Chapter 18

On-Site Resources Availability for Space Agriculture on Mars

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18.1 Overview of Space Agriculture on Mars

Mars is the second target of our manned space flight next to the Moon, and possibly the most distant extraterrestrial body to which we could travel, land and explore within the next half century. The requirements and design of life support for a Mars mission are quite different from those being operated on near Earth orbit or prepared for a lunar mission, because of the long mission duration. A Mars mission must include at least 2.5 years for round trip travel, and a restricted opening of the launch window, both for forward and return flights once every two years. Precursor manned mission to Mars might be conducted with a small number of crew and a conservative life support system on the space ship. Once the scale of the manned mission is enlarged, an advanced bio-regenerative life support system provides an “economical” advantage over the open loop life support, based on cost comparison between the cumulative sum of consumables with the open loop system versus the initial investment for a recycling system. We further propose use of on-site resources to supplement loss of component materials in the recycling process. Reproducing recycling materials on an expanded scale is another advantage of the use of on-site resources for space agriculture.

In addition to producing foods, the function of biological and ecological systems in space agriculture can revitalize air and refresh water (Alling et al. 2005). An argument has been made for 100 % closure in the materials recycle loop, given the advantages of closed ecological life support over conventional life support in space. However, without having huge stock and sink in the loop, strong control is required to achieve full closure or such a system will be inevitably unstable. From an economical standpoint, investment or efforts to attain a higher degree of closure shall be compared to the amount of supplementary materials required to replace the dropped-out materials over the mission period. Space agriculture is based on “more than 100 % closure” by utilizing on-site resources. Full use of on-site resources may largely reduce required mass that must be transported from Earth, particularly for expansion of life support capability to increase number of crew for extended exploration on Mars.

In order to reduce the penalty of the heaviest mass of consumption, water is partially recycled even on the International Space Station orbiting Earth. Oxygen for breathing is generated by electrolysis of water. Carbon dioxide, a metabolic product, is removed by regenerative adsorbent chemicals. Food is supplied from Earth, and feces are dumped. The distance to Mars makes it costly and difficult to send all these consumables, so space agriculture should regenerate water, oxygen and foods from metabolic waste. Space agriculture will recycle most materials, but supplement deficient components if it is economical. We aim to enlarge the scale of agriculture on Mars through a reproductive process employing on-site resources.

Prior to habitation on Mars, a small expedition crew will need to transport all required materials from Earth. There would be several phases of exploration and habitation on Mars. Early phases will consist of accumulating system components and materials resources. The space agriculture phase will begin after more than 20 years of system operation, and will need about 100 people. Instead of describing the course of development from the beginning, space agriculture at the stage of 100 people and 20 years is explained first, followed by a scenario of phased development. We will conclude with the expected requirements for on-site resources, both energy and materials, to configure and operate space agriculture for sustainable habitation on Mars.

18.2 Building a Space Agro-Ecosystem on Mars

In an ecological system, there are three members, i.e., producer, consumer and decomposer. Humans are the top consumer in agro-ecosystems. Supplying food, oxygen, and water for humans is the primary issue in engineering space habitation (Yokota et al. 2006). The main producers are photosynthetic plants, which convert solar energy to a chemical form of energy fixed in their biomass. Plants in space agriculture also act as water distillers. Processed waste water gets transported through the plant body and evaporates from leaves. Decomposers are the bridge between the consumers and the producers, and drive materials recycling. Human waste and inedible biomass are composted by bacterial action, and used to fertilize the soil with nutrients for farm plants. If no substance or element drops out from the recycling loop, the same amount of food is regenerated with oxygen in a stoichiometric relation to the biomass revitalized. Plant transpiration ratio is the ratio between amount of water transpiration and photosynthetic fixation of energy, dry mass. This ratio can estimate quantity of water that could be recovered from air in the farming space. If food and oxygen are produced by plants to fill the requirements of people, the amount of water recovered from the air in the system must exceed 200 liters per person, the typical consumption by a person on the ground.

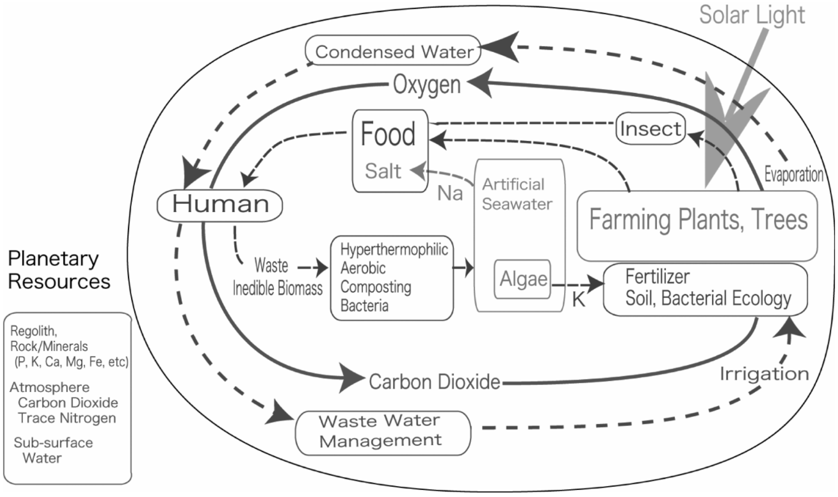

Fig. 18.1 Concept of space agriculture for habitation on Mars. On site resources are employed to make the system for more than 100% recycle possible (Yamashita et al. 2005b)

Three loops of water, oxygen, and food recycling are shown in Fig. 18.1 with major members of the agro-ecosystem on Mars. Planting trees is intended to help achieve the goal of "more than 100% closure," since ordinary crop plants produce returns to carbon dioxide and water after metabolic consumption. By keeping biomass not oxidized, oxygen is left as excess. Wooden lumber can also be used for housing interiors and other uses in the living compartment. Leakage of air from the pressurized structure of the habitat and farming sections can be replaced with excess oxygen. Such extra production of biomass is enabled with use of the on-site resource of carbon dioxide and water available on Mars. Another by-product of having trees on Mars is the ability to rear insects on tree leaves. The addition of insects to the human diet is recommended because the placement of the consumer in the food web determines efficiency of use of original energy resource fixed by photosynthesis. Given that only 10 % of biomass energy is converted with each to that of one step up in the ladder, the higher in the ladder, the less efficient the usage of energy. Insect as part of the human diet is chosen in this context given the desire to maximize energy-efficiency of conversion.

Though elimination of sodium in processed compost is somewhat peculiar to space agriculture, terrestrial agriculture is facing salination problems in many areas now. Space agriculture provides an extreme case of salination, because of high dominance of humans in its materials loop. We propose adding marine algae and salinity resistant plants to solve this problem.

