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Biological challenges of true space settlement

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A B S T R A C T

"Space Settlements" – i.e., permanent human communities beyond Earth's biosphere – have been discussed within the space advocacy community since the 1970s. Now, with the end of the International Space Station (ISS) program fast approaching (planned for 2024–2025) and the advent of low cost Earth-to-orbit (ETO) transportation in the near future, the concept is coming once more into mainstream. Considerable attention has been focused on various issues associated with the engineering and human health considerations of space settlement such as artificial gravity and radiation shielding. However, relatively little attention has been given to the biological implications of a self-sufficient space settlement. Three fundamental questions are explored in this paper: (1) what are the biological "foundations" of truly self-sufficient space settlements in the foreseeable future, (2) what is the minimum scale for such self-sustaining human settlements, and (3) what are the integrated biologically-driven system requirements for such settlements? The paper examines briefly the implications of the answers to these questions in relevant potential settings (including free space, the Moon and Mars). Finally, this paper suggests relevant directions for future research and development in order for such space settlements to become viable in the future.

1. Introduction

"Space Settlements" defined as permanent human communities beyond Earth's biosphere have been discussed within the space advocacy community since the 1970s. The use by space advocates of the term "settlement" deliberately hearkens back to the long era of human exploration and settlement here on Earth. The most famous early advocate of space settlement was Prof. Gerard K. O'Neil of Princeton University who proposed exceptionally large, rotating habitats orbiting in near-Earth space within which tens of thousands of individuals would live and work for indefinite periods of time [1–4]. Fig. 1 presents photographs of Dr. O'Neil and the cover of his seminal book on this subject "*The High Frontier*". Fig. 2 presents several such space habitat concepts. Now, with the end of the International Space Station (ISS) program fast approaching (planned for 2024–2025) and the advent of low cost Earth-to-orbit (ETO) transport appearing to be likely in the near future (e.g., vehicles in development by companies such as SpaceX, Blue Origin, etc.), the concept is coming once more into mainstream discussions about the possible future in space.

Considerable attention has been focused over the past forty-plus years on various issues associated with the engineering and human health considerations of space settlement, including: the level of artificial gravity required and the diameter of the habitat and consequent rotation rates to achieve artificial gravity, radiation shielding requirements and approaches, space transportation, atmospheres and life support for human crew members, etc. These and other factors are exceptionally important. However, relatively little attention has been given to the biological implications of a self-sufficient space settlement.

Three fundamental questions are explored in this paper: (1) what are the biological foundations of truly self-sufficient space settlements in the foreseeable future, (2) what is the minimum scale for such self-sustaining human settlements, and (3) what are the integrated biologically-driven requirements for such settlements? The paper examines briefly the implications of these questions in relevant potential settings (including free space, the Moon and Mars). Finally, this paper suggests relevant directions for future research and development in order for such space settlements to become viable in the future. Fig. 3 illustrates a diagram of the logic for the explication presented in this paper.

2. Foundations

There are a number of "biological foundations" – i.e., considerations drawn from the science of agriculture, available technologies, etc. – upon which must be built requirements and/or plans for any truly self-

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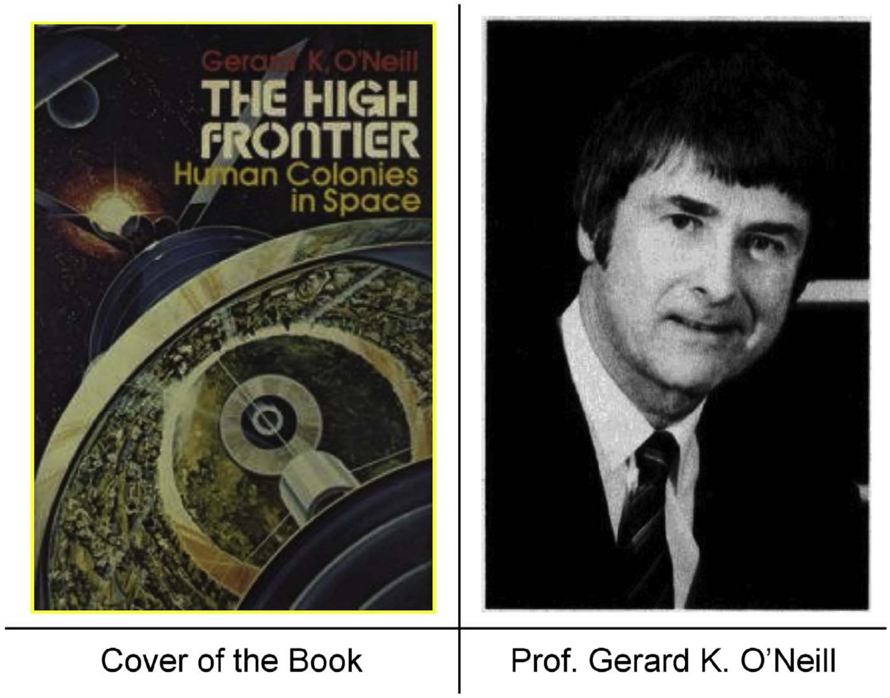

Fig. 1. Princeton Professor Gerard K. O'Neil and his Seminal Space Settlement Book in the 1970s.

sustaining space settlement [5]. The following are assumptions implicit in the use of the term "*settlement*" in this paper.

- First, a settlement must involve long-duration, biologically self-sustaining human habitation.
- Second, for the foreseeable future a settlement must involve more or less conventional agriculture (there are no "replicators" at this time).
- Third, the systems of a settlement (engineering, biological, human) must be self-sufficient and resilient in the event of probable "disturbances"; in other words, these systems must be able to recover from reasonably anticipated problems with no more than local human intervention.

