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Entomophagy: A key to space agriculture

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Abstract

The intentional inclusion of insects in space-based agricultural schemes and their use as human food (entomophagy) were examined. Insects could be useful both from an ecosystem design point of view, as well as serving as a protein-rich food for human occupants. Some candidate species are the silkworm, the hawkmoth, the drugstore beetle, and the termite. Plants in the ecosystem would include rice, soybean, sweet potato, and green–yellow vegetable but in combination they still lead to a diet that is deficient (for humans) in several nutrients. Normally these are supplied with animal-derived foods such as meat, poultry, fish, eggs, dairy products, etc. However, they can also be derived from insects which may be much easier to produce than any of the foregoing, and can also fulfill other useful ecological roles. Spinoff from this research could include some solutions to terrestrial problems such as supplying critical amino acids to people who suffer from a shortage of more conventional animal-derived proteins.

Keywords: Entomophagy; Space agriculture; Silkworm; Hawkmoth; Drugstore beetle; Termite; Insect

1. Introduction

Supplying food for human occupants remains one of the primary issues in engineering space habitation (Yokota et al., 2006). Evidently, for long-term residence on another planet or in a space vehicle it is essential to operate an agricultural system to generate food as well as decompose and recycle waste products. Historically, humans have consumed a variety of animals, and this will also be necessary and desirable when they live in space. Thus, interesting, varied, and high quality food may very well be a crucial factor in creating a liveable environment. Among the many candidate groups of animals that might be chosen as components of a space-based agro-ecosystem, insects have several advantages (Kok, 1983), especially in small-scale systems. Humans have historically eaten insects, as is evident from the analysis of fossilized feces. Accordingly, we suggest that entomophagy (Mitsuhashi, 1997) be considered in conjunction with a space agriculture to support human life in various forms of space habitation.

In a system sense, the function performed by insects in space agriculture is to upgrade inedible or low-grade biomass to higher-quality food for humans or feeds for animals. Overall, insect culture should not compete for space or other resources with plant culture. Instead, it should complement it. Thus, insects should feed on plants

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or plant parts that are not suitable for human consumption. In this regard, silkworm larvae consume mulberry leaves which are not suitable for human consumption. Other insects are able to degrade the inedible parts of vegetables. Even better is if the insects degrade materials which are problematic in a space-based situation. For example, woody materials will sequester carbon, and insects are able to accelerate their degradation by fungi and other soil organisms through mechanical action and partial digestion. Thus, insects will be able to make a major contribution to closing the materials cycles. Insects pupae, larvae, or adults can also be consumed by other farm animals such chickens, cattle, fish, etc. The feces of mass-raised insects (e.g., of the silkworm) can also be used as feed for fish, either in its raw form or through culturing plankton.

Overall, by selecting and incorporating appropriate insect species, the materials loops in a space-based agro-ecosystem can be closed and the utilization efficiency of the incoming energy can be improved.

2. Animal-derived materials to fill nutritional requirements

The design of a space agriculture system must be based on the requirements to recycle the materials necessary for life support, to remove materials that would be harmful to life, and to provide food (Alling et al., 2005). Thus, oxygen must be added to the gas phase while carbon dioxide must be removed, and food must be produced. As well, water that is evaporated by plants must be condensed to liquid form. The species that are chosen for the system should be selected on the basis of their nutritional content. Since both the area and the volume available for agricultural production are limited, the yield per unit area or per unit volume, per unit time, will also need to be taken into consideration so that oxygen and food can be produced at a sufficient rate.

As plant species for a space-based agro-ecosystem rice (*Oryza sativa*), soybean (*Glycine max*), sweet potato (*Ipomoea batatas*), and green–yellow vegetable (Komatsuna (*Brassica camperstris* var. *peruviridis*), or equivalent) are selected to provide occupants with metabolic energy, dietary fiber, protein, fat, vitamins, and trace elements such as iron and calcium. The best combination of these four, in terms of nutrition, was determined to be the following, per person per day: 300 g rice, 100 g soybean, 300 g green–yellow vegetable, and 200 g sweet potato (fresh weight). 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. Thus, it is low in sodium and in lipids, 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 protein in the form of insects.

