How Much Space is in Space?

By Frank White

Introduction

Advocates of space exploration (myself among them) are often heard to say something like "Once we're able to leave planet Earth, infinite resources will be available to humanity."

This assumption exerts a powerful influence *philosophically* on how we approach the expansion of human migration beyond planet Earth.

Certainly, once we have faster-than-light propulsion, and the rest of the galaxy is open to us, this statement might be true. However, for the foreseeable future, we have to think about migrating outward into the rest of the solar ecosystem. Therefore, we need to think about this question in more detail.

To answer it, we can consider the land area that is available by simply calculating the surface areas of all the planets and moons in the solar ecosystem where space developers might create human habitats. We can make a few additional assumptions before proceeding, which is that humans are not, in the near future, going to live on Venus, Mercury, or Pluto. As far as we can determine, Venus is the closest thing in the solar system to our vision of Hell, and it would require enormous effort to create habitats for people there. Some have talked about living in the Venusian clouds, but we are limiting our discussion in this essay to relatively solid surfaces.

Mercury and Pluto meet the criterion of having a solid surface, of course. However, Mercury is so close to the sun that life there would probably be unbearable; Pluto is so far away from the sun that it would be an unlikely candidate for migration in the near future.

(NASA has recently announced that two probes will be traveling to Venus in the near future, so we may discover new facts about our "sister planet" that will alter our perspective.)

The Importance of Population and Density

Before we consider "how much space is in space," we should ask the question "Why?" In other words, why is it important to make these calculations? The answer can be found in familiar terms like population and population density, and in another term that may be less well known, i.e., "carrying capacity." At the moment, all human beings in the universe live on the Earth, except for a very few who are living on the International Space Station (ISS). Currently, the total number of humans is around 7.6 billion people. Some projections say that we will have 10 billion by 2030. Others suggest that the population will actually peak in the coming years and then decline significantly, perhaps to 8.8 billion. (1) Those are large numbers, but that is not a negative thing in and of itself.

The key to understanding this number is the *carrying capacity* of the planet on which we are living. Can the terrestrial ecosystem support billions of people (whether it be 8 billion or 10 billion), and their accompanying technological civilization, without collapsing? If not, what can we do about it? And even if the global population were to decline in the next decade, we still have to consider how we can support billions of humans living a high-tech lifestyle on a planet that is limited in terms of land area and resources.

Population density is a second, critical variable in this analysis. Social scientists have had a hard time deciding if high population densities are positive or negative in terms of a "social good." Some pioneering studies in the 1960s convinced many observers that high densities should be avoided. However, others pointed out that the actual nature of dense populations should be taken into account. For example, a luxury high-rise apartment building in New York City might have the same density as a *barrio* in Rio de Janeiro. However, the lives of the inhabitants in those two situations would be quite different. (I am not making a value judgment about their lives, either, just saying that they would not be the same.) Ultimately, it would seem that quality of life is the key to evaluating whether population density is desirable or not.

The most famous density experiments were carried out by John C. Calhoun, who built "rat cities," in which the animals were provided with everything they needed, *except space*. Without predators and with plenty of food and water, the result should have been "Ratopia," but it devolved into "Ratdystopia." Without going into all the gory details, the population initially grew rapidly, then collapsed as the inhabitants became increasingly aggressive and conflict dominated their behavior. (2)

Limits to Growth

These experiments fit nicely into the “limits to growth” scenarios that were gaining traction in the early 1970s. The Club of Rome commissioned a study that led to a book by Donella and Dennis Meadows and Jorgen Randers, called *Limits to Growth.* This book chronicled what was called the “Club of Rome Study,” which was brilliant because it focused on systems theory and ran computer-based scenarios of Earth’s future, rather than coming to a single, final conclusion.

The computer model considered several variables in constructing possible futures:

- Population
- Food
- Capital
- Resources
- Pollution
- Energy

As the researchers ran the model, the variables interacted to illustrate different scenarios in which each affected the others. As population grew, for example, so did energy use, pressure on the land, and pollution. Of course, population density increased as well, and that was a concern.

