flowing water, together with a thick, mostly carbon dioxide atmosphere. These conditions might have persisted long enough for the early stages of chemical and cellular level evolution to occur. It is largely for these reasons that some scientists plan to search for chemical and fossil evidence of extinct life during future missions to Mars, and why they have begun to consider whether the planet might ultimately be returned, by human intervention, to a habitable state.

If the surface crust and polar caps of Mars still possess sufficient and accessible quantities of carbon dioxide, water, and nitrogen, and if acceptable planetary engineering techniques can be devised to initiate planetary warming and thereby securing their release, then Mars could support a stable and much thicker carbon dioxide atmosphere than it does at present. The atmosphere would be warm and moist, and water would flow again in its dry riverbeds. The average temperature at the surface would rise to about 15°C and the atmospheric pressure would be roughly twice that on Earth. Appropriately selected, or genetically engineered, anaerobic microorganisms, and eventually some plants, should be able to grow and proliferate under these conditions.

For many people, including some knowledgeable scientists, such an enterprise sounds more like science fiction than any justifiable program for the national space agencies of the world. The technical difficulties posed by the Martian environment, quite apart from the costs entailed, seem almost insurmountable. In addition, the prospect of implanting life on Mars as a long-range objective for human activities in space raises many ethical, political and legal questions. Put most simply, do humans have any right to "play God" on another planet?

On the other hand, migration and the colonization of initially inhospitable in environments has been one of the most astonishing historical features of biological evolution. The first living cells were formed about 3.8 billion years ago, presumably in the darker reaches of the primeval, anaerobic seas. At that time, much of Earth's environment, and certainly its land areas, would have been hostile, even lethal, to most of the organisms, which flourish here today. However, in an amazing biotic diaspora, microorganisms, followed by plants and animals, migrated from marine and freshwater environments and then onto barren land. None of this would have been possible were it not for the evolutionary development, by living cells of the "technology" of photosynthesis. Essentially all of the free oxygen (and the resulting ozone shield) in Earth's atmosphere was and is generated by photosynthesis. Even though oxygen is poisonous to most anaerobic organisms, its accumulation in the atmosphere about 2.5 billion years ago created the conditions necessary for the ultimate flowering of aerobic life as we know it today. The slow chancy processes of genetic variation, natural selection and species diversification made possible the dispersal of nonhuman life across the globe.

In contrast, the migration and dispersal of *Homo sapiens* has not entailed any significant biological evolution, and certainly no speciation, ever since the emergence of "modern" humans with linguistic and tool-making capabilities about 100,000 years ago. Rather, it has been the amazingly rapid and efficient processes of social and technological evolution, which have facilitated the propagation of our species across every continent, and most recently into space.

In 1969, astronauts first set foot on the moon. If all goes well, others may arrive on Mars early in the next century. Against this background is it just an idle dream to imagine that people might yet "slip the surly bonds of earth" to pioneer new habitats in the sky? Further exploration of Mars may well reveal that ecopoiesis, and even terraforming, are feasible on that planet. Such a discovery could provide our descendents with a tremendous challenge and an exhilarating vision of the role of humankind as a catalyst in the creation of new worlds. The propagation of life from Earth to other planets may well prove to be the ultimate legacy of our species in the universe.

Those inclined to deny the possibility of implanting my life on Mars should recall that future discoveries often confound the negative prophecies of even the most accomplished scientists. For example, a few years ago before Enrico Fermi built the world's first nuclear reactor, Lord Rutherford, the founding father of nuclear physics, stated publicly that anyone who "looked for a source of power in the transformation of atoms was talking moonshine." And at the 1963 international Congress of genetics, J. B. S. Haldane, one of the greatest geneticists of this century, declared that the deliberate genetic modification of humans must surely lie millennia in the future.

It is rash to proclaim that any process or project that does not obviously violate the laws of physics is impossible. Pliny the Elder (A.D. 23 - 79) wisely remarked, "How Many Things, too, are looked upon as quite impossible until they have been actually effected." We simply do not yet know enough about the geological history and chemical resources of the planets in the solar system, or the origin, evolution and behavior of Earth's biosphere, to pass judgment today on the ultimate feasibility of the fascinating ideas presented in this book.

