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The New Moon Race: Lunar Agriculture

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Abstract

A lunar base is valuable economically as a foothold with relatively easy access to all of space. The burden of such a base will be providing it with resources. If a base can grow food for itself then it will become much less of a burden. Many factors surrounding lunar agriculture have been studied although plants have never been grown on the moon. This report examines the problem and proposed a strategy for productive agriculture on the moon.

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1 Introduction

What need do we have for agriculture on the moon? Don't astronauts just eat those dehydrated meals in aluminum foil? So far they have, but my team has been envisioning a larger, more long-term base. See “Proposal for the Development of an Economic Viable Lunar Base” by Scott Gary, Oscar Nemeth, Daniel White, Cody Wojcik from 4/28/2008. Our goal has been to design a sustainable, permanent base that would hold people by the year 2050. It would also probably be underground. This base would be implemented in the near future so one can assume only current chemical rocket technology. (Other technology- like space elevators, magnetic launch spaceports- would be welcome future additions, but one must have a design that is functional without those capabilities. There certainly will be improvements in our space technology, but one also can't be sure that they will be done being tested when the first moon base gets built, starting in 2020.

Any agricultural strategy for Luna will have to acknowledge conservation, sustainability and scarcity. The whole base will have to be conserving the limited material on the moon. The agricultural strategy will be designed to provide enough food for the base. The largest problem is the scarcity of many minerals needed for plant growth.

2 Literature Review

2.1 IQP: Sustaining Agriculture on the Moon

In 2007 a team of undergraduates established that it was possible to grow potatoes on the moon. It isn't that hard- it is possible to convert moon rock or regolith into a soil or medium for plant growth. The basic composition of soil is a sandy medium, nutrients, water and air. A drawback of having soil agriculture is that it takes a lot of water. Something that's already scarce. We also aren't sure that the lunar regolith would be a good soil medium- since it's likely to be too dusty and when it gets wet it will be similar to clay, harden like concrete, and be difficult for plants to grow in. If that's the case the base workers would have to collect lunar rock and grind it into sand rather than use the available regolith, or sift the regolith looking for the larger particles (Groezinger et al., 2007).

The previous agriculture group chose to work with potatoes, because they can be grown in many rough soils. That was a decent decision, because it's likely that soil made on the moon would have several imperfections. However, the team did not examine alternative methods of farming, which effects the choice of the plant. They also did not examine the total nutritional requirements for astronauts.

This team also looked at different strategies for giving the plants light, finally deciding to reflect it in for a side lit underground greenhouse. This is a challenging construction project. If the lunar base was large enough to have a nuclear reactor then it would be simple to have grow lamps feeding off of that power. Using power from solar panels is also possible, although solar panels are expensive and they would have to be made out of mostly local materials. Other base functions might be higher priority demand for the power most of the time.

2.2 IQP: Proposal for the Development of an Economically Viable Lunar Base

In 2008 a proposal for the development of a sustainable lunar base was written by four WPI students (Gary et al., 2008). The report covered the phases of development for a lunar base, the habitat design, the power source and the mining of regolith. The most complicated phases of development are the first ones since the following phases will be repeats of the established lunar base design. The transition from unmanned probes to sustainable human occupation is covered. The habitat design includes structural models of what modular units and hallways would look like (Gary et al., 2008).

The team also covered the details for providing power to the lunar base. Multiple strategies were discussed for generating, storing and using power. The challenging logistics for mining the lunar regolith were also explored.

3 Lunar Conditions

The moon is a separate celestial body from Earth, though it is made of the same basic raw materials at the level of rocks. It is hydrogen, and nitrogen that are scare and necessary for plant life. Hence it has different conditions that will have implications for agriculture. The almost total lack of an atmosphere has immediate implications for plants. There are 2×10^5 molecules / cm^3 in the lunar atmosphere, which produces $3x10^{-15}$ Earth atmospheres of pressure (Encyclopædia Britannica, 2008).

The gravity on the moon is one sixth of Earth's gravity. This will have strong implications on human habitants and how long they can stay on the lunar base before not being able to return to Earth without massive health problems. Plants handle low gravity much better than people, and have already been shown to be able to grow in microgravity. See figure 1 (Croxdale et al., 1997).

Figure 1: Potato tubers formed in ground and space.

