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FARMING IN SPACE: ENVIRONMENTAL AND BIOPHYSICAL CONCERNS

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ABSTRACT

The colonization of space will depend on our ability to routinely provide for the metabolic needs (oxygen, water, and food) of a crew with minimal re-supply from Earth. On Earth, these functions are facilitated by the cultivation of plant crops, thus it is important to develop plant-based food production systems to sustain the presence of mankind in space. Farming practices on earth have evolved for thousands of years to meet both the demands of an ever-increasing population and the availability of scarce resources, and now these practices must adapt to accommodate the effects of global warming. Similar challenges are expected when earth-based agricultural practices are adapted for space-based agriculture. A key variable in space is gravity; planets (e.g. Mars, 1/3 g) and moons (e.g. Earth's moon, 1/6 g) differ from spacecraft orbiting the Earth (e.g. Space stations) or orbital transfer vehicles that are subject to microgravity. The movement of heat, water vapor, CO_2 and O_2 between plant surfaces and their environment is also affected by gravity. In microgravity, these processes may also be affected by reduced mass transport and thicker boundary layers around plant organs caused by the absence of buoyancy dependent convective transport. Future space farmers will have to adapt their practices to accommodate microgravity, high and low extremes in ambient temperatures, reduced atmospheric pressures, atmospheres containing high volatile organic carbon contents, and elevated to super-elevated CO_2 concentrations. Farming in space must also be carried out within power-, volume-, and mass-limited life support systems and must share resources with manned crews. Improved lighting and sensor technologies will have to be developed and tested for use in space. These developments should also help make crop production in terrestrial controlled environments (plant growth chambers and greenhouses) more efficient and, therefore, make these alternative agricultural systems more economically feasible food production systems.

INTRODUCTION

The colonization of space rests on our ability to provide adequate life support to a crew of space colonists. This means providing for all the biological needs of the crew: e.g. food, water, oxygen, and essential nutrients. A brief historical review of farming is presented to illustrate how changes in Earth-based agricultural methods have occurred over long periods of time. Modern agriculture has become increasingly dependent on technology to keep up with the demands of an increasing population and space-based farming research can help in the continued development of new technologies for increasing food production on Earth.

EARLY AGRICULTURE

Agriculture probably began in the Neolithic age (c. 8000 B.C.), when domestication of wild varieties of crops and animals allowed groups of hunters/gatherers to develop sedentary agrarian societies. Domestication occurred near several centers of origin around the world where wild plants with useful hereditary traits were gradually selected to develop improved varieties of crop plants. Several changes in plant phenotypes were selected for: determinate growth habit, reduced grain shattering, shorter maturity, synchronous ripening, reduced bitterness and

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toxin content; reduced seed dispersal, sprouting and dormancy; increased fruit size and productivity. These traits increased usefulness to society but reduced survivability of these crops in the wild (Prakash, 2001).

The development of traditional agricultural farming practices has been a gradual process whereby cultures adapt their cultural techniques to their local terrain and climate. Early civilizations began along major rivers: the Egyptians near the Nile river, the Harappa along the Indus, the Chinese along the Huang river and the Mesopotamians (Sumerians, Babylonians, and Assyrians) along the Tigris and Euphrates. These rivers provided a source of silt from yearly floods and plentiful water. The Harappa established a large-scale crop production system in the fertile plains of the Indus around 3000 B.C. (Stamp, 1961). They used dams and drainage systems, and practiced terracing to produce wheat, barley, sesame and dates. In Mesopotamia, agriculture was entirely dependent on the efficiency of the irrigation system. The main crops were wheat, barley, dates, figs, olives and grapes. The Tigris and Euphrates rivers brought large amounts of silt, which clogged man made irrigation systems. The yearly floods came in late spring /early summer, which was too late for the spring crop and too early for the autumn crops (Grigg, 1974). There was also a high saline content in the soil, and the yearly rainfall was not sufficient for crops (Gill and Dale, 1974). These conditions resulted in food shortages whenever the irrigation ditches were not maintained.

Early man occupied many climatic zones and, as a result, developed many cultural practices to accommodate these different zones (Stamp, 1961). In East Africa, coffee, sorghum, millet and watermelon were domesticated, and farmers used grinding wheels and sickles (Harlan, 1971). In Egypt, the Nile brought fertile silt and humus deposits in yearly floods. The Egyptians invented the water wheel to allow them to grow two crops per year, and the shaduf to 'pump' water into their irrigation canals (Leonard, 1973). The Egyptians constructed large dikes and irrigation systems to regulate the yearly floods (Stamp, 1961) and developed drainage (water removal), irrigation (artificial supply of water), and land preparation (hoeing and plowing) techniques. The Greeks had to accommodate to mountainous terrain. They used terracing and farmed in hills to grow their crops (Gill and Dale, 1974). They also studied plant function. Theophrastus published a botanical study describing 500 plants, provided the first insights into plant function and studied pollination, propagation, and classification. In Mesoamerica, the American Indian civilizations (Olmec, Aztec, Inca, Maya, and others) were perhaps the best plant domesticators. In Central America, the main agricultural practice in poor jungle soils was slash and burn. The ashes of the native vegetation provided sufficient nutrients for crops (Crisp, 1993), but the fields had to be left fallow once the nutrients were depleted. The main crops were maize, squash, pumpkins, chili peppers, and avocados (Harlan, 1971).

New cultures have developed new approaches as well as improved upon what previous cultures have done in the past. In the Andes, the Pucaras, Quechuas and Aymaras, living in the Lake Titicaca Basin at altitudes above 3800 m employed raised field culture from 1000 B.C. to 400 A.D. Raised fields increased soil fertility, improved drainage, and improved the local micro-climate to reduce the risk of frost damage and thereby maximize crop yields (Erickson, 1988). Potato and quinoa were grown in raised fields surrounded by 1 m deep and 10 m wide canals. The water in the canals stored heat during the day and radiated it at night to minimize frost damage, which improved root zone and air temperatures. In recent tests, the unfertilized raised fields produced an average potato yield of 10 metric tons per hectare compared to the current regional average yield of 4 metric tons per hectare in conventional fertilized fields. In Europe, the Romans inherited many cultural practices from people they conquered. They understood that the soil becomes depleted if not fertilized and developed the concept of crop rotation (Gill and Dale, 1974). They fertilized with manure and conserved water from rainfall for use when water was scarce in the summer. They studied budding and grafting, used cultivated varieties, legume rotation, and developed greenhouses.

Improvements in farming have targeted new ways to reduce the amount of labor needed to sustain a given population for a given area to be farmed. The greatest advancements in farming have been achieved since the Industrial Revolution as mechanization replaced manual labor. The new mechanized methods (plow, reaper, seed drill) powered by horses and oxen combined with crop rotation, fertilization with manure, the use of New World crops, and better soil preparation led to a steady increase in crop yield in Europe (Grigg, 1974). In 1910, a farmer could feed 7 people, by 1982, a farmer could feed 80 people. Production from the 1880's to the 1920's increased due to expanded use of available land, and from the 1920's until the present yield increases have been fueled by advancements in technology (chemical fertilizers, herbicides, fungicides, growth regulators, use of plastics in nurseries and greenhouses, hydroponic culture) as well as improved plant breeding programs (Janick et al., 1981; Huxley, 1984).

