Feeding One Million People on Mars

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ABSTRACT

Food production on Mars is usually thought of in terms of growing plants to partially support small exploration crews for short- to medium-term stays. Here, we consider the more radical goal of producing enough food on Mars to sustain a permanent settlement of private citizens that increases to 1 million people within 100 Earth years. We modeled a population that grows from immigration as well as naturally. Calorie needs were calculated on a per-person basis, and land use was modeled with a diet that includes staple crops, insect products, and cellular agriculture. Food self-sufficiency can be attained within 100 years with reasonable inputs, but massive amounts of imported food would be needed in the interim. Various strategies can reduce the amount of imported food significantly, balanced against the rate at which pressurized food facilities are constructed. Developing a commercial food industry on Mars will involve high up-front costs, but in situ *resource utilization will be able to help close the business case. Future research should focus on methods to produce plant nutrients, insect feed, and cultured cell feedstocks from mostly local resources on Mars. Engineering and architecture efforts should develop automated methods for rapidly building shielded, pressurized volumes to house food production facilities.*

Keywords: Mars, *in situ* resource utilization, food production, plant growth

INTRODUCTION

Human activity on Mars has mostly been planned by using NASA-derived mission architectures, but these may not accurately reflect the near-term plans of commercial space companies and the long-term aspirations of private citizens and corporations who want to move to Mars. In NASA's previous Human Exploration of Mars Design Reference Architecture 5.0,[1] missions were decades away and they were designed around brief sorties or outposts; it was assumed that people would not stay on Mars to start a permanent settlement. Under these parameters, it may not make sense to carry out *in situ* resource utilization (ISRU), except in a limited case to generate propellant for a Mars Ascent Vehicle.[1,2] Plants or other foods produced on the martian surface would serve a psychological purpose and as a minor dietary supplement, as they do on the International Space Station (ISS).[3] The more recent NASA Evolvable Mars Campaign took steps toward a sustainable presence, but it still imagines small crews and brief sorties, and has now taken a backseat to a lunar return.

The rise of commercial space companies with ambitious goals and agile development practices will likely disrupt these canonical architectures. The stated objective of SpaceX is to establish an independent civilization on Mars, with cargo and then crewed ships projected to start launching within 3–5 years. Vehicles for the transportation system are already being built and tested. Detailed plans have not been published, but a rough sketch of the SpaceX campaign calls for: (1) an initial crew of $\sim$12 people; (2) multiple ships of $\sim$100–200 passengers sent at every 26-month launch opportunity; and (3) an eventual population of 10^6 living on the planet within 50–100 Earth years.[4] By providing a transportation backbone, SpaceX hopes to stimulate corporations and private individuals to move to Mars and take up development projects to support a growing settlement. At these scales, ISRU will be necessary for economic reasons, although cargo resupply ships will be needed for materials such as uranium, and platinum group metals that may not be economically concentrated in the martian crust. These elements are particularly useful for nuclear power and advanced manufacturing, respectively.

Growing food locally on Mars will be one of the more challenging ISRU processes, but it must be accomplished to support permanent inhabitancy. The five major consumables needed for a martian settlement include energy, water, oxygen, construction material, and food. The first four are abundant in economic concentrations and extractable forms on the surface of Mars: solar for energy, likely supplemented with nuclear fission reactors,[5] hydrated minerals, ice, and bulk regolith for water,[6] atmospheric CO_2 for oxygen,[7,8] and regolith derivatives (bricks, fibers, etc.) for building supplies.[9–11] By contrast, food is not available and cannot easily be created from the raw materials present on Mars (*i.e.*, in a simple chemical reactor). This begs the question of how one million people (or 12) will eat on a planet with no native flora or fauna. Relying on imported food is a poor solution: as the

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martian population grows, it would depend more and more on the Earth over time, negating the goal of a self-supporting or self-sufficient civilization. Food must be produced on Mars by using local resources. The goal of this article is to evaluate different food sources and quantitatively model the balance between food produced locally on Mars and that imported from the Earth. With a projected commercial human landing as early as the mid-2020s, the discussion here is not far-off science fiction, but a practical issue that should be considered when fleshing out the development of a martian settlement.