Robert H. Haynes
Toronto, 1994

Acknowledgments

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Preface

In late May 1993, just weeks after the contract to write this book was signed, I was on a plane flying from London to Denver. My eventual destination was the University of Colorado in the foothills of the Rocky Mountains at Boulder. My purpose in going there was to present a paper at the *Case For Mars* conference, at a session that was to be held to discuss the possibilities of terraforming Mars, that is, to render Mars habitable for terrestrial life. The whole trip was in daylight and, once the cloudy Atlantic had been crossed, the unfolding panorama below, all the way from the Southern tip of Greenland to Colorado, was unobscured. From that point onward, I noticed three distinct kinds of landscape over which the plane passed.

The first was a spectacular wasteland of ice, dazzling to look at, that gradually gave way to a more somber, greenish-gray tundra, pock-marked with glacial lakes and moraines. Eventually trees appeared, sparse and stunted at first, but becoming more abundant until, from horizon to horizon, the land was cloaked in dark green forest. From Greenland through Newfoundland to Northern Quebec, scarcely a sign of human presence was visible. All was wilderness. The immensity of it was breathtaking. *What fools we are to even think of remaking planets!,* I thought to myself, shaking my head.

Only when well into the skies of Ontario did artificial markings on the ground become obvious. Pencil-thin and rules-straight lanes in the forest marked the presence of power lines and on the northern shores of Lake Superior the first towns could be seen, with their nested hierarchy of houses, blocks and neighborhoods, connected by streets, roads and highways. But my second landscape came after the vastness of the lake had been traversed and was equally extraordinary to look at, if only because of it being so diametrically opposed to what had come before. Now the aircraft was crossing the domesticated prairies of Minnesota and South Dakota and this time, as far as the eye could see, there was laid out and entirely anthropogenic landscape. Agroecosystems – huge fields of grain – were set like tiles in a mosaic, a patchwork of geometric, mathematical shapes: squares, rectangles, circles and the occasional trapezium, colored from bright green to a tawny brown, according to the ripeness of the crop. Wilderness was banished from this place of functional necessity. Perhaps after a while it became monotonous, but still not without a workaday beauty of its own. As well as its different appearance, it conveyed an opposing message to that scenery of just two hours before: hubris opposing humility – *we do not need to dream of remaking worlds when we are already doing so.*

It is difficult enough to speculate how we might introduce viable ecosystems onto an inhospitable planet, much less produce the mature forests and grain fields over which I had flown. Thus, it was perhaps the third landscape that was the most inspiring of all. As the plane passed into Nebraska, the land gradually became more rugged and the agroecosystems fragmented and eventually all but vanished. Replacing them was an extraordinary green and corrugated landscape of winding, parallel ridges. I was puzzled for some time before I realized what I was looking at: a literal desert of grass, the so-called Nebraska Sand Hills. Coincidentally, I had attended a lecture on their geomorphology just the week before! The ridges are transverse sand dunes and the green shade a grassy sward that has fixed them in place. Apparently, the steepness of the ridge slopes indicates that they are quite fresh and that just a few centuries ago this area was a dry desert with mobile dunes of saltating sand grains, much as one would find in the Sahara. Then there was a modest climate change – it became wetter – and life seized its opportunity, even on ground as poor as wind-blown sand, rooting the topography in place and turning it green.

What a marvelous metaphor the Nebraska Sand Hills are for terraformers: a verdant wilderness made from desert, engineered by a natural quirk of climate and the reproductive imperative of life. *What if we could* *engineer the sand seas of Mars,* I asked myself, *so that life of some sort could thrive there?* Then those pioneer organisms, sown by the careful human hand, would become a multitude and would fill their habitat to its interstices. *The sands of Mars would become green too.* Like the Earth, a "fully" terraformed planet should have its balance of mature wilderness and agroecosystems: but perhaps the way terrestrial life will gain its first toe-hold on alien soil might be something akin to the greening of a terrestrial desert, like what happened in Nebraska in historical time.

To help appreciate the Earth as a living planet and home for civilization it can be useful sometimes to take a trip into the stratosphere and book a window seat. The view can be such that you are on the verge of a real feeling for the Earth as a globe; the dark blue of what is left of the sky above leaves one in no doubt that here is the roof of the biosphere and space is not far away. Those who have looked down from space itself claim that the sight conveys an even more powerful impression of the beauty, richness and unity of our home world as an abode of life, but also one of seeming delicacy, of fragility. In space, however, there is another viewpoint that is irresistible and that is *outward* – to other worlds of bare rock and sterile winds, places that perhaps could live as the Earth lives, if intention was turned to that end.

