Lunar Agriculture

FARMING FOR THE FUTURE

A Southern Hemisphere Space Studies Program 2020 Report

11 February 2020

University of South Australia

INTERNATIONAL® SPACE UNIVERSITY
ISU

LUNAR AGRICULTURE

Farming for the Future

Final Report

International Space University Southern Hemisphere Space Studies Program 2020

The 2020 Southern Hemisphere Space Studies Program was held at the Mawson Lakes campus of the University of South Australia (UniSA), Adelaide, by the International Space University (ISU) and UniSA.

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The cover depicts the view of the North polar region of the Moon obtained by NASA's Galileo camera during the spacecraft flyby of the Earth-Moon system on December 7 and 8, 1992, juxtaposed with a field of wheatgrass.

ISU PARTICIPANTS

The team of students represented below are graduates of the Southern Hemisphere Space Studies course of 2020. They represent an interdisciplinary mix of engineers, scientists, business focused and humanities focused individuals who, through the SHSSP program, have learned to work together and overcome the challenges presented.

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This report was written on Kaurna land; in Adelaide, South Australia. The authors would like to pay their respect to the Traditional Owners of the land on which this report was written, and pay their respects to Elders past, present, and emerging.

Contents

List of Acronyms

3D	Three-Dimensional
BMR	Basal Metabolic Rate
BLSS	Bioregenerative Life Support System
°C	Degrees Celsius
CERN	Conseil Européen pour la Recherche Nucléaire
cm	Centimeter
COPUOS	United Nations Committee on the Peaceful Uses of Outer Space
ESA	European Space Agency
FAO	Food and Agriculture Organization of the United Nations
g	Gram
GCR	Galactic Cosmic Ray
Gy	Grays
IP	Intellectual Property
ISRU	In-situ Resource Utilization
ISS	International Space Station
ISU	International Space University
K	Kelvin
kcal	Kilocalorie
kg	Kilogram
kW	Kilowatt
LED	Light-Emitting Diode
LRO	Lunar Reconnisance Orbiter
m	Meter
NASA	National Aeronautics and Space Administration
PR	Public Relations
SDG	Sustainable Development Goal
SHSSP	Southern Hemisphere Space Studies Program
SPE	Solar Particle Event
UniSA	University of South Australia
UN	United Nations
UNOOSA	United Nations Office for Outer Space Affairs
WHO	World Health Organization
yr	Year

Abstract

As NASA prepares to return to the Moon with the upcoming Artemis program as a stepping stone to Mars, humans will be required to survive in outer space for longer periods of time and in harsher environments. As humanity gets closer to living off world, we need to consider the complexities that will make this possible and the steps towards reaching this goal.

Recommendations are made for the early stages of a lunar farm. These recommendations include the use of semi-subsurface or subsurface structures for a lunar farm to mitigate the impact of harmful radiation, micrometeorites and severe temperature variations; and the construction of a settlement at a polar location, to increase insolation and access to water ice.

Food sources, including plants, cell cultures, and insects, have been selected for their nutritional value and ability to create diverse meals that suit the physiological and psychological requirements of humans. The construction and management of the lunar farm must align with international treaties, including the Outer Space Treaty, and therefore an international authority model is likely to be the most appropriate management structure for the farm. Although further scientific research is required before the realization of the lunar farm, it is expected that by implementing these recommendations, the farm would be a viable option for sustaining humans on the Moon.

Recommendation Summary

ONE

Ensure that ISRU of lunar materials such as lunar basalt rock and the lunar regolith sourced from rock debris is used to lower the costs and the number of resupply missions and materials needed from Earth.
Establish structures on the lunar surface that are built subsurface or semi-subsurface with a regolith barrier above in order to protect from damage from micrometeorites, radiation, and temperature variations.

TWO

Establish a lunar farm that produces plants, insects, and cell cultures for human physiological and psychological benefit and nutritional diversity. These sources should include tomatoes, carrots, garden cress, sweet potatoes, soybeans, peanuts, rice, oyster mushrooms, cloudberry cell cultures, and crickets.

THREE

Prioritize agricultural methods including soil-based farming, hydroponics, insect growth, and cell cultures for growth of food sources on the lunar surface. Ensure that appropriate technologies provide light, water supply, and temperature stability for the successful growth of living organisms.

FOUR

Establish an international authority management structure similar to the "CERN model" to manage the international obligations and coordinate and regulate a lunar mission. Incorporate the applicable *UN Guidelines for the Long-term Sustainability of Outer Space Activities* into the planning, design, development, and implementation of the lunar farming initiative.

FIVE

Establish a regulatory and economic approach that would enable the free flow of scientific and technology transfer, and educational exchanges that lend credibility to the establishment of a lunar farming settlement and provide a return on investment, while remaining in compliance with the Outer Space Treaty and the Moon Agreement.

Prefaces

FACULTY PREFACE

In January and February of 2020, an international, interdisciplinary, and intercultural group of professionals came together at the University of South Australia (UniSA) to take part in the International Space University's (ISU) Southern Hemisphere Space Studies Program (SHSSP). Twenty-seven remarkable individuals from eight countries (a subgroup of the larger SHSSP class) worked together on a team project for five weeks on the important topic of Lunar Farming.

We stand at the cusp of a new age of exploration and development of space. More and more governments, organizations, and private individuals around the world are creating new opportunities in deep space as Earth extends its economic sphere outward toward the Moon. For the expansion to be sustainable, we need to locally produce and manufacture everything that we need to work and live healthily and happily in space. Producing enough food for an extraterrestrial closed loop system has long been a major issue for space farers. The lunar farming team project has taken on this important challenge. The team has researched the whole problem domain from a multidisciplinary point of view. They studied all sides of the problem, including: legal, policy, economic, engineering, scientific, applications, and humanities aspects. The insights they gained gave rise to a series of important recommendations for future space architectures addressing sustainable solutions. These results support the UN Office for Outer Space Affairs (UNOOSA) goals for space supporting the United Nations (UN) Sustainable Development Goals (SDGs).

It has been an amazing experience for me to work with this talented group of professionals focused on such a significant topic to future space activities. I invite the reader to use this document as a foundation for future work in the area of closed life support systems.

Gary Martin
Project Chair
Vice President of North American Operations
International Space University

PARTICIPANT PREFACE

The SHSSP is a five-week, intensive program, run jointly between ISU and UniSA, that brings together space professionals, graduates and students from around the world to engage in an international, intercultural and interdisciplinary experience. In 2020, SH-SSP was held in Adelaide, South Australia, at UniSA, Mawson Lakes. The program hosted 53 students from 13 countries; the largest southern hemisphere program to date.

Lunar Agriculture: Farming for the Future is a report developed by 27 SHSSP participants, of varying backgrounds and experiences. The value we gained from developing this report goes far beyond the academic - we developed professional relationships, lifelong friendships, and learned to work in intercultural teams. An experience like this only comes along once in a lifetime.

We are incredibly grateful for the assistance provided to us throughout this course - from the ISU staff and volunteers, to the guest lecturers, visiting instructors and other academic support. We would especially like to thank our team project chair, Gary Martin and our team project associates, Femi Ishola and Anisha Rajmane for their advice and support over the course of this project. Your thoughtful and generous assistance has helped make this report possible, and we are grateful to have had the opportunity to work alongside you.

Lunar Agriculture Team
Farming for the Future
SHSSP 2020

'LEARNING IS FOOD FOR THE SOUL'
- ADY JAMES, 2020

Mission Statement

TO RECOMMEND AND OUTLINE
A VISION FOR SUSTAINABLE LUNAR AGRICULTURE
THAT CAN SUPPORT THE NUTRITIONAL REQUIREMENTS OF HUMANS AND ALLOW THEM TO THRIVE.

Introduction and Scope

As NASA prepares to return to the Moon as a stepping stone to Mars with the upcoming Artemis program, humans will be required to sustain life in outer space for longer periods of time and in harsher environments.

Discussions on lunar settlement continue within the space industry and may become a reality for people who are already alive today. As humanity gets closer to living off world, we need to consider the complexities that will make this possible and the steps towards reaching this goal. The pursuit of a lunar settlement requires international support - as we grow closer to leaving Earth, nations will need to work together to achieve a shared goal for the whole of humanity.

The scope of this report is limited to providing recommendations for the development and maintenance of a lunar farm to support the physiological and psychological nutritional requirements of ten people. It is assumed that this farm will exist not in isolation, but within a wider lunar settlement. Recommendations regarding the settlement, therefore, are considered to be outside the scope of this project. Extensive research has been undertaken to produce this report, and therefore only highlights have been recorded.

This report will discuss, in order: situating the lunar farm; building the farm; food and sustenance choices; agricultural methods; maintenance and upkeep; risks and dangers; and policy, leadership and ethics.

Definitions

SUSTAINABILITY

The following definitions have been adapted from *The Three Pillars of Sustainability* (Thwink.org, 2014).

ECONOMIC SUSTAINABILITY
Practices that support long-term economic growth without negatively impacting social, environmental and cultural aspects of the community.

SOCIAL SUSTAINABILITY
A process or framework that promotes wellbeing within an organization’s own members while also supporting the ability of future generations to maintain a healthy community.

ENVIRONMENTAL SUSTAINABILITY
The rates of renewable resource harvest, waste management, and non-renewable resource depletion that can be continued indefinitely.

Definitions

AGRICULTURE

The following definitions have been adapted from the Food and Agriculture Organization of the United Nations (FAO, 2007).

LUNAR AGRICULTURE
The interdisciplinary pursuit of managing, developing and cultivating a lunar location to develop crops and animals. Agriculture is also related to the outputs of the process - the products, knowledge, and services that stem from an agricultural practice.

LUNAR FARMING
The practice or act of maintaining and running a lunar farm, including the act of growing plants, animals and other food sources on the Moon.

Project Objectives

SCIENCE AND TECHNOLOGY	Investigate the science and technology needed to ensure the successful growth of food sources on the lunar surface.
FOOD SOURCES	Investigate the highest priority food sources that would be needed for a sustainable lunar farming settlement.
ENGINEERING	Discuss engineering demonstrations that would likely lend credibility to the prospect of such a settlement.
ECONOMICS AND LEGAL	Understand the economic and legal challenges that will need to be overcome.
SUPPORT	Discuss the available routes toward gaining international support for a lunar farming program

Situating the Lunar Farm

- SUNLIGHT
- WATER
- TEMPERATURE

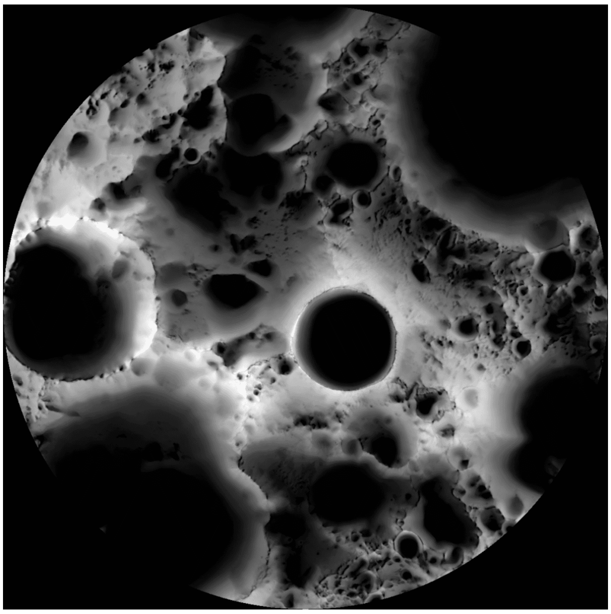
To develop a lunar farm, the most appropriate location must be considered. The lunar surface is known for its harsh environment - the first plant on the Moon did not survive the lunar night (Jones, 2019), and the lack of atmosphere results in high levels of radiation and micrometeorite impact.