FOOD SOURCES AND INDUSTRY

Agriculture, food, and related industries made up 5.4% of GDP in the United States in 2017, worth $1.053 trillion.[12] These existing food supply chains cannot be directly transplanted to Mars in their current form, but more-or-less similar end products can be re-created with local resources. An average U. S. diet contains large amounts of dairy, eggs, and farm-raised animal protein that are exorbitant in energy, land, and water use.[13,14] Raising farm animals for dairy and meat will not be practical on Mars in the near term because of the challenges of transporting large animals in space and the types of facilities needed to house them on the surface. As well, terrestrial factory farming practices are hardly ethical. Models and experiments on Bioregenerative Life Support Systems (BLSS) often assume a 100% plant-based diet,[15,16] but despite the hype of vegetarian and vegan diets, their actual prevalence in 2018 remained very low and has not increased significantly in recent decades.[17] Overall, 84% of people who switch to vegetarian or vegan diets go back to eating meat.[18] Most people simply do not want to eat a plant-based diet, and foods besides plants will be produced on Mars: This will include insect-based products and cultured meat (aka clean meat). Based on trends in consumption on the Earth, a free market system of food producers and consumers will gravitate toward more choice for people living or working on Mars, far beyond plant-based options. For example, grocery stores today carry 40–50,000 unique items, compared with just 7,000 in the late 1990s.[19]

Plant-Based Foods

Higher plants produce carbohydrates, fats, and proteins by converting CO_2, H_2O, and photons into macromolecules (*i.e.*, $C_6H_{12}O_6$) and O_2. They also convert gray water into potable water through transpiration, and the presence of plant life in isolated environments has well-known psychological benefits. Many studies by space agencies and universities have modeled or built a BLSS, and they have directly experimented with plant growth for space applications. Wheeler[20] provides a review of the accomplishments from decades of this research. Other useful information comes from experiments on the ISS[4] and Antarctic research stations.[21] An impressive study by Fu *et al.*[22] in China's Lunar Palace 1 created a menu of cultivated plants and insects mixed with externally supplemented foods that fed 3 humans for 105 days. Together, these studies show that it is feasible to support at least part of a diet with indigenously grown plants.

The surface of Mars will not be covered with fields of wheat any time soon, and pressurized volumes are needed to protect against the thin atmosphere and subzero temperatures. Concept art of martian settlements usually features gratuitous greenhouses, but there may not be a net advantage to growing plants in translucent structures on the surface. The ostensible benefit of a greenhouse is that photons are used directly, rather than converting them to solar power and then back to energy-intensive electric lighting. However, even at the equator on Mars, the average photosynthetic photon flux (PPF) is only about 25 mol/m^2/sol (similar to Alaska).[23] Greenhouse transmittance values are typically 50%–70% on the Earth,[24] they and may be even lower on Mars because a stronger material would be needed to support a pressurized greenhouse interior. A transmittance of 70% reduces the PPF to 17.5 mol/m^2/sol, which is not sufficient for staple crops and barely capable of growing plants such as lettuce or tomatoes.[25] LED lighting could supplement natural sunlight, but this type of hybrid greenhouse would have both high mass costs and relatively high energy costs. An attractive alternative is to grow plants in tunnels with high-strength LED lighting, supplemented with sunlight collected and piped down through fiber optic cables.

Another key trade is the growth medium: soil versus soil-less systems (hydroponics, aquaponics, and aeroponics). A major Mars-specific advantage of soil-less systems is that they would work starting on day 1 based on well-known practices, but they require more mass in the form of trays, pumps, and reservoirs, and they may be more vulnerable to plant disease. In terrestrial agriculture, soil-less systems are typically used for low-calorie foods such as lettuce and strawberries instead of high-calorie staples needed to feed a large population; however, experimental studies have reached extreme yields (2–4 × world records at the time) for staple crops with hydroponics.[26,27] Nutrient solution solutes for soil-less systems would have to be shipped from the Earth until the requisite inputs can be produced on Mars. Soil-based systems may be more robust against plant disease, but it would be necessary to transform the inorganic martian regolith into a "living soil" to support plant growth.[28] A previous study grew various plants in martian regolith simulant,[29] but the simulant used (JSC

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Mars-1A) is just terrestrial soil from Hawaii. Initial efforts using the inorganic, high-fidelity MGS-1 simulant developed by Cannon *et al.*[30] resulted in rapid death of plants and suffocation of earthworms (A. Palmer, pers. comm.), suggesting that plants will not necessarily grow in Mars dirt, at least in raw form. A period of trial and error would be needed to: (1) determine the toxicity of the actual martian regolith, similar to how Apollo samples were tested against plant and animal phyla[31]; (2) remove perchlorates and other salts as necessary; (3) adjust the physical texture of the soil; (4) add fertilizers; and (5) allow time for nutrient cycles to develop and for organic acids to break down the primary silicate minerals. This effort could be started immediately by the first people on the surface, then scaled to produce large amounts of living soil needed for crop growth.