This book is about *planetary engineering*, i.e., the conscious role in planetary habitability. It includes geoengineering – options for the artificial maintenance of our own world as a habitable and civilized planet, but more prominently *terraforming* – the creation of global biospheres on such planets as Mars and Venus. Such a concept remains futuristic, but is no longer science fiction. A significant number of researchers are now taking the concept seriously enough to devote some of their time to exploring its possibilities.

My intention is to review the entire field while it is still possible to do so in a single volume. In general, I have tried to be inclusive, rather than exclusive. This is to say that while I reflect various opinions in what I write, I have made an honest effort to suppress any tendency to censor contributions with which one might disagree on grounds of taste or fashion, rather than science. I have thus had to cover a wide range of thinking, varying greatly in its speculative content and philosophical standpoint. For some, this coverage may seem excessively speculative, whereas to others I may in places appear too cautious. This criticism, however, I can take: We cannot escape arbitrariness in drawing many of the boundaries within which we attempt to constrain the future.

This is the first technical-level book to attempt some synthesis of geoengineering and terraforming as processes of planetary engineering and it has been a great pleasure to write it. However, it turned out to be a much greater task than I bargained for. Having considered myself to be familiar with virtually all of the pre-existing material on planetary engineering, I was surprised – and daunted – by how much more came to my attention when I actually got down to doing a proper literature search. In addition, while being well aware of the subject's interdisciplinary nature (nothing less than applied planetology in all its glory), I was still unprepared for its tendency to delay me down unexpected, but delightful, avenues of inquiry – but then, this is the nature of any attempt to appreciate a planetary biosphere, where there is much to fascinate, whether out view is through a microscope or from a 747.

Martyn J. Fogg
London, 1994

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Glossary

Albedo: The fraction of the total incident light reflected by a given surface. In this book albedo is often meant as the Bond albedo, the reflectivity over all wavelengths of a spherical body.

Aphelion: The most distant point from the Sun in the orbit of a Solar System body.

Asteroid: A mass of rocky, metallic or carbonaceous material, meters to hundreds of kilometers across. Several thousand have been cataloged, most orbiting in the asteroid belt between Mars and Jupiter.

Astronomical Unit (AU): A convenient unit of measurement for planetary distances. It is the mean distance between the Earth and the Sun: 1 AU = 1.496×10^{11} m.

Autotrophs: (Literally, "self feeding") Organisms capable of exploiting an inorganic carbon source, such as CO_2, and manufacturing organic matter from inorganic material. Autotrophs are the "producers" at the base of the food chain. Examples are phototrophic and lithotrophic bacteria, algae and green plants.

Biogeological Cycles: The cycles of matter within, into, or out of the biosphere. Biochemical cycles involve biologically mediated exchanges within ecosystems, i.e., between the biota, the atmosphere and hydrosphere: the geological cycles involve geologically mediated exchanges with the planet's crust. At the grandest level of organization and over long periods of time they can be considered as an integrated whole.

Bioregeneration: Biological matter cycling within a life-support system, e.g., plants regenerating oxygen for the use of animals and animals regenerating carbon dioxide for the use of plants.

Biosphere: The contents of the volume englobing a planet, extending as far up into the atmosphere and as far down into the crust, in which life can exist

Black Hole: An astrophysical object collapsed to the extent that its escape velocity exceeds the velocity of light.

Comet: A mass of frozen ices, dust, and carbonaceous chemicals, typically a few kilometers across, thought to have formed in the outer Solar System.

Cosmic Rays: Energetic radiation emanating from outer space and consisting chiefly of charged particles.

Cyanobacteria: A large and heterogeneous group of oxygenic phototrophic bacteria that used to be called "blue-green algae." They are widespread in nature and are to be found in some of the most extreme environments.

Delta Vee (ΔV): A velocity increment imparted to a payload by rocket thrust or by some other method of acceleration.

Deuterium (D): A heavy isotope of hydrogen (mass number 2) with a neutron contained in the atomic nucleus. The abundance of deuterium in natural hydrogen is 0.0156%.

Eccentricity (of an Elliptical Orbit): The factor by which an orbit deviates from circularity; defined as e = 1 - (p / a) or e = (q / a) - 1, where a is the semi-major axis of the orbit, p is the perihelion distance, and q is the aphelion distance.

Ecocentrism: A philosophy of terraforming that maximizes the role of biology and restrains that of technology. Human inhabitants of a terraformed world are not a necessary ingredient of Ecocentrism.

Ecological Climax: The "mature" state of an ecosystem where (in the absence of exports of organic matter) net growth ceases and hence NCP tends to zero.

Ecological Succession: The sequence of biotic communities that replace each other in a given area until a stable ecological climax is reached.