While avoiding specific predictions, the book that chronicled the computer modeling warned against “overshoot,” a point at which human civilization pushed the planet beyond its “carrying capacity.” Once that tipping point had been reached, “collapse” was necessarily the next phase. (3)

In an updated version published in 2004, the remaining two authors (one, Donella Meadows, had died in the interim) asserted that the Earth had, in fact, entered overshoot mode and was beyond its carrying capacity. (4)

More recently, geographer Chris Tucker has published a book called *A Planet of Three Billion.* The title tells us a lot about his thesis, which is that three billion humans, not 8 or 10 billion, is the right number for this planet:

> The key premise of this book is that Earth's carrying capacity is only about three billion—a number that humanity surpassed in the mid-twentieth century. As a consequence, I conclude that humanity and the planet that supports it are living on borrowed time. (5)

The approach taken by *Limits to Growth* and *A Planet of Three Billion* has provided inspiration for my work on the question, "How much space is in space?" If the Earth has indeed reached and exceeded its carrying capacity, that provides a powerful new rationale for large-scale space migration (LSSM), i.e., for large numbers of humans leaving the home planet and migrating to other places in the rest of the solar ecosystem. Indeed, it suggests that many other movements, especially those focused on the terrestrial environment, ought to join with the space migration movement, for the good of the planet. We need a new name for our combined movements, i.e., "envirospace," or something like it. At the Human Space Program (HSP), we have adopted this term and we consider ourselves an environmental organization as well as a space organization. We would assert that the dichotomy between the two movements is a false one.

Interestingly, then, we are carrying forward a discussion that began in the 1970s and yet has garnered little attention in recent years. However, in all that time, as far as I know, we have not taken the broader view of the solar ecosystem as humanity's real environment and asked about *its carrying capacity*.

In this paper, then, let's stipulate that we are looking at large-scale migration into the rest of the solar ecosystem as one option, and perhaps even a necessity, for reducing the population on Earth, which will then restore our planet's carrying capacity to a tolerable level.

In so doing, we should make the following additional assumptions clear:

- We acknowledge that there may be other approaches to restoring our planet's carrying capacity that does not require LSSM. It could be argued, for example, that technology might expand the Earth's carrying capacity, obviating the need to reduce population;
- There may also be other (acceptable) ways to reduce global population without LSSM;
- It also makes sense to consider large-scale relocation of industry off of the Earth, which will improve carrying capacity and potentially reducing the need for LSSM;
- We are not advocating forced migration, only creating the opportunity for LSSM to occur voluntarily and without hindrance.

Having said all of this, it is up to others to provide details about the other options. This paper is a thought experiment to consider the question, "Can large numbers of people sustainably migrate into the solar ecosystem?"

Our purpose will have been achieved if those who are concerned about the terrestrial ecosystem are willing to expand their thinking to the solar ecosystem, and consider LSSM as one option for confronting the current environmental crisis.

How Much?

That said, let's begin by considering how much surface area is available for human communities in the solar ecosystem under different scenarios. Is there really unlimited space available?

Let's start with the Earth, our home planet, but let's not call it "Earth." As I have pointed out in my book, *The Overview Effect: Space Exploration and Human Evolution,* the Earth as a physical system has been transformed into an "overview system," with layers on the original planet of a living system, human system, and technological system. I call this overview system "Terra," so let's use that term as we do our calculations. (6)

Case #1: Terra

Numerous observers have suggested that the original Earth was mis-named, and it should be called "Water." Indeed, most of the planet is covered by water, not land. For other planetary bodies in the solar system, we can usually calculate surface area to determine how much room there might be for human communities. This is not the case with Terra.

The terrestrial surface area is 510 million square kilometers, while the land area is only 148 million square kilometers. This means that less than 30 percent of the planet's surface consists of areas where two-legged mammals like us can easily build homes and factories, live and work, and enjoy life. It has often been said that we know more about the rest of the solar ecosystem than we know about our own oceans, and some have suggested that we should expand into the seas all around us instead of into outer space.

This is a valid point, and worth examining in more detail. However, very few people have expressed an interest in living on or under the water, and little or no money is being invested in such a project. At the same time, there is intense interest in space exploration, development, and migration, and significant amounts of capital are being invested in this enterprise.

Realistically, though, when we begin to ask, "How much space is in space?" Terra only contributes 148 million km^2.

With 7.64 billion humans now on Earth, We find that the population density, or PD, is 52 people per KM^2.

(Of course, in rural areas, the PD is much less and the ratio is reversed in urban areas. However, these measurements are valid for the planet as a whole.)

Some estimates place the population of Terra at 10 billion people in the near future. If we enter that number into the model, the PD becomes 68. These changes are significant. Moreover, research is under way in a number of quarters on life extension, or anti-aging, therapies, which could create an even higher density worldwide. For example, what would it look like if people began to live to an age of 150 and the global population reached 20 billion humans? The PD rises to 135.

As noted earlier, there is appropriate debate about whether population density is always a negative factor, or negative only under certain circumstances. Without ignoring that debate, *let's stipulate that lower population densities can be desirable for humans and the environment, and that we would like for every human being on Terra to have as much "space" as possible. Logically, people will have more space as population density declines.*

In an interesting play on words, we get more space by going into space!

