the plants if the product is to be successful. However, the best new plant in the world will never be successful if a propagation method cannot be established to supply the quantities that the consumer will demand. If the evaluation and propagation of new plant selections is done in a scientific and appropriate manner and marketed correctly, then the new product will be a success for the consumer, retailer, and wholesaler.

Growing Plants for NASA — Challenges in Lunar and Martian Agriculture©

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INTRODUCTION

Technology advanced rapidly during the 20th Century. One hundred years ago, 17 Dec. 1903, the Wright Brothers flew the world's first powered aircraft at Kitty Hawk, North Carolina. It was a flight of 37 m (120 ft) that lasted 12 sec at a maximum speed of 16 kmph (10 mph). Forty-four years later Chuck Yeager would break the sound barrier — Mach 1 at 1086 kmph (675 mph). Twenty-two years after that in 1969, Neil Armstrong landed on the moon.

So what is the role of plants for human life support? Plants reduce the level of carbon dioxide (CO_2) and produce oxygen (O_2) during photosynthesis. They can also help convert wastewater into potable water through transpiration and subsequent condensation and collection of clean water. Plants also produce carbohydrates and food for human consumption (Fig. 1). In the international space station and NASA's space shuttle, physical-chemical methods are primarily used to produce oxygen and absorb or vent carbon dioxide from the cabin atmosphere (Fig. 2). NASA plans to use plants to supplement physical-chemical systems to produce oxygen and absorb carbon dioxide. Plants also have a role in supplementing human nutrition as part of NASA's "salad bar" program of fresh greens and vegetables. Plants are also important for the psychological well being of the crew.

THE PROBLEM

It will be a tough environment to grow plants in lunar and Martian agricultural systems (Salisbury, 1991; Bugbee, 1999; Corey et al., 2002;). The atmospheric pressure of the moon is a vacuum and Mar's atmosphere is 1/100th of the earth's pressure. Gravity is another factor — the moon is 1/6th and Mars is ²⁄₅ths that of earth's gravity. Capturing, producing, and using light for plant growth is another challenge. The moon has 14.8 days of consecutive darkness followed by 14.8 days of consecutive light. While Mar's has an atmosphere composed of 95% CO_2 (compared to 360 ppm or 0.036% CO_2 on earth), the moon has no CO_2, nor the carbon needed to produce it, i.e., carbon, oxygen, nitrogen, and carbon dioxide will need to be transported from earth or artificially produced in controlled environmental structures on the moon and Martian surface. Another problem is that travel to Mars and the return flight to Earth is a 3-year process, i.e., you cannot cram enough food into a

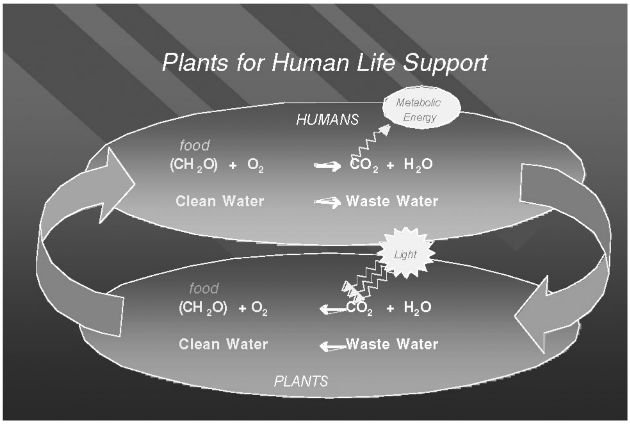

Figure 1. The role plants will play in human life support systems on lunar and Martian Agricultural Systems (from R. M.Wheeler).

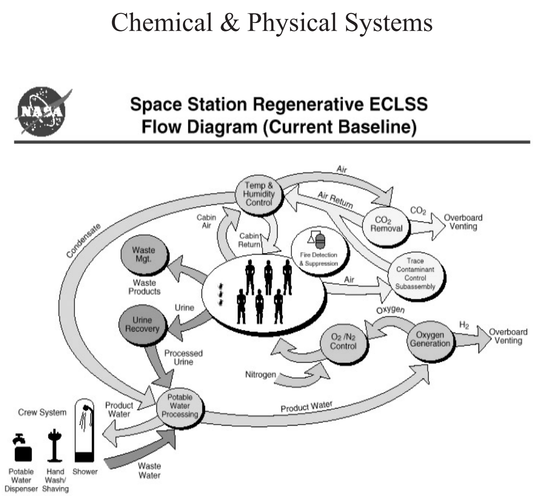

Figure 2. Chemical and physical systems for recycling and controlling water, oxygen, carbon dioxide, and nitrogen on the International Space Station.

space ship with today's current technologies. There is the need to incorporate Biogenerative Life Support Systems (i.e., closing the "loop" and creating a sustainable system through recycling using plants and physical-chemical systems), rather than just depending on "resupply" and chemical methods.