Presumably, any plant that can be grown from a seed on the Earth can be brought to Mars. Many authors have listed and ranked different plants for space applications, and they commonly include carrot, lettuce, wheat, soybean, rice, cabbage, radish, and green beans.[32] Certain calorie crops stand out based on growth period, average yield per area, and macronutrient contents: corn, wheat, and sweet potatoes for carbohydrates, soybeans for protein, and peanuts for fats. Of course, culinary tastes, variety, and human psychology must also be considered: A study of participants on a long-term Antarctic expedition found that the most missed foods from home included tomato, strawberry, cucumber, and bell pepper,[33] none of which is particularly dense in calories. Genetic modification can be used to tailor plants to hybrid growth environments that are intermediate between the Earth and ambient Mars conditions, for example increasing yields in high-CO_2, low-temperature environments to lessen costs of running indoor martian farms.

Plants can also be modified to synthesize provitamins and increase micronutrient contents, as was done to introduce the β-carotene synthesis pathway to create golden rice.[34] More recently, both RNAi and CRISPR have proved effective for rapidly improving crop productivity, as demonstrated by Lemmon *et al.*[35] and South *et al.*[36] Producing and distributing plant-based foods to feed a city on Mars will create an industry based heavily on agriculture, biotech, and robotics. Recent advances in "cyber agriculture" with food computers[37] are directly applicable, and the indoor vertical farms being set up in urban centers can serve as test beds for building similar facilities on Mars, although with a necessary shift toward high-calorie crops.

Insect Farming

Insect farming is well suited for Mars: It provides a large amount of calories per unit land while using relatively minor amounts of water and feed. Compared with plants and farm animals, insects have similar macronutrient contents per unit mass, but significantly higher yields per square meter.[38] They also have much higher food conversion ratios than livestock, although feed must be of relatively good quality.[39] Insects are not rooted in Western diets and are met by neophobia, especially in unprocessed forms.[40] However, there are many private companies working to change attitudes and introduce insect-based products in North America and Europe as environmentally friendly alternatives to traditional animal protein. The global edible insect market is projected to reach $1.18B by 2023,[41] and in a martian economy it may become a much more important industry than the current niche status in western countries. House crickets (*Acheta domesticus*) are one of the more promising examples of edible insects, and processed cricket flour can be incorporated and hidden in many different recipes, avoiding neophobia to some extent. Feed for insects can come from plant crops and/or spoiled foods, and a major advantage for Mars is the low maintenance: Most aspects of a cricket farm can be automated with housing bins stacked vertically. Continued innovations by insect farming and robotics companies will further improve the business case for producing edible insects on Mars.

Cellular Agriculture

Growing protein-rich foods from cells in bioreactors will allow people to eat a familiar diet within the constraints imposed by Mars. Algae, clean meat, clean fish, cow-less milk, and chicken-less egg all involve producing food on a cellular level by using appropriate nutrient solutions. On the Earth, algae-based foods are more accepted, with spirulina and nori as prominent examples. Clean meat and fish are in the final stages of development before commercial sales begin later this year, and investors are pouring large amounts of money into refining the technology and driving down costs (the price of a cultured meat burger fell from $325,000 to $11 per patty in 2 years). Clean meat and fish offer many of the same advantages as insects: significantly more calories produced per units of water and land compared with traditional farming or aquaculture.[42] These features translate well to Mars because "land" on Mars really means a heated and pressurized volume, water is somewhat scarce (but can be recycled efficiently), and feed for higher trophic levels must be synthesized from scratch or imported. Clean fish may be favored over other cell-grown meats on Mars, because the cultures can be maintained at temperatures closer to 20°C rather than elevated temperatures (~37°C) needed for warm-blooded animal cells.[42] Cyanobacteria are used as a growth medium for cultured muscle cells, and bioreactors with various cyanobacterial strains will

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also find other uses in a martian settlement.[43] Instead of meat being a rare treat brought in dehydrated packets from the Earth, cellular agriculture will allow companies to produce and sell ethical, palatable, and fresh animal proteins on Mars, further expanding choice in the food market.