In regard to carrying capacity and overshoot, we can also stipulate that larger numbers of people put a strain on Terra's resources, and that lower population numbers are more in line with the planet's carrying capacity.

However, very few people who are concerned about this issue consider space migration to be a potential solution. In fact, most environmentalists focus instead on increasingly restrictive measures to control human behavior on Terra.

Government's willingness to clamp down on individual liberty in the name of the common good has been amply illustrated during the COVID-19 pandemic. As more crises of this kind loom, we can assume that this trend toward increasing control will continue as well.

How might the conversation change, then, if we assumed that large-scale human migration into the rest of the solar ecosystem were encouraged as one way to ease the strain on the terrestrial environment?

Cast #2: Terraluna

When we talk about large-scale space migration, we often point to "the Moon and Mars" as if they are similar destinations, but they are in fact very different. Our Moon, or Luna, is three days from Earth with 1960s technology. Mars is about eight months away with current technology. That is a very big difference in terms of cost, travel time, and isolation from the home planet.

Increasingly, space entrepreneurs today talk about a "cislunar economy" that includes Terra, Luna, and the space between the two, and rightly so, given the Moon's proximity. By contrast, the Martian economy is probably going to need to be self-sustaining early on because of the time and cost of transporting people and materials from Earth. In fact, an analysis of the likely trade patterns between Terra and Mars would be very interesting.

While proximity to Earth is a plus for Luna, we have to consider the negative fact that Luna only has 17 percent of the Earth's gravity field, while Mars has 38 percent, and this is a non-trivial difference in terms of impact on everyday life in the two environments. Not only are the two very different physically but the psychology of living on one or the other contrasts dramatically.

In particular, immigrants to Luna will experience the Overview Effect continuously, but "Martians" will not. "Lunarians" will be able to see their home planet every day, hanging in the sky against the void of the cosmos. We don't know much about the resulting psychological shifts that will accompany this experience, only what the Apollo missions have told us. However, it will certainly be something else from the Martians, who will see the Earth only as a point of light in the sky—which is basically how we see Mars from the surface of the Earth.

Because Luna is close to Terra, it is reasonable to talk about "Terraluna" as a place that might exist in the near future. And when we add the land available on Luna to that which is available on Terra, the result is that we have 186 million km^2 of land to work with. This new addition would reduce the current overall population density from 52 to 41 people per km^2. Moreover, if the human population were to reach 10 billion people, the overall PD would be 55, close to the current number for Terra alone. In other words, having Luna available to the Terran population would theoretically offset the impact of any significant projected growth. Of course, we must bear in mind that we are looking at "land" without making any distinction between that which could be used to grow food and that which is barren, or land where there is water and land and where there is not.

(As the old joke about the restaurant on Luna goes: "Great view, no atmosphere.")

We are also not asking the fundamental question (yet) about the carrying capacity of other celestial bodies.

For now, we are just looking at planetary surfaces where people could, in theory, construct a habitat of some kind—solid ground, in other words. With that in mind, let's extend our survey to Mars, or "Ares."

Case #3: Terralunares

As noted earlier, the distance from Terra to Mars is significant. At the same time, just about every plan for human migration into the solar ecosystem considers Mars to be an ultimate destination. There is no discernible reason for this tendency, other than the obvious reality that Mars is the best option for human habitation after Luna.

Mars shares many common characteristics with Terra, including a day of similar length and ice caps at the poles. If you take a look at Google Mars and compare it with Google Earth views of Arizona, you will see striking similarities.

For our purposes, however, *the most striking feature is the available land mass of Mars.* Although the Red Planet is much smaller than Terra, it has no oceans or seas. As a result, its land mass of 144 million KM^2 is about the same as that of Terra! Thus, when we add Mars, or "Ares," to the overall equation of Terralunares, the total rises to 330 million KM^2 and the PD for our current population drops from 52 to 23. In other words, it is almost halved. If we consider low population density as a societal good, then the Terralunares scenario makes a lot of sense.

Even if the human population reaches 10.7 billion, the PD only rises to 33 overall when the three entities are combined. Of course, this calculation does not take into account how many humans are living on Terra, Luna, and Mars. The next step would be to think, realistically, about the proportion of the population in each place.

Let's imagine, for example, a human population of 10 billion in 2030. Let's stipulate further that Elon Musk's vision of a million-person city on Mars has become a reality, along with 500,000 people on Luna. The result would be a very low population density on Ares and Luna, but barely a blip on Terra! Although the overall PD drops when we add in Ares and Luna, 1.5 million subtracted from 10 billion leaves the vast majority of humans still on Terra.