SUNLIGHT
The Moon rotates around its axis once every 28 Earth days and equatorial regions may be in darkness for up to 14 days. Locating a farm at the lunar poles could provide near continuous insolation (exposure to the sun) and avoid the 14-day lunar "night" experienced at equatorial locations. This would contribute to thermal stability.

Ideal locations with approximately 98 percent insolation exist at the lunar north pole, especially surrounding the Peary Crater (Bussey, et al., 2005). The lunar south pole hosts a number of recommended candidate sites with high insolation (Bussey, et al., 1999), including the rim of the Shackleton crater with up to 80 percent insolation. The NASA Artemis program is also intending to visit the lunar south pole.

Figure 1 - This insolation composite image is recorded over the lunar south pole. The bright areas show high relief regions that stay in sunlight for longer periods of time than the dark areas. This series of composite images was taken by the camera on the LRO orbiter. The Shackleton Crater is in the center of the image.

Image credit:
NASA/GSFC/Arizona State University



Situating the Lunar Farm

WATER

In-situ resource utilization (ISRU) – the ability to use local resources – is vital to reduce the overall weight, cost, and risk of missions (Anand, et al., 2012). For this reason, a farming site with readily available resources, including water, is favored. Both lunar poles are promising sites due to the potential availability of water ice, which is essential to life on the Moon as a medium for growth and as a source for generating oxygen and hydrogen fuel. Finding extractable water on the lunar surface is a prerequisite for any type of lunar farming facility.

Absorption spectra from experiments performed by Li, et al. (2018) show that higher levels of water ice exist at latitudes closer to the poles, at depths of less than a few millimeters. More recent results suggest that at least 600 million metric tons of ice are available at the lunar north pole, in at least 40 craters and in sheets that are meters thick (Keeter, 2010). The Shackleton crater at the lunar south pole has been studied using orbital radar on NASA's Lunar Reconnaissance Orbiter (LRO) and confirmed that up to 1 percent of the material is lunar water ice (Anand, et al., 2012).

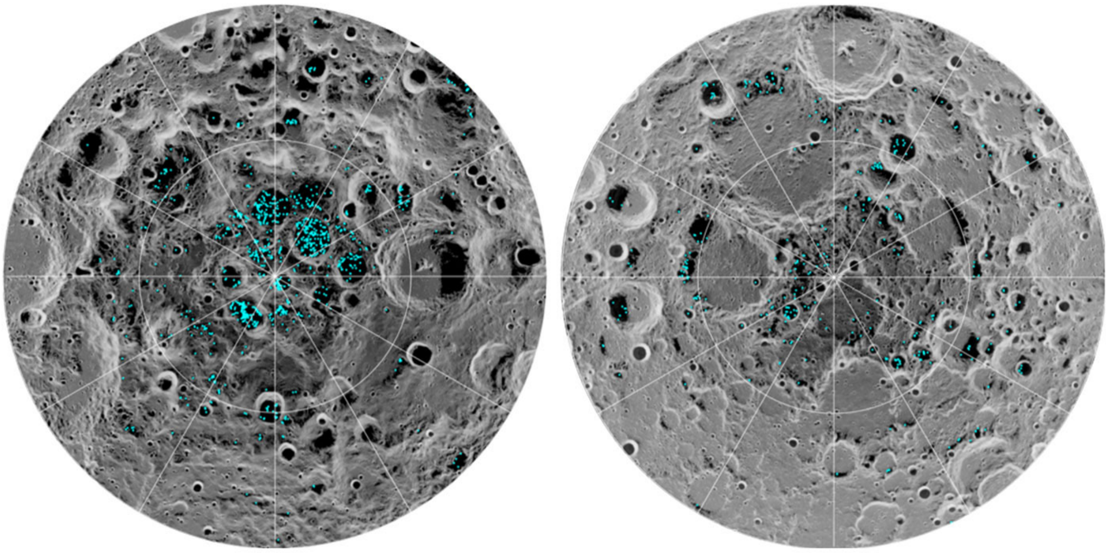


Figure 2 - Maps of the south and north poles (respectively) of the lunar surface showing potenital ice deposits. Reconstructed from measurements by NASA's Moon Mineralogy Mapper (M3) *Credit : NASA*

TEMPERATURE

Understanding lunar temperatures and thermal properties is essential for planning a lunar farm. Temperatures fluctuate significantly over the course of a day, with highs of nearly 387 Kelvin (K) (114 degrees Celsius (°C)) in daylight and lows of 102K (-171°C) at night, with the large temperature range mainly due to the lack of atmosphere (Reitz, et al., 2012). These variations differ in magnitude depending on latitude and surface features such as peaks and craters. Most of the equatorial regions experience these extremes.

The surface regolith, which is loosely packed and nearly 2 centimeters (cm) thick, is understood to have very low thermal conductance (Chancellor, 2014). The deeper, fluffy regolith and subsurface (30cm deep) has better conductance. Thermal model simulations reveal that temperatures in the subsurface area are nearly constant and do not change much during the day—night cycles (stable at ~250K, -23°C) (Malla, et al., 2015).

One thermal analysis study shows that the interior of subsurface habitats could potentially be held at a constant temperature of nearly 293K (20°C) without requiring any external energy sources (Malla, et al., 2015). This would greatly reduce the energy requirements for habitat thermal regulation making it ideal for a lunar farm. Options for subsurface or semi-subsurface structures, which take advantage of this property, are explored below.

Building the Lunar Farm

- IMPACTS
- RADIATION
- MATERIALS
- STRUCTURE
- THERMAL CONTROL
- ENERGY PRODUCTION AND STORAGE

MICROMETEORITE IMPACTS

The Moon does not have a protective atmosphere to disintegrate micrometeorites, therefore the lunar surface is regularly impacted by collisions (Speyerer, et al., 2016). This regular impact rate will need to be managed with appropriate protection for farms, habitats, and astronaut suits. Subsurface or semi-subsurface structures would minimize the consequences of micrometeorite impacts on the farm.

RADIATION

Radiation on the Moon comes from three main sources: solar particle events (SPEs) consisting of protons and alpha particles emitted by the sun, galactic cosmic rays (GCRs) consisting of heavier ions emanating from beyond the solar system, and secondary radiation consisting of neutrons and gamma rays (high energy photons) produced when SPEs and GCRs interact with matter (typically shielding). Total annual equivalent radiation dose rates on the Moon, taking into consideration all of these types of radiation, have been estimated at around 1.12 grays per year (Gy/yr) without any shielding. This is reduced to 47 percent of this value if a shielding of 50cm of aluminum is provided (Y. Jia, 2010).

The effect of these radiation levels on plant growth is not well understood. However, it has been established that much higher levels of gamma radiation can have a detrimental effect. During a plant's growth phase, gamma ray exposure of up to 100Gy on seeds has shown to reduce germination percentage length, and shoot length (Marcu, et al., 2013) and those exposed to over 500Gy did not survive. Few studies were found on the effects of exposure to radiation from protons and alpha particles (the particles involved in SPEs) and heavier ions (the particles involved in GCRs) on plants or food. Long term exposure to low doses of ionizing radiation is shown to have more influence than acute short-term doses (Kovalchuk et al, 2000). This is likely to affect the plants genetically over multiple generations and may impact farming (Wolff, 2014).

Once the food has been harvested for consumption, however, gamma ray exposure on the Moon should not be a problem as studies have shown that even with very high doses of radiation of up to 1000Gy (orders of magnitude greater than that on the Moon), there was no observed effect on the nutritional quality of macronutrients (Diehl, et al., 1991).

Since little research was found on the effects of radiation present on the Moon (that from protons, alpha particles and heavy ions) on plants and food, it is recommended that further research be done to better assess how SPE and GCR radiation will affect lunar farming and the humans who consume food produced on these farms.

RECOMMENDATION 6A
Conduct further research into the effects of SPE and GCR radiation on plants in a lunar farm, and the humans who eat them.

MATERIALS

As construction materials tend to be heavy and therefore costly to transport, ISRU of lunar materials is a favored pathway for construction. Key resources include the lunar basalt rock and the lunar regolith sourced from rock debris.

Lunar basalt rock is rich in iron, titanium and other metal elements. Material properties of these metals such as tensile strength, compressive strength, and wear resistance make lunar basalt useful for construction of structures such as a lunar farm (Cliffton, 1990). Lunar regolith, with a powdered consistency could be used *in-situ* and converted into structural materials (Toutanji, 2011; Montes, 2015; Taylor, 2018; Allen, 1994; Nakamura, 2008).

STRUCTURE

Structures built on the lunar surface may be subject to damage from micrometeorites, radiation, and temperature variations, so a subsurface or semi-subsurface structure with a regolith barrier above, is recommended.

Dose estimates based on previous solar flare events clearly demonstrate the need for radiation protection on the lunar surface. A lunar regolith covering of 50cm, or a water barrier of 30cm, should be enough to reduce the radiation dose to half the annual limit for humans (Simonsen, et al., 1991). This is a good starting point for protecting a lunar farm. However, further research is needed to understand the radiation limits for safe, successful agriculture. There may also be effects from secondary radiation that need to be considered.

Laser three-dimensional (3D) printing technology can be used to print modular standard bricks using lunar basalt. Current 3D laser printer technology is small, lightweight and can be used to quickly manufacture complex structures; therefore, the potential applications of 3D laser printing in the construction of a lunar base are very broad. However, the extreme environmental conditions on the Moon's surface pose some complications. Due to the low gravity and low atmosphere on the Moon's surface, any project that requires liquid materials, such as "D-shape process" and "ink" 3D printing, would be difficult to carry out.

RECOMMENDATION 6B

Laser 3D printing shows promise as a construction method, but further research is needed to establish the viability of this technique in a low gravity environment.

Chinese mortise-tenon construction techniques (two pieces of material that slot into each other) (Cheng, et al., 2019) may also be used to erect the farm structure using standardized building modules, which may be connected using flexible buildings. Thus, a farm building can be adjusted at any time according to the changing needs in construction scale and layout. Some excavation will be required for subsurface structures, which will require further engineering research.

OPTION ONE: SEMI-SUBSURFACE STRUCTURE MODEL

A suggested structural model is based on a concept proposed by the European Space Agency (ESA). This model contains four regions with different environmental conditions. Each region can set temperature, humidity and other environmental parameters independently through an intelligent control system that can adapt to different crop growth requirements. The structure proposed is partially below and partially above the surface, to give crops exposure to incident light. The layout is shown in figure 3 below.

Incident visible light is critical to the plants or algae in a lunar farm, which use photosynthesis to convert carbon dioxide and water into carbohydrates and oxygen that can then be used by other agricultural species or humans.