The following paragraphs discuss these assumptions in somewhat greater detail.

2.1. Basics

Overall, breathable air and potable water must be available indefinitely, minimum nutrition must be created locally, and most important: there must be children (produced by a sufficient number of breeding pairs to assure genetic viability over time). Secondary requirements that result from these ground-rules include availability of the following: sufficient energy (solar insolation, thermal, electrical, etc.), adequate radiation protection and artificial gravity, sufficient habitable volume, and so on. A "space station" like ISS is not a settlement, but only a temporary camp. Similarly, science outposts in Antarctica, on the Moon or Mars, or elsewhere where crews rotate and supplies are delivered – even though they last for decades – are not settlements.

2.2. Biological thresholds

There are a number of biological thresholds that must be considered for a self-sustaining space settlement:

(1) the essential flora, fungi and fauna (e.g., selected molds, microbes, insects, etc.) to create viable soil,
(2) the internal and external microbiota population required for healthy humans,
(3) the viruses and bacterial populations needed to keep human and animal population immune systems strong, and
(4) there must be measures in place to ensure genetic diversity in human, animal, plant, etc. populations (the Noah's Ark problem: e.g. having sufficient numbers of genetically disparate breeding pairs).

For each of these, the available resources in space (e.g., regolith on the Moon, etc.) must be examined and a determination made as to what must be imported from Earth. Concerning soil flora, etc., the examination must include not only the individual species but also consideration of how they work together in creating viable soil, and the balance to be maintained after these species are introduced to the settlement's environment. The viability and the self-sustainability of the ecosystem of the soil can ensure the agricultural needs of human settlers can be met, however it does not address the problems related to subsequent generations of human beings born at the settlement.

2.3. Internal microbiota [6,7]

Concerning internal microbiota populations, past studies have examined the biological transference from mother to child and from environment to child during pregnancy and early childhood. Humans born in a settlement must have a healthy gut fauna similar to individuals born on Earth. The microbiota within the human stomach are particularly important: the gut-brain axis has a strict balance, without which an individual is likely to suffer mental deficits, be unable to gain proper nutrients from their food, be immuno-compromised, etc. Also, when considering the creation of a self-sustaining and yet not dangerously isolated population one must consider the need for maintaining the immune systems of the human and animal populations, which will require exposure to, treatment for, and natural evolution of a host of viruses and bacteria. It may seem counterintuitive, but it is necessary for individual humans to be sick some of the time, so that the population of the space settlement will be healthy in the long run [8].

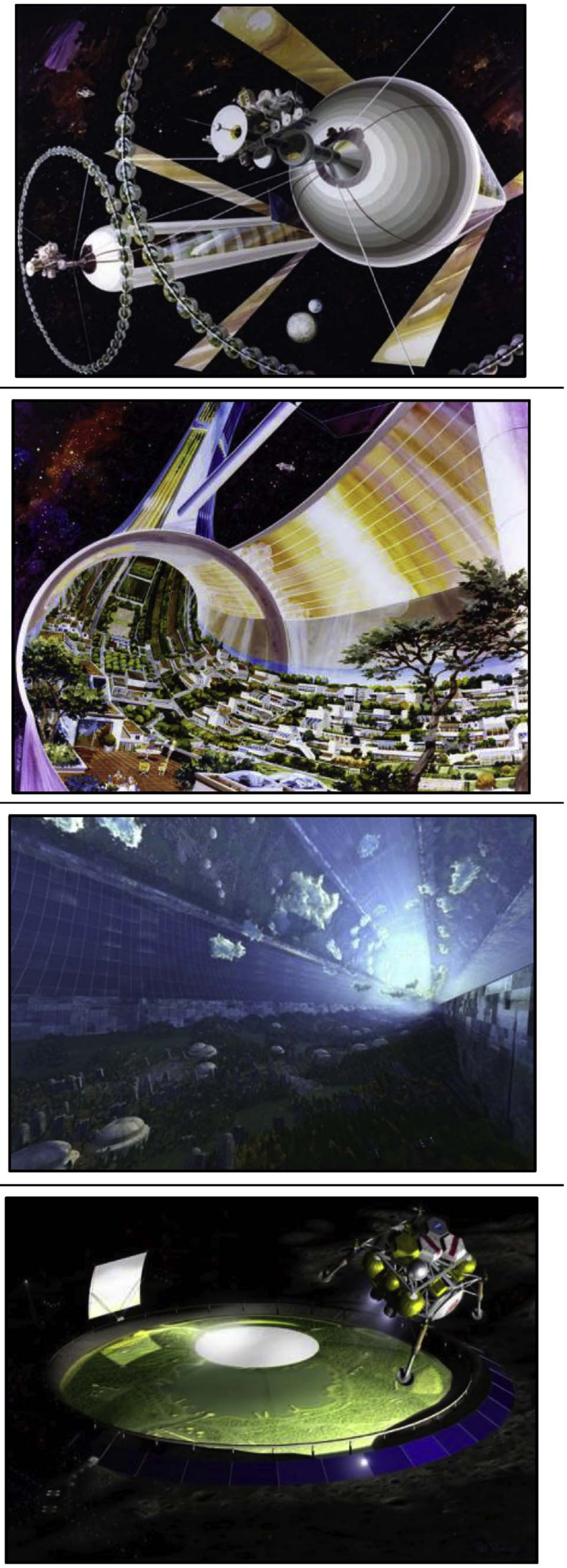

Fig. 2. Several candidate space habitat concepts, including top: "O'Neil cylinder concept – exterior view (1970s), second: "Stanford torus" space habitat concept (c. 1980); third: "O'Neil cylinder concept – interior view (1970s); and bottom: Shackleton lunar surface domed habitat concept (1990s).