Figure 1: Cv. Norland potato axillary buds of leaf cuttings grown for 15 days. The Space grown potatos were on the Space Shuttle STS-73 mission. The development of tubers were equal. (from Croxdale et al., 1997 as displayed in Wheeler, 2006).

There is no dipole magnetic field on the moon. The magnetic field of Earth protects Earth from harmful radiation from the sun. The lack of this field on the moon has to be considered in the lunar base. The chief risk is to humans and electronic equipment. Plants are resistant to radiation due to their structure. Plants can live even if many of their cells are killed by radiation. Due to the stable cell walls and plant structure it is essentially impossible for plant cancers to metastasize. Additionally the growing time of the plants will be so short that cancer will not be something lunar horticulturists will worry about. Whatever radiation protection that is provided for the human habitat will also probably be applied to the garden. Radiation should not be an issue. Gary et al., 2008, plan to cover the living quarters with regolith for radiation protection.

Examining the chemical content of the regolith is essential for lunar agriculture. Materials for plants will be needed and finding what resources the moon already has is a key step. Here is a table of the molecular content of the regolith, taken from "Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development" by Smith and West, 1983.

Figure 2: Chemistry of Major Lunar Rock Types

	Highland Rocks		Mare Basalts	
	Anorthositic Gabbro	Gabbroic Anorthosite	Olive Basalt (A12)	Green Galss (A15)
SiO_2	44.5	44.5	45.0	45.6
TiO_2	0.39	0.35	2.90	0.29
Al_2O_3	26.0	31.0	8.59	7.64
FeO	5.77	3.46	21.0	19.7
MnO	--	--	0.28	0.21
MgO	8.05	3.38	11.6	16.6
CaO	14.9	17.3	9.42	8.72
Na_2O	0.25	0.12	0.23	0.12
K_2O	--	--	0.064	0.02
P_2O_5	--	--	0.07	--
Cr_2O_3	0.06	0.04	0.55	0.41
Total	99.9	100.2	99.77	99.4

Another feature of the moon is its distance from Earth. Even though it is relatively close, it still took the Apollo 11 astronauts more than three days to travel to the moon. That time was just flying time, and preparation for missions can take days to months. The cost of exiting Earth's gravity well is difficult, with a cost of $1300/lb for taking material into orbit although CEO/CTO Elon Musk of Space Technologies Group believes the cost can be reduced to $500/lb with existing technology (Musk, 2004). A pound delivered to the Moon could cost as much as $10,000/lb, and will certainly be five times that of reaching LEO.

Due to the moon’s rocky crust and lack of atmosphere there is very little erosion. Crater impacts are maintained as they were, and they are only changed by new meteorites or comet impacts. At the poles the craters would act as shades for the interior of the craters no matter what time of day it is (Haskin et al., 1985). The poles may harbor potentially valuable harvestable water in the form of ice in the shaded inner walls of the craters. The pole location would also be valuable because there would be constant or near-constant access to sunlight. This will be detailed more in the Light Sources section.

4 Agriculture Strategy

4.1 Growing Techniques

There are a variety of classic ways to grow plants without soil. The reason for not using soil is that shipping soil from Earth will be extremely expensive. Soil might be able to be manufactured on the moon, or the plain regolith might be able to be used, but relying on regolith being a proper soil growth is risky. The regolith has fine of particles and might suffocate the plant, or have clay-like particles that causes difficulties in air-flow within the soil. Soilless systems can be tested on Earth before being deployed on the moon. One study done a decade ago examined growth of potatoes in hydroponic systems and in a peat/sand soil mixture. The hydroponically grown potatoes had larger yields (Muro et al., 1997). The hydroponic potatoes were also healthier because the water in the hydroponic system contained perlite substrate which prevented the spread of disease (Tello, 1990).

The four most common soilless growth systems are hydroponics, nutrient film, aeroponic, and ebb and flow. None of these systems have soil, so the base of the stem is suspended in mesh that is embedded into the ceiling of the device. Roots descend from the mesh mount. The differences in these growth systems comes from the environment the roots are in.