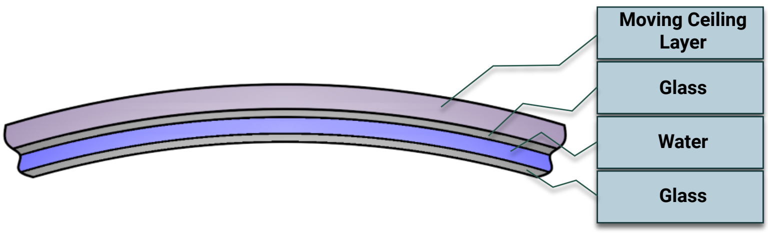
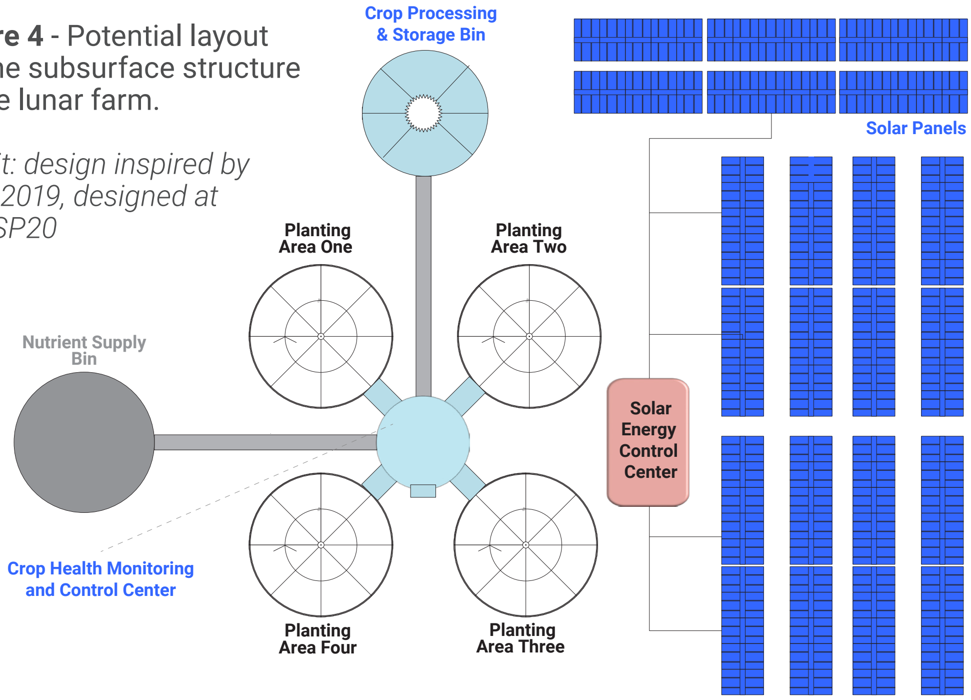


Figure 3 - Hemispherical ceiling structure diagram.

Building the Lunar Farm

Figure 4 - Potential layout for the subsurface structure of the lunar farm.

Credit: design inspired by ESA, 2019, designed at SHSSP20



A transparent, hemispherical ceiling for the lunar farm (see figure 3) would allow sunlight to reach the plants, but would be a major engineering challenge. Liquid water of approximately 30cm depth could reduce radiation exposure to the plants sufficiently, but supporting this mass above the farm with a transparent structure (glass or polycarbonate) durable enough to withstand micrometeorite impacts would be a significant challenge (Simonsen, et al., 1991). Challenges may exist in using glass for the structure, as it can be heavy, difficult to transport, and manufacture with high purity.

RECOMMENDATION 6C
Glass roofing will need to be explored further to ascertain whether it is a plausible option to consider.

OPTION TWO: UNDERGROUND STRUCTURE MODEL
Alternatively, a lunar farm could be built underground (subsurface) or covered over with lunar regolith for radiation protection, with sunlight either guided into the enclosure or used to power solar panels and interior lighting such as light-emitting diodes (LEDs). For an subsurface or semi-subsurface farm, Nakamura, et al. (2013) provide a comparison of lighting either using solar panels to power artificial lighting (e.g. LEDs), or using solar light collectors and an optical waveguide to transfer only the visible component of sunlight to the underground farm. They conclude that the second option is more efficient, reduces heat production and requires less than half the equipment mass per unit of visible light energy delivered to the farm.

RECOMMENDATION 6D
If glass roofing is not realistic, the lunar farm should be lit by solar light collectors and an optical waveguide.

THERMAL CONTROL
Although subsurface locations maintain close to consistent temperature, some thermal control will be required to keep the temperature of a farm within a range conducive for agriculture. The heat generated by electric heating and hydrogen fuel cell operation can be used to heat the lunar base modules. Cooling can be achieved using a fluid loop system, consisting of two fluid loops, one inside and one outside the farm.

ENERGY PRODUCTION AND STORAGE

There is almost no atmosphere on the Moon to attenuate solar radiation before it reaches the surface, which provides easier power generation. Based on a solar energy density of 1.353 kilowatts per meter squared (kW/m^2) (Sima, 2006) and a currently achievable photoelectric conversion rate of 20 percent, a 100m^2 array of solar panels could generate 27kW power continuously. This sustainable energy source should have the potential to supply energy for a lunar farm of the scale that supports ten humans.

RECOMMENDATION 6E
Use solar panels to supply energy to the lunar farm.

Landis (2005) suggested that solar cells could be produced through ISRU from the materials present in lunar soil. Silicon, aluminum, and basaltic glass ingredients, three of the primary materials required for solar cell production, are found in high concentrations in lunar soil and can be used to produce solar cells. The native vacuum on the lunar surface provides an excellent environment for direct vacuum deposition of thin-film materials for solar cells.

Alternatively, a nuclear power source could be used. NASA's Kilowatt Fission Generator system is a modular plutonium generator capable of providing up to 10kW per unit installed (Gibson, et al., 2017). This system could be used for initial or emergency backup power, however, it is not suitable to sustain a farm due to the lack of *in-situ* availability of plutonium and uranium in sufficient quantities.

Millions of metric tons of helium-3 reserves have been detected on the lunar surface (Fa, et al., 2010). Fusion of helium-3 with deuterium is a promising future energy source for the Moon, but further fusion technology developments are needed due to the extremely high temperatures involved (Jassby, 2017).

Energy storage will be required for backup energy and mobile activities such as maintenance outside of the lunar farm. For space activities, lithium-ion batteries are often used. However, the mass to power ratio is very high (Ren, 2018) and they are therefore inconvenient and costly to transport. ISRU for energy storage could circumvent this problem - thermal storage using lunar materials is a promising option, but to date, a lunar solution has not been developed (Belen, 2003).

Chemical storage is considered the most promising solar energy storage method due to high energy storage density, low energy loss, and the flexible applications for which it is suitable (Sun, 2015). In a regenerative hydrogen fuel cell, electricity from solar panels can be used to split water into hydrogen and oxygen through electrolysis (Jan, 1993). The energy stored in chemical bonds can then be recovered by recombination into water. Given that the proposed south pole site is in darkness for 20 percent or 5.6 terrestrial days of a lunar rotation, the fuel cell systems would need to store at least 5.6 terrestrial days' worth of power.

MAJOR RECOMMENDATION 1
Ensure that ISRU of lunar materials such as lunar basalt rock and the lunar regolith sourced from rock debris is used to lower the costs and the number of resupply missions and materials needed from Earth. Establish structures on the lunar surface that are built subsurface or semi-subsurface with a regolith barrier above in order to protect from damage from micrometeorites, radiation, and temperature variations.

Sustenance Choices for the Lunar Farm

- ENERGY AND MACRONUTRIENTS
- DIETARY PLANS
- THERMAL CONTROL
- ENERGY PRODUCTION AND STORAGE

Human dietary plans need to consider physiological factors such as energy requirements, as well as psychological factors, incluiding the need for diversity and food freshness (ISU, 2019).

To estimate the energy, macronutrient, and micronutrient requirements for humans in space, a 75 kilogram (kg) man and a 65kg woman were taken as average masses. Required nutrient values were taken from from the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) reports. (WHO, et al., 2004a; WHO, et al., 2004b; WHO, et al., 2007; FAO, 2010; WHO, et al., 2019). The basal metabolic rate (BMR) is only an estimation, as it varies between individuals depending on their physiological metabolic rate and activity level. Table 1 represents the summary of daily energy expenditure in kilocalories (kcal) and macronutrients in grams (g).

TABLE 1 - Estimated daily expenditure requirements of macronutrients

ASTRONAUT PARAMETERS 30-60 years	**MALE** 75kg		**FEMALE** 65kg	
Basal metabolic rate (BMR) kcal	1734		1374	
Food Digestion (10% BMR) kcal	174		137	
Physical Activity (30% BMR) kcal	520		412	
Total Energy Needs kcal	2427		1923	
CONSUMPTION LIMITS	lower	upper	lower	upper
Protein g	63	189	54	162
Fat g	41	95	32	75

According to NASA (2019a), there are no studies that have shown that energy requirements change during spaceflight, however, it is not known whether requirements change during long-duration (>6 months) missions or extraterrestrial habitation. Moreover, optimal space provisions of carbohydrate, protein, and fat macronutrients have not been assessed.

VITAMIN AND MICRONUTRIENT REQUIREMENT

It is pertinent to consider which micronutrients are important for lunar inhabitants. There is some concern that the low sunlight levels in an underground lunar habitat would cause a vitamin D deficiency, contributing to a loss of bone density and muscle bulk. However, it has been shown that 20 µg of vitamin D per day is sufficient for long-duration space flight (NASA, 2019c).

Given the long-term nature of a lunar settlement and the inability to obtain enough vitamin D through non-animal products, a half-yearly vitamin D supplement in addition to dietary sources is recommended for inhabitants.

Furthermore, according to Takahashi, et al. (2017), the body is at a significantly greater risk of oxidative stress and cell damage in space, due to factors such as psychological stress, microgravity, radiation exposure and EVA-related hyperoxia. Oxidative stress can affect all cell types, including those of the blood vessels, which may increase predisposition to atherosclerosis (Beheshti, et al., 2019). A weaker immune system is also implicated in periods of oxidative stress (Crucian, et al., 2018). Dietary countermeasures against oxidative stress due to radiation include antioxidants, with vitamins A, C and E being the most effective. These three vitamins are abundant in some of the foods that have been recommended in this report, including tomatoes, carrots, water cress and cloudberry cell cultures (Crucian, et al., 2018).

Additionally, a deficiency of B vitamins, especially B2 (riboflavin), B6, and B9 (folate) have been correlated with increased ocular damage in spaceflight. Therefore, adequate supplementation with oyster mushrooms and tablets is proposed (Zwart, et al., 2016).

Selection and quantities of foods have been guided by human nutritional requirements and viability of growing techniques. The micronutrient recommended daily intakes (RDI) are Earth-based values which have been obtained from reports by the WHO, the FAO and the UN University. Due to the increased risk of oxidative stress in space, only antioxidant vitamins A, C, and E, as well as B vitamins, have been considered, whereas amino acids and minerals such as calcium have not been considered.

EDIBLE PLANTS

Current space-based agricultural efforts focus on understanding the science of growing plants in space. These efforts confirm that plant growth in the Moon's low gravity is possible and that plants do respond to minimal gravitational forces (Böhmer, et al., 2019).

The desirable criteria for plants in space include

- The ability of the plant to grow under low light intensities
- A compact size
- High calorific productivity
- A good tolerance to osmotic stress from urine recycling (Wheeler, 2017).