Local monitoring of the genome of the species brought to the settlement over multiple generations will be required; monitoring of human internal microbiota diversity would also be necessary.

Lastly, when considering the need for genetic diversity, all species brought to the settlement will have a minimum required number of individuals capable of reproduction to ensure there is no inbreeding or genetic drift. These considerations - including "engineering margins" on such populations - must be included in framing the requirements for a settlement.

3. Minimum scale

A fundamental question is the following: what is the minimum scale for such self-sustaining human settlements? However, in order to answer this question, one must first address the most basic issue: *how many humans* are required? There are several factors that inform a judgment as to the minimum acceptable scale for self-sustaining space settlements. First and foremost is the minimum gene pool for long-term viability of the population. In addition, there should be provision for robustness in the event of accident or disaster; hence, the minimum population at the settlement should grow to a somewhat larger total and then stabilize – pending availability of additional living volume/ resources.

Finally, there is another issue: what is the required set of skills and/ or areas of expertise that must exist among the individuals at the settlement?

3.1. Genetics

The human population for any settlement that is to be largely self-sufficient must be capable of reproducing without undue risk of genetic maladies (i.e., from in-breeding). In this assessment, the question of genetics for settlers was approached very simply. Fig. 4 illustrates the very high-level basis for the following estimate of the minimum number of breeding pairs required for a sustainable space settlement. In order to avoid marriage to "third cousins", at least 32 genetically unrelated individuals (16 "breeding pairs") are required; to provide resiliency (i.e., in case of accidental deaths), this number should increase. Also a provision of frozen fertilized embryos from unrelated donors to broaden the amount of available genetic material may be needed. Additional familial lines (frozen and still viable) of other species would also be beneficial in the event of an unforeseen "die off".

As a result, it is estimated that a resilient human "genetic pool" will require approximately 20 sexually active unrelated pairs (40 individuals) on a steady basis, with approximately 40 children and 40 individuals who are no longer child-producing. These considerations lead to an initial settlement with some 40 people (in the age range from 20 to 30 years), increasing over the course of roughly 40 years to 120 individuals (including 40 in the range 40–50 years, about 40 less than 20 years, and roughly 40 in the range 60–70 years).

These numbers assume/include: (a) allowance for "Risk" – i.e., premature deaths, birth defects, etc.; and, (b) additional births by artificial insemination, embryo implantation, etc. (applicable for other mammalian and avian species as well).

3.2. Expertise

One may approach the question of minimum number of settlers from an entirely different angle: diversity of expertise. Fig. 5 summarizes the results of a preliminary and somewhat subjective assessment of the numbers of individuals required at a settlement based on the personal expertise of the settlers. The result is quite similar to that derived above: about 40 individuals appear to be required assuming some degree of cross-training and individuals playing multiple (sometimes redundant roles) within the settlement.

From these preliminary assessments, one can develop an internally-

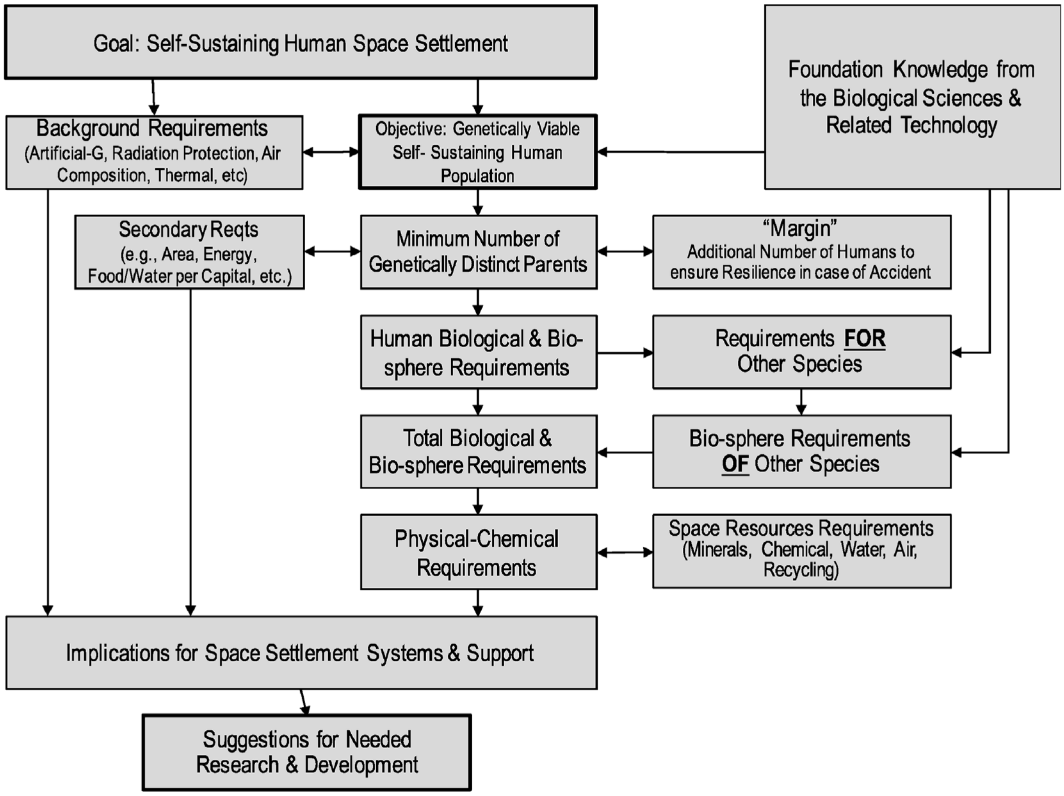

Fig. 3. Logic diagram for this discussion.