Ecosphere: The zone surrounding a star where planets are thermally compatible with life.

Ecosystem: A biotic community and its non-living environment when considered as a functional whole.

Effective Temperature: (T_{eff}): The mean temperature at which a planet radiates into space. If there are greenhouses gases present in an atmosphere, the mean surface temperature, T_{surf}, will be greater than $T_{eff.}$

Exosphere: The uppermost level of an atmosphere where it merges with the interplanetary medium. Collisions between atoms or molecules in the exosphere are infrequent and those particles traveling above escape velocity can be lost to space.

Gaia Hypothesis: The hypothesis that life, on a planetary scale, demonstrates certain characteristics analogous to those of a unitary living organism. A major property of such a "geophysiology" is "planetary homeostasis" where life, via negative feedback effects that influence the environment, enhances the stability of the biosphere and maintains its habitability.

Geothermal Energy: Heat emanating from the interior of a planet. For terrestrial planets that are the age of those in the Solar System, The chief source of this heat is naturally occurring radioactive isotopes.

Greenhouse Effect (ΔT_{green}): The warming of a planet's surface above that temperature at which the planet radiates into space caused by the trapping of outgoing infrared radiation by the atmosphere.

Halophile: Microorganism adapted to optimum metabolic activity within a saline environment.

Heterotrophs: (literally, feeding from sources other than oneself) Organisms that use organic materials as energy and carbon sources, e.g., heterotrophic bacteria, fungi and animals.

Hydrological Cycle: The cycling of water on a global scale by evaporation and precipitation.

Hydrosphere: The watery portion of a planet's crust, consisting of oceans, seas and all other waters.

Impact Erosion: The loss of gasses from a planetary atmosphere to space following the impact of a cosmic body.

Insolation: The amount of solar radiation received from the sun, integrated over all wavelengths, at the top of a planetary atmosphere, per unit area and unit time normal to the sun's rays. In this book, insolation is thus equated with the solar constant, which for the Earth is $S_{\oplus} = 1370\ W/m^2$, (See also Total Insolation and Mean Global Insolation.)

Lagrangian Points: Five points in the orbital plane of two massive bodies in circular orbits about their center of mass where much less massive objects can remain in equilibrium. The L4 and L5 points lie at the vertices of equilateral triangles formed by the two massive bodies and are stable. The L1, L2 and L3 points are located on a line connecting the bodies and are unstable.

Lithotrophs: Organisms which use inorganic chemicals as energy sources. These are all bacteria of various types, some of which are autotrophic.

Main Sequence Star: A star that is fusing hydrogen in its core and which is thus partaking in the most stable and long-lived phase of its evolution. The main sequence is the location where such stars plot in the Hertzsprung-Russell diagram. The Sun is such a star, about 4.6 billion years old, and is approximately halfway through its residency on the main sequence.

Mass Driver: An electromagnetic catapult capable of accelerating masses to high velocities. They have many proposed applications, including launching payloads off the Moon and propelling asteroids by ejecting some of their substance as reaction mass.

Mean Global Insolation: The globally averaged sunlight received at the top of the atmosphere. It is equal to insolation / 4. (See also Insolation and Total Insolation.)

Mesosphere: The region of the Earth's atmosphere between the stratosphere and the thermosphere, at a height between ~40 - 80 km.

Moist Greenhouse Effect: A climatic regime proposed for early Venus characterized by a volume fraction of water vapor in the atmosphere of >20% but where the vapor pressure of water at the surface remains less than the atmospheric pressure. The water vapor greenhouse effect is inevitably strong, but hot oceans remain stable in this model–if they are massive enough–up to the critical temperature of water at 374°C.

Net Community Production (NCP): The amount of organic matter accumulated by a biotic community. It equals the NPP of that community minus heterotrophic consumption. In an immature, growing community, NCP is positive; in a community at ecological climax, NCP tends to zero.

Net Primary Production (NPP): The amount of organic matter fixed in photosynthesis minus the amount consumed in plant respiration, usually measured in terms of accumulated biomass per unit area per unit time. NPP represents the plant growth available to consumers.

Noosphere: Hypothetical concept of the biosphere (acting as planetary life-support system) and technosphere (the products of conscious design) cooperating in a symbiotic relationship. More succinctly, but less accurately, a noosphere can be described as a consciously directed biosphere.

Obliquity: The angle between a planet's axis of rotation and the plane of its orbit.