THE CURRENCY OF SPACE IS MASS (WEIGHT) AND POWER

Energy will need to be produced and stored, i.e., the energy for light production and plant growth. It is also very expensive to ship materials into space, as much as $15,000 per pound ($33,000 per kg). If normal earth atmospheric pressure is to be maintained for growing crops, than large support structures for crop production will need to be shipped and assembled in space. The vacuum of space makes the transport and assembly of such large structures very difficult.

The Kennedy Space Center in Florida has been focusing on smaller production systems, supplemental crops, and flight environments for growing plants (Wheeler, et al., 2001). Potential "salad bar" crops include: radish, onion, lettuce, tomato, pepper, and strawberry. Space flight, lunar and Martian production conditions will likely include low to moderate light levels (as low as 15% of normal full sunlight), super-elevated CO_2 [from 360 ppm (ambient) to more than 5000 ppm, or 5%, or 0.5 kPa], and water and nutrient delivery systems compatible with microgravity (weightlessness). Mixed species testing is also being done.

Crop testing at the Kennedy Space Center is also being conducted on onions comparing different sources of light: high-pressure sodium and cool-white lighting. Crop growth is also being controlled with energy efficient light emitting diodes (LED lighting). Light quality is also being tested. It's known that red light is important for photosynthesis and phytochrome responses (i.e., it helps a plant determine environmental cues such as long-day or short-day conditions, which are important for flowering). Blue light is important for phototropism (i.e., plant response to gravity, development of compact or elongated shoots) and stomatal control, whereas green light is important for human vision (human vision is most receptive in green) and is also being tested for enhancing light penetration into the plant canopy.

ADVANTAGES OF PLANT GROWTH AT SUB-AMBIENT ATMOSPHERIC PRESSURES

There are tremendous cost savings, engineering and production advantages of growing plants in space in modified growth rooms under lower atmospheric pressure. Advantages of growing plants under low total pressure include: (1) less structural material for housing and growing plants needs to be shipped into space, (2) there is less leakage of gases (oxygen, nitrogen, carbon dioxide) from a low-pressure crop production atmosphere into the vacuum of Moon or near vacuum of Mars, (3) lower total levels of nitrogen, oxygen, and carbon dioxide would be required, which otherwise would have to be transported or produced artificially in space, and (4) with an external oxygen supply, astronauts could tend crops down to a third of normal atmospheric pressure without having to suit up into cumbersome space suits.

At Texas A&M University in the Departments of Horticultural Sciences and Biological & Agricultural Engineering, six low-pressure chambers have been designed and built to control atmospheric pressure from ambient (101 kPa) to very low pressure (less than 20 kPa) (Figs. 3 and 4). We can also control the partial pressures of nitrogen, oxygen, and carbon dioxide. We have been able to germinate seeds and

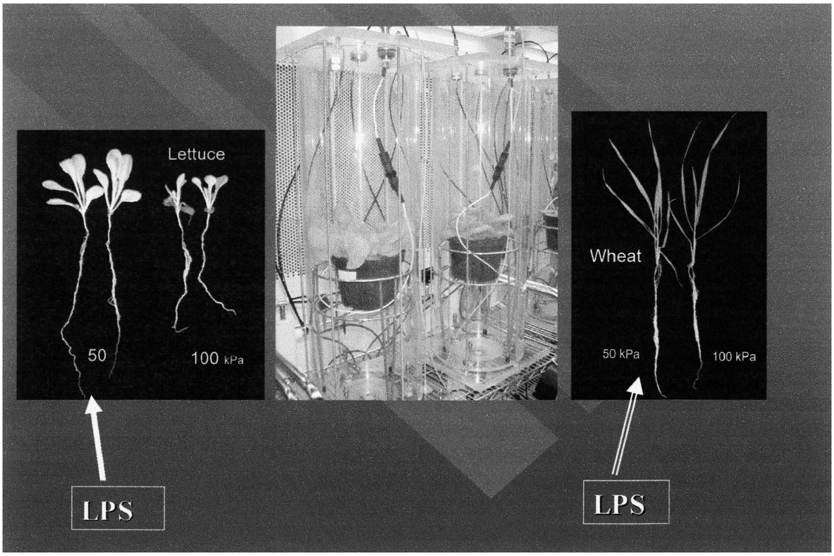

Figure 3. Effect of low pressure [(LPS) at 50 kPa] on growth of lettuce and wheat seedlings. Notice that the lettuce seeding (left) has greater shoot and root growth than the ambient (100 kPa) lettuce plant, whereas the wheat plant (right) is only slightly larger (+10%) at low pressure (He et al., 2003).