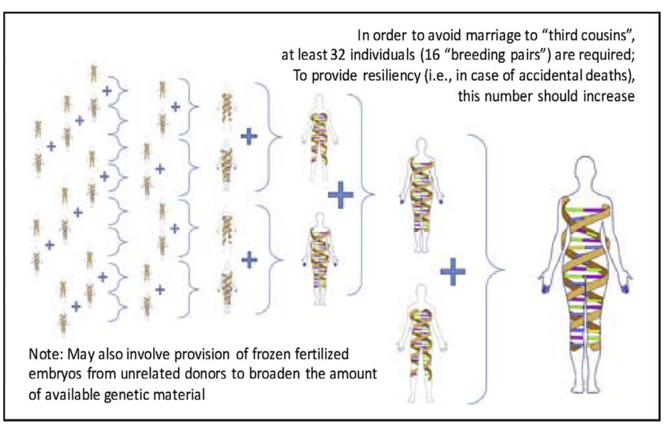

Fig. 4. First-order "gene pool" considerations.

consistent set of the settlement's biological requirements.

4. Integrated requirements

What are the integrated biologically-driven requirements for such settlements? There are several topic areas to address; including the following key topics:

- Other "Setters": we won't go alone
  o Including the question: what comprises a "human"?
- How much "land" is needed for agriculture?
- Required cycles and flows
- Special Topic: thermal management/heat rejection requirements

The following paragraphs address these questions.

4.1. *Other settlers [9 – 11]*

Without detailed modeling and considerable future research, there is no way to know precisely how many "external species" will be required in the foreseeable future for a self-sufficient/sustainable human settlement beyond Earth. However, that number won't be "zero".

In general, Earth's biosphere comprises a stupendous number of species. For example, across the five known Eukaryote kingdoms of life (which includes humans), it is estimated that there are roughly 9–10 million species on Earth, including animals, plants, fungi, protozoa, algae, etc. (Some 1.5 million species are known, but it is estimated that there are about 6–times that number in total.) For the Prokaryotes (bacteria) the number of individual species is very roughly estimated at perhaps 1,000,000,000 ± 3 orders of magnitude. For viruses, it is estimated that there are more than 100,000,000 types. And for Prokaryotes and/or Archaea, there are also various types (ranging from those that generate Methane, those that seek hot environments, etc.).

Within Kingdom Animalia, of which humans are members, there are about 50,000 vertebrate animals, including birds (~10,000 species), fish (~25,000), mammals (~5000), reptiles (`8000), and amphibians (~4000). There are also about 50,000 invertebrate animals (including sponges, jellyfish, worms of various Phyla, and mollusks such snails, clams, octopi, etc.). At a more tactical level in viable soil (essential for sustainable agriculture), there are literally thousands of billions of organisms, ranging from bacteria to fungi to insects and arachnids, and other species. Overall, there is about 15,000 kg per hectare (10,000 square-meters) of soil, which is equivalent to 1.5 kg per square-meter of topsoil.

4.1.1. *How many others?*

Given the tremendous number and diversity of species that humans share Earth with and that live internally in human bodies, the following estimates were made for two basic types of living things (i.e., "biota"): those internal to the human body, and those external to the human

Medicine: ~ 10 individuals
- General Practitioner / OB-GYN
- Surgeon
- Pharmacologist / Toxicologist
- Oncologist
- Psychologist
- Psychiatrist
- Dentist / Dental Assistant
- Veterinarian

Engineering / Sciences: ~ 10 individuals
- Space Systems Engineering
- Physicist / Chemist
- Electrical Engineer
- Mechanical Engineer
- Electronics Engineer
- Computer Scientists / Software
- Roboticist

Governance: ~ 5 individuals
- "Oversight"
- Law Enforcement
- Judiciary

Biological / Life Sciences: ~ 10 individuals
- Biologist
- Botanist
- Agronomist
- Micro-biologist
- Macro-biologist
- Horticulturalist
- Nutritionist

Other Disciplines: ~ 10 individuals
- Clergy
- Teachers (Math, Physics, Chemistry, Engineering)
- Historians
- Writers / Poets
- Artists
- Musicians
- Culinary Experts
- Economists
- Etc.

MINIMUM REQUIRED FOR "KEY EXPERTISE"
≥ 40 INDIVIDUALS

Fig. 5. Preliminary assessment of the number of individuals required for a sustainable space settlement based on personal areas of expertise.

body.

- Internal to the human body biota: about 1000 species
- External to the human body biota: roughly 10,000 species

The latter figure includes plants, animals, fungi, viruses, fish; and including soil species, human food sources and associated species (e.g., grass for ruminants, etc). The former figure includes well-known species such as gut fauna, as well as various others. These estimates may be too high or too low, but represent a reasonable starting point for further discussion.

4.1.2. What comprises a human?

Human beings are complex systems-of-systems, comprising diverse elements that work in concert to live and thrive. There are diverse ways to view this system. For example, a human comprises diverse elemental constituents (discussed below). In addition, humans comprise various specific functional systems, including the muscular system (~54% of total mass), the Integumentary/Exocrine system (i.e., the skin) (~14% of total mass), the skeletal system (~13%), the cardiovascular/circulator/blood system (~7%), the digestive system (~5%) and so on. The nervous system (including the brain) comprise less than 2% of the total.

In addition, humans comprise more than simply a collection of cells sharing common DNA. As presented in Fig. 6, in addition to human cells, there is a host of other species living within each human.

For example, by mass humans are about 98% human DNA cells and about 2% non-human DNA organisms. However, by number of cells the picture is very different. By species, a human is comprised of a remarkable ~99.9% non-human cells, and only ~0.01% human DNA cells. As a last perspective, by count of the number of individual cells or organisms, a human comprises only about 10% human DNA cells, and about 90% other DNA cells, including microbes, viruses, fungi, etc.