WHAT'S BEEN GROWN IN SPACE

The following list of plants have all been successfully grown in space, either on ISS, STS, MIR, Salyut, or Soyuz (Zabel, et al., 2016). However, not all of the plants in the experiments reached a mature growth state. *Image Credit: NASA*

Barley, cabbage, carrots, chinese cabbage, corn, cress, cucumbers, dwarf pea, flax, garlic, leek, lentil, lettuce, mizuna, mustard, onion, parsley, pea, radish, rice, soybean, spinach, swiss chard, tomato, wheat, coriander, dill, pepper, strawberries, oats, kale, and herbs.

Sustenance Choices

CELL CULTURES

Bioreactors that cultivate cell cultures can create a wide variety of edible food materials including mycoprotein, algae (such as spirulina), plant cells, cultured meat, and nutritional yeast.

The criteria for choosing cell cultures for cultivation are:

- Minimal growth medium requirements and simplicity to mix growth mediums
- Speed of cell growth
- Comparatively high nutritional value
- Simplicity of technology to cultivate cells
- Hardiness of seeder cells (i.e. special storage requirements, lifespans)
- Requirements for long-term storage.

The highest priority cellular agriculture choices are relatively simple to produce, have considerable scientific backing, or are mature technologies used in the marketplace. These include genetically modified cyanobacteria for glucose generation, *Fusarium venenatum* for mycoprotein, and Cloudberry, Lingonberry or Stoneberry cell cultures for fruit plant sources

Future cellular agriculture choices could also include cultured meat (animal) cells. This requires higher technological requirements and therefore would not be ideal for initial phases of a lunar farm but could be considered for later stages of expansion.

INSECTS

Insects can provide a valuable source of protein in the human diet. Insect farms require relatively small amounts of space and lower water usage when compared with conventional meat protein sources on Earth. Insects also have a short life cycle and reach maturity quicker, which allows for faster harvesting times. The two main stages of life during which insects are consumed are the larval stage and the adult stage.

Post harvest, insects can be consumed after roasting or further processed by dehydration and milling to a powder to be used as a supplement, like flour. This minimizes cultural issues associated with people who are unaccustomed to consuming insects as part of their regular diet.

The criteria for choosing insects for cultivation are:

- Short life cycle
- Comparatively high nutritional value
- Simplicity of rearing, including maintaining a stable population
- Ability to eat a wide variety of biomass
- High efficiency in converting biomass to proteins
- Taste profile and the ability to process into different forms for human consumption.

Potnetial candidates include three types of crickets, (*Acheta domesticus* L, *Gryllus bimaculatus* De Geer, ***Teloegryllus testaceus*** Walker, *Gryllotalpa africana* Beauvois), silkworm pupae (*Bombyx mori* L) and palm weevil larvae (*Rhynchophorus ferrugineus* Oliver) (Hanboonsong, 2013).

EXAMPLE MEAL PLANS

Table 2 shows the food sources recommended for the lunar farm. These foods have either been successfully grown in space (Zabel, et al., 2016) or considered by the literature for long-duration extraterrestrial habitats (Perchonok, et al., 2012).

An approximate daily meal plan is included (see right). All initial nutritional calculations have been made based on the nutritional requirements for a 75kg male, however additional future studies need to be carried out for people of other weights and genders. The combination of foods with the least mass has been chosen based on optimization calculations.

MEETING PLANT GROWTH GOALS

In 2015, astronauts aboard the International Space Station were the first humans to eat food grown in space. The crew members of Expedition 44 ate lettuce grown in the VEGGIE Food Production system, after thoroughly sanitizing the crops. (Zabel, et al., 2016; NASA, 2015). *Image Credit: NASA*

In 2018, ISU launched their Hydra-1 experiment to the ISS. Seeds were germinated by hydrating with water, and illuminating with LEDs. The plants were subsequently DNA sequenced upon return to Earth (ISU, 2018).

In 2019, China's Chang'e-4 mission included the first plant to be grown on the Moon - two cotton leaves. However, with no power to provide heat to the experiment, the cotton leaves died upon the onset of the first lunar night (Jones, 2019).

TABLE 2 - Meal planning to meet daily energy and nutritional requirements of inhabitants

CULTIVATION TECHNIQUE	SCIENTIFIC NAME	FOOD TYPE	FOOD NOTES	SERVING SIZE	# OF SERVES	SERVING MASS	CALORIES
Soil Based	*Solanum lycopersicum*	Tomato	*Widely consumed worldwide, low water consumption, variety of textures and vitamin-rich*	1 tomato	4	182	129
	Daucus carota s. sativus	Carrot		1 carrot	4	72	163
	Lepidium sativum	Garden cress		1 cup	4	50	128
	Ipomoea batatas	Sweet potato		1 potato	1	130	112
	Glycine max	Soybean (cooked)		1 cup	4	65	248
	Arachis hypogaea	Peanuts		1 serving	3	28	444
Hydroponic	*Oryza sativa*	Rice (cooked)		1 cup	1	202	49
	Pleurotus ostreatus	Oyster mushrooms	*Consumes waste biomass*	1 mushroom	1	148	173
Cellular Agriculture	*Rubus chamaemorus*	Cloudberry cell culture	*High glucose density*	1 cup	1	100	486
Insect Ranching	*Acheta domesticus*	Crickets	*High protein density, Positive taste profile*	1 cricket	9	15	514
					TOTALS	**2056g**	**2446 cal**

MAJOR RECOMMENDATION 2

Establish a lunar farm that produces plants, insects, and cell cultures for human physiological and psychological benefit and nutritional diversity. These sources should include tomatoes, carrots, garden cress, sweet potatoes, soybeans, peanuts, rice, oyster mushrooms, cloudberry cell cultures, and crickets.

Agricultural Methods

- CULTIVATION TECHNIQUES
- GROWING PLANTS IN LUNAR REGOLITH
- HYDROPONICS
- CELLULAR AGRICULTURE
- INSECT RANCHING

Indoor terrestrial farming technology can be adapted to suit lunar farming constraints. Terrestrial agriculture options that may be modified for a lunar environment are shown in table 3.

TABLE 3 - Terrestrial agricultural techniques and needs for adapting these for lunar use

CULTIVATION TECHNIQUE	GROWTH MEDIUM	NUTRIENT SOURCE	INFRASTRUCTURE NEEDS
Garden Beds	Soil (mix of inorganic and organic particles)	Organic inclusions broken down by bacteria and invertebrates	Area intensive Reliant on organics
Hydroponics*	Water	Animal waste, natural and artificial fertilizers in liquid water	Water intensive
Aeroponics*	Air	Fertilizsers provided via a fine mist	Fans and power to circulate the fine mist
Zeoponics*	Zeolite	Zeolite adsorbs potassium, nitrogen, water and nutrients	Zeolite (a synthetic, microporous, lightweight substrate)
Aquaponics*	Hydroculture bed	Waste from fish	Fish ecosystem High water requirements
Cellular Agriculture	Varies	Varies, Vogel media based on glucose for fungi and plants, fetal bovine serum (FBS) for meat	Incubation tank, with filtration, aeration, blending capabilities Electricity intensive Growth medium is specialized and resource-heavy
Insect Ranching	Enclosed space, insect feed	Biofortified feed appropriate for the species	Harvesting, dehydration and milling facilities Environmental control facilities

Soil-based, hydroponic, insect ranching, and cell culture methods are recommended for the lunar surface as the cheapest and most scientifically plausible methods, when considering the lunar environment and the stresses to which the food sources may be subjected. Further research is necessary to understand how microgravity affects these recommended crops and their cultivation methods.

GROWING PLANTS IN THE LUNAR REGOLITH

Lunar regolith may be utilized for soil farming on the Moon; however, elements will need to be added and extracted to make it suitable for plant growth. Research shows both similarities and differences in lunar and terrestrial soil compositions (Paul, 2007; Benaroya, 2010). The most obvious differences observed are the negligible levels of nitrogen in lunar regolith (Benaroya, 2010), contrasted to nitrogen's prevalence in terrestrial soil (Greenwood, et al., 1997).

According to Benaroya, (2010), the lunar regolith is composed of the elements listed in Table 4.

TABLE 4 - Lunar regolith composition by elements

ELEMENT	PERCENT BY WEIGHT
Oxygen	42
Silicon	21
Iron	13
Calcium	7.9
Aluminium	7
Magnesium	5.8
Titanium	3.1
Sodium	0.29
Chromium	0.26
Manganese	0.17
Sulfur	0.12
Potassium	0.11
Phosphorous	0.07
Carbon	0.02
Nitrogen	0.01
Hydrogen	0.01
Helium	0.01

Some of these nutrients can be extracted *in-situ*, some may initially need to be supplied from Earth, and all will be recycled as much as possible to close the lunar farm system loop and minimize further re-supply from Earth. At this stage, trace element supply will need to be transported from Earth, though this requirement may be re-evaluated in the future as more becomes known about lunar mineralogy.

RECOMMENDATION 6G
Initially supply trace elements from Earth, until further is known about lunar mineralogy.

Nitrogen is used to promote plant growth as a central and rate limiting step in the production of chlorophyll. Since native nitrogen sources on the Moon are limited, a possible source of nitrogen is the on-site human population. Ten healthy individuals, who eat 0.33g of protein per kg of body mass per day, are likely to produce an estimated 7 to 10.5g of urea per day (Rudman, et al., 1973). The recycling of human urine will therefore be beneficial in maintaining the nitrogen content of lunar soil.

It is also assumed there will be access to the ten humans' fecal waste. On average, each person can excrete 128g of feces per day, which breaks down as 96g water (75 percent) and insoluble organic solids consisting of bacterial biomass, protein, undigested cellulose and fibers, and undigested fat (Rose, et al., 2015). These proportions can vary considerably depending on many factors, but primarily diet and body weight.

This fecal waste can be managed to provide organic material for the soil. In a closed loop system, human fecal matter composition will contain the plants and animals that will be produced on the lunar farm. The risk of concentrating natural and medical metabolites must also be mitigated. For this reason, the use of mushrooms to decompose human fecal matter and to serve as a food source supports the lunar farm closed loop system.

Humans will also provide a source of carbon dioxide for the farm, a vital ingredient for plants to consume. Oxygen and carbon dioxide could be recycled between the farm and settlement; however, additional supplementation of carbon and/or oxygen may be required from other resources. Carbon dioxide is also available within the lunar regolith. In 2009, a NASA mission found volatiles including carbon molecules frozen in regolith in the shaded regions of lunar craters, in as much as 20 percent of the debris material analyzed. Compounds from these volatiles can be easily extracted as they vaporize when heated (Fegley, et al.,1993).

RECOMMENDATION 6H
Enrich the farm's atmosphere with carbon dioxide, to increase photosynthetic rates and yields.

Agricultural Methods

HYDROPONICS

Hydroponics is a technique of growing plants without soil in water containing dissolved nutrients (Dos Santos et al., 2013). Advantages of hydroponics include lack of soil processing, easier byproduct recovery, low nutrient wastage, and fine control of plant growth. NASA, in its Controlled Ecological Life Support System program, has conducted studies of hydroponics with re-circulated solutions for long durations, nearly 400 days. However, sustained production experiments at NASA have shown that with successive planting, plants exhibit shorter shoot length, earlier tuber initiation and maturation (Stutte, 2006). This issue will need to be explored further if used in a lunar farming system.

