Entomophagy; a key to space agriculture

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Abstract
Feasibility of entomophagy and use of insects in space agriculture were examined. Candidate insect species are silkworm, hawkmoth, drugstore beetle, and termite. Function of insects breeding in space agriculture is argued based on their characteristics in the ecological system and their position in the food chain. A combination of rice, soybean, sweet potato, green-yellow vegetable was selected as the core recipe to find an achievable set for space agriculture. Nutritional evaluation of this set indicated deficiency of several nutrients, which are supplied by animal food materials. Insect was added to the core recipe to include animal food. After iterative consideration, avian egg, meat and mushroom, or fish were supplemented to meet the nutritional recommendation and maintain human health. Spin-off of space agriculture could be beneficial to solve the terrestrial problems, such as food shortage at increasing the world population.

Introduction
Supplying food for human occupants remains one of the primary issues in engineering space habitation (Yokota, et al, 2006). Evidently, for long-term occupation on a distant planet, it is necessary to start agriculture on site. Historically, humans have consumed a variety of animals, and it is required to fill our nutritional need when they live in space. Among many candidate group and species of animal to breed in space agriculture, insects are of great interest since they have a number of advantages over mammals and other vertebrates or invertebrates. It is evidenced by fossilized human feces that many insects have widely taken into human diet since old era before the start of cattle breeding and agriculture. We highlight entomophagy (Mitsuhashi, 1997) for application in space agriculture at its feasibility to support human life under the constraints of space habitation.

Animal Originated Materials to Fill the Nutritional Requirements
Design of space agriculture is based on requirements to recycle materials for life support. Recovery of evaporated water from plant leaves, conversion of carbon dioxide to oxygen, and food production are three major functions imposed on space agriculture system. Nutritional requirements determine what species to be cultivated. Since space and volume for agricultural production is limited, selection of species should be made at consideration of production yield per area or volume at postulating best multiple cultivation cycle in a year, to provide biomass and oxygen in order to support human life.
We selected rice, *Oryza sativa*, soybean, *Glycine max*, sweet potato, *Ipomoea batatas*, and green-yellow vegetable (Komatsuna, *Brassica camperstris* var. *peruviridis*, or equivalent) to provide energy source, protein, dietary fiber, vitamins, minor elements such as iron and calcium. The best core composition of the four food materials above, in terms of nutrition, was determined as 300 g of rice, 100 g of soybean, 300 g of green-yellow vegetable, and 200 g of sweet potato per day for a person. Criteria considered at this selection were total energy intake, amino acid score (Schaafsma, 2000), fulfillment of each nutrients in the recommended range, and the energy ratio between protein, lipid, and carbohydrate. The set of plants products, however, is found insufficient to fill the nutritional requirements. Shortage in the composition is sodium, ratio of lipid, and unbalanced amino acids score, which is a common feature of plant biomass. In order to meet the nutritional needs, sodium is supplied in a form of cooking salt. Insects are considered to fill other deficiency above.

Candidate Insect Species for Space Agriculture
About 70-75% of all species living on the earth are insects, and they play an important role in materials recycle loop of terrestrial biosphere at their various niche. Phylogeny tree of animals we eat is shown in Fig. 1. We accept quite wide group of animals for daily food, corresponding to ecological diversity and its richness (Marconi, et al, 2002). In a biological view, insects are phylogenetically close to a group of shrimp and crab (Eigen, 1992). Taste and texture of insect meat resemble to those of shrimp and crab.
The great diversity of insects originates in their co-evolution with plants. Inter-species interaction among insects and plants is seen in the specificity in plant species of leaf eaten by certain insect species at breaking the plant defensive mechanism, or in pollination made by specific pollinator at a cost of providing honeydew. Because of such ecological feature, the design of whole space agricultural system depends largely on the selection of species for

foods material and their recycling loop. In order to conduct engineering of ecological system, we should understand the web of interaction among biological species and organisms.
In the standard tables of food composition in Japan summarized by a governmental committee, two insect items, i.e. the rice hopper and maggot of wasp, are listed. For space agriculture, we propose several insect species, such as the silkworm, *Bombyx mori*, the hornworm (hawkmoth), *Agrius convolvuli*, the drugstore beetle, *Stegobium paniceum*, and the termite, *Macrotermes subhyalinus*. Among many advantages, these insects do not compete with human in terms of food resources, but convert inedible biomass or waste into an edible food source for human.