All of the above translates into a firm requirement for these diverse species to be considered.

4.2. How much land (area and mass)?

As discussed above, it has been estimated that a resilient human "genetic pool" would require approximately 20 sexually active pairs (40 individuals) on a steady basis, with approximately 40 children and 40 individuals who are no longer child-producing. This foundation results in an initial settlement with some 40 people (in the age range from 20 to 30 years), increasing over the course of roughly 40 years to 120 individuals (including 40 in the range 40–50 years, about 40 less than 20 years, and roughly 40 in the range 60–70 years).

4.2.1. Land area per person [12]

It has been estimated that approximately 1 acre of "normal" farm land (~4000 square-meters) is capable of producing about 2700 calories per day. As a result, it was assumed that 2700 calories per day per person will meet the requirement of one adult (with margin). Note that consumption in the US corresponds to 3800 calories/day, whereas consumption in India consumption is only 2300 calories per day. As a result, for a space settlement "crop land" area requirements become: (1) initially 40 individuals would require ~160,000 m^2, while (2) a steady state of 120 individuals would require ~480,000 m^2.

4.2.2. Soil mass per square-meter [13]

In order to provide sufficient soil for root systems, aeration, and supporting species (e.g., fungi, insects, etc.), two options have been examined: shallow soil (a soil depth of 0.5 m), and moderate depth soil (a soil depth of 1.0 m). And two options for typical soil density were identified, including dry soil at roughly 1200 kg per m^3 and wet soil at approximately 1300–1700 kg per m^3 depending on the moisture content.

4.3. Living mass per square-meter

However, as noted viable agricultural soil is more than minerals; it also entails a thriving population of supporting species such as insects, small mammals, fungi, etc. On Earth, this involves approximately 1.5 kg of living mass per cubic-meter of viable soil. For an estimated 1 acre of agricultural land per person, 40 individuals would require ~240,000 kg of living mass, while 120 individuals would require ~720,000 kg of living mass. The latter figure is equivalent to ~1000 cattle where the mass of an adult cow is estimated at 1600 lbs. The topic of associated species will be discussed in greater detail below.

As a result of the above considerations, for a depth of soil of 1 m of moist viable soil, 40 individuals (initial settlement) would require ~208, 000, 000 kg of soil, and 120 individuals (steady state population) would require ~624, 000, 000 kg.

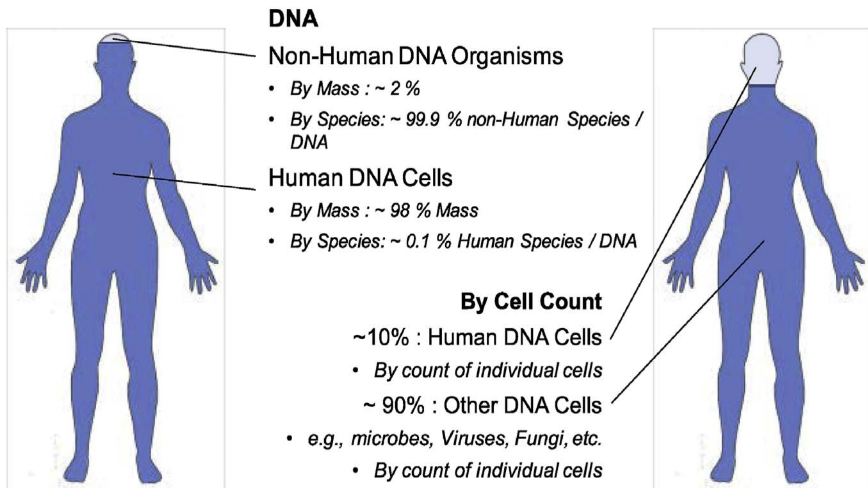

Fig. 6. Summary of the living organisms that comprise a typical human being.

4.4. Required cycles and flows

Many chemical cycles (e.g., the water cycle, the carbon cycle, etc.) and flows (e.g., energy in, waste heat out) are involved in any living ecosystem. For purposes of this initial analysis, an emphasis was placed on the major drivers of overall habitat mass, including primarily air (taken as a whole) and water. (This is not to suggest that the numerous other cycles (e.g., Potassium, Carbon, Sulfur, etc.) are any less critical.) See Fig. 7 for a simplified sketch of the various cycles involved in any sustainable space settlement.

4.4.1. Air [14]

The atmosphere in a hypothetical settlement has been treated in this preliminary analysis as an integrated volume, comprising air for both human settlers and for agriculture, with the assumption that this air mass is dominated by agricultural requirements. Also, it is assumed that the virtual "altitude" for the settlement corresponds to the United States Midwest – i.e., less than 1 km, and that the composition of the air is relatively "moist". As a result, the density of moist air for this analysis is estimated at $\sim 1.3\ \mathrm{kg/m^3}$.

As discussed, the crop area for an initial population of 40 individuals requires $\sim 160{,}000\ \mathrm{m^2}$ (e.g., a surface 320 m × 500 m), while in the steady state –assumed here to be 120 individuals – would require $\sim 480{,}000\ \mathrm{m^2}$ (e.g., an area of at 480 m x 1000 m). The optimal height of the ceiling in the habitat depends on several factors, including the means of illumination, the importance of uniformity, the height of desired vegetation (trees or no trees?), and others. For various habitat ceiling heights, the results are presented in Table 1.