RECOMMENDATION 6I
Conduct further research into the effects of a lunar environment on plants grown via hydroponics.

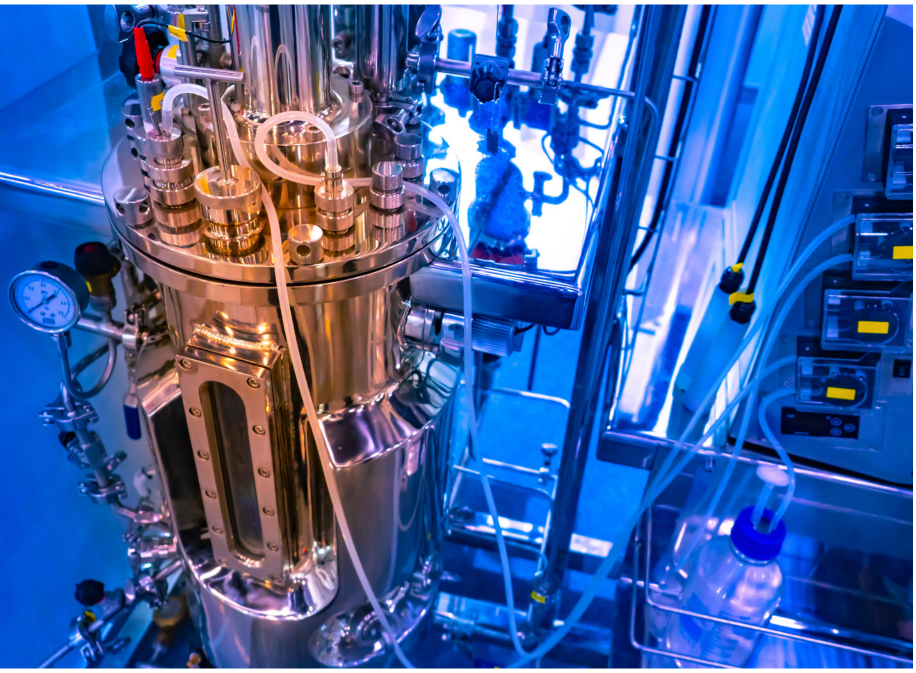
Figure 5 - Sharon Edney, with Dynamac Corp at Kennedy Space Centre measures photosynthesis on Bibb lettuce being grown hydroponically Credit: NASA Image

CELLULAR AGRICULTURE

Cellular agriculture creates food by providing the right environment for fungi, plants, or animal cells to rapidly replicate. Cellular agriculture is highly suited to the lunar environment as its food outputs are calorie dense and highly nutritious. Bioreactor vessel sizes can be adapted to meet requirements, from bench scale to industrial food production scale.

There are few studies or experiments pertaining to cellular agriculture in microgravity or low gravity environments. Many physical phenomena will influence both cell function and replication on the lunar environment and these will need further investigation. The lack of gravity-induced sedimentation, buoyancy-driven convection, hydrostatic pressure changes, and interactions among physical transport processes could all impact cell growth and development (Todd, 1989).

RECOMMENDATION 6J
Conduct further investigation into the effects of microgravity and low gravity on cellular agriculture.



BIOREACTOR TECHNOLOGY

Bioreactor technologies provide controlled environments which support the growth of cells in a culture medium. Bioreactors can be used to cultivate cells for harvest, such as animal cells for lab-grown meats (Allan, 2019), or to harvest substances derived from cells or microogranisms, such as fermented products produced by bacterial cultures (Li, 2016). The selection of bioreactor model is a factor strongly dependent on the type of application (i.e. whether for cell harvest or biochemical product harvest). Bioreactor model selection and large scale bioreactor expansion methods should be investigated for lunar farming applications.

INSECT RANCHING

Insect breeding is a part of human culture in many parts of the world. It can be conducted as a low-tech or highly sophisticated operation (van Huis, et al., 2013). The insects recommended by this study are easy to rear and in some cases have already formed part of existing terrestrial BLSS studies (Fu, et al., 2019). The environmental requirements are similar to humans, and they will consume a wide variety of biomass. Processing facilities for insects to make them suitable for consumption will need to consider the low gravity on the Moon, however this is not seen as a limiting factor for utilizing insects as a source of nutrition.

RECOMMENDATION 6K
Conduct further research into the effect of a BLSS on the life cycle and nutritional content of candidate insects for lunar farming.

ROBOTIC INSECT FARMING

Companies such as Aspire Food Group in Ghana have the technology to autonomously monitor and control cricket farming from beginning to end. They use a high technology solution with Internet of Things connected sensors to maximise production as well as modular design and robotic automation to allow quick productions scaling.

Automated technology should be investigated for any lunar farming installaton. (Aspire, 2016)

MAJOR RECOMMENDATION 3
Prioritize agricultural methods including soil-based farming, hydroponics, insect growth, and cell cultures for growth of food sources on the lunar surface. Ensure that appropriate technologies provide light, water supply, and temperature stability for the successful growth of living organisms.

Operations and Maintenance for the Lunar Farm

- FARMING PRACTICES
- ATMOSPHERE MANAGEMENT
- LIGHTING MANAGEMENT
- CROP MANAGEMENT
- PLANT TREATMENT
- WASTE MANAGEMENT

Being a closed environment with comparatively low environmental buffer zones, monitoring and control of the biosphere elements are critical for long-term sustainability. Automated measurement and analysis of monitoring data are required to reduce crew time required for performing these tests.

FARMING PRACTICES

With the absence of terrestrial processes, human intervention will be needed in lunar agricultural practices that happen naturally on Earth. Crop rotation is a common agricultural practice for maintaining healthy soil, occasionally including the practice of leaving a field fallow (Hanson, et al., 2014). A three-year example of crop rotation is: year one - a legume crop planted to enrich the nitrogen in the soil, year two - barley planted to make use of the nitrogen in the soil, year three - leave this field fallow so it can rest (Ward, 2020a; Ward, 2020b).

Reduced gravity environments influence the water, solute, and gas exchange between a plant and its surroundings. Experiments conducted on the International Space Station (ISS) reveal that plants suffer from microgravity-based root-zone hypoxia and reduced uptake and absorption of nutrients (Stout, et.al., 2001; Porterfield, et al., 2002).

For this reason, a precise monitoring and control system should be used to check the oxygen and nutrient content of the water. This system can replenish the soil and support the plants in performing active absorption. Further research is required for understanding plant nutrition processes, along with research in the field of sensor technology for surveillance of nutrients in the solution (Wolff, et.al., 2014). Replenished soil may then be used for cultivation and the soil containing harmful substances may be disposed of safely, if it cannot be used.

RECOMMENDATION 6L

Use a precise monitoring and control system to check the oxygen and nutrient content of the water used in lunar farming.

ATMOSPHERE MANAGEMENT

Plant growth cannot be considered in isolation, as it contributes to all major functional subsystems of a lunar settlement by closing the different loops in a human and plant habitat (Zabel, et al., 2016). For lunar settlements, plants primarily used for nourishment are also are also expected to provide atmospheric regeneration functions in the wider settlement, such as air revitalization, carbon dioxide reduction, oxygen production, water recycling, and waste recycling (Furfaro, et al., 2016; Wheeler, 2017). The plant atmosphere can also be enriched with carbon dioxide to increase photosynthetic rates and yields (Wheeler, 2017).

RECOMMENDATION 6M
Enrich the farm's atmosphere with carbon dioxide, to increase photosynthetic rates and yields.

LIGHTING MANAGEMENT

Light is a basic requirement for plant growth. However, there are many factors to consider when designing a lighting system. Techniques that may increase viability of crops include: simulating daily and seasonal variations with light cycling, using the far-red spectrum for flower initiation, and optimizing energy consumption by minimizing the thermal burden and weight of the system. One notable example of lighting management is Bios-3, a closed ecosystem in Russia. It supported plant growth using xenon lamps, which have a similar light spectrum to that of daylight. (Massa, et al., 2006)

Recent studies indicate that LED lights are an optimal solution with lower mass, low thermal burden and the ability to generate multiple frequencies without change in the emitter. NASA has developed a reconfigurable and highly efficient array of lights called "lightsicles", which can be programmed to emit different wavelengths and intensities (Massa, et al., 2006).

RECOMMENDATION 6N
Employ LED lighting within the lunar farm.

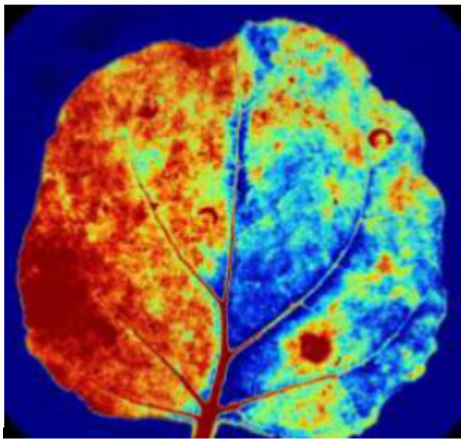
Figure 6: Lighting management with a mixture of red and blue LED lighting optimised for plant growth.
Credit: NASA Images

Operations and Maintenance

CROP MANAGEMENT

Although humans are likely to conduct the initial lunar farming activities, additional technologies may help them maintain the farm and optimize the health and productivity of the crops. An intelligent monitoring system could utilize hyperspectral technology to identify plant stress (Lowe, et al., 2017).

Figure 7: Pseudocolor image of a leaf based on hyperspectral imaging data (Waltho, 2018).



A fully integrated control system could monitor plant health and crop yield, automatically managing illumination, temperature, humidity, atmosphere, water, and nutrient supply to optimize farm performance. The environmental control technology equipment would consist of detection systems, a control system, and an execution system. The control system would manage the environmental factors based on data provided by the detection systems. Once developed and tested, these systems could also be used for Earth-based applications.

RECOMMENDATION 6O
Employ integrated environmental controls to optimize farm performance.

PLANT TREATMENT

After harvesting the inedible parts of fresh plants, plants may be dried at 343K (70°C) for 4-5 days using closed-loop air-drying technology to recover moisture. The dried inedible part of the plant can be pulverized in two stages and then processed in a high-temperature oxidation unit. The carbon dioxide produced can be discharged into the farm for photosynthesis and collected ash can be used to prepare a plant nutrient solution. Inedible parts of plants, such as dried wheat straw, can be processed by insects, or mixed with feces for aerobic composting after primary crushing and the products used as organic fertilizer for plant cultivation. The combination of physical, chemical, and biological treatments can achieve stabilization, safety, and resource treatment of all inedible parts of plants (Chongyang, et al., 2018).

RECOMMENDATION 6P
Treat solid plant waste through multiple methods, including pulverization and oxidation, and composting, to be reused in the lunar farm.

SOLID WASTE MANAGEMENT

A regenerative life support system is the core technology requirement for long-term lunar farming, as it can continuously regenerate plant growth nutrients such as oxygen, water and nitrogen in a closed system. The system can provide lighting conditions sufficient for plant growth, including sunlight and artificial light sources, and to effectively isolate radiation from space. Additionally, it can achieve environmental control of plant growth, to provide suitable temperature and humidity conditions and atmospheric components, including the supply of oxygen and carbon dioxide. Finally, it can provide the necessary nutrients for plant growth, while collecting and processing waste generated. As phosphorus is a key element in DNA structures in all proposed food sources, it is critical that the regenerative system reuse this rare resource (Schirber, 2012). If sufficient quantities of phosphorus cannot be extracted through ISRU or regenerated, it would be a critical resource for resupply trips.