Hydroponics is a system where the roots have a water solution immediately below them. The solution has nutrients required for plant growth and to keep the water aerated there is an air stone that bubbles air into the water. In the nutrient film system the root tank is shorter and has a gentle slope. Water is pumped into the root tank at the top and the water trickles down to the return, where it goes into a water tank. The water is not aerated enough just from running along the root tank slope so there is an air pump in the water tank too. The ebb and flow system has a tidal method of watering the plants. Periodically water is pumped into the root tank from the solution tank, and the water from the root tank slowly drains into the solution tank. The water has to be aerated in this system too (Taiz and Zeiger, 2006).

The final most common method is aeroponics, or “air growing”. In this system the roots are never actually immersed in water. A mister is inside the root chamber and it is turned on periodically (typically the misters or on for a few minutes every half hour). The plants are able to recover enough water just from the mist, since the water particles will naturally condense onto the roots. After the spray the water will slowly drop out of solution, but the moisture in the air will remain for some time. The roots are also constantly surrounded by air and do not have problems with not getting enough air, unlike the other systems that required aeration of the water supply (Taiz and Zeiger, 2006). There is a risk in aeroponics: if the misters malfunction the plants will die very quickly. If there is a mechanical failure with the misters then plants being grown in the misting section can be flooded with water, and the crop can be saved. It requires a large amount of water, but being able to save a crop is very important. The base should have a back-up supply of water anyway, in case water is lost. Since aeroponics saves the water from being locked into the soil or a hydroponic tub, the base can be use the saved water for rocket fuel, life support and even cosmic ray shielding. For security, some water should be in a “backup” system.

In addition to saving water, the efficiency of the systems should be looked at. Hydroponics and aeroponics systems were compared for the growth of potatoes. In the aeroponics system there was a 70% increase in yield (Wheeler, 2006). Plant diseases are also less likely to spread from plant to plant the in aeroponics growth system. Soils and water allow viruses, bacteria and fungus to spread but if the plants are hanging in air there is almost no chance of disease spreading, unless the roots are literally brushing against each other.

4.2 Garden Atmosphere

The whole growing environment will be manufactured, and this includes the atmosphere. The lunar base will be able to manage the atmosphere of the garden habitat. The chief implication of this is that the CO_2 concentration can be modified as needed. Plant growth is effected by CO_2 concentrations, as it is an essential molecule for photosynthesis. Earth's atmosphere has between 0.036% (360 ppm) and 0.039% (390 ppm) CO_2 (U.S. Department of Commerce, 2009). CO_2 toxicity in humans first occurs at 1% or 10,000 ppm (Davidson, 2003). Humans may also gradually adapt to CO_2 concentrations of 2-3% (Lambersen, 1971) (Glatte et al., 1967). The research for this was originally used in the context of submarines, and allowing submarines to have looser CO_2 scrubbing mechanisms. The effect on designing lunar agriculture is even more leeway to lower or raise the CO_2 concentration.

CO_2 exchange rate into plants is dependent on CO_2 concentration (Wheeler, 2006). The rate of CO_2 exchange is directly related to plant growth, since CO_2 is added to sugars and other plant biomass (Taiz and Zeiger, 2006). See Figure 3.

Figure 3: CO_2 concentration vs. CO_2 exchange rate from Wheeler, 2006.