Environmental control, including building pressurized greenhouses, is essential for operating agriculture on Mars, where atmospheric pressure and temperature are both incompatibly low for farming plants and animals. Figure 18.2 summarizes our design of environmental factors in the pressurized Martian greenhouse

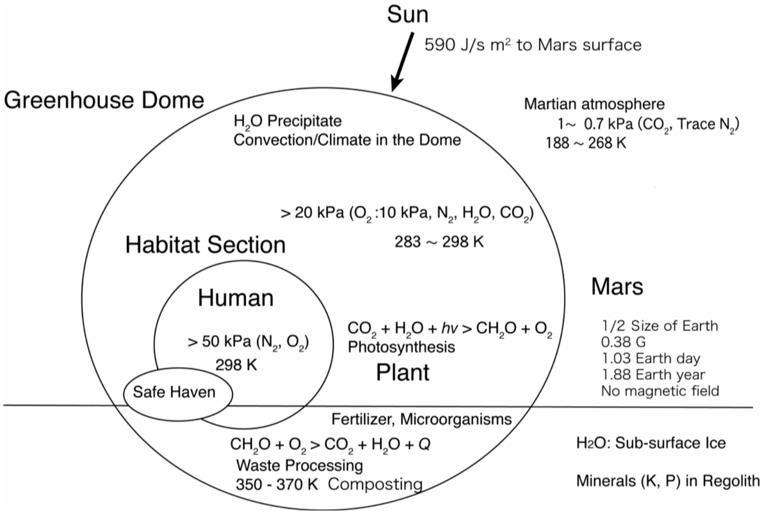

Fig. 18.2 Scheme of pressurized Martian greenhouse for space agriculture (Kanazawa et al. 2008)

structure. Pressure and the composition of the atmosphere inside the greenhouse are determined by the physiological requirements of plants. Goto et al. (2003) established a lower limit at 10 kPa of oxygen partial pressure for plant cultivation. They also showed enhanced permeation of oxygen through the seed sheath at reduced total pressure. By this enhancement, maturation of seeds was accelerated. Hinokuchi et al. (2005) and Levine et al. (2008) studied the lower limit of pressure for germination of plant seeds, and found most seeds germinate under 10 kPa of oxygen as well. For the fire safety concerns, total pressure is set to 20 kPa, balanced by inert nitrogen, together with carbon dioxide and water vapor at minor level (Yamashita et al. 2007).

Environmental conditions in the human living section were designed to meet the physiological and medical requirements for humans. A human living compartment is sectioned in the greenhouse and pressurized at a level higher than the rest of the greenhouse. Pressure in the compartment will be maintained higher than one half of Earth atmospheric pressure determined by the physiological requirements for humans. This cabin pressure would be set to higher value, if human productivity and amenity can be shown to improve with the higher pressure. Another consideration could be a pre-breathing protocol where an extra-living-section activity suit with lower inner pressure could be worn.

The highest altitude of ordinary living on Earth is around 4,000 m, where atmospheric pressure indicates 60 kPa. Many climbers require an oxygen cylinder at 8,000 m (35 kPa). In space agriculture on Mars, oxygen will be selectively transferred from the plant compartment to the sectioned human compartment using a physico-chemical membrane principle.

18.3 What to Eat on Mars

Even though the task of space agriculture is not limited to production of food, but includes the revitalization of air and water, the choice of farming species is the start of designing agriculture on Mars. The species should be selected on the basis of their nutritional content that will meet human requirements for a healthy life. Secondly, crop efficiency should be considered. Since both the area and the volume available for agricultural production on Mars are limited, the yield of crop species per unit area or per unit volume, per unit time, needs to be considered so that oxygen and food can be produced at a sufficient rate. Robustness of crop production might be further assessed, as survivability of agricultural plants is the top priority for life support on a distant planet. Several crop plant species were compared in this sense. Harvest of energy and protein is compared among species listed in Table 18.1. As an important variable for the comparison, required farming area was estimated from yield of crop, period of culture, and energy or protein content in crop. Amino acid score was an additional factor to be considered for the protein source.

Table 18.1 Evaluation of crop plant species. Modified from Katayama (2005).

Crop Plant	Yield	Period of Culture	Energy Content	Required Farming Area for Energy	Protein Content	Required Farming Area for Protein	Amino Acid	Mode of Reproduction
	kg/1000m^2	month	kcal/100g	2000 kcal/(daym^2)	g/100g	60g protein (m^2)	Score	
Rice	526	4	356	130	6.8	204	64	Wind pollination
Wheat	280	7	337	451	10.6	430	42	Wind pollination
Soybean	367	3.5	417	139	35.3	49	86	Insect pollination
Buckwheat	106	2.5	364	394	12.0	359	100	Insect pollination
Quinua	178	3	403	254	13.4	230	85	Wind pollination
Potato	3000	3	76	80	1.6	114	73	Vegetative propagation
Sweet potato	3180	5	150	64	0.9	319	83	Vegetative propagation
Cassava	7000	11	160	60	1.4	205	52	Vegetative propagation

Among major cereal crop species, rice (*Oryza sativa*) was found greatly superior over wheat (*Triticum aestivum*) and others. Modern agriculture improved yield of rice by developing proper use of fertilizer and agro-chemicals, and breeding high productive strains. Soybean (*Glycine max*) is an excellent species for providing protein, though its amino acid score is not perfect. Sweet potato (*Ipomoea batatas*) shows a higher efficiency for energy supply than potato (*Solanum tuberosum*). It also provides a sweet taste, and rich dietary fiber necessary for maintaining healthy digestive organs. Champion harvest data for Cassava (*Manihot esculenta*) exceeds sweet potato. Cassava is a quite tolerant species grown on less fertile soil.

Thus, in a space-based agro-ecosystem, the best combination of plant species to fill needs of metabolic energy, dietary fiber, protein and lipid are rice, soybean, and sweet potato (and cassava in part). In order to provide vitamins, and trace

Fig. 18.3 Model food materials to meet the nutritional requirements for one person a day. Rice 300g, soybean 100g, sweat potato 200g, green-yellow vegetable (Komatsuna) 300g, silkworm pupa 50g, loach fish 120g, and sodium salt 3g (Yamashita et al. 2007)

elements such as iron and calcium, a green-yellow vegetable such as Komatsuna (*Brassica camperstris* var. *peruviridis*) or equivalent is added to the original selection. The best composition of these four, in terms of nutrition, was determined by iterative process of computation to be 300g rice, 100g soybean, 300g green-yellow vegetable, and 200g sweet potato (fresh weight) per person per day. Criteria used for this selection were: total energy intake, amino acid score (Schaafsma, 2000), adequacy of supply of each nutrient, and the energy ratio between proteins, lipids, and carbohydrates. This combination of plant products does not, however, completely meet all nutritional requirements, as it is low in sodium and lacks animal-origin vitamins and fat such as B_{12} and cholesterols, and its amino acid content is not balanced. This is a common feature of plant-based diets. To overcome these deficiencies, sodium can be supplied in mineral form and the other problems can be addressed through supplying animal diet. Insects and fish are appropriate animal food sources in a space agro-ecosystem, given the limited area available for their rearing, and for efficient use of other resources to fill the nutritional requirements. A promising combination of the selected food substances is shown in Fig. 18.3 at an amount for one person per day.

18.4 Planting Trees and Eating Insects

Harvesting excess oxygen is the major purpose of growing trees on Mars. Wooden lumber may provide a more amenable interior for the living cabin compared to those made of metals and plastics. In order to make efficient use of bio-resources produced in space agriculture, it is essential not to downgrade bio-substances, such as combustion of bio-molecules of high entropy to produce heat, and oxidized molecules of carbon dioxide and water. If organic materials can be upgraded to substances for a use of higher priority, total efficiency of the materials loop can be improved. Converting inedible biomass to edible biomass is one “improvement” of the use of resource in space agriculture. For example, leaves of the mulberry tree are edible only at a young stage but are hard to eat after that. Mulberry leaves contain high protein compared to other plant species. Furthermore, silkworm larvae eat mulberry leaves, and their pupae can be eaten by humans. The advantage of eating insects is that food of animal origin can be provided with less competition with other major agricultural products.