3. Candidate insect species for space agriculture

About 70–75% of all animal species living on earth are insects and, together, they play an important role in recycling materials in the terrestrial biosphere. A phylogenic tree of animals that are eaten by humans is shown in Fig. 1. As is evident, a rather wide range of creatures are acceptable as food, corresponding to the diversity of the natural ecosystem (Marconi et al., 2002). Biologically, insects are quite similar to the shrimp, lobster, and crab which are commonly eaten (Eigen, 1992) and the taste and texture of insect meat is quite similar too. The great diversity of insects originates in their co-evolution with plants and many inter-species interaction among insects and plants can be readily found. Thus, in many instances, the leaves of a certain plant will only be eaten by a one insect species, which has the capacity to overcome the plant's defenses. Similarly, a particular plant will depend on a specific insect for pollination, at the cost of providing floral nector. Because of such ecological features, the design of a space-based agricultural system will depend heavily on the natural interactions between components so that the food relationships will work out and the recycle loops can be closed. Thus, for the engineering of ecosystems we should have a good understanding of the web of interaction among organisms.

For space agriculture purposes, we will examine several insect species: the silkworm (*Bombyx mori*), the hawkmoth

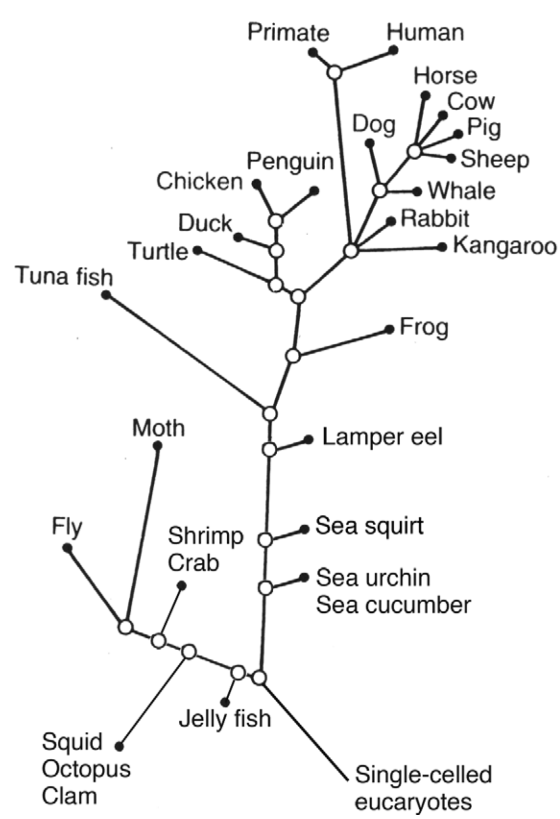

Fig. 1. Phylogenic tree of animals to eat (except human). Modified from Eigen (1992).

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(hornworm), (*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 edible food for humans.

4. Silkworm and hawkmoth

The silkworm (Fig. 2) has been domesticated for 5000 years in China and, as a result, has lost its ability to fly. Evidently, this is advantageous in rearing them. Rearing methods are well established and, 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. About 40% of the feed is digested, with the remaining 60% being excreted as feces. Final biomass of silkworm pupa ends about 10% of the feed. Together with other constituents such as the larval casts, silkworm feces can be utilized in many ways such as feed for fish. It can also be composted to increase soil fertility. Of course, the main reason for raising silkworms is the production of silk which can be woven into a high-quality cloth. Both the silkworm pupa and the moth are quite widely accepted as snack foods in east Asia. The Kaneman Co. Ltd. (Japan) sells canned silkworm pupae and moth cooked with soy sauce and sugar (www.kaneman1915.com).

Hawkmoth (hornworm) larvae feed on the leaves of sweet potato and other plants. This species is model insect