Silkworm and Hawkmoth

The silkworm has been domesticated since 5,000 years ago in China. Insect species domesticated so far are limited to silkworm and honeybee. Silk moth has lost capability of flying after its domestication history. This feature is rather advantageous in control of their rearing. Silkworm larvae eat specifically mulberry leaves, and metamorphose to pupa in their cocoon (Akai & Kuribayashi, 1990). Rearing methods have been well established for silkworm, including farming of mulberry trees. Silkworm feeds mulberry leaves of ten times greater mass against body mass of pupa. About 40% of leaves is digested, and the remaining 60% is excreted into feces. Chloroplast is left indigested in feces of silkworm. Together with other constituents, silkworm feces can be utilized in many ways including fish farming. Composting waste generated by sericulture would increase fertility of farming soil. As another by-product of silkworm rearing, silk fiber obtained from cocoon can be used to weave cloth. Silkworm pupa and moth are quite widely accepted as food or snack in East Asia. Kaneman Co. Ltd. in Japan sells canned pupa and moth of silkworm cooked with soy sauce (http://www.kaneman1915.com).

Hornworm larvae feed leaves of sweet potato. This species becomes a model insect for scientific studies (Kiguchi & Shimoda, 1994), and rearing technology has been well developed. The pupa is twice or three times bigger than silkworm, and tasty after fried. Since the hornworm does not spin a cocoon, most of nitrogen digested from plant leaves is used for synthesis of storage protein (animal protein), and stored in the fat body. In silkworm, more than 65% of nitrogen digested is converted to silk fiber of its cocoon. In this sense, efficiency of biomass conversion from plant leaves to insect body is higher than silkworm. Even leaves of sweet potato is categorized edible biomass, hornworm larvae could be reared on a portion of sweet potato leaves to produce pupae, which is more appropriate for human diet. One issue is that they have to fly for normal mating. It should be studied whether adult hawkmoth could fly under reduced gravity and pressure in the Martian greenhouse.

Drugstore Beetle and Other Species

Farming system of the drugstore beetle is an established as an off-the-shelf technology. Termite is a common insect food in Africa. Both the drugstore beetle and the termite convert cellulose or other inedible biomass efficiently to animal proteins and their substances. Symbiotic bacteria in digestive organ of the termite (Brune & Friedrch, 2000) are responsible to process cellulose to smaller sugar molecules, which are utilized by insects. Furthermore, nitrogen fixation is made by the symbiotic microbial community established in the termite gut (Noda, et al, 1999). Technical maturity for adopting the drugstore beetle in space agriculture has been well established (Kok, 1983), and the breeding system produces larvae to feed various pet animals. It is adopted as confectionary for human, which is distributed and sold in North America by Hotlix, California (http://www.hotlix.com/).

The function performed by insects in space agriculture is to upgrade inedible biomass to edible materials or feeds for animals. It is hard to design partitioning the farming area to breed insects, instead of cultivating ordinary agricultural plant species. Even we select entomophagy for our food habit, it should not compete farming of edible crops, but utilize the inedible part of biomass to feed insects. Planting trees is aimed to produce excess oxygen and wood lumber for space habitation. Silkworm eats mulberry leaves. Wooden stems left over will be composted, and provide organic substrate and create physico-chemical environment for soil bacteria and fungi. Harvested plants usually have inedible part depending on plant species. Sweet potato leaves the least amount of inedible part. Inedible part of crop plants is about half in general. If there could be a good match between inedible plant biomass and insect, space entomaphagy is a valuable approach to improve the degree of closure in materials recycle loop.
Pupae or larvae of the candidate insect species can be eaten by humans and other animals such as the chicken, *Gallus gallus,* and a variety of fishes and cattle. Feces of silkworm larvae can also feed fishes by either in raw or through culturing plankton with it. We can design materials recycle loop in space agriculture by selecting appropriate insect species, and improve the degree of closure. Use of insects are also effective to raise the efficiency of utilizing biomass by converting the lower graded inedible biomass to human food or feeds for animals bigger than insects. Efficiency of utilizing chemical energy originally fixed by photosynthesis of plant is lowered by about 90 %, when one layer up in the food chain in ecological system. By this reason, it is better to select organisms from lower ladder in the food chain, in case the resources of agricultural production is limited in terms of energy and materials as in space and also the terrestrial case.