FOOD MODEL

Model Inputs and Assumptions

Based on the food sources described earlier, we built a computer model to calculate the food needs of a martian population that grows to at least 10^6 people and achieves food self-sufficiency within 53 Mars years ($\sim$100 Earth years) or sooner. We used a SpaceX-like transportation architecture, but the analysis was general enough that it need not be tied to a specific company. The martian population started with an initial crew of 12, then increased naturally, as well as from immigration at every $\sim$26-month launch opportunity (with a linear increase in the number of ships per opportunity). The reference model used a crude birth rate of 10 per 1,000 people per Earth year, typical of developed nations. The initial crew had an age distribution with a mean of 35 and a standard deviation of 5, whereas the subsequent immigrant population had a larger age spread (standard deviation = 10). Death probabilities per year were taken from terrestrial actuarial tables[44] and adjusted for the length of a Mars year: This is a simplification that assumes that higher death rates from the hazards of living on Mars will be roughly balanced against future advances in medical technology. However, dramatic progress in anti-aging research is possible in the long timelines considered.

Calorie needs[45] were based on a 50–50 male–female ratio, an active lifestyle; adjusted for the age of each martian resident; and, finally, scaled for the length of a sol compared with a day. A 20% margin was added to account for food security, spoilage, and seeds set aside for the next crop in farm facilities. We also assumed that 2×10^5 kg of packaged food would be launched before the first human landing and would be available to the initial population. An adjustable delay was included in the model to account for the time needed for companies to construct initial food production facilities. After this, indigenous food production must catch up to the needs of the growing population: This can be done in an instantaneous step, a linear increase in the fraction of total calories produced locally, or an exponential increase (or any other function). The tradeoffs of these various strategies are discussed next.

The goal of the model was to quantify calorie needs and associated land use for a self-sufficient city, and to determine which parameters will: (1) reduce the number of cargo resupply ships required for food, and (2) ease the transition to producing 100% of calories locally. The limiting factor in producing food on Mars is likely to be the volume (or area) that must be constructed, pressurized, and actively heated and/or lighted. Tunneling may be an effective strategy, but tunnel walls will still need to be reinforced and sealed to prevent gas leakage. Boring through weak megaregolith would present challenges, and a settlement located near intact young lava flows or strongly lithified sediments would be advantageous.

Modeled Diet

A simplified diet based on plants, insects, and cellular agriculture was used in the model to calculate land requirements for locally produced food (*Table 1*). This indigenous diet consisted of: (1) a generic staple crop, (2) insect products represented by crickets, and (3) cultured meat represented by ground chicken. The generic plant crop was derived from the average macronutrient contents of wheat, corn, sweet potato, and soybean,[46–49] and their current world record yields as grown in the field.[50–53] Although earlier hydroponic studies achieved multiples of record yields,[26,27] these studies took place 30 years ago when crop yields were significantly lower. Current field records can likely be improved with further genetic modification and with high CO_2 partial pressures and photon fluxes as in previous BLSS studies,[20,26] such that our

Table 1. Food Sources Used in the Simplified Indigenous Martian Diet

Food	kcal Carb[a]/100 g	kcal Protein[a]/100 g	kcal Fats[a]/100 g	Yield (kg/m^2/cycle)	Production Cycle (Earth Days)	Land Requirements (m^2/kg/Mars year)
Generic plant crop[b]	199.0	57.1	60.0	1.6	110	0.0959
Insects (crickets)	20.4	51.6	49.5	9.0	45	0.0083
Cultured meat (chicken)	0.2	69.8	72.9	4.4	60	0.0201

[a]Carbohydrate and protein calories are calculated as 4 kcal/g, whereas fats are calculated as 9 kcal/g.
[b]Based on averaged data from wheat, corn, sweet potato, and soybean.

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yields are conservative. Cricket nutrition data were taken from whole crickets,[54] and yields (in kg/m^2) were based on the floor area of experiments and actual cricket farm operations.[38,55] These 2D yields may vary because cricket habitats can be built up vertically with corrugated substrates. Additional land area was not modeled for insect feed, because the feed can come from spoiled food and inedible plant mass. For cultured meat, nutrition data from ground chicken were used,[56] and the yield was a conservative estimate that also takes into account the land needed to produce cyanobacteria as the bioreactor feedstock.[42] The basic modeled diet breaks down as ~40% carbohydrates, 30% protein, and 30% fats. For 2,000 kcal, the diet contains 934 g of wet mass with a ratio of 3 parts plants to 3 parts clean meat to 1 part insects. In reality, many different crops, insect species, and meat/seafood can be produced for variety and culinary purposes: There is no point creating detailed hypothetical menus at this time, and a free market of food producers and consumers will ultimately dictate what types of products will be available on Mars.