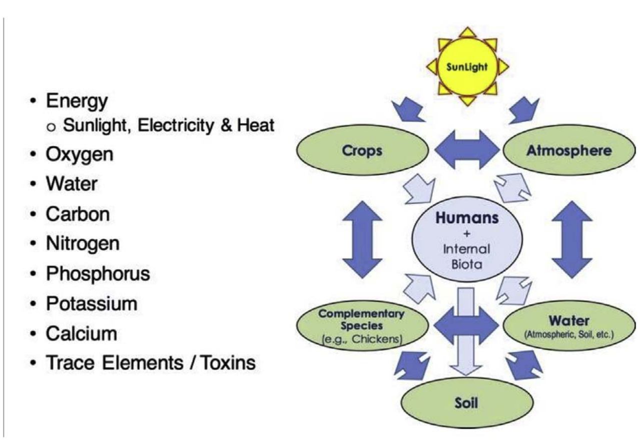

Fig. 7. Simplified diagram of the cycles that will be involved in a space settlement.

Table 1
Mass of Air Required for Different Ceiling Heights and numbers of Settlers.

# of Settlers	Ceiling Height vs. Mass of Air		
	5 m	10 m	30 m
40 settlers	1040 MT	2100 MT	6200 MT
120 settlers	3100 MT	6200 MT	18,700 MT

In summary, for a biologically self-sustaining space settlement, the mass of atmosphere required may range between 3,100,000 kg and 18,700,000 kg.

4.4.2. Water for settlers [15]

There are two core requirements for water cycles in a space settlement: water required for direct human consumption and use, and water required for agriculture (including supporting species).

A reasonable assumption for drinking water per adult human being is about 3 kg per day (i.e., 2–3 L/day). The numbers for personal use (e.g., for hygiene, washing clothing, etc.) vary greatly from country to county, with a minimum of about 20 L/day, and a maximum of about 200 L/day. For purposes of our analysis, a value was assumed of 110 kg/day (i.e., 110 L/d). The actual amount of water required depends on the frequency with which this water is recycled. In addition, the overall amount of water for human consumption must allow for "margin" – i.e., extra water must be available "just in case" water recycling systems might fail for some period of time. For various habitat personal water (i.e., "fresh water") recycling timeframes, the results are presented in Table 2.

In summary, for a biologically self-sustaining space settlement, the mass of water required for direct human consumption may range between 131 MT and 1200 MT, depending on the pace of recycling.

Table 2
Mass of human-consumable water required for different numbers of settlers and recycling times.

# of Settlers	Consumable-Water Recycling Period		
	10 days	30 days	90 days
40 settlers	45 MT	131 MT	407 MT
120 settlers	131 MT	407 MT	1200 MT

4.4.3. Water for agriculture [16–18]

The water required for agriculture not surprisingly far exceeds that needed for direct human consumption. To calculate this, the analysis began with an estimate of the amount of food required per person.

It was assumed that a daily average consumption of food of about 2700 calories per day (equivalent to 1.5–2.0 kg/day) would be required for each settler, which is somewhat higher than consumption in India (about 2400 calories/day), but well below the average consumption in the US (~3800 calories/day). For this analysis, it was estimated that a total average daily food consumption mass of about 1.75 kg/day per person. Also, it was assumed that the other material constituents of the food (e.g., Carbon, Nitrogen, Potassium, etc.) will be recycled over time. The amount of water in each kilogram of food varies widely depending on the food type. There are two main components: (1) the water in the food, and (2) the water used to grow the food. The following paragraphs examine each in turn.

4.4.4. Water-in-food

As has been observed before, the total requirement for a consumable material depends upon the rate at which it can be recycled. Making two very simple assumptions – first, food is mostly water, and second, that the timing for recycling food is tied directly to the crop growing cycle – then the various agricultural water recycling timeframes, the results are summarized in Table 3 which follows (see Table 4).

4.4.5. Water-used-to-grow-crops

The amount of water used to produce different foods varies widely. The supporting data are presented in the tables following for "Case A" (10% of calories from meat), and "Case B" (5% of calories from meat)

Individuals will not live at a space settlement if only one type of food is available. And, there are serious risks to over-reliance on a single species or group of species of food. Hence, it assumed that settlers will require a mix of nutrients from various types of food.

Taking the average of the two cases, the water required to grow the food for settlers becomes ~1624 kg-water/kg-food per day of food consumed.

Summary. Taking these two considerations together, the overall requirement for water to feed the settlers becomes the amount presented in Table 5 below.

Hence, the steady-state requirement for water for food varies from about ~340 MT (90-day recycling) to up to ~10,000 MT (1-year recycling).

Next, the assessment turns to the question of energy flows into and out from the space settlement in general, and thermal management in particular.

4.5. Energy flows and thermal management

Energy flows into and out from any space settlement are of central importance. For the sake of this initial discussion, these have been divided into two broad categories: basic energy for living in space, and energy for self-sufficient agriculture.

4.5.1. Energy to live in space

On the International Space Station (ISS), a steady power level of about 100 kW is required for an average crew of approximately 4 individuals (including cooling for the electronics and the crew). Hence, a general parametric estimate of the power required may be made of 25 kW per person. This implies a steady state power requirement (not related to agriculture) of ~1 MW for 40 individuals, and ~3 MW for 120 settlers. This power requirement is dwarfed by the energy consequents of agriculture.

Table 3
Mass of water-in-food required for different numbers of settlers and recycling times.

# of Settlers	Agricultural Water Recycling Period		
	90 days	180 days	365 days
40 settlers	6 MT	13 MT	26 MT
120 settlers	19 MT	38 MT	77 MT

Table 4
Water required per unit mass for different food profiles.