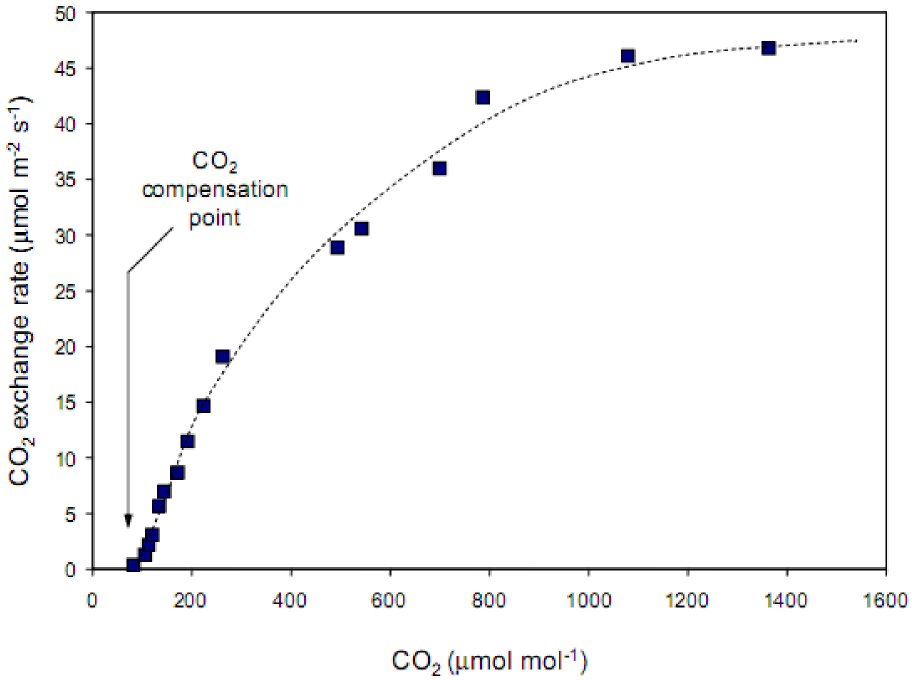

Figure 3: The exchange rate was for 20 m2 stand of potato (cv. Norland). The potato becomes saturated with CO_2 around 1000 umol mol^{-1}, which is a typical response of C_3 plants. Note that umol mol^{-1} equals ppm.

When CO_2 concentration was raised from 500ppm to 1000ppm the starch production of potato was increased 60%. Potatos grown in $[CO_2]$ 2000ppm has another 15-25% increase in foliar starch (Cao and Tibbitts, 1997). Since 2000ppm is still well below the first threshold of carbon dioxide toxicity, and because humans can withstand higher carbon dioxide concentrations when exposed to it over time, there is no reason not to have a garden carbon dioxide concentration of 2000ppm. However, since this trend has only been proved for potatoes additional experiments will need to be done on the other crops that will be used, but it is likely that other plants follow this general trend.

4.3 Light source

Gary, Nemeth, White and Wojcik have outlined a strategy for providing energy for a sustainable lunar base. The first phases rely on solar power but after some expansion a nuclear reactor will be built (Gary et al., 2008). This report will rely on the assumption that the lunar base will provide power for light bulbs, but there might be limited power as our design of a lunar base becomes more complex, developed and workable as a final plan.

If there is a problem of limited electrical power there was the simplistic solution provided by Groezinger et al. of basically having a lens focus light and then send a beam underground. It would reflect a few times while going around the regolith of an underground base that maintains protection from harmful solar radiation. The concentrated light would then be refracted in the plant chamber. This is a good long term plan, it only requires a few manufactured pieces two lenses and a pressure proof window that can maintain its integrity when large amounts of light passes through it. It's possible to manufacture all of these on the moon with silica, but it is not too efficient and does require some lunar production infrastructure. The question is how to get an initial system operational before one can bulldoze and make glass, and polish it on the moon?

4.4 Crops

Scwartzkopf et al. designed a minimally balanced diet for astronauts living on the moon that could be grown on the moon:

Figure 4: Proposed Daily Crew Diet (Scwartzkopf et al., 1991)

Food	Daily portion [grams]
Soybeans	100
Peanut	100
Wheat	400
Carrots	300
Lettuce	200
Tomato	200

Figure 4: A modified proposed daily crew diet from Scwartzkopf et al., 1991 as quoted in “Luna Gaia”, 2006.

The amount of space needed for the crops can be calculated. Commonly accepted values for bushel/(acre*$\text{Time}_{\text{Growth}}$), kg/bushel and $\text{Time}_{\text{Growth}}$ were used in the calculations. These numbers come from traditional soil based crops without CO_2 manipulation. $\text{Time}_{\text{Growth}}$ is in days. A 70% increase was calculated for aeroponics and a 75% increase was calculated for CO_2 concentration at 2000ppm. There are 4046.85 meters^2/acre. The equation used is:

Figure 5: Equation for Crop Area Per Crew

$$\text{Meters}^2\text{/acre x (acre*Time}_{\text{Growth}}\text{)/bushel x kg/bushel x Time}_{\text{Growth}}^{-1}\text{ x Daily Portion (kg) x Aeroponics Mod. X CO}_2\text{ Mod. = Crop Area per Crew}$$

Figure 6: Crop Area Per Crew

Food	Bushel*Acre^{-1} *TimeGrowth^{-1}	kg/Bushel	$\text{Time}_{\text{Growth}}$ (Days)	Required Nutrition (kg)	Crop Area
Soybeans	40	27.215	33	0.1	2.80
Peanut	100	32.5	90	0.1	0.49
Wheat	50	27.215	120	0.4	2.47
Carrots	350	20	70	0.3	0.33
Lettuce	360	22.7	35	0.2	0.49
Tomato	150	25	85	0.2	0.53
				TOTAL:	7.12