MODERN AGRICULTURE

Agriculture has converted millions of acres of forested land around the world, and introduced numerous alien plant species into natural ecosystems in the pursuit of food, fiber, and timber, causing large disruptions to the flora and fauna of the planet. There have also been many impacts on crop biodiversity, as well as on air, water and soil quality; however, food has been adequately provided for the world's population (Prakash, 2001). Farming has kept pace with the population explosion of the last century mostly through scientific crop improvement methods (such as hybrid vigor, shortening growing seasons, developing greater resistance to diseases and pests, developing bigger seeds and fruits, and breeding for better digestibility and nutrition and for reduced toxins). These scientific crop improvements were bolstered by improved methods of irrigation, mechanization and disease control (Conway, 1999).

The challenge of modern agriculture lies in sustaining high production rates while coping with new challenges brought about by changes in the global climate: increased frequency of extreme weather events, increased demand for water resources, increased pest and disease problems as global temperatures increase. In conventional agriculture, the climate limits yearly crop production to one season because year-round farming is not possible except in certain tropical and subtropical regions of the world (Dalrymple, 1973). Further increases in crop yields, far exceeding those attained in field settings, have only recently been achieved in controlled environments (greenhouses and small plant growth chambers) optimized for use in future space farms (Salisbury and Bugbee, 1988). Although the degree to which the environment can be manipulated is considerable in greenhouses and plant growth chambers, these systems are limited by economic considerations related to the costs of controlling temperature, light intensity and spectral quality, atmospheric composition, and the rooting medium (Dalrymple, 1973).

PLANTS AND ADVANCED LIFE SUPPORT SYSTEMS

In nature, plants play a central role for mankind because we are entirely dependent on agriculture for food. What should be the role of plant-based food production as we venture into space? Myers (1963) developed a graphical method of conducting trade studies among the various options available for providing life support in space in terms of initial launch mass. The simplest option, stowage and periodic resupply of consumables without recycling, has been used in all manned missions to date. The initial launch mass increases linearly as mission duration or distance from the Earth increases because the cost to launch consumables is nearly constant. Adding life support hardware for recycling water, for regenerating the atmosphere or for food production increases the initial launch mass, but decreases the need to resupply consumables. Thus, the rise in launch mass with mission duration is not as steep. Breakeven points between various degrees of recycling and the simplest option can be used to evaluate the feasibility of numerous physicochemical and bioregenerative technologies in providing sustained life support. The most efficient designs of regenerative life support systems combine both physicochemical and plant-based systems (Olson et al., 1988; Schartzkopf, 1992). Crop plants produce food for the crew, regenerate the air by removing CO_2 and producing O_2, and purify water through transpiration. The remaining functions: food and waste processing, and temperature control can be accomplished with physicochemical systems. These hybrid plant-based bioregenerative systems become economically feasible compared to the simple resupply option after a 3-year, six crew-member mission (Drysdale, 2001), which coincides with the duration of a Mars mission.

The diet requirements of humans dictates that up to 15 species of plants must be grown to ensure a complete menu (Olson et al., 1988). These crops must be selected for small size, fast growth, nutrition, short plant cycles, and high harvest indices. However, these traits only address the food production aspects of the crops. Other aspects must include atmosphere and water recycling capabilities. These considerations require characterizing physiological responses of these crops to numerous environmental parameters before they can be deployed as part of a bioregenerative life support system (Muhlestein et al., 2000; Stutte et al., 1999; Goins et al., 1998; Monje and Bugbee, 1998; Monje, 1998; Wheeler et al., 1993; Wheeler et al., 1994; Bonsi et al., 1992). Once a crop is characterized, this knowledge can be used to throttle water or CO_2 recycling by simple environmental changes in atmospheric CO_2 concentration or light intensity (Wheeler et al., 2001). The performance of plants in microgravity must also be studied (Levinskikh et al., 2001; Monje et al., 2000c; Brown et al., 1997; Tripathy et al., 1996; Morrow et al., 1995; Morrow et al., 1993), but much more work is needed because there have been very few long duration plant experiments in space to date. The main goals of these studies should be to develop the appropriate technologies and cultural conditions for providing stress-free plant growth in microgravity.

FARMING IN SPACE

The goals of the space farmer are to provide food for human crews living in microgravity aboard spacecraft or in planetary bases. Thus, Earth-based cultural practices and crops must be adapted to grow optimally in new environments with new biophysical combinations (e.g. microgravity, low atmospheric pressures, and supra-elevated CO_2 concentrations) encountered only in space. The process of adaptation to new environments will be no different than what farmers have done in the past as new environments on Earth were colonized. The space farm modules will be built as flight hardware because they will be used by manned-crews in space. However, there are vast differences between spacecraft and planetary bases in terms of the resources available for farming and in the constraints that must be accommodated. Therefore, farming in space will be conducted in controlled environment chambers of varying sizes and power demands depending on the amount of local resources available. These chambers will provide programmable levels of light, air temperature, relative humidity, and carbon dioxide. They will also provide adequate ventilation and automated water/nutrient delivery systems to sustain plant growth.

Space Farms on Spacecraft

Space farms in microgravity will most likely be constrained to supplementing the dietary requirements of crews during short-term missions (MacElroy et al., 1992). Spacecraft like the ISS offer limited volume, mass and power for farming. Small payload launch masses of current heavy lift vehicles and an inefficient power supply by arrays of solar cells impose spartan resources for food production. Thus, resources are primarily used for crew life support and maintaining the spacecraft in a stable orbit. Little crew time for processing and cooking crops is likely so that initial efforts at space farming will probably provide just a few fresh foods; this concept has often been referred to as a salad machine (MacElroy et al., 1992). Salad crops (i.e. lettuce, radish, tomato, carrots, onions, and cabbage) that can be picked by hand and eaten fresh are prime candidates for supplementing crew diets in microgravity. The Vitacycle is a prototype greenhouse concept for microgravity (Berkovich et al., 1997). It consists of a rotating inner cylinder containing ten plant troughs where plants are seeded periodically and harvested after 30 days. The rotating cylinder is contained within a lamp bank housing arranged in the shape of a spiraling cylinder, which holds lamps 8cm over the first plant trough and 30cm over the tenth trough. The light level is 270 μmol m^{-2} s^{-1}, the lighting area is 1.1 m^2 and the planted area is 0.48 m^2.