18.4.1 Trees for Space Agriculture

Although trees have been quite common in our terrestrial life and used in many applications, wooden materials have never been employed for spacecrafts. The reason might be the high priority of safety and materials performance, rather than amenity for crew. Once mission duration exceeds a year, the choice of comfortable materials becomes essential for the refreshment of human spirit and provision of a less stressful environment. Thus wood production on-site will be beneficial for productive exploration and habitation on Mars, even though it requires extra area or space in the greenhouse.

A pioneering study by Nagatomo (2003) assessed the use of wooden materials for space ship or cabin based on fundamental properties of wooden materials. He also verified, with experimental evidence, the possibility of tree growth under hypobaric conditions, even as low as one-tenth of surface pressure on Earth (Nagatomo 2005). The use of wooden material can be expanded beyond providing excess oxygen, wooden cabin interiors, and insect rearing habitat. Wooden biomass can be converted to edible biomass, i.e., insect meat, by termites (*Macrotermes subhyalinus*). Culturing of wood-degrading fungi, such as Japanese mushroom (*Lentinula edodes*) or Jew's ear fungus (*Auricularia auricula*), is common in terrestrial agriculture. Vitamin D, a component deficit in the plant-based diet, is rich in these mushrooms, especially after the drying process and irradiation by ultraviolet light.

Trees are the largest living terrestrial organisms on Earth. Tree height is limited by gravity (Koch et al. 2004). Under reduced gravity on Mars, about 1/3 magnitude of terrestrial gravity, trees might grow taller. A similar phenomenon is the height of a Martian volcano, which is three time higher than Everest. Wooden plants may exhibit a physiological response to hypogravity, and reduce the production of hard components in the cell walls. Plants typically resist gravity by hardening cell walls to support their own weight. Resources allocated to hardening cell walls under normal gravity are directed to other functions when plants are exposed to reduced gravity (Hoson et al. 2002).

18.4.2 Eating Insects

Insects are a successful animal group, and about 70-75% of all animal species living on Earth are insects. They play an important role in recycling materials in the terrestrial biosphere. Furthermore, insects have been a good source of food for humans since early era, as evidenced by fossilized human feces. Because of wide availability of insects, insects have been eaten almost everywhere on Earth. Phylogenically, insects are closely related to shrimp, lobster, and crab which are commonly eaten (Mitsuhashi 1997; Katayama et al. 2008) and which have a taste and texture similar to that of insect meat. The great diversity of insects originates in their co-evolution with flowering plants. Inter-species interactions among insects and plants can be readily found. Thus, in many instances, the leaves of a certain plant are only eaten by one insect species, which invented the capacity to overcome the plant's defenses. Similarly, a particular plant may depend on a specific insect for pollination, at the cost of providing floral nectar and pollen. Because of such ecological and evolutional features, the design of space agriculture will depend heavily on the natural interactions between components so that the life cycle of each species will be performed, the food relationships will work out and the recycling loops can be closed. Thus, for the engineering of ecosystems we should have a good understanding of the web of interaction among species.

For space agriculture purposes, we will examine several insect species: the silkworm (*Bombyx mori*), the hawkmoth (hornworm; *Agrius convolvuli)*, the drugstore beetle (*Stegobium paniceum*), the termite (*Macrotermes subhyalinus*), and fly (Diptera). Among their many advantages, these insects do not compete with humans for food resources, but convert inedible biomass or waste into edible food for humans.

18.4.2.1 Silkworm

The silkworm has been domesticated for 5,000 years in China, and probably in India too, and as a result, has lost its ability to fly. Obviously, this is advantageous for ease of rearing them. Rearing methods, including automated feeding machinery, are well established with many strains derived for producing different kind of silk fiber or attaining resistance against microbial disorders. Since the larvae feed exclusively on the leaves of mulberry (Akai and Kuribayashi 1990), the horticultural production of mulberry trees is really part of this agricultural system, and various mulberry strains are available to adapt to different farming conditions. About 40% of the leaf is digested, with the remaining 60% being excreted as feces. Final biomass of silkworm pupa is about 10% of the food consumed during its larval stage. Together with other constituents such as the larval casts, silkworm feces can be utilized in many ways, including as feed for fish. It can also be composted to increase soil fertility. Although the main reason for raising silkworms on Earth is the production of silk which can be woven into a high-quality cloth, both the silkworm pupae and the moth are quite widely accepted as snack foods in East Asia. The Kaneman Co. Ltd. sells canned silkworm pupae and moth cooked with soy sauce and sugar (www. kaneman1915. com).

18.4.2.2 Hawkmoth

Because the breeding of silkworms has been aimed at making high yield and quality of silk fiber, a large portion (65%) of amino acids goes to silk fiber, and less to the pupa meat. Silk fiber can be edible after its decomposition to small oligomer or monomer of amino acid. A wild moth species that keeps a larger portion of protein for the pupa body, and hawkmoth (hornworm) might be a good candidate for insect food. Its larvae feed on the leaves of sweet potato and also other plants. This species is a model insect for scientific studies (Kiguchi and Shimoda 1994) and its rearing technology has been well developed. The pupa is two or three times larger than that of the silkworm, and it is very tasty when fried. Since the hawkmoth does not spin a cocoon, most of the nitrogen absorbed from plant leaves is used for the synthesis of meat protein. In this sense, the efficiency of biomass conversion from plant leaves to insect biomass is higher than for the silkworm. Even if sweet potato leaf is considered edible by humans, the use of a fraction of the leaves available for animal protein production would be advantageous because of the high dietary value of the insects. One issue that needs to be considered with this species is that they need to be airborne for normal mating to occur. It should be studied whether the adult hawkmoth is able to fly under conditions of reduced gravity and atmospheric pressure such as are likely to occur in a Martian greenhouse. Flying performance of insects in helium replaced air (Roberts et al. 2004) mimics that under hypobaric condition.

18.4.2.3 Drugstore Beetle, Termite, and Fly

Both the drugstore beetle and the termite are able to convert cellulose to animal biomass. Like ruminants, they accomplish this by having symbiotic protozoa in their gut which break down cellulose into sugars which can be utilized by the insects (Brune and Friedrich 2000). Nitrogen fixation in the termite is also accomplished by the symbiotic microbial community in the gut (Noda et al. 1999). Some work has been done on the mass production of the drugstore beetle (Kok 1983). Fly larvae grow on rotten biomass including dead animals. Fly larvae can then be fed to fish. This food web feature can upgrade biomass to edible food. Mitsuhashi (2007) suggested the use of fly larva in funeral service protocol on Mars for deceased human, a tradition in ancient China.

18.4.2.4 Model Insect Diet and Its Nutritional Value

The nutritional value of insects was examined to establish whether they could form a viable alternative to vertebrate meat and dairy products. Comparison between the protein content and amino acid composition of silkworm pupae and mulberry leaves indicates how much "vegetable" biomass can be converted to "animal" food by insects. Although mulberry leaf has relatively high protein content as compared to other plants, there is a considerable upgrading when the protein is passed through the insect. Thus, the protein content is improved and several critical amino acids are enriched. The lipid content of the silkworm pupa is another index of "animal" food composition, and is eight times that of the mulberry leaf (Katayama et al. 2005).