The total area required per crewmember is roughly 7.12m^2. To have a margin of safety and to build up a food reserve the base should have 10m^2 and this number does not take the agricultural-support equipment into the picture. Further, all of these plants are much shorter than 2.96 meters, the proposed height for the habitat modules. The agricultural support, such as pumps, nutrient solution mixers and water tanks, could be placed above or below the crops. The floor space of each habitat module is 38.5m^2 (Gary et al., 2008), so if extra room is planned in each agriculture module will feed three astronauts. This is a large but acceptable restraint in infrastructure that can be delivered from the Earth, to use – if it can be buried and covered with regolith.

There has been a switch from potatoes as a source of starch to wheat as the major source of starch. The diet designed by Scwartzkopf et al. included wheat, not potatoes, in the model. Gram for gram potatoes are not nearly as nutritious as wheat. At a glance, potatoes have about 1/14th of the calories that wheat does. However, this may be able to be made up by the density at which potatoes can be grown. Figure 6 indicated that 400 grams of wheat would require 2.45 meters squared of space. A rough estimate of area needed to produce 400 grams of potato was 0.15 meters squared, or 6% of the area of wheat. These numbers do not take the height of the plants into account, but one can project that wheat will be taller. A detailed analysis of the yields would be a good area for future research.

5 Materials Required for Growth

There is naturally a large amount of oxygen on the moon, and some carbon in the rusts (metal oxides) and rocks on the moon. As soon as one can process the lunar rock we shouldn't have serious supply problems for those two elements. One can also get small amounts of potassium from moon rock, which is needed in small amounts as a fertilizer.

What is really lacking on the moon is He, N2 and H. This brings me to the LEO/LOX project, which stands for low earth orbit liquid oxygen. A LEO satellite designed by Paul Klinkman could harvest oxygen from the upper atmosphere of Earth. The main purpose for this satellite is to collect to relatively heavy oxygen part of rocket fuel, so that spacecraft can refuel in orbit. This would be cheaper than carrying all the rocket fuel with them to Low Earth Orbit.

The proposed LOX in LEO system also collects helium and nitrogen. We need nitrogen for plants – though it can also be used in rocket fuel. Helium has some uses, though not specifically related to lunar agriculture. Adding helium into the base atmosphere would act as a fire suppressant, if only to displace excess oxygen. What is needed is an inert gas to use for inflating, pressurizing places that people or plants aren't needed, and avoiding the use of dangerously flammable pure oxygen.

Finally a small amount of hydrogen, roughly 1% of the gases, would be collected. This is good news for us because we need hydrogen – but the demand for hydrogen is high, because it's also a component of rocket fuel.

There are a few alternatives to collecting hydrogen in LEO. High in Earth's orbit there is a layer of mostly hydrogen. Unfortunately it is very diffuse, so there is less gas to collect than at lower orbit but a large iron satellite would be able to collect a layer of hydrogen over its surface area. This would be eternally replenishable, and while probably insufficient to support a rocket fuel depot, it might be productive enough to support a slowly growing lunar agriculture effort that can recycle the hydrogen indefinitely once it is acquired and put into a closed loop system that loses no more than 5% of the gas on every pass through the animals and plants in the lunar habitat.

Candidly, the need for hydrogen in LEO to go with the LOX means that there will be regular hydrogen deliveries from Earth to LEO and a small proportion of that gas stream can be delievered. Later a more elegant solution should be possible involving capture of the hydrogen passing by the moon on the solar wind or obtaining what is capture in the regolith as it has passed by in the recent or not so recent past.

As noted, the moon's regolith includes some hydrogen. However it is only weakly bonded to the regolith, and only bonded to certain metals. Iron is one of the best hydrogen-binders, which is why we would use it for a hydrogen-collecting satellite. The hydrogen in the regolith can be released easily with any disturbance. The lunar base IQP team is not positive how to delicately collect this hydrogen, but Paul Klinkman has a proposal involving a tentlike covering under which the regolith is heated and all the gases are released and sorted later. About 1% of that obtain would be hydrogen. Most would be oxygen, as much at 55% in some places. In the worst case scenario hydrogen will be shipped from earth.