In fact, this analysis shows us that we would need to have a *very large number of people* migrate to Ares and Luna to ease the population burden on Terra, and bring the situation into harmony with the carrying capacity. This calculation, again, has philosophical implications. Many of us are awed by the notion of a million humans living and working on Mars. It seems like an enormous enterprise to make that happen, and it is. However, if our goal is to ease the population pressure on Terra, it is not going to make a lot of difference. This is a sobering thought.

Therefore, let's increase our vision of out-migration to one billion people on Ares and 500 million on Luna by 2030.

The resulting population density on Terra would be 61, on Ares 13, and on Luna 7. For Terra, this would be a decrease from 66, which is helpful, but certainly not substantial.

The picture that is emerging is this: if we are going to use space migration to significantly lower population numbers, and density, on Terra, then Luna and Ares will need to support larger populations than we have imagined so far.

If we could increase the out-migration to two billion people on Ares and one billion on Luna, that would maintain the PD on Terra at its current level, and increase it significantly on Luna and Ares. It raises the serious question of carrying capacity on these two celestial bodies. How do we calculate that?

This is a topic that deserves much more attention than it has received, and we will tackle it in another essay.

Case #4: Terralunares/Moonland

Until recently, the other moons in the solar ecosystem did not get a lot of attention, but there are a number of them, some are quite large, and some potentially harbor life. (One of the reasons they may be good places for life to flourish is that they are "ocean moons," i.e., they are covered with ice, with liquid oceans deep beneath the surface.) (7)

These moons, which we might dub "Moonland," may have some major problems for habitation because they are far from the sun and life there might be intolerable. If we are going to exclude Mercury and Pluto from the analysis, perhaps we should leave the moons out as well.

However, keeping them in the discussion is tantalizing. If we add to our total the land available on these moons, the overall availability rises to 631 million KM^2. This is almost double the amount for Terralunares. *And if the human population rises to 10 billion, the overall population density would be 16.* As we did before with Luna and Ares, we would have to consider how many people might be realistically supported on each of the moons, but the overall density is reduced considerably.

This is a significant decrease and one that is worth understanding in more depth.

For the record, here are the moons we are discussing, and the planets with which they are associated:

Moon	**Planet**	**Land Mass (Millions of KM^2)**
Titan	Saturn	42
Enceladus	Saturn	1
Dione	Saturn	4
Ganymede	Jupiter	86
Europa	Jupiter	31
Callisto	Jupiter	73
Io	Jupiter	41
Triton	Neptune	23
Total		330.0

For the sake of discussion, let's assume the following:

- The overall human population has grown to 10 billion by 2030;
- The population on each planetary body is equal to its percentage of the total land available;
- Although they are called “ocean moons,” most of the liquid on them is under a solid surface of ice or rock.
- Titan also houses large pools of methane on the surface, and we can only assume half the surface might be habitable. For the others, we will assume all of their surfaces are fit for habitation.

If we make this calculation, the results are very interesting. The chart below shows the various planetary bodies and their percentage of total land in the solar ecosystem. It then allocates 10 billion humans to these planetary bodies according to their percentage of the whole.

Planetary Body	**Percent of Total Land**	**Population (Millions)**
Terra	.23	2347
Luna	.06	603
Ares	.24	2284
Ganymede	.14	1364
Callisto	.12	1158
Titan	.07	660
Io	.07	650
Europa	.05	492
Triton	.04	365
Dione	.01	63
Enceladus	.002	16

Totals	100 percent	10 billion

Note that because we have spread the population out proportionately, the density is the same on every planetary body. *Moreover, this simulation brings the population of Terra under the three billion mark that has been touted by Chris Tucker as the optimal level for the planet*.

Is this reasonable? What questions do we need to raise to determine if this calculation makes any sense at all?

The primary question, of course, is whether anyone would want to live on any of the surfaces in Moonland. Based on what space advocates say, we know that some people would make a go of it on Luna and Ares, but very little has been said about those moons. This is an issue that requires much more research. On the other hand, if we simply return to our original question, which was whether large-scale space migration might reduce population density on Terra, we can answer in the affirmative, especially if the moons are included.

However, we have to bear in mind that having such a large number of people on these planetary bodies might have a huge impact on each one of them. Do we want that?

Who Would Go?

As noted above, another approach to this issue is to ask “Who would want to live off of planet Earth, regardless of the conditions?”

National Geographic published an article a few years ago that considered whether humans might carry an "exploration gene." This gene predisposes those who have it to risk-taking, experimentation, and exploration. It doesn't mean that individuals with the gene will be explorers of physical space, of course. They might be medical researchers, spiritual seekers, or race car drivers. The article also notes that if the society as a whole supports exploration, the gene will be expressed in individuals who have it and are members of that society. If not, the gene will not show up as often. (8)

If the human population reaches 10 billion by 2030, we can assume that two billion (20 percent) will have the "explorer gene." Let's further assume that all two billion of them leave Terra to live on Luna, Ares, and Moonland (this is highly unlikely, but let's stipulate it for the sake of discussion).