In our model diet we have added 50g of silkworm or other insect to the core composition of the four plants described earlier, i.e., rice, soybean, sweet potato, and green-yellow vegetable. In order to supply this quantity of silkworm every day, the area required for mulberry farming is estimated to be 64m^2/person. For farming the four core plants, 200m^2/person in addition to the mulberry farming is expected to be needed (Yamashita et al. 2006). Although insects can not provide a full replacement of nutrients obtained from vertebrate meat or avian egg, they can supply the majority of those required nutrients. Remaining nutrient requirements, vitamin D, B$_{12}$ and cholesterol, can then be met in different ways described in the next section. The Japanese mushroom is included mainly as a supply of vitamin D. The amount of mushroom required in the diet can be greatly decreased if it is finely cut or powdered and then irradiated with ultraviolet light to induce the conversion of a precursor substance to vitamin D. Other trace nutrients could be fed as supplements in the form of food additives or tablets, at a minor penalty of their openness of the materials flow.

18.5 Tri-Culture of Rice, *Azolla* and Loach Fish in Rice Paddies

In order to fill the nutritional needs provided by animal origin substances, it is better to choose animal species phylogenically close to human because of higher commonality in bio-materials. Insects are phylogenically quite far from humans or vertebrate animals as shown in Fig. 18.4. Fish may be an alternative source of animal-origin nutrients. Aquaculture of fishes is a well established technology. Compared to other vertebrates, fish can be easily confined in their culturing water. Among many fish species that can be bred, we selected the loach fish (*Misgurnus anguillicaudatus*) for several reasons.

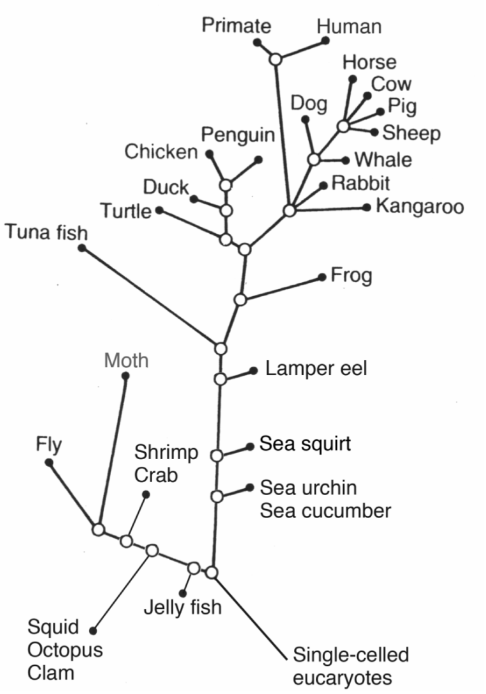

Fig. 18.4 Phylogenic tree of animals we eat (except human). Modified from Eigen (1992)

The raising fish in rice paddies is done in many places, and the loach is one of the common species that naturally live in this environment. Loach is a robust species. It is resistant to adverse conditions such as poor water quality and partial drying of the rice paddies. It is able to gulp air into its digestive tube and exhaust it from its anus after absorbing oxygen in its gut. During the winter dry season, loach survive in the deep muddy layer until spring.

Loach has a high nutritional value. A model diet with 120g of loach fish added to the vegetable and insect diet meets nutritional requirements all within the allowable range or close to the recommended level. Key point of this fulfillment is utilizing the whole loach body including internal organs. Because of small body size of loach, traditional cooking of loach accomplishes this requirement. A Korean recipe, Chueotang, minces the whole fish body into a tasty soup.

Co-culture of loach in rice paddies is extended to tri-culture of rice, *Azolla*, and loach. *Azolla* is an aquatic fern that houses symbiotic cyanobacteria in its body. Cyanobacteria in *Azolla* can quickly fix nitrogen when there is a shortage of nitrogen fertilizer. *Azolla* is an effective green manure, and also suppresses the growth of weeds by covering the water surface and blocking solar light. Even though *Azolla* itself is an edible substance, the co-culture of fish is advantageous, by converting *Azolla* to animal meat, and upgrading biomass to fish meat. The mixing action of fish in the mud and water layer in rice paddies also has other positive effects on rice production. Based on these factors, co-culture in rice paddies enhances productivity under limited available resources (FAO 1988; Watanabe and Liu 1992).

18.6 Compost Waste Safely and Quickly

Historically, recycling of human waste to fertilizer for farming has been widely performed since ancient times (Takahashi 1987). Once lifestyles were modernized and eating raw vegetables became popular, recycling of human feces and urine to soils was considered inappropriate, because of the high risk of propagation of parasites and pathogens. Even though there remain technical problems to be solved, composting is recognized as a very beneficial practical technology for solving problems of solid and organic wastes (garbage) collection and its processing. One way to accomplish a reduction in waste is by composting garbage through biological combustion. A new composting method is based on fermentation under high temperatures at 80ºC to 100ºC. Typical operation time of a kitchen trash box-sized composting machine is 4.5 hours for processing 1.5 kg of fresh weight of vegetable and other organic wastes. In a small sized composter, the fermentation temperature is elevated and controlled electrically to the appropriate range, because heat loss is dominant at its large ratio of surface area and volume.

In this new composting system, hyperthermophilic aerobic bacteria are utilized to attain a higher operating temperature than in an ordinary composting system. Bacteria in the hyper-thermophilic composter are active and viable under high temperatures in the range of 80ºC to 100ºC or even higher. Biological combustion releases heat and the temperature increases, when air is force fed through the reaction bed. Since microbial activity decreases at higher temperatures (above 100ºC), temperature in the reacting bed is naturally regulated to that temperature range. Large-scale facilities using hyperthermophilic aerobic microbial systems process active sludge from sewage treatment plants and are also being used for processing other waste materials brought from farming sites or food-related industries. The ecology of these composting bacteria is structured on intensive symbiotic interactions among multiple species that participate in various reaction networks together (Ueda et al. 2002; Oshima et al. 2007).

When hyperthermophilic composting system will be operated in the Martian greenhouse, thermal condition of reacting bed might differ from that of its terrestrial facility. Under reduced total pressure, diffusion of oxygen is enhanced. However, partial pressure of oxygen is set to a half. Reduced gravity and ambient pressure make less loss of heat from the surface. These factors affect on whether composting temperature could reach high without supplementary heating or not at a certain scale of composting facility.

Compost produced by hyper-thermophilic aerobic bacteria was well characterized by Kanazawa et al. (2003) for its application as fertilizer for cultivated plants. Soil fertilized by this compost keeps nutrient ions in forms easily accessible for uptake by plant roots. Nitrogen in organic compounds is converted to ammonium ion through hyper-thermophilic aerobic fermentation. Since typical pH of compost is weak alkaline, ammonia may be lost from composting product. The oxidative process producing nitrate ion does not take place during composting because *Nitrosomonas* or *Nitrobactor* cannot survive or be active under temperatures higher than 80ºC. For the same reason, the denitrification process might not be activated. Organic nitrogen, typically amino or heterocyclics group of bio-chemicals, is either converted to ammonium or remains in an undigested form in the compost, thus reducing any losses of nitrogen.

The fate of phosphate in hyper-thermophilic aerobic composting has not yet been studied in detail. Precipitates that appear to be calcium phosphates are present on side walls of the reactor after long operation. However, identification has been made neither on this precipitate, nor any phosphate in the compost.