Space Farms on Planetary Surfaces

In contrast to space vehicle systems, planetary bases are envisioned as being composed of large modules where larger growing areas and potentially larger power budgets could be available. In this case, more conventional controlled environment farming of staple crops (wheat, soybean, potato, sweet potato, and rice) could be sustained, provided there is adequate lighting either from direct solar light, or electric lighting systems. However, use of electric lighting systems would require sufficient power, which may be supplied by nuclear power plants. These bases would have the added benefit of some gravity, e.g., 1/6 g on the Moon or 1/3 g on Mars. Gravity makes the use of hydroponic systems more feasible by providing gravity-driven drainage capabilities, alleviating such problems as the degassing of fluids in microgravity and the need for triple containment of water in space vehicles, and allows better moisture distribution near the roots of the crops (Wright et al, 1988). In addition, planetary bases can make use of important local resources such as regolith, water (on Mars and possibly the poles of the Moon), and CO_2 (Mars), which all defray some of the energy and mass costs required for farming in space. Regardless of the location, the future space farm will have to accommodate many of the mass and volume constraints imposed on current flight experiments and technologies designed for STS and ISS missions.

Another environmental factor that must be considered for space farming systems is the total atmospheric pressure. Reduced pressures can reduce gas leakage and structural mass costs for both vehicle and surface systems (Andre and Massimino, 1992), but the ability to manage environments at low pressure and thorough understanding of its effects on plants (crops) are needed. Several studies have shown that plants can grow well at reduced pressures, but that transpiration rates can increase (Andre and Massimino, 1992; Daunicht and Brinkjans, 1992). If very low pressures are used, e.g., <50 kPa, then human access to the plant growing areas would likely require some protective suits or assistance. In spite of this, it still might be advantageous to use such low pressure for economic reasons, and lower pressure structures may use transparent materials for direct solar lighting; in other words, increase the potential for building "greenhouse" like structures (Wheeler and Martin-Brennan, 2000). Maintaining adequate O_2 levels for the plants at reduced pressures may pose a challenge, particularly for managing the root-zone. Likewise, the tendency for higher evaporation rates and reduced ability to convectively transfer heat may pose challenges for maintaining acceptable humidity and temperature control.

DESIGNING THE SPACE FARM

Flight hardware is built to ensure crew safety and to operate reliably. However, power, mass, and volume constraints, as well as limited crew time dedicated to spaceflight-rated plant growth systems can indirectly affect their performance because limited resources constrain engineering solutions available to the designers of these systems. Furthermore, these payloads must also provide atmospheric control of CO_2 and ethylene, and adequate ventilation and cooling, which are necessary in an optimal environment conducive to stress-free plant growth.

Several tenets for designers of life support systems for the space environment were identified recently (Graf et al., 2001). Among the numerous challenges in developing microgravity-compatible life support equipment, the lack of buoyancy-driven convection is prominent because it impacts processes utilizing phase separation (solid, liquid, and gas), heat transfer. Other challenges are the requirements for triple containment of loose particulate matter and liquids and for noise reduction hardware (i.e. mufflers) to protect the crew. Heat transfer and heat rejection are probably the most important of these factors because most life support hardware generates large amounts of heat (i.e. motors, pumps, lamps, computers) that can be coupled to circulation loops of cooled liquid (when available). The heat rejection system will always represent a significant portion of a flight environmental control system and will consume much of the available power when precise thermal control is required. Typically, high cabin air temperatures result in spacecraft because most heat is dissipated into cabin air, and temperatures within the hardware can be several degrees above that due to poor heat rejection (Graf et al., 2001).

Many of these tenets were utilized in the design of the Biomass Production System (BPS). This plant growth hardware was designed by Orbitec (Madison, WI) and was used during the Photosynthesis Experiment and System Testing and Operation (PESTO) spaceflight experiment launched on STS 110 to the ISS and returned to Earth on STS-111, a 73-day mission. This mission represented an incredible opportunity to test the performance and integration of several hardware components, as well as for implementing numerous science protocols. The knowledge gained during the PESTO experiment suggests that the following tenets also need to be incorporated into future designs: 1) use of multiple redundant chambers to maximize both yield and allow for the necessary flexibility to deal with anomalies, 2) crew accessible ports for maintaining critical systems (e.g. for repriming humidity control systems or for replacing fans), 3) redundant fans and circuitry for ensuring that airflow is not interrupted, 4) anemometers for monitoring the amount of ventilation in the chamber, 5) infrared temperature sensors or cameras for monitoring plant temperature, and 6) modifying current NDS systems for controlling root zone temperature. The implementation of these additional tenets would increase hardware reliability, which can directly affect optimal plant growth, as well as assure that maximum crew time could be allocated to science related operations such as planting and harvesting.

Other design tenets stress thorough testing of individual components as well as integration of the entire system prior to flight. This ensures that sensors, software, and control systems operate reliably because of the limited availability of crew time for maintaining a flight system or changing software in space. Maintaining small experiments in space is frequently more expensive than the total cost for designing and manufacturing the flight hardware itself (Graf et al., 2001). These concerns also extend to the need to minimize consumables because of the large costs for resupply from Earth. Considering human factors and human interfaces early in the design is also important, since humans and hardware are typically in close proximity within the spacecraft. Another important factor affecting mission success is testing communications and interactions between teams of scientists, hardware developers, payload managers and mission managers. This last tenet is often overlooked although it plays a central role in the day to day planning of the mission because it impacts crew time allotment and the time required to repair and mitigate the impact of hardware anomalies that may arise.

DESIGNING ROOT ZONES (NUTRIENT DELIVERY SYSTEMS) FOR SPACE

The Aeronautics and Space Engineering Board (ASEB, 1997) evaluated programs that will apply to NASA's long-term goals and the eventual human exploration of space. Recommendation 2-13 (p. 53) explicitly states that "plant research should focus on resolving issues unique to growing plants in controlled environments for space applications. Some of these issues include optimization of environmental conditions during different periods of plant growth to increase production efficiency as well as techniques for providing aerobic, well- watered root zones to reduce plant stress". Adequate root zone aeration ensures that soil structure does not limit root respiration through a reduction in the oxygen supply to the external surface of plant roots (Lemon, 1961). The oxygen concentration in the root zone environment is determined by the supply of oxygen to the rooting media and the consumption by roots and microbial populations in the rhizosphere. In agricultural systems, both supply and consumption vary with soil type, water status, crop, root zone temperature, and organic content (De Willigen and Van Noordwijk, 1984).

It is well known that flooding the air-filled pore space of soil results in roots suffering severe oxygen deficiency. Prolonged flooding reduces growth and causes epinasty, leaf chlorosis and death, and the development of adventitious roots near the water line. Root elongation stops and mineral absorption are also reduced (Kramer and Boyer, 1995). Although injury to roots in flooded soil has been attributed to the accumulation of products of anaerobic respiration (aldehydes, organic acids, and ethanol), acidification of the cytoplasm is probably responsible for injury in root tips in response to hypoxia. Hypoxia can be common at ambient oxygen concentrations, especially in large diameter meristems, and can be detected by measurements of metabolic indicators of hypoxia such as alanine, ethanol, lactic acid, and elevated activities of ADH and pyruvate decarboxylase (Bidel et al., 2000).