Model Recipe and Nutritional Value of Insects,

Nutritional value of insects was examined and accessed whether they could be an alternate of vertebrates meat. Table 1 shows contents of protein and composition of amino acids in silkworm pupae, excretion of silkworm larvae, and mulberry leaves. Mulberry leaf contains proteins at relatively higher concentration compared to other plant

species. Animalization made by silkworm in its biomass composition is found in the contents of whole protein, and relative abundance of amino acids. Certain amino acids, such as methionine, tyrosine, and histidine, are enriched from mulberry leaves. It is characterized that silkworm meat is partially "animalized" from mulberry leaves. Amount of lipids and their composition are summarized in Table 2. Even content of lipids is eight times greater than mulberry leaf, they are in a "partially animal like" lipids composition.
We add 50 g of silkworm or other insects to the core composition of four plants, rice, soybean, sweet potato and green-yellow vegetable, described earlier. In order to supply this amount of silkworm every day, required area for mulberry farming is estimated as 64 m^2. For farming four core plants, 200 m^2 is expected to be cultivated for agriculture. As described above, insects do not fully offer the nutrients obtained from the vertebrate meat or avian eggs. However, they would replace a great amount of them. Based on the nutritional requirements for human diet, a model recipe is formulated for the modern way of insect eating by adding mushroom, avian meat, internal organ of chicken, and its egg to supplement the deficiency of vitamin D, B_{12} and cholesterol. Amount of those items designed are shown as the recipe ***A*** in Table 3. Japanese mushroom is mainly adopted for supply of vitamin D, and its amount can be reduced greatly if its fine cuts or powder are irradiated by ultraviolet light to induce conversion of precursor substance to vitamin D. Minor in quantity but important nutrients would be supplemented in a form of food additives or tablets, if it is stable over a period under regulated condition. However, needs of amino acids and lipids are summed up to an appreciable amount when duration of mission extends.

Robustness of breeding animals is an important factor at selecting species for space agriculture. Fish is a candidate group, other than avian, for animal composition in space agriculture. Breeding fish in rice pad has been conducted in many places. Loach fish, *Misgurnus anguillicaudatus*, is one of common species naturally live in rice pads and their surroundings. Breeding and farming of loach fish have been studied at its decreasing population in rice fields. Loach fish is resistant against severe environment, including poor water quality and partial dry out in rice pad. They are capable to gulp air into its digestive tube and exhaust it from anus after air exchange in their gut. Since nutritional value is high, 120 g of loach fish, replaced for mushroom, avian egg and meat in the above recipe ***B*** shown in Table 3, might provide a good source of animal constituents in recipe for space diet.
Evaluation of nutritional values made on the model recipe ***A*** and ***B*** is summarized in Table 4. Items listed in this table are within the allowable range or close to the recommended level. There are some other items remained to examine for assessing the nutrition in detail. However, they are minor in their amount, and not a critical factor for designing the concept of space agriculture.

Conclusion

Entomophagy could be a promising part of the foods habit that adapt to space habitation. Insects, as a member of agro-ecosystem, will recycle materials, process waste, serve as food and feed, and pollinate plants. A model recipe of rice, soybean, sweet potato, green-yellow vegetable, silkworm pupa, and loach fish were found to fill the nutritional requirements for space habitation. Performance of the space agriculture can be improved at adopting insects as its member. Merits of the insect usage are given in several ways, such as converting inedible mass or waste to edible substances without competing against agricultural production of the main crops. The design of systems for space agriculture will also provide insight into improving the management of Earth's biosphere for its sustainable civilization. Entomophagy may be very well proven as a key idea in solving the world's food problems, to which we are facing now.