Potassium is the last of the three major macro-elements in fertilizer. Ring structures formed in clay minerals are known to enclose potassium ions. High affinity of potassium to such mineral structures may function as storage of potassium to provide resistance to wash-out during watering. Heavy metal ions such as copper and zinc ions are known to accumulate in farm soils where sewage sludge is misapplied. Products of the hyper-thermophilic aerobic fermentation have heavy metal ions chelated or fixed by either organic or inorganic compounds. This leads to reductions in the levels of soluble heavy metal ions. A related microbial technology can be applied in the process to clean up soil that is contaminated with heavy metal ions. It should be also recalled that certain trace amount of heavy metal ions are required for plant growth and human health.

Microbes and other organisms such as nematodes in soils are important for agriculture either positively or negatively. Little has been thus far studied about the mechanisms and factors that explain the advantage of hyper-thermophilic aerobic composting, but there are many examples showing their good performance in agriculture, and positive impact on the ecology of soil bacteria and arbuscular mycorrhizal fungi. This soil ecology is known to be effective and essential for supplying nutrients around plant root systems. No negative impacts from thermophilic aerobic composting products on the symbiosis between plant roots and soil bacteria and fungi have thus far been seen. Because of exposure to high temperatures close to 100ºC during fermentation, harmful or pathogenic organisms are killed and excluded by this natural autoclaving. Even though it should be further verified, composting bacteria themselves are presumed to be safe for humans, agricultural plants, and animal species. Hyper-thermophilic bacteria are only active at elevated temperatures, and presumably do no harm at ordinary temperatures. A further advantage of applying the compost in agricultural fields is that the chemical and micromorphological features of compost produced by the hyper-thermophilic aerobic bacteria effectively control the ecology of bacteria and other organisms, even though the hyper-thermophilic bacteria themselves are inactive (Yamashita, et al, 2005b).

As a safety measure, the processing bed of the composter should be isolated by equipping the inlet and outlet air ports with HEPA filters. This isolation is simpler and less energy-demanding compared with the option of incineration. Hyperthermophilic aerobic composting is superior to ordinary composting in many aspects including processing time and bio-safety. In comparison with physico-chemical waste processing, a biological system consumes less energy, and requires neither high temperature (>300°C) nor high pressure (>3MPa for the wet oxidation process). Emission of odor and harmful volatiles is a big concern in the use of any microbial system for waste processing. Odorous compounds are produced typically in anaerobic condition. The hyper-thermophilic aerobic composting system is capable of trapping many odor components even by just mixing waste materials with its seed bed materials.

18.7 Sodium Management for Sustainable Agriculture

Human nutritional requirements include sodium salt in addition to other factors. Human excreta contains sodium. Waste and inedible biomass are composted to produce fertilizer for recycling bio-elements. This composting product contains a high concentration of sodium salt relative to potassium. However, sodium is toxic to plants at high concentrations, and ordinary plants are not grown at high salinity. Potassium is an alkali metal like sodium, and is one of the three major components of plant fertilizer.

Circulation of sodium (Na) and potassium (K) in the Earth's biosphere, and the ratio of these two elements in each part of the terrestrial ecosystem are regulated by selective absorption and desorption by clay minerals in soil and seabed, selective uptake and extrusion by plants, and other processes shown in Fig. 18.5. In space agriculture, material circulation through the human body dominates the flow of materials in the ecological system (Yamashita et al. 2005a). Therefore, salination might be a crucial problem for space agriculture.

Sodium should be separated from the compost and fertilizer, or reduced by some other measure, to prevent reduction of plant productivity. Several approaches have been proposed to solve the problem of Na and K processing in space agriculture (Yamashita et al. 1985). One is the physico-chemical process to separate the two elements (Kurokawa et al. 1992). The difference in temperature dependence on solubility of the salts of Na and K could be utilized to separate them by altering temperature to drive the dissolution and precipitation cycle. However, a problem with this kind of process is the removal of some less soluble ionic substances, such as phosphate, which are essential for plant growth.

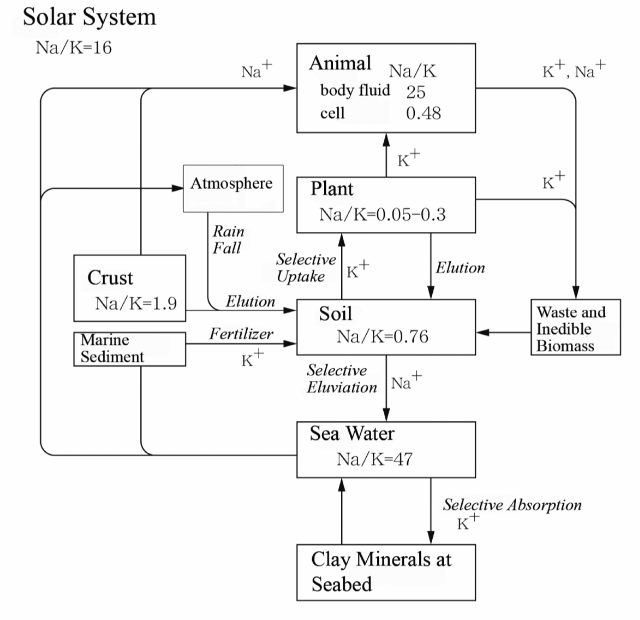

Fig. 18.5 Circulation of sodium and potassium in terrestrial biosphere. Modified from Yamashita et al. (1985).

Biological processes might be adequate to handle sodium and potassium circulation. One possibility is to harvest potassium taken up in plant growth, and then to compost this organic material. Cultivation of marine algae to harvest potassium from the medium, and increase sodium content in artificial seawater, is one candidate technology for this purpose. An alternative approach is the selection of salinity tolerant halophytes as agricultural plant species (Ushakova et al. 2005).

18.7.1 Marine Algae to Harvest Potassium

The ionic composition of marine algal cells is high in potassium and low in sodium, similar to common land plant cells. The concentration ratio of elements between seawater and various marine algal species indicates that most elements are enormously enriched in algal bodies, compared to seawater. The few exceptions are: sodium (ratio 0.1), boron (0.1-0.3), fluorine (1), and chlorine (1). In the case of potassium, magnesium, and calcium, the ratio varies between less than and greater than 1, depending on the algal species. If algae have a homeostatic capacity to keep intra-cellular sodium and potassium stable at various sodium and potassium incubation medium concentrations, and if the ratio of intracellular sodium and potassium is rich in potassium, then the sodium rich effluent from the composting system could be managed by some marine algae.

Among many marine algal species, *Ulva* is selected as a candidate to harvest potassium from processed compost, and recycle sodium in space agriculture (Yamashita et al. 2009). *Ulva* grows in eutrophic coastal waters. It is tolerant to a wide range of salinity levels, and grows well in estuaries where salinity levels change with the tides. *Ulva* can withstand salinity levels both higher and lower than normal seawater. The ratio of sodium/potassium in *Ulva* was found to be about 0.58 under a wide range of total salinity levels, and sodium/potassium ratio in the incubation medium spanned almost two orders of magnitude: 47 (sea water) to 0.5. Threshold concentration of potassium for the growth of *Ulva* ranges from 0.052 to 0.062 M. *Ulva* body potassium content was around 0.21 M, based on fresh weight of the specimen. This potassium content is approximately three to four times higher than the growth threshold of *Ulva*.