Plant stress is often avoided in NASA crop yield ground studies in recirculating hydroponic systems (Wheeler et al., 1996), but these systems are difficult to implement in microgravity (Wright et al., 1988). Hydroponic nutrient delivery systems (NDS) are more appropriate for planetary surface applications because they are more massive (i.e. pumps, tubing, large water volumes) and are susceptible to fluid handling problems (i.e. gas-liquid phase separation) in microgravity. A major concern to designers of microgravity plant growth systems is simultaneously providing plant roots with ample water and oxygen. Because of the triple containment requirements of liquids that must be met to prevent the release of water into the cabin environment of manned spacecraft, substrate-based NDS that supply water on-demand have been used in space.

Solid substrates are currently preferred for long-term flight experiments because they provide a large specific volume for water transfer to the root zone, and can be made mechanically simple and reliable. Avoiding plant stress caused by poor aeration of the root zone has proven a difficult task to achieve in these systems; however, the shallow, substrate-based NDS system used in the PESTO experiment has demonstrated that high germination rates and stress-free plant growth in microgravity can be achieved reliably and repeatedly.

Planetary Surface: Hydroponic NDS Systems

Crop performance in recirculating hydroponic systems is strongly dependent on dissolved O_2 concentration (DOC), pH, and nutrient content of the hydroponic solution. Dissolved O_2 concentration is strongly dependent on solution temperature and flow rate near the root zone, as well as on the growth rate of the crop, and may be influenced by the bacterial community present in the solution (Monje, Garland, and Stutte, 2000). Solution temperature determines the solubility of O_2 in water, which is 10 mg/L at 15°C and decreases to 6.9 mg/L at 35°C.

Control of solution temperature may become a limiting factor in these NDS systems when the solution volume is minimized to reduce overall system mass. As solution volume decreases, the solution temperature may increase due to heating by the pumps employed to circulate the solution. Significant reductions in mass are possible by reducing the height of the solution bathing the root zone, as exemplified by systems using the nutrient film technique (NFT). In space, smaller volumes are preferred, but shallow root zones can become very dense and limit solution flow rates. These factors may lead to the development of anaerobic pockets where N losses by denitrification can take place, but yield reductions will not occur while the DOC being supplied to the rootzone is above a critical threshold of oxygen supply (Lemon and Wiegand, 1961; Letey et al., 1962). Bacterial communities may also compete with plants for the same pool of DOC, especially when the NDS is used for recycling gray water streams.

Microgravity: Substrate-Based NDS Systems

Substrate-based NDS systems (Figure 1) are simpler than aeroponic or hydroponic systems for use in space because they avoid many fluid-handling problems encountered in microgravity (Peterson *et al.*, 1991; Dreschel and Sager, 1989). On Mir, wheat was successfully grown from seed to seed to seed using the Balkanine substrate of the Russian SVET Greenhouse (Sychev et al., 1999; Levinskikh et al., 2001). However, avoiding plant stress caused by poor aeration of the root zone has proven a difficult task to achieve in these systems, as evidenced from measurements of alcohol dehydrogenase (ADH) activity, an indicator of root zone hypoxia (Porterfield et al., 1997a). ADH activity was significantly higher in spaceflight roots of Arabidopsis (CHOMEX-3 and CHROMEX-5; Porterfield et al., 1997b), wheat and Brassica (Astroculture-4; Morrow et al., 1995; Porterfield et al., 2000b) when compared to ground controls.

Nutrient supply is further simplified in substrates because nutrients can be provided by either a nutrient solution or may be present in the solid substrate. The use of nutrient-rich substrates or slow release fertilizers avoids the need to supply a complete nutrient solution to the root modules because transpired water can be recycled into the root module. Thus, crew time to mix fresh replenishment solutions or the need to recirculate the solution in order to prevent development of low nutrient patches in the media are avoided.

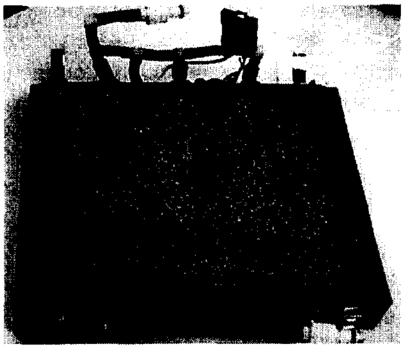

Fig. 1. Substrate-based BPS root module containing 1-2 mm arcillite/Osmocote mix. Water is delivered through porous tubes made of sintered metal.

Water for most space substrate-based NDS is delivered through porous tubes made of sintered metal (with pores ranging from 2-30 μm) or through drip irrigation tubing. The substrates most commonly used in recent flight experiments have been nutrient zeoponic and a mixture of arcillite with Osmocote (14-14-14 N-P-K slow release fertilizer), because they provide the necessary nutrients for plant growth. A major difference between these two nutrient-rich substrates is that zeoponic substrates provide ammonia-N, and arcillite/Osmocote mix provides both ammonia-N and nitrate-N (Goins et al., 1997b).

The particle size of the substrates used in space has ranged from <0.5 mm to >5 mm., although the most commonly used particle sizes in spaceflight experiments have been 0.5-1 mm (zeoponic) and 1-2 mm (arcillite). The smaller particle sizes have higher hydraulic conductances, however, they require the NDS systems to operate at greater suction (lower matric potentials) and they also have lower air-filled porosity (Jones and Or, 1998a). The matric potentials used to grow plants in recent and ongoing experiments range between –0.5 kPa and –0.3 kPa; however, the volumetric moisture content in the root zone will depend on the hydraulic properties and the pore size of the substrate used.

Nutrients

The amount and type of nutrients present in a substrate-based NDS may have a large impact on plant growth. Ground studies conducted at the Kennedy Space Center (KSC) in support of the PESTO ISS flight experiment have measured the nutrient levels in the substrate-based NDS of the Biomass Production System. The seed germination of wheat cv. SuperDwarf was found to be sensitive to the concentration of slow release fertilizer (Osmocote) in the media (Figure 2). A 30% increase in germination was obtained as the Osmocote concentration was reduced from 15 g/L to 5 g/L (Stutte et al., 2000). In other ground studies at KSC, biomass production of spinach and radish in zeoponic substrate was lower than in hydroponic systems fed with nitrate-N (Goins et al., 1998). In contrast, lettuce was not affected by N-form. The reduction in growth was attributed to a decrease in root zone pH below 5.0, caused in response to the predominantly NH_4-N form in the zeoponic substrate (Allen et al., 1995). These effects of lower pH on crop growth may have also occurred because pH was not controlled in these studies (Muhlestein et al., 2000). The increased NH_4-N form was also responsible for increased tillering of wheat grown in zeoponic substrates (Goins et al., 1997b).

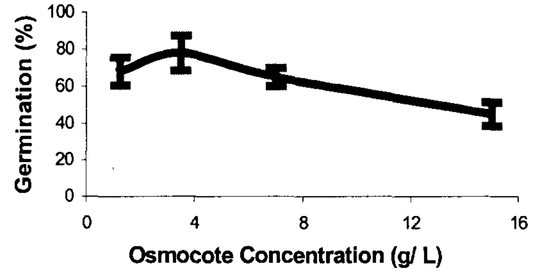

Fig. 2. Germination of wheat cv SuperDwarf is sensitive to the Osmocote (slow release fertilizer) concentration in arcillite.