SOLID WASTE MANAGEMENT CONTINUED

Solid wastes that require treatment mainly include inedible plants, cell culture waste, human feces, and domestic waste. The main objectives of solid waste treatment under space conditions are to achieve safe and stable treatment of solid waste, volume reduction treatment, and to complete the recovery of water in solid waste as much as possible. Recovery methods include compression technology, drying technology, oxidation technology, pyrolysis (thermal decomposition of materials at elevated temperatures in an inert atmosphere), gasification technology, and biological treatment (Wu, et al., 2018).

Wastewater recovery is also a key part of the regenerative life support system. The wastewater generated by the system is treated to meet the requirements for plant growth and utilization, which can not only make the system circulate, but also control the cost of tasks. The ISS has completed the recovery of water from wastewater, which can be recovered from the urine and humidity condensate to bring it up to drinking water standards (Fisher, et al., 2019). At the same time, we can also use the solid waste treatment methods mentioned above to recover water from solid waste.

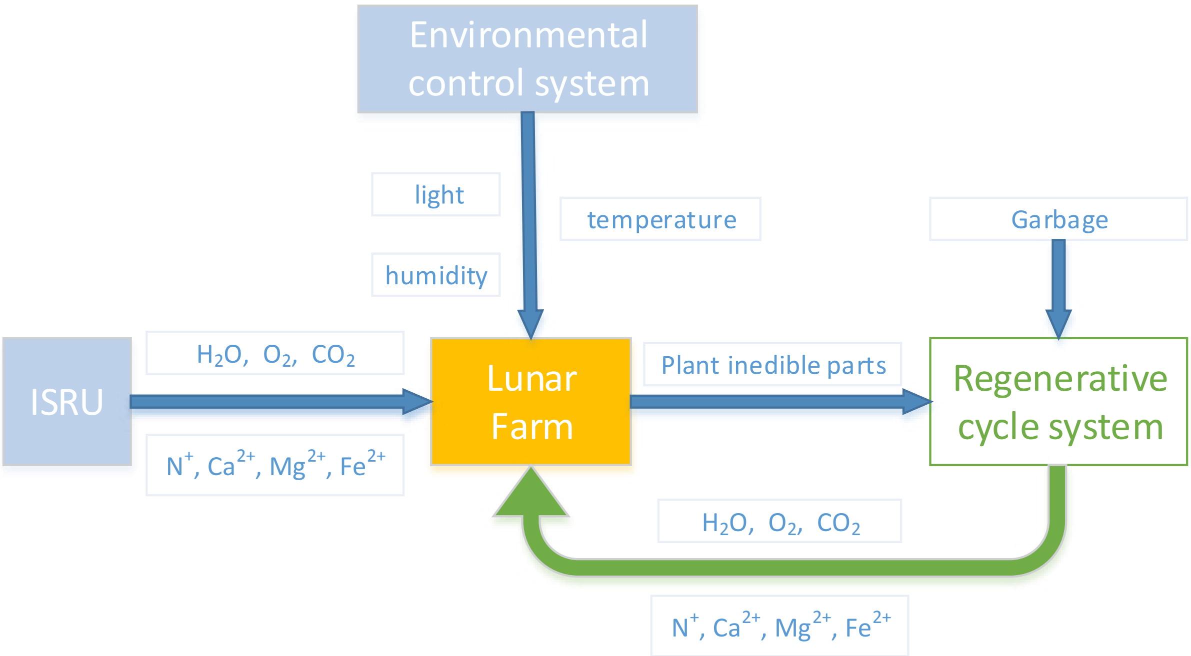


Figure 8: Regenerative Environmental Control and Life Support System.

CASE STUDY: BIOSPHERE 2 AND THE IMPORTANCE OF MICROBES

Biosphere 2 was an experiment conducted at the University of Arizona which initially ran for two years from September 1991 to September 1993. The goal of the program was to provide a closed-loop habitat within a hermetically sealed biosphere in which eight people (four men and four women) would attempt to survive for an extended duration.

The experiment was considered a success in terms of engineering as it was demonstrated that all of the food required for the inhabitants could be grown, and all water and waste could be recycled. However, maintaining the correct chemical balance of the atmosphere presented a major challenge. Microbes in the soil absorbed oxygen and released carbon dioxide at a rate that caused the oxygen content of the atmosphere to degrade (Severinghaus et al., 1994) to a point where the inhabitants were unable to survive without supplemental oxygen. This experiment demonstrated that it was possible to build an engineering apparatus but that the soil and chemical composition would need to be closely monitored in order to make the closed-loop system viable in habitats outside our planet.

Risks and Dangers for the Lunar Farm

- PSYCHOLOGICAL RISKS
- BIOSECURITY AND PATHOGENS
- ECONOMIC AND PUBLIC RELATIONS RISKS

PSYCHOLOGICAL RISKS

A successful lunar farm should not only consider the dietary needs of a population but also their psychological well-being. Dietary factors influence mental health, which may impact brain structure, function, and plasticity. Psychosocial-nutrition outcomes are linked bidirectionally - inadequate nutritional intake may contribute to poor mental health outcomes and vice versa (van der Pols, 2018). The selection of food items for a lunar farm should be carefully considered to maximize satisfaction as well as nutrition.

Depending on the insect species and life cycle stage at consumption, insects provide a high protein, amino acid, vitamin and mineral content and have low cholesterol concentrations when compared to traditional westernized meat alternatives (Belluco, et al., 2013; Verkerk, et al., 2007). However, cross-cultural differences may present barriers to implementing an insect diet due to varying attitudes towards insects as a food source.

As a pioneering agricultural experiment for all human beings, this mission values cultural diversity. In order to support space exploration projects and value for all of humankind, the practices performed on the Moon must consider cultural inclusivity. Food is not sufficient if it provides only energy; humans have a special connection to food that gives them mental satisfaction associated with the food's smell, taste and appearance. Commercially available foods often do not fulfill many of the roles that local foods play in communities and cultures (Philip, et al., 2009). Hence, if the food cultivated on the Moon has a cultural connection, then it will also help to satisfy human psychological needs.

BIOSECURITY AND PATHOGENS

To prevent biosecurity issues associated with plant competition, insect depredation of plants, and introduction of pathogens from plant, animal, or pathogenic sources, a systems-based approach to biosecurity risk management is recommended (FAO, 2007). Current practices in biosecurity have moved from separation and fragmentation into a harmonized and integrated approach to evaluating complete exposure pathways. This evaluation of biosecurity issues can include the use of a quarantine. No matter how sterile the the infrastructure of a lunar farm, there is always the chance that a pathogen could develop into a crop disease and it is vital to explore all scenarios to ensure crop welfare. It is recommended that facilities that house soil-based farming be physically separated to at least three different locations on the settlement base, not only to allow for crop variety but also to separate and save the remaining two facilities in the event of an outbreak. The introduction of a seaweed mixture to the soil is also considered an effective way to increase resistance to pathogens (Khan, et al., 2009).

RECOMMENDATION 6Q
House soil-based farming in multiple locations to decrease risk of pathogenic contamination.

Pesticides and insecticides have long been thought of as a method of increasing crop yields by eliminating competition for plants. More recent research is beginning to show that pesticide overuse can lead to the destruction of soil microbes used for nitrogen fixation and to long-term degradation of the soil as a growing medium (Mahmood, et al., 2016). Soil treated with strong pesticides over a long period of time may become sterile, ultimately decreasing the crop yield quality. Therefore, it is strongly advised not to use strong pesticides without extensive testing (Eichler, 2020). It is important that the agricultural process not negatively affect the lunar surface and that necessary steps are taken to ensure any practices on the Moon do not damage the lunar surface irreparably.

ECONOMIC AND PUBLIC RELATIONS RISKS

For investors, Public Relations (PR) risks are as important as financial risks when considering the underlying socio-cultural reasons for space exploration (Dougherty, 2020), and there is evidence that bad PR can have a crippling effect on stock prices and revenue. This consideration will be important for initial Earth-based investors. Demonstrating compliance with international legal obligations, implementation of best practice sustainability processes, and methods for heritage preservation will lower perceived ethical risks for investors.

Use of reliable technologies can help lower operational risks, however the technology may need to be demonstrated on Earth to establish its reliability. This technology can help establish a pathway for demonstrating future lunar intellectual property (IP) applications on Earth if using a location for multi-use technologies. Note that on-Earth technology demonstrations would provide both additional costs and additional investment opportunities.

As markets and demand grow, so must the volume of production and the additional investment required for scalability. As the settlement grows over time, demand is expected to increase, but there will also be a need to increase the scale of production. Sustainability factors for expected increase in energy and resource demands over time are an important factor in planning for continued operations over many years.

Figure 9: Risk Management Process Wheel (Tioga Security, 2018)

Policy, Leadership and Ethics for the Lunar Farm

- SUSTAINABILITY
- INTERNATIONAL TREATIES
- MANAGEMENT STRUCTURE
- ETHICAL CONSIDERATIONS

SUSTAINABILITY

In June 2019, the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) adopted a preamble along with 21 “Guidelines for the Long-term Sustainability of Outer Space Activities’”commonly referred to as the “Guidelines”. The Guidelines provide direction on policy and regulatory frameworks for space activities, safety of space operations, international cooperation, capacity-building and awareness, and scientific and technical research and development (UN COPUOS, 2019).

The Guidelines provide a useful lens through which to view proposed lunar farming approaches in order to support the long-term sustainability of outer space activities. They also encourage any space activities to link into the Sustainable Development Goals (SDG) framework. The Guidelines call for activities in space to support the SDGs on Earth.

Lunar farming provides numerous opportunities to benefit Earth and support the SDGs. A subset of examples includes the development of technologies to support SDG 2: Zero Hunger through improvement of food production systems, SDG 6: Clean Water and Sanitation through new water purification and utilization systems, and SDG 13: Climate Action and SDG 15: Life on Land, which both address development of less resource-intensive, more sustainable farming techniques (United Nations, 2019).

Figure 10: The UN Sustainability Guidelines

RECOMMENDATION 6R

Incorporate applicable Guidelines into the planning, design, development, and implementation of the lunar farming initiative, support the SDGs to the maximum extent possible through the planning, design, development, and implementation of the lunar farming initiative, and initiate a review of the Guidelines to understand their applicability to orbital, surface, or subsurface activities on or around non-Earth celestial bodies.

INTERNATIONAL TREATIES

Farming on the Moon and other celestial bodies using *in-situ* resources raises a number of legal and policy challenges, which would have to be overcome. The 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, commonly referred to as the Outer Space Treaty, is the primary basis for international space law. The Outer Space Treaty's main principles include that no nation may claim sovereignty of outer space or any celestial body (UNOOSA, 2020). Therefore, one of the central questions that needs to be addressed is whether recognizing a permanent lunar farming settlement claims to land around their lunar base would violate the Outer Space Treaty, especially claims to sovereignty.

