Space Agriculture: Going Where Farming Has Never Gone Before

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Agriculture has been practiced by humans for millennia and when one considers space exploration, it is logical to assume agriculture will follow. Indeed, it is already happening on a small scale on the International Space Station (ISS), where astronauts grow leafy greens such as lettuce, mizuna, pak choi, kale, and even chile peppers in small plant chambers [1,2]. These chambers provide only about 0.15 m^2 or less growth area and so this form of agriculture is intended to only provide supplemental fresh foods [3], which can still have a profound impact on the crew nutrition and mental well-being [4,5].

But the question of using agriculture in space runs deeper than producing occasional fresh food and has been asked since the beginning of the space program: Can we use agriculture to provide more full life support for humans in space [6,7]? Can plants be used to supply large portions of the diet, thereby reducing, or perhaps even eliminating the need for food resupply? Can the plants be used to provide oxygen for the humans, remove the noxious carbon dioxide that builds up in space habitats, and perhaps even be coupled to water recycling systems? The answer to all these questions is YES [8].

First it is important to consider the constraints and challenges for growing plants in space. We don't have a small farm on the International Space Station because there isn't enough volume to accommodate large plantings, nor is there sufficient electric power to run the lighting systems that are typically used in plant factories or vertical farms. The mass, power, and volume costs must always be considered for space. But as we go farther and stay longer, the resupply costs for food become prohibitively expensive, and at that point, regenerating some of the life support commodities like food, O_2 and water becomes a necessity. For example, a commonly discussed "reference" mission to the surface of Mars might take 6-9 months transit time to get there, then a stay on the surface of about 500 days to account for the changing positions of Mars and Earth in their orbits, and then 6-9 months back. By some estimates, this could require nearly 10 metric tons of packaged food for a crew of four. But just as with the ISS, we won't be setting up a large farm on the first visit. A better way to think of it might be an evolution or sequential expansion of agriculture as the habitat infrastructure and capabilities expand with subsequent missions [9].

So let's envision humans have arrived at Mars. How do we grow the plants? Unlike the weightless situations one must deal with on the ISS or during Mars transit for small plant growth systems, you will have some gravity (3/8 g) on Mars. This means that you can use conventional watering techniques, such as recirculating hydroponics where water runs downhill (down a trough to a reservoir). These hydroponic approaches are used widely on Earth and allow the greenhouse or vertical farmers to continually recycle their water and nutrients, and then just add back what the plants have used. This avoids any waste of water and nutrient fertilizer, which is a necessity for space. Such hydroponic systems will require hardware like pumps, pipes for plumbing, troughs or trays for growing the plants, sensors, and so forth. But in turn, they allow relatively easy cleaning and turnaround for replanting subsequent crops. However, you will need some additional water and nutrients. Where will you get those? These might come from in situ resources in the surrounding environment, such as Martian ice or minerals from the regolith. The number one element needed by plants to grow is nitrogen, and there is evidence of nitrate like minerals in some of the regolith of Mars [10]. But there are other resources, such as the inedible plant biomass, which can be processed (degraded) to recycle the nutrients to grow more crops, and of course wastes from humans, especially urine, which is rich in nutrients needed by plants (nitrogen, phosphorus, calcium, magnesium and more) [11]. But urine also contains a lot of sodium, which plants don't need and can't tolerate in high concentrations.

Can you use the Martian regolith (Martian "soil") directly? Perhaps, but you will need supplemental fertilizer. The Martian regolith doesn't contain sufficient nutrients to sustain healthy, fast growing plants; in addition, the regolith contains potentially toxic perchlorate compounds that would need to be removed. Think of it as trying to revegetate a mine tailings pile or a rocky terrain. Some plants might be able to germinate and survive, but they will need nutrient supplements to grow. Even farmers in Iowa with some of the best soils in the world still add fertilizer to their corn crops to get high yields. Remember, mass, power, volume… if we use plants for life support, we need high yields per unit area and per unit volume to be cost effective and sustainable. But regolith could be amended with organic matter (like from compost) to improve the nutrient and water holding capacity. Hydroponic systems such as the nutrient film technique have very little water holding capacity in the root zone. If the circulation pumps fail, you must respond very quickly to avoid a catastrophic wilting of the crop. With a 3-dimensional soil from regolith that has water holding capacity, you are less prone to consequences from pump failures. But remember, all the water used by the plants or leached through the soil has to be captured and recycled – this is a must.

If you meet the water, nutrient, temperature and carbon dioxide (for photosynthesis) needs, the number one factor that stands out for growing plants for life support is light! Light's effects on photosynthesis and yield are almost linear—1 X light, 1 X yield, 2 X light, 2 X yield, and so forth until you get to higher light intensities where photosynthetic rates begin to "saturate". You might consider transparent structures like greenhouses, but this presents challenges—finding transparent materials that hold pressure, getting the needed thermal insulation qualities, and holding up to the degrading effects of high UV radiation on the Martian surface. Plus you must consider the effects of dust storms and light dark cycles. Alternatively, you can use electric lighting, such as LEDs, which are remarkably efficient now, converting as much as 70-80% of their incoming power into light [12]. This is how much of the current life support testing with plants is proceeding, i.e., using LED lighting systems. But now you need electric power, another challenge. This is something mission planners could accommodate, perhaps with the use of small nuclear fission power generating capabilities.

Finally, what types of crops? If we think about sequential development of space agriculture, it might be best to first start with small plantings of fresh food (perishable) crops, like leafy greens and small fruits like tomatoes, peppers, and strawberries. These won't last for a 6-month shipment from Earth and could have positive effect on the crew nutrition, provide dietary variety, and boost crew well-being [4,5]. Plus they have no processing requirements… they are pick and eat type crops. Then, perhaps you expand into "minimally" processed crops like potato and sweet potato that provide more calorie dense foods with some protein but with little preparation, perhaps just cooking or baking. Finally, for more mature systems, begin adding grains and legumes, such as wheat, rice, soybean, and peanut to get a better balance of protein and fat with the carbohydrates[13], just as we do on Earth.

An additional step, but with added complexity, is to consider using secondary consumers for converting inedible plant biomass, such as leaves and stems, into food. These might be organisms like mushrooms (fungi), or insects that can consume cellulosic biomass, or fish like tilapia [14]. Then you could increase the production of total food from a given area of crops [9]. Another important factor is to select or breed plants that partition a lot of their growth into edible biomass, such as seeds, fruits, or tubers. This means more food production per unit area and less waste biomass. Indeed, this was one of the underpinning steps for the green revolution in the 20th century, e.g., grain crops with a higher harvest index. But in this case, we must select or develop the crops for the space environment, where we must deal with higher radiation levels, fractional gravity levels, and perhaps peculiar atmospheres with high CO_2 and reduced overall pressure. As with terrestrial agriculture, you must also consider the possibility of plant pathogens (even if "only" those hitching a ride with us from Earth, so selecting diverse crops that have good disease resistance and implementing so-called integrated pest management strategies should be considered [15]. Understanding the overall microbiome of the plant systems and the space habitats will also be critical. In many ways, missions into space will be studies of "island biology" and understanding and managing the stability of these isolated ecosystems will be revealing, both for space and for Earth.

Space agriculture related research by NASA was the first to use LEDs to grow plants, the first to carry out volume efficient vertical farming concepts, and the first to grow a wide range of field crops, including root zone crops in hydroponics, demonstrating yields 2-5 X greater than world record field yields. As we learn more about supporting sustainable agriculture in space, we will learn more about sustainable agriculture on Earth—and vice versa.

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