Moisture Distribution in Root Modules in Microgravity

Studies conducted in substrate-based root modules deployed in space have led to great insight into fluid behavior in porous media (Jones and Or, 1998a; Jones and Or, 1998b; Podolsky and Mashinsky, 1994). The wetting and drying substrate water retention curves in Balkanine, a nutrient-charged zeoponic substrate, were characterized, and soil moisture data from the SVET root module was used to model and compare water distribution between microgravity and 1g (Figure 3). In space, water distributes in concentric circles around the water supply tubes due to capillary forces. In 1g, water drains to the bottom of the root module due to the pull of gravity. Measurements of canopy evapotranspiration on Mir using an open gas exchange system indicated that stomata of plants did not close at night in microgravity (Monje et al., 2000b; Monje et al., 2000c). This behavior has also been observed with well-watered plants growing in hydroponics at 1g (Monje and Bugbee, 1996). These results suggest that moisture distribution within the substrate-based NDS in space approximates the moisture distribution of a hydroponic system in 1g.

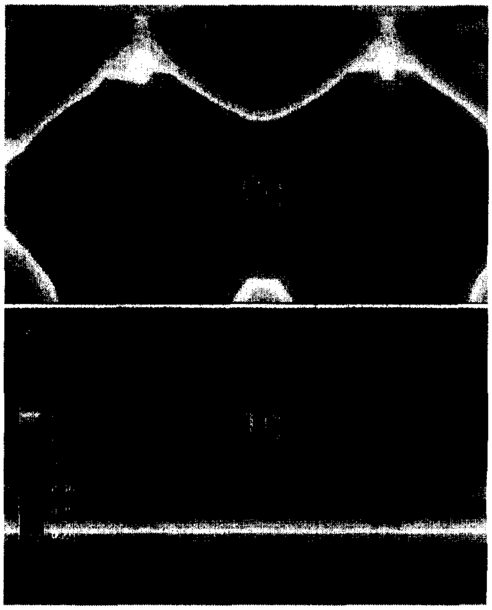

Fig. 3. In space, water distributed in concentric circles around the water supply tubes (black circles) due to capillary forces. In 1g, water drained to the bottom of the root module due to the

Jones and Or (1998b) hypothesized that fluid behavior in porous media in microgravity is significantly different than at 1g because capillary forces dominate in microgravity. As water content increases in the substrate, a water film forms around the surface of the substrate particles. This effect is shown schematically in Figure 4 for an ideal pore in a capillary tube. Basically, as the pore wets at 1g, the pore-space fills from the bottom because gravity pulls the water to the bottom of the pore, causing the wetting front to sag. In this case, gravitational forces are greater than surface tension forces and the water film around the particles remains thin. Oxygen diffusion via interconnected pore-spaces is possible until the pore-space becomes completely filled and the air-filled porosity becomes zero. In microgravity, surface tension forces dominate and surface films thicken during wetting; however, the pores may seal before air-filled porosity goes to zero, trapping air bubbles. The pores with trapped air can quickly become O_2 deficient due to root metabolic consumption, and can also reduce the saturated conductivity (K_s) of the media because much of the surface area for water flow is reduced. Another consequence of this process is that the substrate becomes effectively saturated at lower substrate moisture contents, thereby cutting off oxygen diffusion into the substrate at much lower water contents compared to 1g. This hypothesis for fluid behavior in porous media in microgravity suggests that models of oxygen diffusion in substrates calibrated with ground-based measurements may give erroneous predictions in microgravity, and that plants may be waterlogged if grown with ground-based control settings (Jones and Or, 1998a). This possibility will be tested by the WONDER flight experiment (Levine et al., 2002).

Moisture Control Systems

Several approaches have been used to control root zone moisture in substrate-based NDS systems. The basic control scheme used to date has been the "on-demand" watering scheme, whereby moisture levels in the root zone are measured and enough water is supplied to maintain a constant matric potential. Monitoring of soil moisture has used either pressure sensors or heat-pulse moisture sensor arrays.

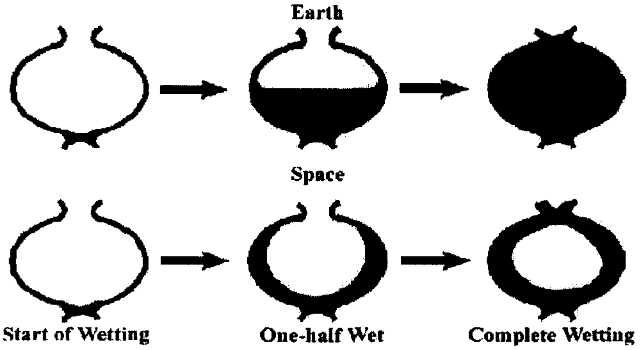

Fig. 4. Differences in wetting of porous substrates in 1g compared to 0g could be explained by pockets of trapped air in 0g. The trapped air would significantly reduce saturated hydraulic conductivity, but may also modify oxygen availability in 0g.

Pressure Sensors

Moisture content can be deduced from measurements of the matric potential in the media. Pressure sensors are currently being used to sense moisture in the root modules of Astroculture and Biomass Production System (BPS, Orbitec) flight hardware. In these systems, the tension measured within the porous tubes used for water delivery is assumed to be in equilibrium with the water potential of the bulk media (Morrow et al., 1993).

Pressure sensors can also be used to fabricate micro-tensiometers, whereby a ceramic cup connected to a pressure sensor through a water-filled tube is placed in contact with the substrate. At equilibrium, the suction inside the tensiometer equals the substrate matric potential. An array of tensiometers is included in the sensor package of the LADA greenhouse. LADA was jointly developed by the Institute of Bio-Medical Problems (IBMP, Moscow) and the Space Dynamics Laboratory/ Utah State University and consists of a 9cm deep root module and a

16x20x26 cm tall leaf chamber. The LADA is scheduled for launch to ISS on a Progress rocket in October 2002. During a 30-34 day mission, LADA will provide mizuna (Brassica rapa cv. Nipposinica) for crew consumption and fresh material for return to Earth, as well as produce a soil water characteristic curve in microgravity using micro-tensiometers and heat-pulse soil moisture probes.

In ground studies with a small particle sized substrate, it was found that high transpiration demand at high light levels caused the matric potential of the media to be lower than the pressure measured within the porous tubes (Steinberg and Henninger, 1997). This effect may be reduced at lower light levels because of reduced transpiration loads, or in media with larger particle size (1-2 mm) because less negative tensions are required; however this assumption has not yet been validated in microgravity. Preliminary observations aboard the ISS during the PESTO experiment have shown that a substrate-based NDS system using a single pressure sensor to monitor and control matric potential was successful in providing excellent germination (>95%) and growth of wheat in shallow (3 cm deep) root modules.