In space agriculture, a cultivation medium (i.e., artificial seawater) for *Ulva* will be created from human excreta. The sodium/potassium ratio in human excreta is about 2. *Ulva* can harvest potassium in its body at a sodium/potassium ratio of 0.58, therefore, enrichment of potassium can be made in the *Ulva* body from human excreta. The use of marine algae, including *Ulva,* for fertilizing farming areas is well established in many areas in the world (Notoya, 2001). Furthermore, *Ulva* itself is human food. Thus, cultivation of *Ulva* is effective and a good candidate for closing the materials recycling loop in space agriculture. *Ulva* can help solve the problem of the mismatch of sodium and potassium between humans and plants.

Ulva growth and photosynthesis has been studied extensively with regards to its applications in human diet processing, fish and animal feed, and bioremediation of the seashore. Primary photosynthetic production of marine alga reaches 1500-2000 gC m^{-2} $year^{-1}$; equivalent to alfalfa production in soil (Mann 1973). Average dry weight production of *Ulva* is 9.63 g m^{-2} day^{-1} (Maegawa 2001). By postulating 3.2 g of potassium content in 100 g dry weight of *Ulva*, an area of 6.5 m^2 of farming *Ulva* is required, for one person, to harvest the quantity of potassium excreted by a human (i.e., 2 g per person per day). To extract the amount of cooking salt required by one person, 0.5 liters of artificial seawater must be processed per day.

18.7.2 Sodium Tolerant Plants

One conceivable method to solve the problem of high salinity is to use composted urine through a channel in an agricultural section for halophytes (salt-tolerant plants), which can grow in the salt-affected soil and accumulate sodium in the edible parts of the plant. Candidate halophytes are the ice plant (*Mesembryanthemum crystallinum*) (Adams et al. 1998), the saltwort (*Salicornia herbacea* L.) (Shimizu 2000), and the New Zealand spinach (*Tetragonia tetragonoides*). Among them, the ice plant is the most capable species to remediate salty soil, and has been proposed to modify reclaimed land from the sea to plant ordinary crop species (Shimoda et al. 2003). Sodium salt is excreted to a bladder, which protrudes from the plant body. Sodium salt content reaches a maximum of 30% of dry weight. The ice plant is a gourmet salad vegetable of French cuisine, enjoyed for its salty taste and peculiar texture.

18.8 Phased Development Scenario of Space Agriculture on Mars and Materials Resources

To initiate appropriate agriculture under the harsh Martian conditions, we must adopt a strategy different from that used to establish terrestrial agriculture. We propose a strategy with two stages. During the first stage, water on Mars will be brought into a pressurized structure, rather than making that recycling loop closed. Regolith, air and water inside the greenhouse will be regulated to approximate their levels on Earth, principally by artificial means, without reliance on the autonomous control in an ecosystem. During the second stage, Martian agriculture will support human life by sufficiently supplying the necessities of subsistence mainly through recycling bio-elements inside the greenhouse. In addition, Martian agriculture will evolve by gradually expanding in its scale by taking resources available on Mars into the recycling loop.

18.8.1 The First Stage of Martian Agriculture

Soon after landing on Mars, habitation and agriculture structures should be set up, and numerous solar panels deployed on the ground surface. The selection of a settlement site is an important early step and must take into account accessibility to on-site resources. Criteria used in the selection of habitation sites on Earth could be applied to the Martian case, with certain modifications. Humans usually dwell in sunny places where both a watering spot and a shelter are within a distance for easy access. This means that detailed topographic maps of Mars are very helpful for selecting the habitation site. Characteristics of the regolith at the selected site is another important factor for conducting agriculture. Because the main goal of Martian exploration is astrobiology to search for extraterrestrial life forms or biotic substances, physical isolation barriers or a minimum distance should be secured between the site of scientific exploration and the dwelling site. Furthermore, careful unmanned exploration should be conducted prior to manned mission and agriculture on Mars (Hashimoto et al. 2006).

The structure of the greenhouse and the materials that sheath them must be tough enough to endure the inner pressure of the greenhouses surrounded by ambient pressure that is 1/100 of terrestrial atmosphere. A multi-layered or -celled structure for the greenhouses is desirable to reduce the mechanical load. In case the greenhouse is constructed on the Martian surface, the filmy sheathing materials themselves should be optically transparent to admit solar radiation necessary for human life and photosynthesis of plants, but opaque to the harmful ultraviolet part of the solar radiation.

Another option is to place the greenhouse sub-surface, where direct exposure to ultraviolet solar radiation is eliminated and cosmic rays can be shielded. Instead of direct introduction of solar radiation, an array of solar light collectors can be set up on the ground surface to guide light into the subsurface greenhouse, after eliminating short wave-length radiation by the color aberration action of an optical lens (Tanatsugu et al. 1985).

18.8.1.1 Treatment of Air and Water

The Martian atmospheric gas outside the greenhouse is pumped into the greenhouse. Appropriate total pressure and partial pressure of oxygen and other gas species in the agriculture area is determined by considering the growth and yield of cultivated plants. A trace amount of nitrogen in the Martian atmosphere is selectively collected and supplemented to the air in the greenhouses. Water can be obtained by melting frozen regolith mined from subsurface layers. The water obtained from the frozen regolith may contain salts, such as NaCl, Na_2SO_4, $NaHCO_3$, Na_2CO_3, $CaCl_2$, $CaSO_4$, or $Ca(HCO_3)_2$. Such a saline solution is unsuitable for both drinking and irrigation and needs to be purified by distillation or other means. Some organisms can help with the modification of Martian air and water. For instance, some calcareous algae grow in saline water, and precipitate $CaCO_3$ from it. *Spirulina*, photosynthetic bacteria and tilapia may flourish in the resulting saline alkaline water, as evidenced at alkaline and/or salty lakes in Africa. *Spirulina* converts CO_2 to O_2 and produces biomass by photosynthesis during its high growth rate. *Spirulina*, tilapia and photosynthetic bacteria are also nutritious foods for humans during the first stage.

18.8.1.2 Formation of Martian Soil from Regolith

The initial mode of agriculture on Mars will be hydroponics. Inedible biomass and human metabolic waste are composted and combined with regolith to form soil to make it habitable for plant roots and soil microorganisms. Unfortunately, information about the regolith is still fragmentary, and somewhat contradictory in certain aspects. We shall explore Mars to map and collect comprehensive data on the regolith, which is required to design space agriculture and select the habitation site. The regolith on Mars is widely covered by hematite. This indicates that ferruginous minerals such as olivine, pyroxene and hornblende have been weathered to release ferrous iron, which is oxidized by mechanisms not yet fully understood. In addition, the presence of $CaSO_4$ and jarosite indicates that even Ca-, Na-, and K-rich minerals such as feldspars have been weathered. However, the common presence of olivine indicates that the degree of the weathering is generally low. Furthermore, the presence of jarosite would mean the regolith is acidic. On the contrary, the presence of $MgCO_3$ or $CaCO_3$ would mean the regolith is somewhat alkaline, as indicated by the Phoenix mission. In any case, the following stepwise efforts are necessary to form Martian soil (Yazawa et al. 2007).

18.8.1.3 Desalinization and Neutralization of Soil

Martian regolith usually contains water-soluble salts. If their concentration is so high as to harm most organisms except for halo-tolerant or halophilous organisms, desalinization (removal of the water-soluble salts) is imperative. Desalinization can be achieved by leaching the salt-affected regolith with non-saline water. The leaching water enriched with the salts can be used to strengthen regolith bricks for use in the construction of space habitation.