Model Results: Reference Model

The reference model was based on reasonable assumptions for a Mars settlement: a lower natural birth rate, a delay of 5 Mars years before native food production starts in earnest, and a linear increase in the fraction of indigenous calories to catch up to population growth within 53 Mars years. In the reference model, the martian population grew from 12 people to 1,000,281 (*Fig. 1*). The total number of immigrants to Mars was 1,032,355, and the number of natural births was 342,086.

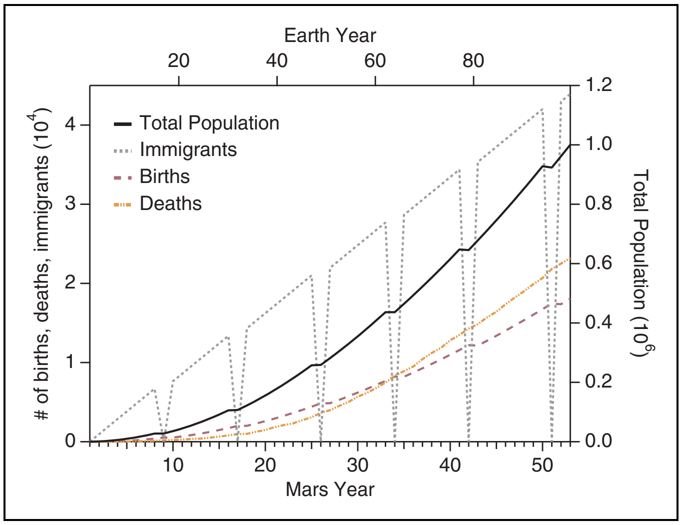

Fig. 1. Population growth over time in the reference model run. Gaps occur where there is no launch window within a given martian year. Color images are available online.

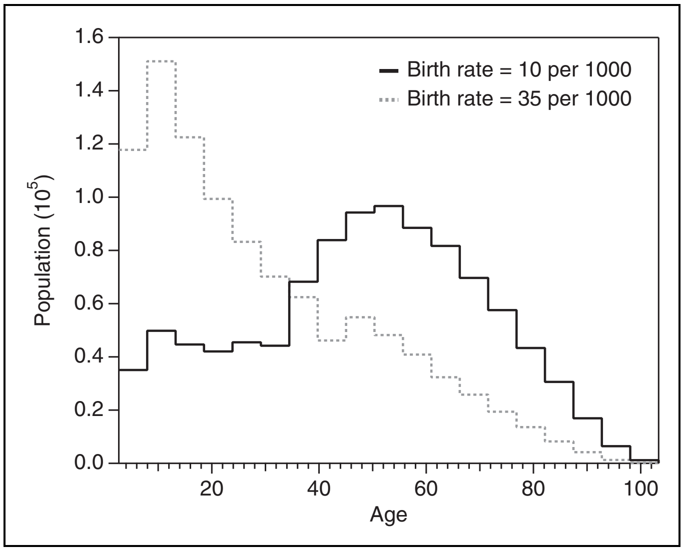

Fig. 2. Population histogram in the reference model (*solid black line*) and model with a higher natural birth rate (*dotted gray line*).

With 150 people per ship, 6,905 crewed ships would be needed for transport, an average of 150 ships per launch opportunity if they were distributed evenly. We did not consider people who move back to the Earth in the model, although this is, of course, possible in reality. *Figure 2* shows the age demographics of the population at the end of the reference model, as well as a model with a higher natural birth rate (see Cargo Resupply and Initial Construction Rates). The bimodal distribution in the reference model resulted from the large-scale

Table 2. Model Results Based on Different Input Parameters

Model	Imported Food (No. of Ships)[a]	Food-Related Construction in First 10 Mars Years (ha)
No local food production	194,361	0
Reference model	53,719	17.9
Start production immediately	48,654	32.5
Self-sufficient by MY25	6,568	43.0
Jump to 100% local calorie production at MY5	209	172.4
Exponential increase in local calorie production	139,551	0.1
Higher crude birth rate	27,563	5.7

[a]Assumes 100,000 kg of food per ship. In reality, cargo re-supply would likely mix food supplies with machinery, electronic components, and other materials.