Moisture Sensor Arrays

Vigorous plant growth was observed in microgravity when the moisture distribution of the growth media was monitored and controlled (SVET Greenhouse experiments on Mir; Bingham *et al.*, 1996ab, Bingham *et al.*, 1997). Many of the poor aeration problems associated with substrate-based systems in early flight experiments may have been reduced through improved water management afforded by the use of an array of heat-pulse moisture sensors (Bingham, et. al., 1996a, 1996b, 1997; Yendler 1996). In SVET and in the recently developed LADA greenhouse system, an array of heat-pulse sensors measures moisture distribution throughout the substrate, however, the spatial resolution depends on the number of sensors present. This is a reliable technology; however, sensor placement was identified to be important during the spaceflight experiments on SVET (Salisbury, 1997). For example, some of the moisture sensors read 'wet' when placed near a wick even though the media (3-5 mm Balkanine) was dry due to poor hydraulic conductivity.

The heat-pulse moisture sensor consists of a temperature transducer (AD590) and a resistive heater embedded in thermally conductive epoxy resin. A 20 second heat pulse is applied and the measured temperature rise depends on the moisture content of the media in contact with the sensor. As more water is present, the media has a greater thermal conductivity and a smaller temperature rise is observed. The moisture level is measured in kg water per kg of air-dried substrate. This moisture level is used to calculate volumetric moisture content using the substrate bulk density (Yendler et al., 1995). During the Greenhouse-2 experiment, an array of moisture sensors provided root module water content, that together with measurements of canopy transpiration, were used to develop a total water balance in microgravity (Monje et al., 2000c).

Moisture can also be measured using time domain reflectometry (TDR), which is based on the propagation of a high frequency electromagnetic wave along a line waveguide (Topp et al., 1980). The velocity of propagation of the wave depends on the dielectric constant of the substrate and is related to the moisture content. However, this technology has not been used in flight experiments because the high frequency wave used may interfere with spacecraft communications.

Oxygen Sensors

Root zone oxygen was not measured in the CHROMEX or Astroculture flight experiments, so the exact oxygen concentrations in the root zone responsible for the observed increases in ADH activity in response to hypoxia are not known. The evidence for root zone hypoxia has prompted the evaluation of two types of oxygen sensor technologies for use in space. The first is the electrochemical oxygen sensor, which consists of a thin layer of electrolyte held between an anode and a cathode. The electrolyte is protected by a thin Teflon diffusion barrier that prevents the electrolyte from drying out and controls the rate of oxygen diffusion into the cell. The operational lifetime of the electrochemical oxygen sensors is determined by the rate of diffusion and by the volume of electrolyte present. The LADA instrument package includes an electrochemical oxygen sensor to measure root zone oxygen.

The second oxygen sensor technology evaluated for use in space is the root oxygen bio-availability (ROB) sensor (Porterfield et al., 2000a), however, this sensor technology is still in its initial stages of development. The ROB sensor is an electrochemical oxygen sensor that can be designed to have the same size, shape, and oxygen consumption as does a living root. These characteristics make the ROB sensor sensitive to changes in oxygen bioavailability. The sensor can readily measure gravity dependent, buoyancy-driven convective oxygen transport as well as indicate and quantify when the environment becomes limited to diffusive movement of oxygen from the bulk media into roots (Monje et al., 2000a). The sensor lifetime may be extended beyond the lifetime of conventional electrochemical oxygen sensors because the ROB sensor consumes oxygen only when power is supplied. This feature makes this sensor well-suited for space applications because it may reduce the need for replacement during extended missions.

SPACECRAFT-SPECIFIC ENVIRONMENTAL FACTORS

Several spacecraft-specific artifacts caused by the altered behavior of fluids and gases in microgravity or by super-elevated CO_2 and ethylene-enriched atmospheres may confound plant experiments in space (Musgrave, 2002). These artifacts can affect above- or below-ground plant organs and metabolic processes resulting in plant stress and poor growth (Porterfield, 2002; Monje et al., 2000b). Understanding the causes of these artifacts is essential to the design of future flight experiments in order to provide a stress free growth environment in space. Furthermore, identification of these artifacts is needed for conducting appropriate ground control experiments, although some of these artifacts may not be reproducible on the ground. Musgrave (2002) presents an excellent review of previous attempts to grow plants through complete life cycles in flight-rated plant growth chambers. Studies of seed germination and plant reproduction in space point to the importance of the gaseous environment in microgravity, which is strongly dependent on adequate ventilation and provision of CO_2 to sustain plant growth. Although plant development, flowering, pollination, and early seed growth proceed normally in space when adequate ventilation is provided via forced convection, major changes in storage reserves were observed in spaceflight. These factors can impact the vigor and the nutritional quality of seeds from space plants (Musgrave et al., 1997).

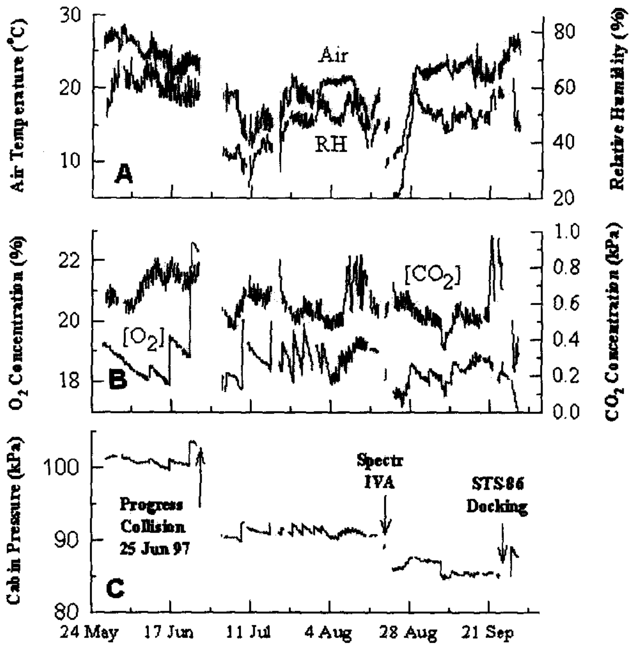

Fig. 5. Fluctuating air temperature and relative humidity (A), oxygen and carbon dioxide concentrations (B), and cabin pressure in Mir from May to September 1997.

Spacecraft Cabin Atmosphere

The cabin atmosphere of spacecraft can be very dynamic. Aboard the Mir orbital station, large fluctuations in air temperature (10-20C), relative humidity (15-20%), O_2 (2-3%) and CO_2 concentrations (2,000-10,000 ppm), and cabin pressure (15-20 kPa) were measured (Figure 5). Elevated air temperatures can result in increased root zone temperatures, and therefore, a higher O_2 demand for respiration (Lemon and Wiegand, 1961), unless root zone temperature is controlled. Elevated CO_2 increases plant biomass and may alter plant transpiration through direct effects on stomatal conductance (Wheeler et al., 1999).