The pH of the regolith may vary from place to place. The pH should be very low in places dominated by jarosite and should be high in places dominated by $NaHCO_3$ or Na_2CO_3. However, in most places, pH may be somewhat high where $CaCO_3$ or $MgCO_3$ is found. Common plants are damaged by soil with too low or too high pH. Accordingly, we must prepare methods of neutralization for both too acidic and too alkaline regolith. The application of calcareous algae rich in $CaCO_3$, or fine regolith rich in olivine, is effective for increasing the pH of acidic regolith. For alkaline regolith, the application of carried peat moss with low pH may solve the problem.

18.8.1.4 Improvement of Regolith/Soil Properties

The sediment of fine textured regolith (texture: particle size distribution) has some properties favorable for agriculture, because its cation exchange capability (CEC), mineral nutrient content, and ability to retain organic matter are high. However, fine textured sediment is problematic because of poor aeration and poor drainage, which result in O_2-deficiency for plant roots and microorganisms living in the sediment. Desalinization by leaching is also difficult. A large portion of the pores in the fine textured sediment is liable to be completely filled with water by capillary force. Accordingly, loamy textured soils are considered desirable for common upland crops in terrestrial agriculture. This suggests that a sandy loam or loamy sand texture of Martian regolith is desirable for Martian agriculture under low gravity. However, the aeration and drainage of soil is controlled not only by texture but also by a mode of aggregation of soil particles. For instance, drainage of terrestrial soils with sandy loam or loamy sand texture is often poor. This problem with the physical properties of terrestrial soil is usually overcome by the presence of aggregates of suitable sizes (e.g., > a few mm), which are naturally formed by a concerted action of biotic and abiotic processes and can be artificially formed by applying synthetic polymers or some materials with coarse pores. Pores among the aggregates of suitable sizes are coarse enough for desirable aeration and drainage. Accordingly, the artificial aggregation of Martian regolith should improve its physical properties. A promising candidate is polyvinyl alcohol (PVA) (Dejbhimon and Wada 2005). Another candidate method to improve the physical properties of Martian regolith is to apply peat moss or an equivalent processed plant material produced in agriculture on Mars (Wada 2008). Both are rich in coarse pores for aeration and drainage.

18.8.1.5 Plant Nutrients

Most of the plant nutrients are available on Mars, because they may take forms accessible to plant roots after they are released from minerals by weathering. Nitrogen is not a component of any minerals and accordingly is utterly absent in the regolith. Application of some nitrogen fertilizer (ammonium nitrate, urea) or cultivation of some green manure crop plants capable of nitrogen fixation, such as *Azolla*, is inevitable. However, the nitrogen fixation will not occur if the amount of available phosphorus is far short of the demand of the green manure crop plants.

Phosphorus is contained in the minerals of the Martian regolith, and may be released by weathering in a similar way as other nutrients. However, the released phosphate is considered to be unavailable for plant roots, due to its strong adsorption (phosphate-fixation) on $CaSO_4$, $CaCO_3$ and iron oxides. Thus, phosphate fertilizers should be applied by three appropriate methods to avoid this phosphate-fixation. The first is to apply phosphate fertilizers mixed with peat moss (Kawakami et al., 2007). The second is the removal of $CaSO_4$ by leaching if the main phosphate-adsorbent is this substance. The third is the adjustment of pH at about neutral where phosphate-adsorption with both $CaCO_3$ and iron oxides is most suppressed if these two substances are dominant phosphate-adsorbents.

Excess amounts of several elements are harmful to common terrestrial crop plants, and this problem may occur on Mars. For instance, if the regolith is enriched with olivine, excess Mg, Ni and Cr may damage common crop plants. The application of $CaCO_3$ may cure excess Mg, while the application of peat moss, which possesses a strong capability to adsorb Ni and Cr, may effectively counteract the harm caused by excess Ni and Cr.

18.8.1.6 Organic Matter in Soil

Organic matter contributes to many important functions of the soil, two of which may be essential in forming desirable Martian soil. One function is to form and maintain aggregates of suitable sizes in the fine regolith. The other is to store nutrients (bio-elements), especially nitrogen. The nutrients stored in organic matter are released when the organic matter is microbiologically decomposed. Therefore, accumulation of organic matter containing nitrogen in the regolith is imperative to establish space agriculture. This can be achieved by applying compost and processed excreta of animals and people.

Hyper-thermophilic aerobic bacteria can also help conserve Martian environment for astrobiology exploration. Since the organic waste cannot be dumped from the spacecraft flying to Mars to meet the planetary protection requirements, the accumulated organic waste can be quickly composted with hyper-thermophilic aerobic bacteria.

18.8.1.7 Soil Microorganisms

Microorganisms inhabiting the soil are responsible for most of the functions of the soil, such as decomposition of all organic waste, release of nutrients stored in the organic matter, nitrification, denitrification and nitrogen fixation. To endow the regolith with these functions, the Martian regolith should be inoculated with desired microorganisms.

18.8.2 The Second Stage in the Initiation of Martian Agriculture

When the goal of the first stage is almost attained, the second stage of space agriculture should be started. The main objectives in the second stage are to establish a sustainable agriculture that can continuously supply to the Martian emigrants clean air and water, as well as foods, fiber and timber, mainly by recycling substances as described in the earlier section of this chapter and summarized in Fig. 18.1. Reservoirs of the recycling flows of substances are not drawn in Fig. 1, but they are necessary for buffering fluctuation of the flows. Oxygen concentration is most critical for life support, and at low oxygen concentrations oxygen is generated by electrolysis of water, as is presently being done on the International Space Station. During the second stage of Martian habitation, most of the tasks in the first stage should continue to work to keep the conditions inside the greenhouses favorable for recycling materials in the second stage.

18.8.2.1 Composting

Organic waste originates from both the living quarter and the agriculture quarter. It should be composted before application to the farming soil. This is the main method of recycling materials in Martian agriculture, because this is the transfer from consumer to producer by the decomposer in the Martian ecosystem. *Geobacter* is another candidate to process organic substances without oxygen, using the iron oxides commonly available on Mars (Lovely 2006). The hyper-thermophilic aerobic composting discussed earlier becomes the major process in the second stage when quick and safe treatment of a large amount of organic waste is urgently needed.

18.8.2.2 Maintenance of Soil Conditions

The soil formed from the regolith in the first stage should be maintained to be productive and manageable. In other words, the application of a suitable amount of compost and/or organic waste is not only necessary for material recycling, but also necessary for maintaining soil productivity. Furthermore, accumulation of organic matter in the soil helps to ensure high O_2 content in the air and acts as a reservoir for bio-elements.

Careful irrigation is necessary for the following three reasons. The first is to save water. The second is to avoid accumulation of salts in the soil by keeping the evapotranspiration rate lower than the irrigation rate. The third is to avoid the damage of dikes and other agricultural landforms by turbation and the formation of deep cracks in the soil. Such a problem is known in clayey terrestrial soils rich in smectite, which are classified as Vertisols. Vertisols swell when moist, and shrink when dry, leading to cracks and turbation of the clayey soils. If such problems are anticipated in Martian soil, the soil should not be exposed to distinct alternation of wetting and drying by improper irrigation.

18.9 On-Site Energy Resources for Space Agriculture

Energy is required for photosynthesis of plants, environmental control and other usages in space agriculture. Solar radiation is the most important energy source. It is the critical driving energy in our life and activities in the terrestrial biosphere, and its role is unchanged in Mars habitation. Since day length on Mars is almost the same as that of Earth, biological organisms including agricultural plants can be expected to have little difficulty adapting their circadian biological rhythm to the Martian day and night cycle.