Baseline Estimates Specific Water Consumption (kg-water-to-grow/kg food)				
Vegetables 200–400 kg-Water/day	Fruit 500–1000 kg-Water/day	Milk/Products 800–5000 kg-Water/day	Corn/Rice/ Wheat 1200–1800 kg-Water/day	Meat/Protein 5–15,000 kg-Water/day
"Case A" Percentage of Each Food Type per Person per Day				
35%	20%	5%	30%	10%
"Case B" Percentage of Each Food Type per Person per day				
40%	25%	10%	20%	5%
Average Daily Estimates Water Consumption by Food Type **Per Person** Water Consumption (kg-water-to-grow/kg food/day)				
113 kg	169 kg	218 kg	375 kg	750 kg

Table 5
Water Required to feed settlers based on different food recycling periods.

kg per# of Settlers	Water-for-Food Recycling Period		
	90 days	180 days	365 days
1 settler	2.8 MT	19.9 MT	85.3 MT
40 settlers	113.7 MT	794.8 MT	3410 MT
120 settlers	341.0 MT	2390 MT	10,210 MT

4.5.2. Energy & thermal for self-sufficient agriculture

As discussed above, for a viable space settlement, the "crop land" area requirements are significant. Here, it has been estimated that at 1 acre per person, an initial settlement of 40 individuals would require ~160,000 m^2, and in the steady state 120 individuals require ~480,000 m^2. How much energy does this imply? To make a preliminary estimate, it was assumed that the required light to enable crop growth will be provided by windows and sunlight, and that it will be similar to the light in the mid-west region of the United States with a filtered intensity of 800 W/m^2 for an average of 12 h/day (with an assumed simulated "night"). This results in solar-related energy input flow, and therefore heating of the settlement equivalent to:

- For 40 individuals ~128 MW, or 1.54 GW-hrs per day of waste heat energy
- For 120 individuals ~384 MW, or 4.61 GW-hrs per day of waste heat energy

In order to realize this cooling with a passive approach, a very large surface area will be required. However, what if an active cooling system is required? The figure here does not include the energy required for such a cooling system (including pumps, refrigeration, heat exchangers, etc.). We've developed a quick estimate for purposes of this discussion based on available online data from the "*BioSphere 2*" test habitat of the early 1990s [19]

In the case of the 1990s "*BioSphere 2*" test, it has been reported that approximately 3-times the energy received from sunlight was required to power the air conditioning system to cool the "habitat". That figure involved use of Earth's atmosphere and large fans to provide the cooling; the effectiveness of cooling without convection may be assumed to be considerably lower. Moreover, significant swings in temperature and oxygen levels were observed in this example.

For a quick estimate here, it was assumed that a total cooling system energy requirement of 4-times the energy to be dissipated for a space settlement habitat in a vacuum (or near vacuum). This assumption results in a rough estimate of the peak power for cooling the settlement of up to ~1,536 MW (i.e., 1.5 GW) for 120 individuals.

It is clear that considering habitat designs (integrating external environment, energy and thermal, agricultural and human factors) that enable a primarily passive approach to thermal management will be very important. The external environment also will play a significant role in thermal management for the settlement. For example, in the case of a settlement on the Moon, location (e.g., at the Poles or not) will be critical. In the case of a settlement in near-Earth space, an unobstructed view of cold deep-space will be crucial to efficient functioning of the thermal management system.

4.5.3. Total energy requirements

So, what are the total energy requirements for a settlement of 120 individuals? It was derived (based admittedly on a set of explicit assumptions and the use of analogues to make quick estimates), that a minimum power input of ~384 MW (input sunlight equivalent and electricity) during "daylight" hours will be required. Two scenarios for heat rejection were considered:

- A minimum passive thermal output ~384 MW-thermal (doesn't account for pumps), and
- For active cooling, a minimum cooling power requirement of ~1.5 GW.

With other personal and electronics power requirements of ~3 MW (average), it must be also noted that the above figures do not take into account power/thermal management requirements of any economic activities (e.g., manufacturing) at the settlement.

5. Settlements in relevant settings

Of course, where a settlement is placed is a crucial consideration. The following section discusses the implications of the above considerations in the context of relevant settings for future human settlements in space.

There are only a handful of candidate locations where human space settlements might reasonably be established in the foreseeable future. These include the locations in orbit (e.g., LEO, GEO, Earth-Moon Libration Points, etc.), the Moon, the Mars System (including the moons of Mars, Phobos and Deimos).

Each of the candidate locations may be compared at a fundamental level in terms of their atomic composition with the requirements at the atomic level of humans (i.e., how much oxygen, how much hydrogen, how much calcium, etc.) Similarly, the composition of various candidate settlement locations may be compared to the composition of soil here on Earth. Fig. 8 presents a summary of a preliminary assessment of this comparison.

The following are the findings thus far:

- No assessment: In many cases, the variation in the elemental composition of various small bodies (e.g., asteroids) is so great that no broad-brush assessment is meaningful; a more detailed analysis should consider particular cases (e.g. Phobos).
- No scarcity: There is no significant gap in Oxygen or Hydrogen (due to presence of ice at the lunar poles).
- Scarcity: There is significant scarcity in the critical element Carbon on the Moon; at both the Moon and Mars there is scarcity in critical elements such as Nitrogen and Sulfur.
- Overabundance: there is an overabundance – which could poison potential soils for agriculture – of Magnesium, Sodium (on Mars) and Chlorine.

In summary, some of the core building blocks of life – Oxygen, Hydrogen – are abundant across the inner solar system. Others are scarce and may need to be transported to a given location (e.g., Carbon on the Moon, Nitrogen, etc.). While still other elements are overabundant (e.g., Sodium on Mars, Chlorine, etc.) and may need to be extracted from local materials prior to attempting agriculture using them. Such extraction will inevitably require energy and chemical processes to be determined. A more in-depth assessment of the material composition of inner solar system small bodies is needed; it seems possible that these will be critical sources for future space settlements wherever they may be located.