Ethylene, a plant hormone, and other volatile organic compounds (VOCs) are commonly found in spacecraft (James et al., 1994). Ethylene in spacecraft is off-gassed from plastic materials, generated from decaying fruits in garbage bags, or produced by plants themselves during their development (Stutte and Wheeler, 1997; Wheeler et al., 1996). Spacecraft are closed systems and these VOCs can accumulate to biologically active concentrations if they are not controlled. High ethylene concentrations (0.6-1 ppm) aboard the Mir orbital space station caused the production of sterile (seedless) wheat heads during longterm experiments conducted in the SVET greenhouse (Salisbury, 1997). This event has prompted experiments to determine the sensitivity of staple crops (wheat and rice; Klassen and Bugbee, 2002) and salad crops (radish; Eraso et al., 2001) to ethylene exposures. The ISS atmospheric control system maintains ethylene concentrations below 50 ppb, but these studies have shown that even these low concentrations can significantly reduce crop yields.

Boundary Layers

Boundary layers are undisturbed (or stagnant) layers of air surrounding plant organs. Gases, such as CO_2 and water vapor, must diffuse through these boundary layers when passing between the bulk air and plant organs. At 1g, the bulk air surrounding these plant organs is turbulent and well-mixed due to the presence of thermally-driven (buoyant) convective heat exchange. In leaves (Figure 6 top), boundary layer depths depend on wind velocity (forced convection) and the shape of the leaf, and are thin enough so that metabolic processes like respiration and transpiration are rarely diffusion-limited.

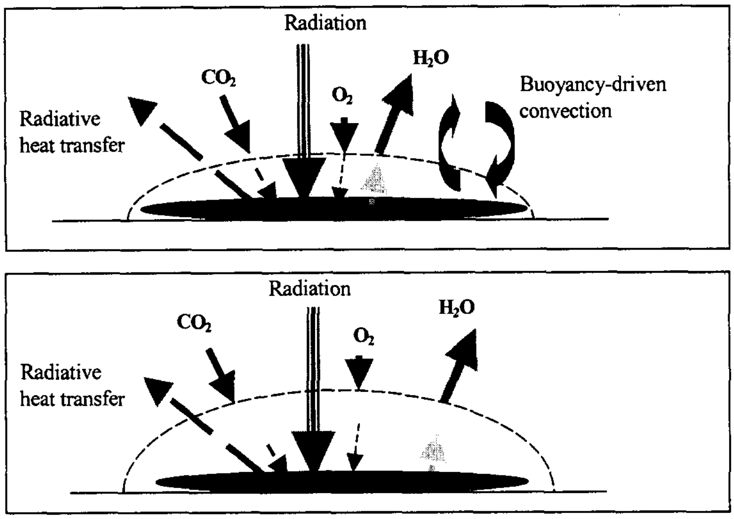

Fig. 6. On Earth (1g, top), buoyancy-driven convective mixing causes boundary layers around plant organs to be smaller than in microgravity (bottom). At 1g, the boundary layers are thin enough so that metabolic processes like respiration and transpiration are rarely diffusion-limited.

In microgravity, the absence of buoyancy-driven convective mixing can allow development of layers of stagnant air that restrict the replenishment of gases consumed by metabolic activity. Thus, the lack of convective mixing in space may cause large boundary layers to surround plant organs with different levels of O_2, CO_2, water vapor, and sensible heat compared to conditions at 1g (Figure 6 bottom). Porterfield (2002) developed a model to calculate oxygen transport through boundary layers in both gravity and microgravity. He concluded that inhibiting gravity-mediated oxygen transport may lead to severe biophysical limitations in O_2 availability, which may explain many hypoxic and physiological responses of plant tissues observed in past spaceflight experiments. Poor air circulation due to increased boundary layers is believed to have caused the reproductive failure observed during CHROMEX 4. Short exposures (2 hrs) to low oxygen concentrations during certain development stages can cause reproductive failure. Increasing the circulation around the plants in CHROMEX 5 resulted in the start of normal seed development in space (Musgrave *et al.*, 1997).

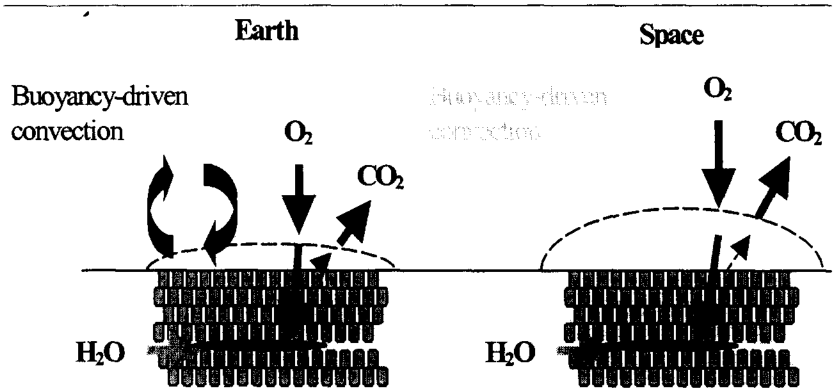

Figure 7: The lack of buoyancy driven convection in microgravity essentially caps off the root zone from O_2 re-supply as boundary layers increase compared to 1g.

The effect of boundary layers on heat exchange and transport processes was tested in parabolic flights aboard the KC-135 aircraft. These tests were part of the risk mitigation studies for the PESTO experiment (Monje et al, 2000a). Both thermal transport around the aerial leaf tissue and oxygen transport within the rooting matrix decreased in phase with changes in gravity. Leaf temperatures measured with infrared transducers increased during periods of microgravity without forced convection, but remained near air temperature when forced convection was present. This result suggests that convective heat exchange is a significant factor for cooling leaves in 1g, and that forced convection must be used to ameliorate the lack of convective mixing in microgravity. In the same KC-135 experiments, the ROB oxygen sensor in moist substrate (Porterfield et al., 2000a) measured decreased oxygen bioavailability in microgravity. These results suggest that larger boundary layers also form in the shoot-to-root zone interface when convective mixing is no longer present in microgravity, which essentially caps off the root zone from turbulent resupply from the air above (Figure 7). Thus, re-supply of O_2 consumed by plant roots in microgravity would occur through diffusion processes alone. Plant roots would become hypoxic whenever the rate of root respiration exceeded the rate of mass transfer of oxygen to root meristems, where respiration takes place.

LIGHTING SYSTEMS FOR SPACE FARMS

Perhaps the most energy intensive subsystem of a space farm is the lighting system (Salisbury and Bugbee, 1988). Plants on Earth have evolved to convert light into the chemical energy via the process of photosynthesis. The amount of light available to a crop determines its daily crop growth rate, which summed over the life cycle of the crop determines the total amount of plant biomass produced (Bugbee and Monje, 1992). In addition to being the energy source for photosynthesis, light spectral composition regulates many photomorphogenic and phototropic aspects of plant development and morphology (Smith, 1982; Kendrick and Kronenberg, 1994). Although only 1% of the incident solar radiation on the Earth is converted into biomass, modern agriculture has been able to feed billions of humans for tens of thousands of years because the source of energy is freely available. In contrast, space farms may have to generate all the light required for crop production from electricity. Thus, food production is severely constrained aboard power-limited spacecraft with only solar cells or fuel cells for producing electricity. These limitations may be reduced in farms located on planetary surfaces, where electricity generated by nuclear power may be used to drive lamp-based lighting systems and lamp systems might be supplemented by sunlight.