Ozone Layer: A region within the Earth's atmosphere (between about 15 - 30 km high) where most of the atmosphere's ozone (O_3) is concentrated. This gas shields the planet's surface from ultraviolet radiation greater than 200 nm.

Parasol: A space based screen, designed to reduce a planet's insolation.

Perihelion: The closest point to the Sun in the orbit of a Solar System body.

Photodissociation: The breakup of a chemical compound as a result of exposure to radiation.

Photoionization: The ionization of an atom or molecule as a result of exposure to radiation.

Phototrophs: Organisms that use light as an energy source, e.g., photosynthetic bacteria, algae and green plants.

Phytoplankton: Microscopic plants that inhabit surface waters and which are the basis for many oceanic food chains.

Plate Tectonics: The movement and interaction of the plates of the Earth's crust by which many of the major structures of the Earth's surface are formed.

Primary Energy: Sources of energy liberated by technology and exploited by civilization. Currently the main sources are fossil fuels such as coal, oil, and natural gas. To these we can add hydroelectric, nuclear, and geothermal energy. "Renewable" primary energy sources are sunlight, the wind, tides, biomass, etc.

Psychrophile: Microorganisms adapted to optimum metabolic activity at temperatures of below about 15°C.

Radiative Forcing: An imposed change in planetary radiation balance that affects temperature, usually expressed as $\Delta Q = \pm x$ W/m^2 absorbed at the surface.

Regolith: The unconsolidated layers of unweathered rock fragments and impact breccias that overlie bedrock. A term usually applied only to extraterrestrial bodies. A Regolith becomes soil when acted on by chemical and/or biological weathering processes. The Moon has Regolith, the Earth has soil, Mars may have both.

Runaway Greenhouse Effect: A catastrophic climatic instability caused by the release of greenhouse gases (e.g., water vapor and CO_2) from surface reservoirs into a planetary atmosphere. This heats the planetary surface, releasing more gas and so on until the climate "runs away" to some stable, high-temperature regime.

Scale Height: The height in a planetary atmosphere above some reference level where the pressure has fallen to 1/e of its former value.

Sidereal Day: he time it takes for a planet or satellite to make one complete rotation on its axis, relative to a fixed direction (and ignoring precession).

Solar Day: The apparent length of day as observed from the surface of a planet or satellite; i.e., the time elapsed between successive noons. The solar day differs from the sidereal day because of the motion of a given body in its orbit.

Solar Sail: A proposed "rocketless" method of space propulsion consisting of a large, thin reflective surface acted upon by photon pressure and towing a payload. The source of light can either be direct from the Sun, reflected sunlight, or from an artificial source such as a laser.

Soletta: A space-based mirror designed to enhance a planet's insolation.

Space Settlement: A concept for a large orbiting habitat, often associated with the work of G.K. O'Neill. Typically such designs are kilometers in extent and spun to simulate gravity within. The difference between a space settlement and a space station is that the former is conceived of as large enough to accommodate a landscaped interior and quasi-natural surroundings.

Stratosphere: Region of a planetary atmosphere above the troposphere characterized by an unchanging or positive temperature gradient with altitude and is hence stable against convection. On Earth the stratosphere extends between altitudes of about 15 - 40 km.

Technocentrism: A philosophy of terraforming that emphasizes conscious direction of the process toward the specific aim of creating a biosphere habitable for human beings. Large-scale technological solutions to this end are considered acceptable.

Terrestrial Planet: Term sometimes used to characterize planets of a predominantly rocky, rather than gaseous composition.

Thermophile: Microorganism adapted to optimum metabolic activity at temperatures of above about 40°C.

Total Insolation: The total solar power intercepted by a planet; i.e., its insolation multiplied by its projected area. The total insolation of the Earth is therefore the square of the Earth's radius multiplied by $\pi S_{\oplus} = 1.75 \times 10^{17}$W. (See also **Insolation** and **Mean Global Insolation**.)

Tritium: The heaviest isotope of hydrogen (mass number 3) with two neutrons contained in the atomic nucleus. Tritium is radioactive, disintegrating by β-decay over a half-life of 12.3 years.

Tropopause: The boundary between the troposphere and stratosphere, where the temperature gradient falls to zero. On Earth, the Tropopause varies in height but is typically at an altitude of about 11 - 15 km.

Tropophase: The lower part of an atmosphere in which temperature decreases with height and convection occurs (except for local volumes of temperature inversion).

Von Neumann Machine: A hypothetical robotic factory which, given available raw materials, can manufacture anything it is so instructed, including copies of itself.