The result is that Terra still has a population of eight billion people, which holds it at a number close to the current level, but not low enough to ease our concerns about Terra's carrying capacity. It therefore speaks directly to our expectations about large-scale migration into the solar ecosystem.

If our primary goal is to have more people live away from Terra, the 20 percent who are natural explorers, and willing to accept harsh conditions on a frontier, will not be enough.

Stop and think about that for a moment. It is extremely important in terms of space policy!

We will need for a lot more people to depart, and that means we will not be able to live lightly on the other planetary surfaces. We are going to need to create environments that are comfortable enough for the "average person," and even more to the point, for families.

My interview with NASA astronaut Don Pettit illustrates the "explorer gene" worldview:

White: So if I were the administrator of NASA and I called up and said, "Don, I don't know if you want to do this, but would you like to go to Mars?" I think your answer would be, "Heck yes!"

Pettit: Yeah, people think I'm joking, but I am serious when I say that if we had the technology, I would load my family and myself on the next rocket and we would immigrate into space and never come back to planet Earth. (9)

Of course, the question is, would Don's family be willing to move to Mars?

Perhaps they would, but it seems likely that if we have a goal of more than two billion people living off of Terra, most of them will indeed want their families to accompany them, and many of those families will not be happy with frontier living. They will be looking for something more like Nuwa, a "sustainable city on Mars" imagined by Abbibo, an architectural firm in Milan. (10)

If you read any of the material produced by Abbibo or watch their video about Nuwa, you might find yourself saying, "I could live there." It's an attractive place, and different from the kind of challenging existence we often imagine for pioneers settling the rest of the solar ecosystem.

(On a personal note, I imagine future space communities being something like the American military base where my family lived when my father was called back into the Army during the Korean Conflict. See Appendix A for details).

If we want to have large-scale migration that will ease the burden of humanity on Terra, we will have to create Earth-like environments for so-called "ordinary people" and their families. This does not necessarily mean terraforming, which would involve a transformation of, say, Ares itself into a "Terra 2.0." Rather, it does mean creating Terra-like environments on Ares, as Abbibo has attempted to illustrate.

Of course, those with the Explorer Gene will always have their day. Once we have escaped the "gravity well" of Terra, it is easy to get almost anywhere in the solar ecosystem. When life on Luna or Ares, or even Moonland, becomes too tame, these hardy souls can strike out for more distant, and dangerous, environments far distant from the sun. Some may even create "generation starships" and head for Proxima Centauri, the nearest star.

On Terra today, we can see adventurers living alongside more settled families and those who have no desire to take risks or live on frontiers. These hardy souls move to Alaska, go on sailing adventures that take them around the world, or simply "go off the grid." So we can expect to have a similar pattern play out in the rest of the solar ecosystem and beyond.

Another Paradigm: O'Neill Communities

This analysis seems to reinforce Gerard K. O'Neill's assertion that a planetary surface may not be the best place to build a space-based community. The numbers we are seeing in this paper raise significant issues of planetary ethics when we realize that we might have to remake significant parts of Luna, Ares, and the Ocean Moons into something that looks a lot like the home planet if we are going to move very large numbers of people off of Terra.

Should we really do that? This is a question that we need to consider as a species and there is no easy answer. On Terra, however, we have established a precedent that says we ought to keep some areas of the planet in its original state, or as close to it as possible. In the United States, this has led to the establishment of National Parks. Even though we clearly have the capacity to develop the entire country, we have chosen not to do so, because we know that it is good for humans, other animals, and the environment to maintain some "spaces" in a pristine state. We might feel the same way about the solar ecosystem if we pause long enough to think about it. But how do we do that and also reduce the Terran population?

An imagined O'Neill community offers a lot of benefits when you consider the direction this analysis has taken:

- Internally, these communities could be quite Earthlike in their environment. O'Neill argued that it might be possible to create a 1-G gravity experience in some parts of the habitat, which would be very helpful in terms of the health of the inhabitants;
- O'Neill started where we began, i.e., with the "limits to growth" issue and the question of how to restore the Earth to a more pristine state by moving people and industry into the solar ecosystem;
- O'Neill imagined mining the Moon, and that may not be acceptable to people today, but his vision could be realized with materials only from the asteroids;
- Using solar power, non-polluting energy would be available not only to the space communities but also to the Earth, reducing the impact of climate change.