If H, He and He3 can be collected from the lunar regolith, that becomes a renewable resource. Current regolith has been collecting those atoms from the sun for millions of years, and the regolith is saturated down to six inches. Unfortunately not all the minerals in regolith bind to hydrogen. If we farmed the regolith the first time it would be easy to relay the regolith so that the hydrogen bonding Iron compounds would be on top. After a 100 years there would be about 3 inches of hydrogen-rich regolith. This would assist the long-term sustainability on Luna. As an economic activity gathering rare gases using sorted regolith would be akin to growing highly valuable but slow growing hardwood trees (like mahogany or maple) on Earth.

6 Closed-Loop Recycling

6.1 Gas Exchange

If one just lets the air mix throughout the moon base there would be problems. First: it is risky to have all the air connected, in the case of depressurization. Secondly, it may not be ideal for plant growth. There would be more O_2 concentration in the plant chamber and more CO_2 in the human living quarters. The best atmosphere for plant growth should be an atmosphere with a high concentration of CO_2, and thus there should be active exchange of gas.

Gas exchange will not be difficult. Lithium Hydroxide is used in the space station right now, but is not designed to support recycling and the lunar system must be able to hold and then release CO_2. The carbon dioxide-accepting reaction is reversed if there is high temperature or low pressure both conditions can be produced readily on the moon. Monoethanolamine also accepts CO_2 when it is cold, and releases it when warmed. One could make a custom atmosphere in the plant chamber to enhance plant growth.

6.2 Water and Nutrient Recycling

The fertilizer for the plants would be included in the solution sprayed on the plants within the aeroponics growth system. One can simply get what is needed in the solution (mainly nitrates, phosphates) by taking them from the leftover plant matter subject to bacteria action or one can also extract it from consumption by worms. The plant matter, human waste, and dirty water could be put through wet oxidation or through supercritical water oxidation. Wet oxidation should oxidize enough of the materials, but to make sure that everything is oxidized one can use supercritical water oxidation. Oxidizing all of the human waste before misting it on the plants provides harmless fertilizers that have no chance of spreading human disease.

Supercritical water oxidation has many benefits. Waste management would be centralized, with a one-size-fits-all strategy for water, organics and refuse. There would be extra potable water for luxuries such as bathing, dishwashing and laundry. Transmission of disease through recycled materials would be eliminated (Sedej, 1985). Sedej elaborates on the technology required to generate heat and pressure for supercritical water oxidation is available. There are at least two options for the heating methods: electrically heating the pre-treatment refuse or taking extra H_2 and O_2 and reacting them in the same chamber as the pre-treatment refuse. Electrically heating the pre-treatment could cause erosion of the feed line, which is undesirable. Reacting them, with a bit of solar energy to provide for the energy input to start the reaction and move the gases around to be a better, though more complicated, solution.

7 Societal Implications of Lunar Agriculture

The ability to design a reliable and sustainable closed-loop lunar agriculture facility that is modular and expandable means that humanity has the ability for humanity to move out from planet Earth to live in extraterrestrial bases. These will be the foundation of research, mining and commerce in our solar system. Planning for sustainable agriculture and shipping the extra resources required will be more costly at first, but it will pay off over the long run. Not doing so would be foolish and end up restricting the potential, some would say the destiny in space, of humanity and its biological partners on Earth. The region right around Earth, that could be supplied from Earth, would be the limit of our habitat.

NASA's plans for the moon were not made with sustainability as a primary goal. This is unfortunate. NASA is planning a semi-permanent base. It would be continuously habited for its mission length for building a base- which will be a 10 year process. There is another 15 years of estimated lifespan for the base. If we are going to inhabit the base during the last 20 years of that period the astronauts should be feeding themselves if only to save on costs, though pioneering lunar (extraterrestrial) agriculture is ultimately more important. The lunar base that exists in 2050 must be sustainable and self supporting in economic terms.