6. Future directions for R&D

Considerable research and development (R&D) must be conducted for sustainable space settlements to become viable in the future. These include the following highly relevant directions:

- Developing integrated models of the "living systems" of a Space Settlement,
- Identifying candidate species for inclusion and testing combinations and their interactions of these analytically,
- Conducting research (modeling, terrestrial experiments, tests in space) to determine the multigenerational response of various species when in an isolated population (including genomic changes as may occur),
- Analyzing the ideal characteristics of the individuals chosen to settle (psychological, genetic, skill sets, etc.),
- Developing technologies to enable safe and long-duration storage of embryos, and their gestation using artificial systems (e.g., artificial wombs),
- Solving thermal management issues,
- Developing strategies and technologies for the conversion of local materials into viable "soils",
- Application of already developed terrestrial genetic testing (and possible need for further R&D) for possible mutations/evolutionary development based on the stresses and factors of Space Settlement, and
- Identifying and developing strategies for local manufacture of required medicines (e.g., in situ pharmacology).

7. Conclusions and summary

The analysis presented here (see the page following) does not include any of the "normal" engineering requirements of a successful space settlement, including habitat pressure vessel mass, power generation systems, waste heat radiators, artificial gravity requirements and systems, and so on. The analysis presented does demonstrate that the biological requirements that must be satisfied to realize a truly self-sufficient space settlement are significant. Fig. 9 presents a summary of the findings above.

The key findings include the following:

- There is a need for at least 40 individuals initially, and a goal to grow to a more robust number of 120 within not more than a few decades.
- We will not go alone: numerous species (internal and external to the humans) must also be sustainable "members" of any settlement. These species must be viable over indefinite generations and type.
- The numbers above, coupled with the requirements for agriculture per person, drive the minimum size and composition of the settlement.
- The available resources in space (e.g., regolith on the Moon, etc.) must be examined carefully in light of biological requirements and a determination made as to what must be imported from Earth.
- Local monitoring of genetics of all species brought to the settlement over multiple generations will be required.

Element	Human Being		Common Earth**	Ave. Lunar	Ave. Mars
Oxygen (e.g., H_2O)	65.0 %	*65.0 %*	49.00 %	~61.0 %	~43.8 %
Carbon	18.5 %	*83.5%*	4.51 %	< 0.1%	Atmospheric CO_2
Hydrogen (e.g., H_20)	9.5 %	*93.0 %*	1.50 %	Polar Ice / Minerals	Ice / Water
Nitrogen	3.2 %	*96.2 %*	1.00 %	< 0.1 %	< 0.1 %
Calcium	1.5 %	*97.7 %*	5.38 %	~5.5 %	~3.8 %
Phosphorus	1.0 %	*98.7 %*	0.12 %	< 0.1 %	~0.9 %
Potassium	0.4 %	*99.1 %*	1.34 %	< 0.1 %	~0.8 %
Sulfur	0.3 %	*99.4 %*	0.12 %	< 0.01 %	~1.8 %
Sodium (e.g., NaCl)	0.2 %	*99.6 %*	0.58 %	~0.4 %	~2.9 %
Chlorine (e.g., NaCl)	0.2 %	*99.8 %*	0.03 %	< 0.1 %	~0.5 %
Magnesium	0.1 %	*99.9%*	0.79 %	~4.5 %	~4.3 %
Iron (e.g., Hemoglobin)	< 0.01 %	*~99.9 %*	2.23 %	~ 3.5 %	~12.1 %
Silicon	< 0.01 %	*~100 %*	28.9 %	~16.5 %	~22.4 %
Other Trace Elements*	< 0.01 %	*~100 %*	< 0.01 %	< 0.01 %	< 0.01 %
Aluminum	~0.0 %	*N/A*	3.8 %	~8.5%	~5.5 %

* *Including: Boron, Chromium, Cobalt, Copper, Fluorine, Iodine, Iron (e.g., Hemoglobin), Manganese, Molybdenum, Selenium, Silicon, Vanadium and Zinc*

** *Not including Water*

Fig. 8. Elemental Composition Comparisons of Humans vs. Various Locations.

	40 Settlers	120 Settlers
Crop Land Area	160,000 m^2	480,000 m^2
Food Used Per Day	70 kg/day	210 kg / day
Water Required for Farming (30 day Recycling)	3,410 MT	10,231 MT
Water Used for Personal Use (30 day Recycling)	131 MT	393 MT
Required Mass of Air (30 m Ceiling / "Earth Normal")	6,240 MT	18,720 MT
Sunlight Required (Filtered)	128 MW-solar	384 MW-solar
Heat Rejection Load	> 128 MW-thermal	> 384 MW-thermal
Farming Thermal Mgt. Power (if Active Required)	> 500 MW-electric	> 1.5 GW-electric
Power for "Personal Use" (Average; ISS Based)	~1 MW	~3 MW
Total Bio-Driven Mass Required	> 9,650 MT	> 29,500 MT

Fig. 9. Summary of the findings presented (for 40 and 120 settlers).

- Humans born in a settlement must have healthy bacterial fauna (e.g. in the gut) just like individuals born on Earth.
- Although counterintuitive, it is necessary for individual humans to be sick some of the time, so that the population of the space settlement will be healthy in the long run.
- When considering the need for genetic diversity, all species brought to the settlement will have a minimum required number of individuals capable of reproduction to ensure there is no inbreeding.
- Just as with human settlers, it will be necessary for individuals in the animal population of the space settlement to be sick some of the time, so that the population will be healthy in the long run.

Only if adequate resources for R&D – including early integrated demonstrations – are dedicated to the challenges described here will true space settlement be realized in the foreseeable future.

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