As originally planned, an O'Neill community would typically house about 10,000 people. Once again, we face the reality that you would need quite a lot of them to make a difference. There have, of course, been variations on the original theme, with the idea of structures housing tens of millions of people. (11)

Let's stipulate more modestly that O'Neill communities were built with the goal of moving two billion people off of Terra, you would need 200,000 of them housing 10,000 each, a very large number by any calculation. Would mining the asteroids for materials be sufficient for this task?

Jeffrey Greenblatt, PhD, Chief Visionary Officer of Orbital Assembly Corporation (OAC), has published an article in *Ad Astra* that answers this question in the affirmative. He considers the carrying capacity of the solar ecosystem, with special attention to O'Neill communities. Having made some extensive calculations, he argues that 200 million O'Neill "cylinders" could be constructed to house one trillion people! (In his analysis, he only requires the O'Neill communities to support 5,000 people each.) (12)

We don't really need to provide "space" for one trillion people at this point, so let's dial it down a bit and use Dr. Greenblatt's model to consider the kind of numbers we have been considering in this paper. Let's say, for example, that in 2030, we want to achieve Chris Tucker's goal and have three billion people living on Terra, with the other seven billion living "out there." With Greenblatt's approach, we would still have to build 1.4 million O'Neill communities, a number he says the solar system can support, even if we only use 1/8 of the asteroids available.

Let's assume further that we adopt a plan that reserves Luna, Ares, and Moonland for scientific study only (no human communities), and only uses asteroids to build the O'Neill space communities.

The total mass of the asteroid belt would then be what we have available for this project. Greenblatt says the mass of the Belt is 10^{20} kilograms.

How much of it can we use safely? Greenblatt invokes a principle that says we should only use one-eighth of any solar system resource (an idea invoked in a paper by Martin Elvis and Tony Milligan) and he says there would still be a substantial mass of the asteroids available for O'Neill communities. He also says we can leave the larger asteroids, like Ceres, intact.

(He further suggests that we include Near Earth Asteroids as resources, since these pose a potential threat to the home planet.)

It is with all of these assumptions in mind that Greenblatt argues we could build 200 million O'Neill communities with room for one trillion people. (13)

This calculation has enormous implications for our future in the solar ecosystem. We don't need to support one trillion people "out there," but Greenblatt is saying we have plenty of room for growth if we go back to Gerard K. O'Neill's original plan. (14) While we may, as a species, choose to have human communities on Luna, Ares, Moonland, and elsewhere, these calculations suggest that we can keep those areas pristine, or limit them to scientific expeditions, while building thriving communities throughout the solar ecosystem. This means that we have some very important choices to make as we begin large-scale migration into the rest of the solar ecosystem.

Modeling

To return to *Limits to Growth,* we can look at this paper not as an end in itself but as the basis for a computer model that would be extremely helpful to the work of the Human Space Program, the space industry, environmentalists, and government policy makers. This model would use the same inputs as did the limits to growth simulation, and even expand on it. Most important is the fact that it could be extended from the terrestrial ecosystem to the solar ecosystem. It could then add other data, including items like the mining of the asteroids to build O'Neill communities. Using the model, we would begin to consider the carrying capacity of the solar ecosystem in the way that the Limits to Growth team previously examined the carrying capacity of Terra.

As the model becomes more sophisticated, it could incorporate the HSP Repository and allow the Task Forces to enter different assumptions to see what the results might be. Ultimately, the model could be the engine for our simulations of the Blueprint.

Although I read *Limits to Growth* many years ago, the value of computer modeling never left my consciousness. Instead of describing one possible future, modeling allows you to consider many options that depend on the assumptions you make about what the variables might be. This way of thinking is helpful in avoiding conflict over a single scenario and expands our vision of possible futures.

That is why I am working with leaders in the space industry and systems thinkers who were originally involved in the limits to growth model to bring an updated version into being.

Policy Implications

Whether we engage in computer modeling or not, the policy implications of this analysis are clear: if we are going to do what may need to be done, we are probably going to have to shift the paradigm from "It would be nice for some humans to live off of planet Earth" to "It may imperative that we find a way to have very large numbers of people migrate into the solar ecosystem." Rather than allocating a tiny percentage of their national budgets to "space exploration," the governments of the world would need to start actively encouraging people to leave. Just as the governments of the Earth are trying to convince citizens to be vaccinated against COVID because it is an important public health goal, they would be urging people to relocate and helping to create the infrastructure that would make it attractive to do so.

I have come to believe that Gerry O'Neill was right so many years ago when he tied the creation of space communities to solving the problems facing Earth. The solution to so many of our terrestrial problems could well be Large-Scale Space Migration (LSSM).