The Outer Space Treaty explicitly prohibits national sovereignty over the Moon and other celestial bodies, not private property rights (Wasser, 2008). Therefore, an argument can be made that private property rights over a lunar farming settlement are permissible so long as governments do not claim any sovereignty rights over the settlement. The Outer Space Treaty only applies to the Governments that have signed it, and not private independent settlers living on the Moon unless they are nationals of signatory States. Such ambiguity in the Outer Space Treaty has left States to enact their own policies and regulations to promote commercial use in space.

Alternatives to directly challenging the Outer Space Treaty also exist. The Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, commonly referred to as the Moon Agreement, provides the necessary legal principles for governing the behavior of States, international organizations, and individuals who explore celestial bodies other than Earth, as well as administration of the resources that exploration may yield (Wilson, 2011). The Moon Agreement, however, has not been ratified by most States.

Donna Lawler (2020), a space law expert and ISU lecturer, suggests that it may be possible to comply with both the Outer Space Treaty and the Moon Agreement, provided that the nature of the lunar farm is scientific and benefits are shared in the form of scientific publications, technology transfer, education, or other media. To ensure international support, the Guidelines should be adopted and adhered to. The Guidelines would provide a framework for establishing a long-term lunar farming settlement while preserving the space environment for future lunar farming missions.

MANAGEMENT STRUCTURE

The non-sovereignty of celestial bodies poses a complication for how the farm can be established, managed, and maintained without direct ownership.

A Public-Private Partnership model would be vital to encourage private industry to take up work on the Moon and in turn develop a lunar economy. However, this model does not address the issue of non-sovereignty and contains the inherent risk of relying on space agencies to maintain consistent policy priorities across changes of Government, as well as the stability of private enterprise in a rapidly evolving sector (NexGen Space, 2015). To this extent, a Public-Private Partnership model would need to be supplemented with some form of international support to mitigate the risk of collapse.

An option for this international support could be an international authority, similar to the "CERN Model". CERN, the Conseil Européen pour la Recherche Nucléaire (European Council for Nuclear Research), is a prime example of international collaboration, with the aim to achieve a common goal in science. This international model provides a solution to the complication posed by the Outer Space Treaty, where States cannot appropriate space, by developing an authority comprised of member states. It also ensures that smaller states do not forgo their say when compared to larger powers, as all member States have an equal amount of representation on the council. This model also allows for political neutrality and independence, which enables CERN to focus on their priorities without political sway or interruption due to changes from the political election cycles.

Policy, Leadership and Ethics

Another option is to use the Antarctic Treaty as a management model for the lunar farm. The Antarctic Treaty is in many ways similar to the Outer Space Treaty, including Article II of the Antarctic Treaty, which sets out "No acts or activities taking place while the present Treaty is in force shall constitute a basis for asserting, supporting or denying a claim to territorial sovereignty in Antarctica or create any rights of sovereignty in Antarctica" (Secretariat of the Antarctic Treaty, 1959). Similar to Antarctica's method of establishing research stations, farms could be established on the Moon for scientific purposes, as well as for sustaining communities. However, this model has some drawbacks, as larger countries establish more bases without explicitly agreed ramifications, the Antarctic Treaty and its related Treaties do not currently cover developing issues, and member States are unable to agree on new content, as explained by Hook (2018).

It appears that a successful model will require a combination of approaches — a form of international authority that supports scientific development (with authority recognized at a national law level), but that also encourages participation from private industry. An authority like this may be difficult to develop and will likely need to be established similarly to the CERN model —as a coordinating and regulatory authority with political neutrality, that is able to represent all member States equally, regardless of political power.

MAJOR RECOMMENDATION 4
Establish an international authority management structure similar to the "CERN model" to manage the international obligations and coordinate and regulate a lunar mission. Incorporate the applicable *UN Guidelines for the Long-term Sustainability of Outer Space Activities* into the planning, design, development, and implementation of the lunar farming initiative.

ECONOMICS

For the purpose of this report, the primary economic role of a lunar farm is to serve as a cost effective alternative to transporting in new food to support lunar operations. Lunar farming is an alternative to regular Earth-to-Moon transport of pre-packaged food supplies. Calculations estimate that the launch and transport cost of annual pre-packaged food supply (excluding water) to the Moon for ten people (14,610 kg) would be $14.6 billion at a cost of roughly $1 million per kg (Astrobotic, 2020) assuming modest future propulsion cost reductions. This means, to be considered a cost saving alternative to transporting all food supplies, the cost of the initial lunar farm establishment must be less than $14.6 billion; and in each subsequent year to establishment, the total annual operational costs plus annual resupply costs of the lunar farm must be less than $14.6 billion.

For economic viability, any initial investment for Moon activities must provide some form of returns to the original investors on Earth if initial investment is to be obtained. Returns could be in the form of cost savings versus the alternatives or producing a profit. Returns from scientific knowledge and IP can be translated into or valued as financial returns if required.

Lunar farming alone may not provide a substantial rationale for lunar activity. Farming is necessary to support or enable more financially viable markets at permanent human lunar settlements; and may provide some sources of returns to offset enabling costs, for example human productivity gains from eating fresh food. Depending on the operational model, IP, surplus ISRU resources, and surplus food products could be sold to the lunar colony, Earth, and in future (with assumption of continued expansion of space exploration) other space populations such as the ISS, Lunar Gateway, and other Earth or lunar orbiting stations.

While there is suggested potential for sale of lunar regolith products from ISRU, it should be noted that this comes with legislative challenges regarding property rights, sustainability challenges regarding environment, and challenges identifying long-term markets (Sadeh, et al., 2005), as well as product transport costs. To mitigate this business barrier without inventing a new propulsion technology, the source of returns can focus on intangible goods and services that do not have to be physically transported - where mass is not a factor of supply cost - this could include IP licensing and applications.

Earth would provide the most likely potential markets large enough to deliver financial returns on IP. Returns to initial Earth-based investors could be delivered through space applications and licensing of the IP generated via novel processes and technologies developed by the lunar venture (Sadeh et al., 2005). For example, remote infrastructure access for collaborative Lunar—Earth research; and closed loop and water conservation systems. Further evaluation is recommended into potential spin-offs, spill-overs, and applications values that the farm itself could produce through IP, to deliver returns on investment into the farm itself.

CHALLENGES AND CONSIDERATIONS

Lunar farming operations and precursor programs would rely on investor support by demonstrating economic viability. It is recommended that Earth-based demonstration of the proposed technologies' reliability and multi-use application potential could lower operational risks and enhance investor confidence needed to establish coordinated precursor programs.

RECOMMENDATION 6S

Test all required technology on Earth before incorporating into the lunar farm, as a method of risk mitigation.

Other challenges to cost-effective, resource-efficient lunar agriculture center around themes of cost, risk, and revenue potential – themes relevant to the drivers that investors use to make investment decisions based on profit (Corporate Finance Institute, 2020; Queensland Government, 2017).

Sustainability factors for expected increase in energy and resource demands over time are important for planning to continue operations over many years, as the scale of the farm increases over time to address growing supply needs if it is assumed that the lunar colony activities will grow to 100 people. Research by de Jesus Lameira, et al. (2013) indicates that best sustainability practices are associated with higher performance, higher value, and lower risk.

To keep costs low, it is recommended that a mix of human and robot labor be used to lower costs, risks, and optimize productivity (Conolly, 2020). Additionally, the settlement should minimize mass of transported materials through the use of ISRU, importing light-weight construction materials and seeds (instead of plants), and exporting IP over physical products. Finally, the use of efficient technologies and processes that need less energy and food sources that require less water, heating, lighting, nutrients, and physical space to grow should be implemented.

MAJOR RECOMMENDATION 5

Establish a regulatory and economic approach that would enable the free flow of scientific and technology transfer, and educational exchanges that lends credibility to the establishment of a lunar farming settlement and provide a return on investment, while remaining in compliance with the Outer Space Treaty and the Moon Agreement.

ETHICAL CONSIDERATIONS

The potential development of lunar agriculture presents a series of ethical challenges. For example, construction of a lunar farm may affect lunar heritage sites, through lunar dust disturbing areas of historical significance during construction or landing of vehicles (Gorman, 2020).

Another ethical question to consider is whether humans should modify the surface of the Moon or preserve it entirely as a pristine celestial body, especially considering the environmental impact that humanity has already caused on Earth. As lunar operations scale, the potential for larger-scale modification of the lunar environment grows. Considerations must be given to the potential implications of human interference on scientific lunar research.

Bringing terrestrial food, especially insects, to the lunar surface can also pose ethical risks. Considerations must also be given to how these food sources will affect the lunar environment, and whether it will cause any biosecurity or scientific implications.

Demonstrating compliance with international legal obligations, implementation of best practice sustainability processes, and methods for preservation of heritage will lower perceived ethical risks for investors.

Recomendations and Proposals

OBJECTIVE 1 Discuss engineering demonstrations that would likely lend credibility to the prospect of a lunar farm

RECOMMENDATION 1 Ensure that ISRU of lunar materials such as lunar basalt rock and the lunar regolith sourced from rock debris is used to lower the costs and the number of resupply missions and materials needed from Earth. Establish structures on the lunar surface that are built subsurface or semi-subsurface with a regolith barrier above in order to protect from damage from micrometeorites, radiation, and temperature variations.

OBJECTIVE 2 Investigate the highest priority food sources that would be needed for a sustainable lunar farming settlement

RECOMMENDATION 2 Establish a lunar farm that produces plants, insects, and cell cultures for human physiological and psychological benefit and nutritional diversity. These sources should include tomatoes, carrots, garden cress, sweet potatoes, soybeans, peanuts, rice, oyster mushrooms, cloudberry cell cultures, and crickets.

OBJECTIVE 3 Investigate the science and technology needed to ensure the successful growth of food sources on the lunar surface

RECOMMENDATION 3 Prioritize agricultural methods including soil-based farming, hydroponics, insect growth, and cell cultures for growth of food sources on the lunar surface. Ensure that appropriate technologies provide light, water supply, and temperature stability for the successful growth of living organisms.

OBJECTIVE 4 Discuss available routes toward gaining international support for a lunar farming program

RECOMMENDATION 4 Establish an international authority management structure similar to the "CERN model" to manage the international obligations and coordinate and regulate a lunar mission. Incorporate the applicable *UN Guidelines for the Long-term Sustainability of Outer Space Activities* into the planning, design, development, and implementation of the lunar farming initiative.

OBJECTIVE 5 Understand the economic and legal challenges that will need to be overcome

RECOMMENDATION 5 Establish a regulatory and economic approach that would enable the free flow of scientific and technology transfer, and educational exchanges that lends credibility to the establishment of a lunar farming settlement and provide a return on investment, while remaining in compliance with the Outer Space Treaty and the Moon Agreement.

OBJECTIVE 6: Provide specific recommendations for the development of a lunar farm

RECOMMENDATION 6 Several specific recommendations have been made for the development and construction of a lunar farm, including

RECOMMENDATION 6A. Conduct further research into the effects of SPE and GCR radiation on plants in a lunar farm, and the humans who eat them.

RECOMMENDATION 6B. Laser 3D printing shows promise as a construction method, but further research is needed to establish the viability of this technique in a low gravity, vacuum environment.

RECOMMENDATION 6C Glass roofing will need to be explored further to ascertain whether it is a plausible option to consider.

RECOMMENDATION 6D If glass roofing is not realistic, the lunar farm should be lit by solar light collectors and an optical waveguide.

RECOMMENDATION 6E Use solar panels to supply energy to the lunar farm.