18.9.1 Energy for Photosynthetic Production

The choice of an energy source is made after considering the energy quantity required for agriculture. On Earth, area of farm land is 2,300 m^2 per person. Solar light energy influx on this farming area is in the order of 1 MW. Interestingly, at the Closed Ecology Experiment Facilities (CEEF) in Aomori, two men and two small sized goats consume 1.5 MW of electric energy in a closed ecological life support system based on physico-chemical principles and hydroponic plant cultivation under mostly artificial light (Nitta et al. 2000). A human being is a 100W animal in terms of energy consumed physiologically. Although a low coverage of plants on Earth's surface and other factors provide the harvest energy index of 5.5 x 10^{-4}, the published physiological plant data (Taiz and Zeiger 2002) show that the conversion ratio (light energy to fixed biomass energy) is as high as 5 x 10^{-2}. The ground surface area required per person in the Martian greenhouse is estimated to be ~ 2,000 m^2, assuming that the surface coverage of plants multiplied by the ratio of light reaching the surface = 0.2, the ratio of edible parts in biomass = 0.5, the conversion ratio 5 x 10^{-2}. irradiance of sunlight (190 W m^{-2} as a daily average at the equator zone on Mars) = 590 J/s m^2, and energy required for habitation = 2 x 10^3 W per person. Thus, the minimum requirement of ground surface area for physiological needs (100W human metabolism, and a safety factor of 2) is reduced to 200 m^2 per person. This areal requirement for the pressurized compartments can be further trimmed down by supplementary light irradiation to plants at a level up to twice as much as solar light. Because of the high profile of light energy required, solar light is the right choice for Martian agriculture. For other energy requirements, electricity is the appropriate form of energy for Martian habitation and agriculture. Generation of electric energy by the solar panels is disrupted due to the non-availability of solar radiation at night, and even during daytime, by dust storms. Consequently, energy storage systems, such as batteries or heat baths, are required to supply energy without disruption and supplement lighting for crop control. For the safety of the habitation site on Mars, it might be equipped with a nuclear power unit or a combination of orbiting solar power satellites and ground rectina for receiving microwave energy (Ishikawa et al. 1990) for back-up of the power system.

18.9.2 Energy for Thermal Control in the Greenhouse Structure

Energy is required to control temperature and drive thermal convection to transport gaseous substances by air currents induced in the greenhouse may be necessary as this section below explains. Terrestrial greenhouses can be either warmed or cooled by solar light and other energy, and inner temperature is maintained at the appropriate set range. Thermal design of the greenhouse starts with examination of its heat balance and budget. Surface temperature on Earth is determined by amount of solar light inflow and equivalent radiative heat outflow proportional to the fourth power of surface temperature. Because solar light intensity is ~ 1/2 on Mars compared to that on Earth (Kieffer et al. 1992), surface temperature is low compared to that on Earth. Temperature inside the greenhouse will be warmer than the ambient atmosphere. This is partly because of absorption of solar energy made by light absorbing materials, and trapping of warm air in the greenhouse. Heat dissipation from the greenhouse in the design where the greenhouse is exposed to Martian atmosphere, has two major paths. One is heat radiation and conductive heat transfer to ambient air from the outer surface of the greenhouse. The other is heat loss to the frozen surface regolith of Mars. Heat dissipation from a subsurface greenhouse can take only the latter path, and this can be controlled by a heat insulation layer. The heat transfer coefficient through the former path is quite low given the very low density of Martian atmosphere. A conductive heat loss from the outer surface of the Martian greenhouse is therefore not extraordinary in spite of the extremely cold outside atmosphere. This makes it possible to maintain a high inner temperature under the condition of 50% heat inflow to the Martian greenhouse as compared with Earth conditions.

18.9.3 Convective Mixing of Gas Components in Greenhouse

Atmospheric convection and localized climates are expected to emerge from heat flows in the Martian greenhouse as shown in Fig. 18.6.

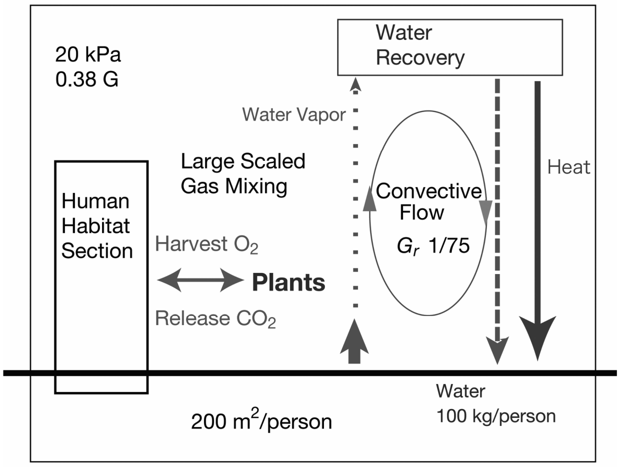

Fig. 18.6 Heat and materials convection in the Martian greenhouse. Modified from Yamashita et al. (2006)

Water vapor evaporated from plants is transferred to the recycling site for collection and recycling. Oxygen produced by photosynthetic reactions is transported to a concentrating apparatus and exchanged with carbon dioxide. All gaseous components need to be distributed uniformly in the greenhouse by the convective mixing. Placement of hot and cold spots in the greenhouse should be well planned in order to induce appropriate convection. The flow induced by thermal convection in the Martian greenhouse is characterized by non-dimensional variables (Kotake and Hijikata 1992). Among them, Grashof number (*Gr)* is used to compare the Martian greenhouse to its terrestrial counterpart. This *Gr* number is defined as the ratio between buoyancy force and viscous force in flow, and it characterizes natural convective flow. Since *Gr* number is proportional to the magnitude of gravity, i.e., 1/3 of Earth's, as well as the square of gas density, *Gr* in the Martian greenhouse is 1/75 of *Gr* in the terrestrial counterpart provided that other variables (characteristic length, thermal expansion coefficient, dynamic viscosity, and change in temperature) are the same. Low number of *Gr* means less natural convection, and forced convection might be required in the Martian greenhouse.

18.10 Summary

A conceivable plan is proposed to realize Martian agriculture in greenhouse on the lifeless barren regolith under hostile conditions, based on the knowledge and experiences of terrestrial ecosystems and agriculture. Our scenario for developing space agriculture with phased development largely depends on on-site resource availability. To lessen the export amount from Earth, we propose more than 100% closure of materials recycle in the life support system. Solar light energy, water, carbon dioxide, and other bio-elements introduced from the Mars surface enable an enlargement of the habitation. To test the feasibility of this strategy, many terrestrial experiments should be carried out to examine each part of the plan under simulated Martian conditions, starting with the first step. Precursor mission to Mars should also be conducted to determine the availability of required resources, and characterize the environment in greater detail.

Currently, many terrestrial ecosystems are being quickly destroyed, leading to a decrease in Earth's biodiversity. At the same time, terrestrial agriculture in many places has been losing its productivity, principally due to soil erosion and degradation. This situation with terrestrial agriculture somewhat resembles the challenging conditions for Martian agriculture. This suggests that the success of Martian agriculture may be helpful for reviving damaged terrestrial ecosystems and renewing impaired terrestrial agriculture. This may be the next revolution of our human history, which has developed through the agricultural revolution, the industrial revolution and the information revolution.

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