On Terra, we keep looking at the problems of climate change, immigration, war, and violence, and we keep asking what is wrong. We keep putting band-aids on this gaping wound and wondering what the cure is. Well, the answer may well be "Birth, the cosmic birth of humanity as a multiplanetary species." (15)

If this is true, the future is not about "space exploration," "space commerce," or "space tourism," it's about space migration, and it will need to happen soon, but on a scale no one (except the O'Neill devotees) have yet imagined.

Summary and Conclusions

Not everyone agrees that there are too many people embedded in a technological civilization living on Terra. However, the authors of *Limits to Growth* thought so, and geographer Chris Tucker thinks so. Many environmentalists think so, and are in favor of limiting population growth and restricting human freedom, but that is a stopgap solution.

Some would argue that new technologies, stronger social controls, and positive behavior changes will be enough to reduce the human impact on Terra. They suggest that we put as much energy into creating a more balanced relationship with Terra as we would put into settle humans in other parts of the solar ecosystem.

This is a valid argument and it should be considered thoughtfully. I would only say that all of us should have an environmental awareness for the entire solar ecosystem, including Terra. If it will improve life on Terra and throughout that system to have humans living elsewhere, we should also pursue that option. At the same time, doing so raises other issues that must be addressed, such as the carrying capacity of the solar ecosystem.

Whatever the questions, now is a time to look for the answers.

Appendix A: Army Bases and Martian Cities

When my father was called back into the Army in response to the Korean War, he was sent, fortunately, to Germany instead of Korea. This began a three-year odyssey for my family that may have relevance to space migration.

My father went to Germany first and our family was split for a year. However, the Army simply assumed that service members would have their families with them, and we settled into a very large base called Vogelveh, near the city of Kaiserslautern. We were told it was the largest community of Americans outside of the United States at the time, with 25,000 of us living there.

The military basically reproduced life in the United States for us, and my dad, a member of the Corps of Engineers, was part of that creation process. He helped to build a PX (post exchange), commissary (grocery store), baseball field, football field, gymnasium, bowling alley, and movie theater.

Some of the soldiers played baseball, others football and basketball, and the theater showed American movies.

We had an American school, with teachers who came from the United States for a year or two of living abroad. There was a German teacher who visited our class to teach us the language of the country we were occupying, but I think I was the only kid who paid any attention to him. I felt bad for him because he was not treated well, and he was simply trying to support his family in the wake of World War II's devastation.

I was around 9 to 11 during this period, and the reaction of us kids to the situation may hold some lessons for future space communities.

For example, we knew of American military families stationed in France and we felt sorry for their children. They had to live in the French cities and towns where their parents were assigned, and they had to go to French schools! (I suppose this was because France was an ally at the time, but the US was occupying Germany.) We thought this would be a horrible situation, and we felt very lucky we didn't have to experience it. Of course, in many ways, it was a more meaningful experience to be immersed in another culture, but we didn't see it that way.

My friends and I were warned not to leave the confines of the base because it was dangerous. After all, we were an occupying power and we were resented by the German populace. We had killed the parents of many kids our age, and there were a lot of orphans in the neighborhoods surrounding Vogelweh. Of course, we paid little or no attention to the warnings. We had an "Explorer's Club," and we went "exploring" whenever we could. We dubbed my miniature Schnauzer Peppy our "club secretary," and off we went. As predicted, the German kids threatened us and sometimes threw rocks at us, but nothing really bad ever happened.

Perhaps most interesting in terms of a city on Mars is this: for the most part, none of the young people wanted to be in Germany, especially children of parents who had been called back into service. For us, "The States" took on a mythical, almost mystical, aura. That was where everything was perfect. In Germany, we couldn't listen to baseball games on the radio because all we had was Armed Services Radio, which was hard to get and static-filled. In The States, you could listen to games and even watch them on something called "television." Heck, you could even go to a major league game there. While the PX and Commissary had a lot of stuff, there were things you just couldn't get there, but they were available in The States (I remember Tootsie Rolls being one of the things I missed!)

Of course, in The States, you could go wherever you pleased, without rocks being thrown at you and without being called names (Of course, that was not true for a lot of people in 1950s, but that was what we believed.)

There was no way to get back to The States because you went by ship in those days and the Army wasn't going to pay for dependents to take an ocean voyage to see relatives.

I am embarrassed to say that we also "othered" some of the kids on the base, those who had been born in Germany or other overseas posts. They weren't "Americans" who had been born in The States, like us, or so we said.

Of course, if you had the right attitude, the situation was incredibly interesting. I carried "The States" myth around with me, of course, but I found my time in Germany to be fascinating. I was very interested in the Middle Ages, knights, and castles, and Germany had a lot of castles to explore. In fact, we could see the ruins of one on a hill not far from where we lived. My greatest treat was going on a driving trip down the Rhine River, which was dotted with castles. My parents were generous with their time on these journeys, knowing it meant a lot to me.