There is a larger problem with NASA's philosophy. NASA isn't going to the moon to establish a base, they're going there to practice for Mars. NASA has already been to the moon, and wants to explore and prove technology. The Space Agency does not want to act as the forerunner and build infrastructure for the capitalists that would follow to set up a mining base camp. Mars is NASA's end goal, and they may accomplish it, but the cost will be excessive, and it won't have the benefit of building infrastructure for the private sector. However, this may be short sighted as a US policy. The private sector is going to be left to its own devices to compete with a Chinese national investment plan and European and Japanese investors who are known for being more patient in awaiting a return on investment. Are we sure this should not be a public- Private joint venture under those circumstances? In addition any agricultural testing they do for Mars on the moon is inappropriate. Mars has a wildly different environment. It has more water and carbon, less sunlight, and there is wind and dust storms to contend with. The natural resource base is larger but the economic potential for a trade system is much smaller.

A mission to Luna will be costly, but if the base was built with a sustainable mindset then it would be the foundation for future business, infrastructure and industry on the moon. There's even a market for foodstuffs grown on the moon because plants don't grow well in microgravity. Transporting food from the moon’s gravity well is still far cheaper than liftting it up from Earth. Lunar agriculture still has a few question marks to be answered, but it has strong potential. It is an art that we should be able to master with a bit of experience.

William Burrows has written about the existential risks that are present on Earth. There are many threats that could totally end civilization on Earth, including but not limited to: nuclear warfare, bioterrorism and asteroid collision. Burrow’s solution to these threats is to create sustainable bases in space (Burrows, 2007). These bases would need to have an independent supply of food that would totally recycle all the elements. The lunar agricultural design proposed in this report would fit the niche for a race survival moon base, from which to colonize and repopulate Earth in the event of a calamity. It is an insurance policy with a relatively modest premium and many potential side benefits that the human race should gladly pay.

8 Conclusion

Lunar agriculture is a real possibility and is an essential part of long-term lunar bases. The chief restriction comes from the amount of resources that can be provided from Earth. However, since the first phases of development will be unmanned (Gary et al., 2008), there is more time for raw materials to be collected at the base, from mining or from rocket cargo containers. Power will also need to be provided by the time agriculture is started. The largest drain on power will be from mining and manufacturing and agriculture will easily be allotted energy. This strategy for lunar agriculture fits elegantly within the report by Gary et al. The lunar gardens can be placed in the same habitat modules that will be used by the astronauts, and use the same air management systems.

There have been significant improvements in the research and analysis of lunar agriculture since the previous IQP on the subject. Expansion of growth systems, recycling, availability of resources and nutrient are all benefits of more study.

The base floor space required to grow the plants has also been reduced with the study and design of artificial factors that will increase growth. The chief factors are increasing CO_2 concentration and using an aeroponics growth system. Aeroponics has been shown to be more effective than the other soilless solutions, in addition to being the best to resist the spread of disease. Increased CO_2 concentration will provide additional growth and is easily tolerable by the astronauts.

The nutritional requirements of astronauts and the crops required to meet them were also examined. A rough estimate of the space required for lunar agriculture was provided. The most data available on crops is in potato, because there are many journals funded by commercial potato interests, but potatoes are not necessarily the ideal crop of lunar agriculture. Continued experiments on the range of crops chosen for the lunar staple diet will be needed.

An analysis of what elements are needed for agriculture and where they will come from is also provided. This is the gravest concern when designing a base that is part of one economic system, even from a non-agricultural point of view. Rocket fuel is incredibly valuable in space, so cargo space is also precious. Some of the materials can be mined (such as Oxygen and Carbon from the regolith) but the rest will have to be found onsite by scavenging on the moon or enroute to it outside of the Earth's gravity well. The scarcity of key agricultural resources makes recycling essential, and a system for closed-loop recycling has also been provided.

Finally the societal implications have been discussed. Clearly the ability to be self-sustaining is a boon for future space travelers. This report is focused on agriculture on the moon but many of the concepts can be applied to space stations, space ships and non-lunar bases. In other cases, the relative ease of agriculture on the moon compared to a space station or hotel facility suggests that food will be a lunar export product to the growing number of facilities in the inner solar system region closer to the Earth than Mars. When exporting food, the lunar farmers will have to make sure to keep a neutral or positive import to export ratio lest they run out of the precious agricultural resources they accumulated.

To communicate these agricultural solutions to the public the author went to the International Association for Science, Technology and Society conference in the spring of 2008 to publically speak. The IASTS audience was small, but had a significant proportion of educators. These people will be crucial in spreading these concepts and solution for growing plants on the moon to facilitate public understanding of how a sustainable moon base could be created.

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