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Fig. 1 Phylogenic tree of animals to eat. Modified from Eigen (1992)

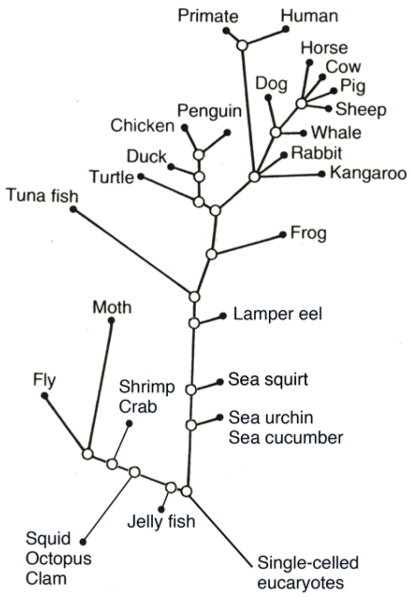

Fig. 2 Silkworm. a) larvae on a mulberry leaf, b) cocoon and pupa. Scale bar; 10 mm.

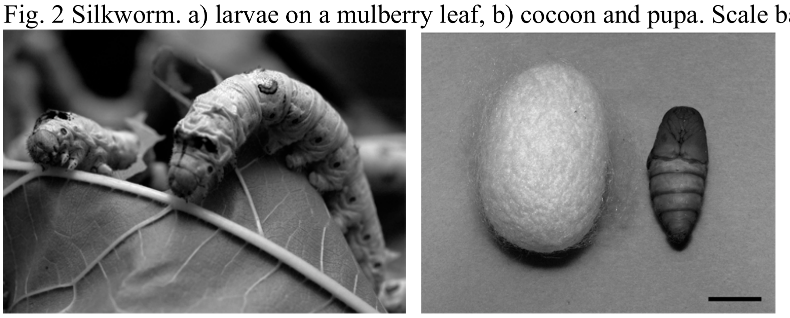

Table 1 Content of protein and composition of amino acids in silkworm pupa, excrement of silkworm larva, and mulberry leaves.

(g/100g)	Protein	Arg	Lys	His	Phe	Tyr	Leu	Ile	Met	Val	Ala	Gly	Pro	Glu	Ser	Thr	Asp	Trp	Cys
Silkworm Pupa	14.8	0.59	0.80	0.51	0.54	0.71	0.75	0.47	0.42	0.63	0.60	0.69	0.54	1.37	0.52	0.50	1.12	0.16	0.20
Silkworm Excrement	4.1	0.08	0.11	0.06	0.08	0.06	0.11	0.08	0.02	0.10	0.09	0.23	0.13	0.37	0.10	0.09	0.31	0.04	0.06
Mulberry Leaf	6.0	0.38	0.37	0.15	0.31	0.18	0.48	0.27	0.09	0.32	0.30	0.29	0.30	0.94	0.28	0.25	0.66	0.09	0.07

Table 2 Amount of lipid, and its composition in silkworm pupa.

		Fatty acid compositon (%)											Fatty acid		
(g/100g)	Lipid	14:00	16:00	16:01	17:00	17:01	18:00	18:01	18:02	18:03	20:00	unknown	Saturated	Mono unsaturated	Poly unsaturated
Silkworm Pupa	8.2	0.2	20.9	0.7	0.1	0.2	7.4	31.2	19.1	18.5	0.2	1.5	1.61	1.93	2.58
Silkworm Excrement	0.8														
Mulberry Leaf	1.0														

Table 3 Model recipe of entomophagy (g/day)

	Rice	Soybean	Green vege	Sweet potato	Mushroom	Silkworm	Loach fish	Chicken egg	Chicken meat	Chicken liver	NaCl
A	300	100	300	200	250	50		30	10	5	6
B	300	100	300	200		50	120				6

Table 4 Nutritional evaluation on model recipe of entomophagy

	Energy (kCal)	Protein Ratio (%)	Lipid Ratio (%)	Carbohydrate ratio (%)	Lipids (g)	Cholesterol (mg)	Dietary fiber (g)	Protein (g)	Amino acids score	Vitamin D (µg)	NaCl (g)
Minimum			20	50							
Recommend	2000						21.0	55	100	5	
Maximum		20	30	70		700					9
A	1953	17.2	17.3	65.6	37.6	153	45.5	83.8	97(Lysine)	6	6.1
B	1928	17.5	14.2	68.2	24.7	252	36.4	89.1	101(Lysine)	5	6.2