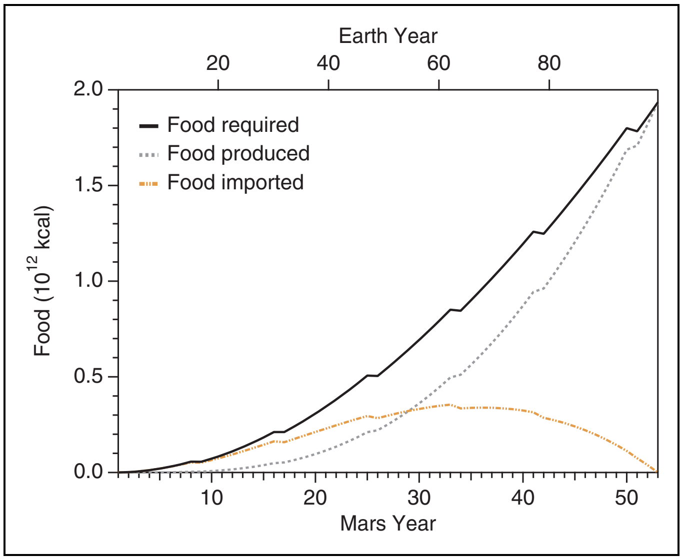

Fig. 3. Total calorie needs in the reference model (*solid black line*), broken down into food produced locally on Mars (*gray dotted*) and imported food (*yellow dash-dot*). Color images are available online.

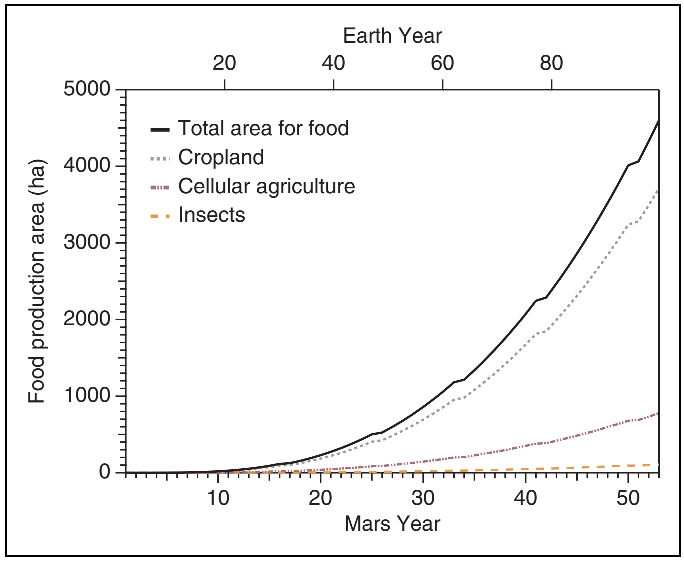

Fig. 4. Areal space needed for food production in the reference model, broken down by food source. Color images are available online.

immigration of mostly middle-aged people, combined with a modest natural birth rate.

If no food was produced locally on Mars, 194,361 ships carrying 1×10^5 kg of packaged food each would be needed to feed this population over the 53 Mars year duration (*Table 2*). With local food production, 53,719 total cargo ships were still required for packaged food to support the settlement, $\sim$25% of that needed in the case where all calories are imported. The amount of imported food decreased to 0 by the end of the reference model after rising to a peak of 3.5×10^{11} kcal/year at 32 Mars years (equivalent to $\sim 1.8 \times 10^8$ kg based on MRE-like packaging) (*Fig. 3*). The total area for food production grew to 4.6×10^7 m^2 by the end of the model (46 m^2/capita), with plants accounting for 81% of this land, cellular agriculture for 17%, and insects for just 2% (*Fig. 4*). If all food was produced in 12-ft diameter tunnels with a flat floor at $^1/_4$ of the tunnel height, then $\sim$14,500 km of tunnel segments (which can be stacked vertically) would need to be operational by the end of the 53rd Mars year. This is feasible for a single tunnel boring machine based on a tunneling rate of 0.03 mi/h anticipated for the Prufrock concept being developed by The Boring Company.