We traveled frequently as a family, going to France, Belgium, the Netherlands, Luxembourg, and other nearby countries. We had an extended visit to Paris, which I loved, and I vividly recall our trip to the "Battle of the Bulge" in Bastogne, Belgium.

I could go on and on, but you get the picture: the Army wanted its service members to be happy while they occupied Germany. To do that, they needed to accommodate the soldiers' families, and to do that, they created a "Little America" to make up for the fact that many of the spouses and children did not choose to be there. The situation created a kind of split personality for the dependents: we were living very well, but missed "The States." Learning opportunities abounded for those willing to take advantage of them.
In fact, memories of my time in Germany were so strong and positive that living abroad was my highest priority after graduating from college. As it turns out, I realized that dream by getting a scholarship to Oxford University!

Living in Germany changed my life for the better, and I am glad I vaguely recognized it at the time.

Implications for Space Migration

I believe there are broad implications in this experience for space migration, as it was analyzed in the body of this essay.

Here are a few analogies that are potentially valuable:

(1) In planning for Large-Scale Space Migration, we might assume that a family member would go to a space community for a year, as occurred with my dad before we joined him in Germany. However, we should also assume that this "pioneer" will want their family to join them at some point;
(2) As "significant others" and families join the first arrivals, they will not tolerate challenging living conditions for very long;
(3) For some young people, it will be difficult to be confined to the "base," as it was for us in Germany (though we found ways around the prohibition);
(4) Unless transport costs come down, it will also be difficult not being able to go "home," as it was for us when we lived abroad;
(5) Perhaps "Earth" will take on a mythical status as a place with abundant water, oxygen galore, "normal" gravity, and other amenities not available off the planet. This may become a serious psychological problem for those living elsewhere in the solar ecosystem;
(6) This mythical status of Earth will increase on places like Mars, where the planet itself will only be visible as anything more than a point of light through a telescope;
(7) There may be a kind of "othering" in a city on Mars, a split between those who have been born there and those who migrated there;
(8) All of these considerations once again reinforce the potential attraction of an O'Neill community, with more of the "comforts of home" than a city on the Moon or Mars. These will have the advantage of being able to see the Earth and even visit the Earth, which is also true of the Moon, but without the harsh conditions of lunar life.
(9) While this essay has demonstrated the advantages of *not* building on the surface of Mars, for example, the analogy to the military base in Germany may offer one example of how to create tolerable living conditions without terraforming the entire planet.

Notes

(1) BBC report: https://www.bbc.com/news/health-53409521
(2) (https://eprints.lse.ac.uk/22514/1/2308Ramadams.pdf)
(3) Meadows, Dennis; Meadows, Donella; Randers, Jorgen, *The Limits to Growth,* New American Library, 1972.
(4) Meadows, Dennis; Meadows, Donella; Randers, Jorgen, *Limits to Growth: The 30-Year Update,* Chelsea Green Publishing, 2004.
(5) Tucker, Christopher, *A Planet of 3 Billion,* Atlas Observatory Press, 2019.
(6) White, Frank, *The Overview Effect: Space Exploration and Human Evolution,* 2021, Multiverse Publishing.
(7) My former student and current colleague Ashley Kleinman has been immensely helpful in her reviews of this paper, with special reference to the "ocean moons." Ashley is a biology student and space enthusiast. Her internship experience includes the European Space Agency, NASA, and Jet Propulsion Laboratory, where her research focuses on oceans on Earth and throughout the solar system. Ashley also serves as the Director of Research and Strategic Partnerships at the Human Space Program.
(8) https://www.nationalgeographic.com/magazine/article/restless-genes
(9) *The Overview Effect, ibid.*
(10) https://www.youtube.com/watch?v=ySERcYMWza0&t=670s
(11) I am indebted to HSP team member Greg Barr for pointing this out to me.
(12) Jeffery Greenblatt, PhD, "The Solar Limits to Growth," *Ad Astra,* Q1, 2021.
(13) Martin Elvis and Tony Milligan, "How Much of the Solar System Should We Leave as Wilderness?", Cornell University, May 2019, https://arxiv.org/abs/1905.13681).
(14) *Ad Astra, ibid.* To learn more about the work of Gerard K. O'Neill, go to Multiverse Publishing, https://multiversepublishingllc.com.
(15) In *The Overview Effect,* Apollo astronaut Rusty Schweickart talks about a "cosmic birth phenomenon."

Note: I also want to express my appreciation to David Peterson of Ventana Systems for his reading and critique of this paper.