Current electric lamps are 15 to 35% efficient in conversion of electrical energy to light, but promising technologies with sources such as light emitting diodes (LEDs), microwave lamps, solar collectors, light pipes, fiber optics, and holographic distribution systems offer the potential to improve these numbers. Testing of new technologies will include quantifying photosynthetically active radiation (PAR) from lamps, finding lamps with longer operating lives, quantifying radiant conversion efficiencies, and evaluating photosynthetic efficiencies and plant growth under the different lamps to define the system efficiency. In plant growth chambers, popular choices for electric lighting technologies include various high-intensity discharge (HID) and fluorescent lamps.

High-pressure sodium (HPS) HID lamps demonstrate a relatively high efficiency for converting electrical power into PAR when compared to other conventional lighting sources (Sager et al., 1982). However, the spectral quality of the HPS lamp is relatively low in the blue wavelengths, which can cause undesirable photomorophogenic development of certain plants (Wheeler et al., 1991; Yorio et al., 1995). Fluorescent lamps meet most spectral requirements for plants in terms of photosynthesis and photomorphogenesis when compared to plants grown under natural light (Smith, 1982). However, the conversion efficiency of electricity into light for fluorescent lamps is usually lower than that of conventional HID lamps (Sager et al., 1982). The relatively short lifetime of fluorescent lamps could potentially become a major drawback for utilization in missions involving extended plant culture. Light-emitting diodes (LEDs) have several appealing features for space applications, including low levels of thermal radiation that can heat the plant growing area, no gas-filled lamps, no hot electrodes, no high-voltage ballasts, and a very long operating life in comparison to HID or fluorescent lamps (Bula et al., 1991). Moreover, implementation of LED arrays instead of conventional lamps may increase crew safety and working space. Red and blue LEDs have great potential for use as a light source to drive photosynthesis due to their output near the peak absorption regions of chlorophyll. Previous research has shown that red LEDs supplemented with blue light can adequately support various crop plants (Brown et al., 1995; Goins et al., 1997; Hoenecke et al., 1992).

Plants are adapted to utilize a wide-spectrum of light to control photomorphogenic responses. Both red light, via phytochrome, and blue light, via blue/UV photoreceptor(s), are effective in inducing photomorphogenic responses (Cosgrove, 1981; Mohr, 1987). Previous studies showed that red-biased, blue deficient light sources increase plant internode length, stem length and leaf elongation (Barnes and Bugbee, 1992; Britz and Sager, 1990; Wheeler et al., 1991). Hence, for supporting optimal plant growth, the ideal combination of blue and red light is still a question.

In contrast to LEDs, the sulfur-microwave electrode-less lamp, (also known simply as the "microwave lamp") produces a bright broad-spectrum visible light (Ciolkosz et al., 1998). The bulb in a microwave lamp is a spherical quartz envelope filled with a few milligrams of sulfur and argon. The argon is weakly ionized using microwaves. The argon heats the sulfur into a gaseous state, forming diatomic sulfur molecules, which emit a broad continuum of energy as they drop back to lower energy states. According to reports by the manufacturer (Fusion Lighting, Rockville, MD), the microwave lamp technology produces a uniform visible spectrum similar to sunlight, but with very little undesirable infrared or ultraviolet radiation, and has a very high electrical conversion efficiency. The efficient high light output from the 1000-W microwave lamp makes it an ideal light source for light pipes and large plant growth chamber systems.

Currently plant experiments on spacecraft have employed fluorescent and LED based lighting systems to supply between 100-300 umol m^{-2} s^{-1} of photosynthetically active radiation (PAR) to small plant growth chambers (0.025-0.05 m^{-2}). New technologies are expected to boost these values to 1000 umol m^{-2} s^{-1} of PAR in chambers as large as 0.5-1.0 m^2. However, the near-term designs for ISS will be limited to 300 umol m^{-2} s^{-1} because of power limitations. Lighting systems for space farms capable of supplying growing areas of 20-40 m^2 per crew $member^{-1}$ are being developed using more energy demanding lamp systems (High Pressure Sodium, HPS; Metal Halide, MH; and microwave lamps).

Lighting System Integration Issues

The growth volume will most likely be limited in space-based controlled environments (Salisbury and Bugbee, 1988); therefore, overall plant growth area and chamber height are of critical importance for future considerations of lighting technologies. Several spatial arrangements (spherical, cylindrical, toroidal) versus the traditional planar arrangement between the lamp banks and the plants are possible, and these arrangements differ in how well the growth volume is utilized (Berkovich, 2000). A cylindrical arrangement was found to be optimal for use in small greenhouses. In optimized, continuous cropping systems, the spacing scheme between plants should change as the plants increase in size between transplanting and harvesting, which maximizes canopy light interception at all growth stages, no matter the lamp source. An engineering solution addressing this issue is the concept of the conveyor-type greenhouse, which was first developed by Russian physiologist Valeri Glevovich in the early 1960's (Yu. Berkhovich, personal communication). This concept has been developed into the Vitacycle prototype greenhouse concept (Berkovich et al., 1997).

HPS lamps act as point-sources of radiation as opposed to CWF and LED light sources, which are intrinsically more diffuse over the plant canopy as a result of lamp design and associated luminarie. The plant canopy under the HPS lamp sources can experience "hot-spots" and non-uniform intensity, especially directly beneath the lamp. Improved light distribution may be achieved by locating the lamp greater distances away from the canopy. However, small-scale plant growth chambers, such as the present designs of prototype space farms, often allocate limited area for mounting lamps. Likewise, current space-based plant growth chambers are usually designed with the light source mounted as close as possible to the plant canopy. Hence, there is a need for further development of focusing materials and diffusers, which will efficiently and evenly distribute point-source light over plant canopies. Current investigations in this area include research with focusing mirrors, prismatic reflecting films, holographic diffusers, and intra-canopy lighting using light pipes (Tibbits et al., 1994; Stasiak et al., 1998; Frantz et al., 2000) in combination with innovative lamp technologies and solar collectors (Mori et al, 1987; Olson et al., 1988; Cuello et al., 1998).

CONCLUSIONS

Space farming has a bright future now that the International Space Station nears completion. The ISS can serve as a platform where many subsystems, theoretical hypotheses, and designs for future plant-based life support systems can be tested. The knowledge gained in these experiments can be used to fuel the technological advances needed to improve current controlled environment systems until they become economically feasible when compared to conventional agriculture. This in turn will be used to provide continued life support to mankind on Earth and in future space colonies.

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