Cargo Resupply and Initial Construction Rates

The model parameters can be adjusted to reduce the total amount of imported food, the rate at which new food production facilities are constructed in the early years, or both (*Fig. 5*; *Table 2*). Reducing the initial delay, achieving self-sufficiency by Mars year 25, or stepping instantly from 0% to 100% indigenous calories at Mars year 5 all had the same effect: less cargo ships needed to import food, but more construction in the first 10 Mars years. Ramping up food production exponentially instead of linearly had the opposite effect: Construction was backloaded, but the total mass of imported food over the course of the model was greatly increased. Interestingly, birth rate was the one parameter that could both reduce food imports and lessen construction burdens. Using a higher crude birth rate of 35 per 1,000 (typical of

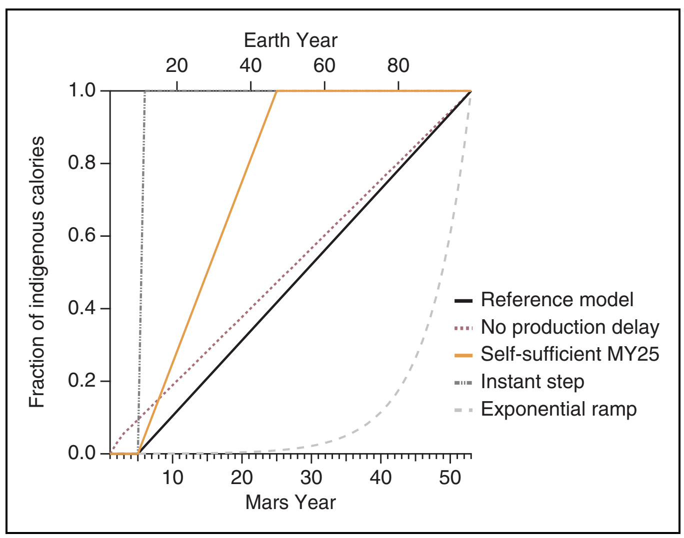

Fig. 5. Fraction of calories produced indigenously over time, comparing different strategies to achieve food self-sufficiency. Color images are available online.

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developing nations) changed the population dynamics significantly: The resulting age structure was highly skewed toward youths (*Fig. 2*). Because children consume considerably less calories than adults, the result was to reduce both the overall number of calories required over the model duration (and therefore cargo resupply) and to reduce initial rates of construction (*Table 2*). Another option, not explicitly modeled, would be to skew the imported foods toward the lowest yield sources, in this case carbohydrate-rich grain crops (*Table 1*): This would have the effect of backloading construction efforts, but with no change in the total number of imported calories.

DISCUSSION

ISRU to Reduce System Mass

Constructing and operating food production systems will involve considerable energy and water, as well as mass for structural components. As described earlier, energy and water are readily available on Mars and are simply a matter of scaling existing technologies. Previous studies have provided baseline values needed to support human bases on Mars or the Moon, including food production,[25] and detailed calculations are not repeated here. However, based on our model results, future advances in LED lighting efficiency (say, from 2 to 3 μmol/J) and in crop genetic editing are probably the best ways to cut down on energy costs involved in feeding future Martians. Water savings are not as important because of the high degree of recycling achieved in closed systems such as the ISS. However, significant mass savings can be realized by placing food facilities in tunnels instead of building 3D structures on the surface. In addition, various ISRU applications can be used to produce parts of the food production system mass out of local resources instead of importing these materials from the Earth. *Table 3* lists some different components of the food facilities, ISRU processes to create them out of suitable martian materials, and a qualitative assessment of the degree of processing required. Components that can be readily produced with minimal processing can be used in the first generation of food facilities, whereas those that need high-energy inputs such as smelting will likely be phased in over time.

Food as Part of a Martian Economy

By analogy to the Earth, a significant fraction (likely 5%–10%) of martian GDP will be based on growing and selling food products. Establishing a market for locally produced food on Mars requires both willing suppliers and customers: The customers will consist of private tourists, permanent immigrants, and astronauts sent by national space agencies on exploration missions. Suppliers will consist of companies that grow, package, and distribute food products on Mars. To close the business case, food must be able to be produced locally for cheaper than it can be imported on cargo supply ships. Using the SpaceX transportation goal of $140,000/ton to Mars,[57] food must be produced locally for <$140/kg, which seems easily doable given that this figure is orders of magnitude higher than the retail cost of food on the Earth. However, there will be significant upfront costs to establish production facilities, restaurants, etc. Bootstrapping with public–private partnerships may be needed to overcome these barriers.