RECOMMENDATION 6F Conduct further research into lunar solutions for thermal storage.

RECOMMENDATION 6G Initially supply trace elements from Earth, until further is known about lunar mineralogy.

RECOMMENDATION 6H Extract volatiles from lunar regolith, in addition to collection from the lunar settlement.

RECOMMENDATION 6I Conduct further research into the effects of a lunar environment on plants grown via hydroponics.

RECOMMENDATION 6J Conduct further investigation into the effects of microgravity and low gravity on cellular agriculture.

RECOMMENDATION 6K Use a precise monitoring and control system to check the oxygen and nutrient content of the water used in lunar farming.

RECOMMENDATION 6L Conduct further research into the effect of a BLSS on the lifecycle and nutritional content of candidate insects for lunar farming.

RECOMMENDATION 6M Enrich the farm's atmosphere with carbon dioxide, to increase photosynthetic rates and yields.

RECOMMENDATION 6N Employ LED lighting within the lunar farm.

RECOMMENDATION 6O Employ integrated environmental controls to optimize farm performance.

RECOMMENDATION 6P Treat solid plant waste through multiple methods, including pulverization and oxidation, and composting, to be reused in the lunar farm.

RECOMMENDATION 6Q House soil-based farming in multiple locations to decrease risk of pathogenic contamination.

RECOMMENDATION 6R Incorporate applicable Guidelines into the planning, design, development, and implementation of the lunar farming initiative, support the SDGs to the maximum extent possible through the planning, design, development, and implementation of the lunar farming initiative, and initiate a review of the Guidelines to understand their applicability to orbital, surface, or subsurface activities on or around non-Earth celestial bodies.

RECOMMENDATION 6S. Test all required technology on Earth before incorporating into the lunar farm, as a method of risk mitigation.

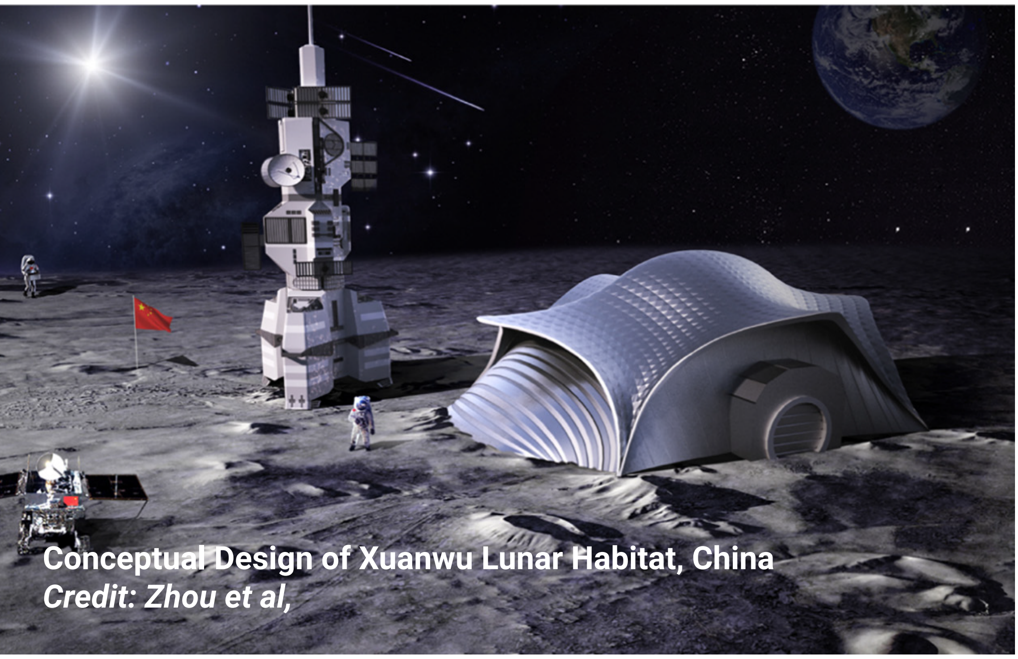
Conclusion

THE LUNAR FARM - IS IT VIABLE?

The establishment of a lunar farm in order to provide sustainable food production in environments other than the Earth is a key enabler if humankind is to go beyond our current planetary home. As Dr. Stephen Hawking pointed out, there is an ever-increasing risk that “life on Earth could be wiped out by disasters such as global warming, nuclear war, or a genetically engineered virus”. Thus, building a self-sustaining lunar farming settlement is paramount if we are to maintain a permanent presence on the Moon and other celestial bodies.

This report recommends the use of semi-subsurface or subsurface structures for a lunar farm, to alleviate impacts from radiation, micrometeorites, and temperature variation and at a polar location, to increase insolation and access to water ice. Food sources including plants, cell cultures, and insects have been selected for their nutritional value and ability to create diverse meals to suit physiological and psychological requirements. The lunar farm must be in line with international treaties, including the Outer Space Treaty, and so an international authority model is likely to be the most appropriate management structure for the farm.

This lunar farm is likely to be a viable proposition, however some scientific and engineering research will need to be progressed before it becomes a reality. A successful lunar agriculture venture may be the definitive requirement for humans to take the next “one small step … one giant leap”, onto the Moon - but this time, to stay.



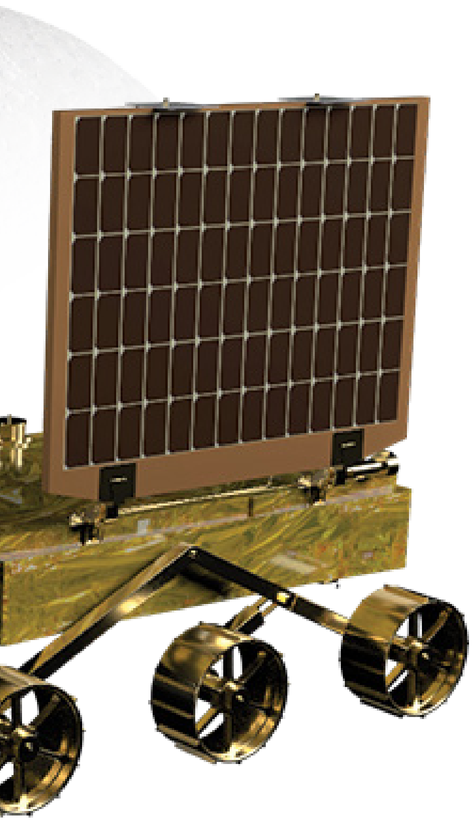
Conceptual Design of Xuanwu Lunar Habitat, China
Credit: Zhou et al,

Pragyan - Chandrayan 2 Rover
Credit: ISRO

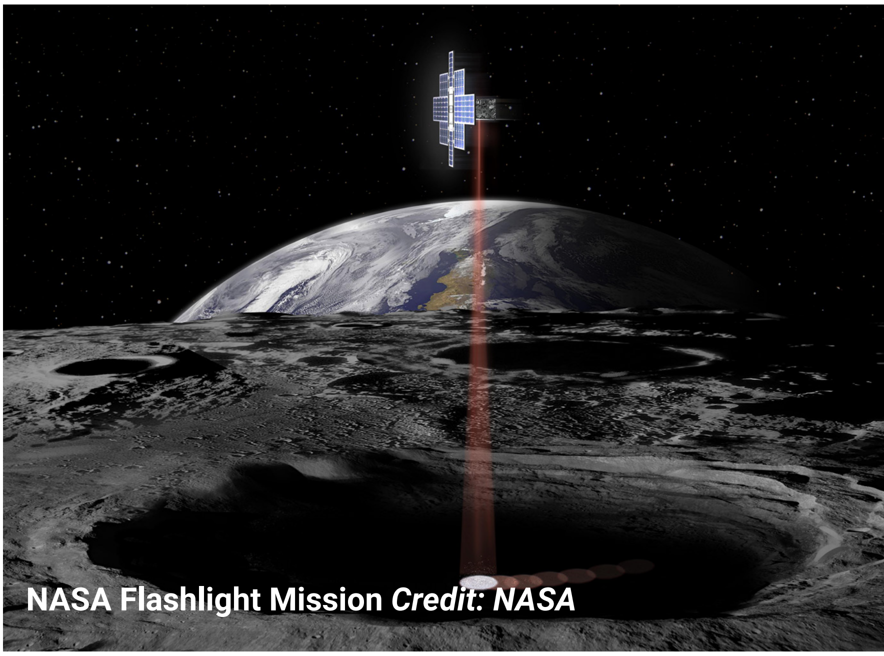
"A blade of grass is a commonplace on Earth; it would be a miracle on Mars. Our descendants on Mars will know the value of a patch of green. And if a blade of grass is priceless, what is the value of a human being?"
CARL SAGAN

"I find it curious that I never heard any astronaut say that he wanted to go to the Moon so he would be able to look back and see the Earth. We all wanted to see what the Moon looked like close up. Yet, for most of us, the most memorable sight was not of the Moon but of our beautiful blue and white home, moving majestically around the sun, all alone and infinite black space."
ALAN BEAN

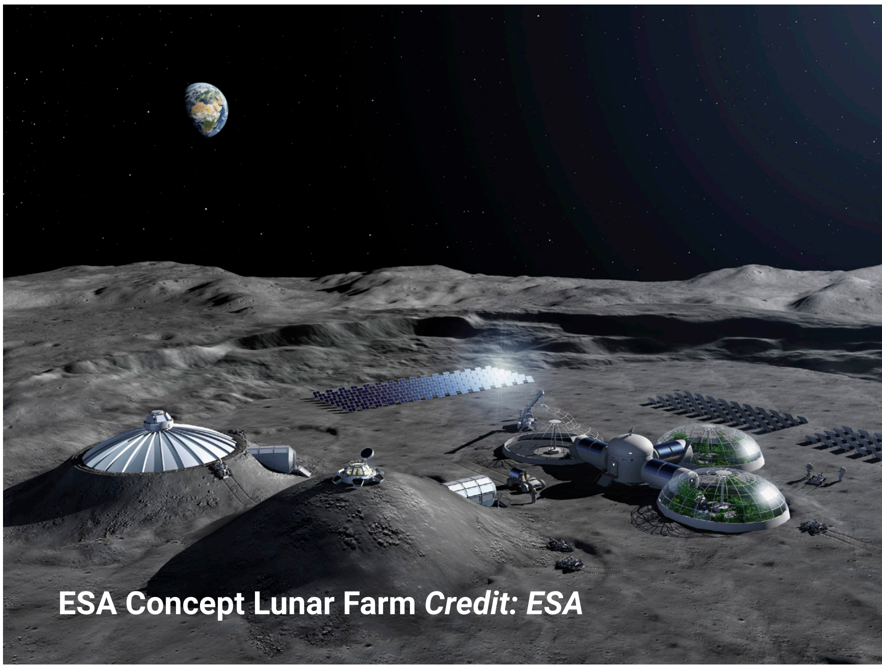
"Since, in the long run, every planetary civilization will be endangered by impacts from space, every surviving civilization is obliged to become spacefaring--not because of exploratory or romantic zeal, but for the most practical reason imaginable: staying alive... If our long-term survival is at stake, we have a basic responsibility to our species to venture to other worlds."
CARL SAGAN



SLS Rocket - *Credit: NASA*



NASA Flashlight Mission *Credit: NASA*



ESA Concept Lunar Farm *Credit: ESA*

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