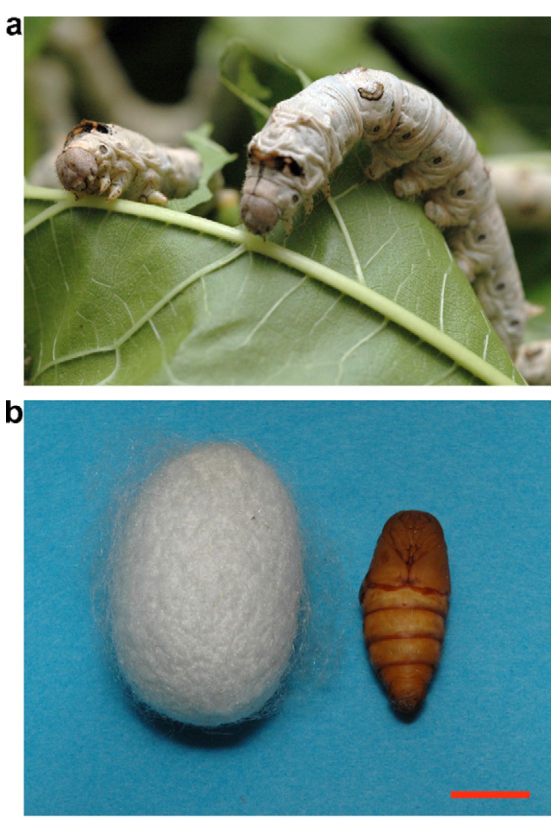

Fig. 2. Silkworm. (a) larvae on a mulberry leaf, (b) cocoon and pupa. Scale bar; 10 mm.

for scientific studies (Kiguchi and Shimoda, 1994) and its rearing technology is well developed. The pupa is two or three times larger than that of the silkworm and it is very tasty after frying. Since the hawkmoth does not spin a cocoon, most of nitrogen absorbed from the plant leaves is used for the synthesis of protein. In contract, the silkworm converts more than 65% of its nitrogen into the silk fiber of its cocoon. In this sense, the efficiency of biomass conversion from plant leaves to insect mass is higher than for the silkworm. Even if sweet potato leaf is considered as 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, e.g., in a Martian greenhouse.

5. Drugstore beetle and termite

Both the drugstore beetle and the termite are able convert cellulose to animal biomass. Like the ruminants, they accomplish this by having symbiotic protozoa in their gut which produce the required cellulase. The cellulose is thus broken down 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).

6. Model diet and nutritional value of insects

The nutritional value of insects was examined to establish whether they could form a viable alternative to the meat of vertebrates. Some data on the protein content and amino acid composition of silkworm pupae, the excrement of silkworm larvae, and mulberry leaves are presented in Table 1. Although mulberry leaf has a 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. Silkworm lipid and its composition is summarized in Table 2. The lipid content of the silkworm pupa is eight times that of the mulberry leaf and it has an "animal-like" composition (Katayama et al., 2005).

In our model diet we have added 50 g of silkworm or other insect to the core composition of the four plants, as described earlier: 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 64 m^2/person. For farming the four core plants, 200 m^2/person is expected to be needed (Yamashita et al., 2006). Although insects do not have the full complement of nutrients that can be obtained from

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

(g/100 g)	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

(g/100 g)	Fatty acid compositon (%)												Fatty acid		
	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

vertebrate meat or avian egg, a major part of these nutrients can be supplied with them. Remaining nutrient requirements can then be met in different ways. A model diet containing mushroom, chicken meat, egg, and liver is presented in Table 3A. In this case the chicken-derived materials are included to address deficiencies of vitamin D, B_{12} and cholesterol in the main diet. The Japanese mushroom is included mainly as a supply of vitamin D. The amount in the diet can be greatly decreased if it is finely cuts or powdered and then irradiated with ultraviolet light to induce the conversion of precursor substance to vitamin D. Other trace nutrients could be fed as supplements as food additives or tablets.

7. Other considerations

The robustness of a species is an important factor for its selection for space agriculture. Various species of fish might be considered for inclusion in an agro-ecosystem. The breeding of fish in rice paddies is done in many places, with the loach fish (*Misgurnus anguillicaudatus*), being one of the common species that live naturally in this environment. It is resistant to adverse conditions such as poor water quality and partial drying of the paddi. It is able to gulp air into its digestive tube and exhaust it from its anus after absorbing oxygen in its gut. It has a high nutritional value. In Table 3B, 120 g of loach fish replaces the mushroom, egg, meat, and organ of part A. The nutritional analyses for both parts are presented in Table 4. The values shown in Table 4 are all within the allowable range or close to the recommended level for human requirements. There are some other items that remain to be examined for the assessment of the diet's nutritional value but these are quite minor, and not critical to the concept of space agriculture.

8. Conclusion

Entomophagy is a promising approach to meet human nutritional needs in space. In a space-based agro-ecosystem insects can recycle materials, process waste, serve as food and feed, and pollinate plants. A model diet consisting of rice, soybean, sweet potato, green–yellow vegetable, silkworm pupa, and loach fish was found to meet human nutritional requirements. overall, space agriculture can be

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improved by incorporating insects as components. They can serve a number of functions without competing with plant production. The design of systems for space agriculture will also provide insight into improving the management of Earth's biosphere and allow for long-term sustainability. Entomophagy may be very well prove to be a key idea in solving the world's food problem.

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