Recommendations for Future Research

How a martian settlement produces food will ultimately evolve organically according to human preferences and free market efficiencies. That said, some general recommendations for future research can come from the results of our modeling and other considerations:

1. A martian city will not be fed on lettuce and tomatoes. Plant growth research for space applications should return to the emphasis on high-yield crops such as wheat and corn, as was the case in the 1980s and 1990s.[20] Genetic

Table 3. ***In Situ*** **Resource Utilization Applications to Reduce Food System Masses**

Object	Martian Material Substitute	Degree of Processing
Hydroponic growth medium	Regolith gravel (porous volcanic lithologies)	Low
Rockwool cubes for germinating seeds; Insulation	Melted and spun basaltic fibers	Moderate
Nutrient solution ions (SO_4^{2-}, NO_3^-, K^+, Mg^{2+}, Ca^{2+})	Leachates from salt-rich regolith	Moderate
Walls for insect pens; corrugated insect substrate	Regolith-based concrete	Moderate
Hydroponic trays	Ceramics, plastics	High
Cellular agriculture bioreactors; Sliding rails for robotic systems	Mongrel alloys or refined alloys from regolith	High

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editing tools[34–36] should be used to optimize strains both for absolute yield (as is already being done for Earth applications) and, specifically, for growth in higher CO_2 conditions. It is probably not necessary to decide between soil-based and soil-less systems until humans get to Mars: A modest delay in starting food production was not consequential to the model results (*Table 2*), as long as the gap occurs when the population is still low. This time can be used for experiments and rapid prototyping of plant growth techniques. Outdoor greenhouses are not appropriate for growing staple crops on Mars, unless supplemented with significant artificial lighting (during dust storms, nearly 100% of photon needs).

2. Insect farming and cellular agriculture should be adapted for space; fortunately, the same drivers for increasing sustainability on the Earth are mostly aligned with producing food in the challenging martian environment. Still, more can be done to work out the most efficient and palatable insect species, improve textures and flavors in cultured meat, and find ways to produce high-quality insect feed and plant/cell nutrient solutions using martian-derived building blocks. Efficient bioreactors, insect pens, and the facilities that house them can be designed and tested on the Earth. For these food sources (as well as plants), production can and should be highly automated.
3. The amount of food imported from the Earth can and should be minimized to greatly cut down on launch costs. The number of cargo ships worth of food can be reduced (*Table 2*), from tens of thousands to only thousands or even hundreds by ramping up food production faster, but at the cost of more extensive construction efforts (which, to some extent, will just trade food for building materials in cargo holds). An early surge in construction is advantageous, because the same amount of material and energy is needed to construct a food facility whether it happens in year 1 or year 50 of the settlement, but the facility built in year 1 produces more food cumulatively. A higher natural birth rate would also reduce the number of calories needed early on, and therefore food imports. However, in this modeled scenario, immigration rates were much lower to achieve the same arbitrary final population, and it is unclear what the ratio of natural growth to immigration will be on Mars.
4. Harsh martian conditions put firm constraints on the ways in which food can be grown locally, but new technologies are poised to get around these barriers and will lead to an expansion in terms of culinary creativity. These technologies will also greatly reduce animal suffering. Exotic meats (even from endangered species) can be produced ethically starting from a single cell, plant genes can be merged to combine traits and flavors, and plant-based protein products can be designed with myriad textures and tastes. Space scientists and companies should engage with the alternative protein movement to take advantage of the latest developments and adapt them to be transported and implemented on Mars.
5. Food production, other ISRU systems, and life support should not be developed as isolated components, but as a connected ecological system.[58] There are countless crossovers that have been described by previous BLSS studies: Plants and cyanobacteria scrub CO_2 and produce O_2, food waste can be fed to insects and earthworms, biosolids can be used to fertilize plants, rice hulls and mycelium can be converted to building materials,[59] and so on. Lessons from sustainable practices on the Earth should be adapted for a martian settlement and, in turn, spinoffs from developing the technology to get humans to Mars can be used to improve sustainability and reduce greenhouse gas emissions on the Earth. In this vein, switching to a "martian diet" will become possible in the near term once cultured meat products are widely available, and we created a companion website (http://eatlikeamartian.org) to offer some loose guidelines of sustainable Mars-like eating habits on the Earth.

CONCLUSIONS

We modeled the calorie needs and land requirements for a permanent martian settlement that reaches a population of one million people and becomes food self-sufficient within a century. In the model, calorie needs were met with food produced locally on Mars combined with imports from the Earth. In the reference model, tens of thousands of supply ships worth of food alone would be needed, but this number can be greatly reduced by a surge in food production capacity during the early years of the settlement. Food sources are constrained on Mars, because plants cannot be grown outdoors and raising farm animals is not feasible; however, new technologies, including food computers, automated insect farms, and cellular agriculture, will allow for complete, nonvegan diets produced locally on Mars. Food production and distribution will likely form a significant part of a growing martian economy, with inputs from traditional industries (biotech, robotics, agriculture) and new ones that spring up.

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