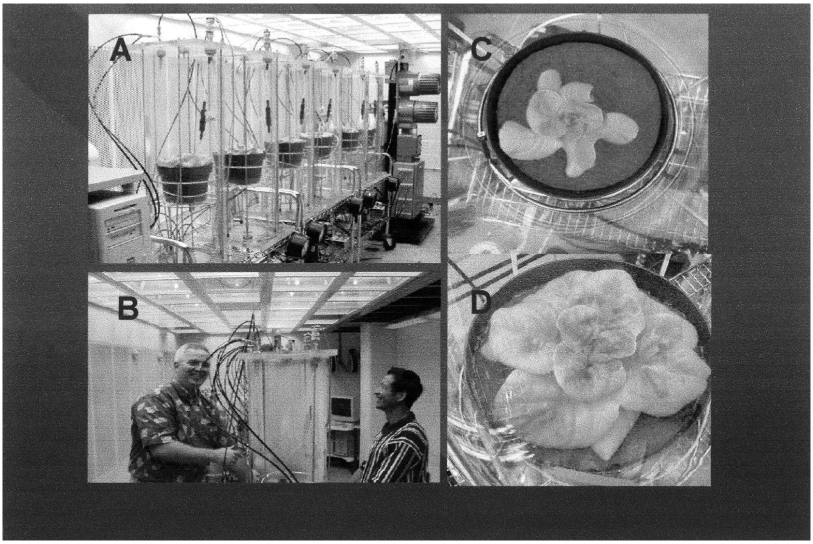

Figure 4. (A) Six-chambered low pressure growth system; (B) Drs. Ron Lacey and Chuanjiu He starting an experiment; (c) Lettuce at early stage of development under low pressure; and at (d) Later stage of development under low pressure.

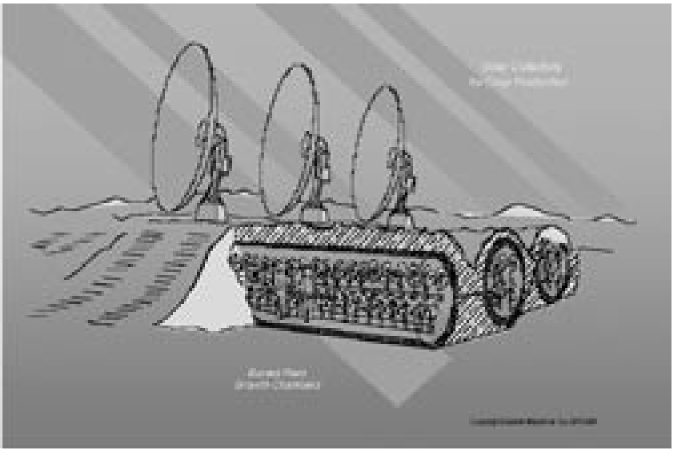

Figure 5. Depiction of a protected culture site with solar collectors for storing light energy needed in the production of plants in a lunar or Martian site.

grow seedlings of lettuce and wheat at 30 kPa (30% of normal atmospheric pressure and oxygen levels) without problems. In fact, plant growth under low pressure conditions is better than ambient (normal pressure ≈ 101 kPa) — because in a very sealed environment, such as an air-tight growth chamber or International Space Station, ethylene levels build up which cause abnormal plant growth and plant sterility (Wheeler et al., 1996; Levinskikh et al., 2000). We are finding that ethylene production is generally reduced under low pressure conditions (He et al., 2003).

To date our research (He et al., 2003) has shown that:

- Lettuce and wheat can be grown under low pressure (Fig. 3).
- Plant gas exchange is not adversely affected, i.e. photosynthesis and stomatal conductance are similar to ambient pressure conditions.
- Accumulation of ethylene in chambers under ambient pressure reduces lettuce and wheat growth. [Normal field conditions are 1 to 5 ppb ethylene, however up to 1000 ppb occurred on the Mir Space Station (Levinskikh et al., 2000)].
- Low pressure environments reduce ethylene production and increase plant growth.
- Dark respiration (which occurs at night) is reduced with a low-pressure system. This means there is more overall plant dry mass accumulation since not as much carbohydrates and other compounds are consumed during the night, i.e. there is greater plant yield.

PSYCHOLOGICAL IMPORTANCE OF PLANTS

We know that besides supplementing recycling systems and supplying fresh food for human nutrition, plants play an important psychological role in human health and well being. It is known that some of the favorite experiments of the Russian cosmonauts were with plants and seedlings that they could nurture, harvest, and eat. Just biting into something with some turgor to it, and not having a diet limited to reconstituted foods has important psychological benefits. In the Antarctic, which is one of the most desolate places on earth, there is a small greenhouse at one of the U.S.A. bases for supplying salad bowl crops (greens, vegetables, etc.) . It is also one of the most popular places on the base, where crew members will retreat from the cold, white barren snow-capped landscape to recharge, rest, and knap in hammocks stretched across the green visual of live, growing, green plants. It is those bright light, colors, aroma, texture, and flavor of plants that attract we humans. Small wonder that the greatest pastime in the U.S.A. is gardening. It will also be an important activity as humankind colonizes space during the 21st Century (Fig 5) (Salisbury, 1991).

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