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FOOD PRODUCTION AND NUTRITION IN BIOSPHERE 2: RESULTS FROM THE FIRST MISSION SEPTEMBER 1991 TO SEPTEMBER 1993

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ABSTRACT

The initial test of the Biosphere 2 agricultural system was to provide a nutritionally adequate diet for eight crew members during a two year closure experiment, 1991-1993. The overall results of that trial are presented in this paper. The 2000 m² cropping area provided about 80 percent of overall nutritional needs during the two years. Adaptation of the crew to the diet which averaged 2200 calories, 73 g. of protein and 32 g. of fat per person over the course of the two years. The diet was primarily vegetarian, with only small amounts of milk, meat and eggs from the system's domestic animals. The crew experienced 10-20 percent weight loss, most of which occurred in the first six months of the closure reflecting adaptation to the diet and lower caloric intake during that period. Since Biosphere 2 is a tightly sealed system, non-toxic methods of pest and disease control were employed and inedible plant material, domestic animal wastes and human waste-water were processed and nutrients returned to the soil. Crop pests and diseases, especially broad mites and rootknot nematode, reduced yields, and forced the use of alternative crops. Outstanding crops included rice, sweet potato, beets, banana, and papaya. The African pygmy goats were the most productive of the domestic animals. Overall, the agriculture and food processing required some 45% of the crew time.

A BRIEF DESCRIPTION AND HISTORY OF BIOSPHERE 2

Aims and Objectives

Biosphere 2, a tightly materially sealed but energetically open structure, situated approximately forty miles north of Tucson, Arizona U.S.A. was designed and constructed by a private company, Space Biospheres Ventures (SBV). The process of design and development started in 1984 and lead to the completion in 1991 of a closed system laboratory of some 1.2 ha. in footprint to be used to study processes and ecosystem dynamics analogous to those of planet Earth, "Biosphere 1." The Biosphere business strategy was to create an entrepreneutial venture marketing closed systems, data management systems, spin-off products, and educational and visitor programs. The strategy envisaged that a great deal of the knowledge gained by building and operating such a system would be applicable to future work in designing and operating closed systems for space colonization. The first closed mission began on September 26 1991 with an eight-man crew, whose aim was to 'test the concept' acting as a 'shake-down' crew for the newly created system, operating it for two years and 'troubleshooting' for areas that needed upgrading or redesign for future missions. They were also to lay the basic ground work for the extensive research programs that would be carried out in all fields once the facility was made operationally easier to manage, the engineering verified and initial problems and surprises dealt with.

History

Food production has been one of the important objectives in Controlled Ecological Life Support Systems (CELSS) which have been developed and researched since the beginning of the space age, especially in the former Soviet Union and in the United States under NASA funding. Soviet and U.S. work began with simple algae-based systems which did a fairly effective job of oxygen and water regeneration for animal and human subjects, but which proved unpalatable for meeting nutritional needs except in small quantities. The institute of Biophysics in Siberia continued the work using algae and food crops in the Bios3 experiments. The experiments lasted up to six months regenerating almost all the air in the 300 m³ system, recycling 90% of the water and producing approximately half the food for the two or three man crews. The NASA work in (CELSS) has focused on high yield hydroponics systems for certain key food crops /1,2,3,4,5,6/, and with the 1986 Breadboard Project, work was scaled up to include the integration of food production, water recycling and atmospheric control in its production chambers. Japanese and European programs in closed ecological systems for life support are also underway /7,8/.

Description

The Biosphere 2 research facility and the research and development work for its preparation have been extensively described elsewhere /9/, so this description will be kept brief. The facility was designed not only to provide human life-support, but also to maintain complex and evolving ecosystems. The area is divided into seven biomes with differing soils, climate regimes, and vegetation. (Table 1) The structure is sealed above ground with laminated glass mounted on a space frame and below ground with a stainless steel liner. Two variable volume chambers (called "lungs") are connected to the main structure. The ecosystems are housed in two wings that share water and air circulation. Screens prevent flying insects and other animals from moving between the anthropogenic biome wing containing the agriculture and the human habitat and the wilderness biome wing containing the rain forest, savannah, desert, marsh, and ocean.

TABLE 1 Dimensions and Volumes of Biosphere 2

Section	Dimensions (meters) N-S E-W height	Areas m²	Volumes m³	Soil m³	Water m³	Air m³
Agriculture	41 54 24	2000	38,000	2720	60	35,220
Habitat	22 74 23	1000	11,000	2	1	10,997
Rainforest	44 44 28	2000	35,000	6000	100	28,900
Savannah/ocean	84 30 27	2500	49,000	4000	3400	41,600
Desert	37 37 23	1400	22,000	4000	400	17,600
West lung	48 48 15	1800	15,000	0	0	15,000
South lung	48 48 15	1800	15,750	0	750	15,000
Totals		**12500**	**185,750**	**16722**	**4711**	**164,317**

Lungs measured at one half inflation

THE AGRICULTURE SYSTEM

Overall Description

The agriculture area of Biosphere 2 consists of about 0.2 ha. of growing space (including the animal area) and was designed to supply a diverse and nutritionally adequate diet for eight people for the first two-year mission. The system utilizes intensive forms of several traditional agricultural systems: rice/azolla/fish, grains, vegetable, tropical orchard, and domestic animals/fodder crops. Overall, including herbs, some 86 varieties of crops are grown in Biosphere 2. Crops of special importance in the diet include: grains (rice wheat, sorghum) starches (sweet potato, white potato, taro), beans (hyacinth), oil seed (peanut), vegetables (chili, squash, beets, tomatoes, cabbage, chard, salad greens) and fruit (banana, papaya, guava, fig, citrus). (see Table 2)

The main growing area is divided into 18 plots, each of approximately 93 m^2. These plots include 2 wetland rice paddy fields. The main field crops were rotated between plots, each plot producing three to four crops per year. The orchard area, approximately 172 m^2, proved to be too shaded by the structure to grow citrus but produced crops of banana, papaya, and understory fodder crops. A basement area toward the south of the Intensive Agriculture Biome (IAB) housed the waste-water treatment system, tanks for rice production, and planter boxes for fruit trees and starchy vegetables. Azolla, grown in the rice tanks and paddy fields, was a source of high-protein feed for the Tilapia fish and is also harvested as chicken food. The animal barn houses chickens and goats and initially, also, pigs.

In the basement area air handler units regulate temperature and humidity. There were two main growing seasons during Mission 1, a winter season from November to April with temperatures between 19 and 27°C and a slightly warmer summer season for the rest of the year with temperatures ranging between 19 and 30°C. Relative humidity was kept as low as possible for pest control and generally averaged below 45%. (Figure 1 and 2). The basement also housed the food drying ovens, storage rooms and processing area and the water recirculation system. Worm beds in the basement supply worms for the soil and for chicken food.

MAINTAINING SUSTAINABILITY IN THE SYSTEM

Recycling

Biosphere 2 with its small buffer sizes of atmosphere, water, and soil and the increased rate of nutrient cycling, mandated a design for the agriculture that emphasized sustainability, high productivity, avoidance of pollutants and non-regenerable inputs, and minimization of labor. Although initial experiments during the design phase of the Biosphere used hydroponic systems, a soil based system was chosen for ease of nutrient recycling, long-term sustainability, and better modelling of Biosphere's tropic agricultural regimes. The soil used for the agricultural area consisted of 75% clay loam pond soil, 10% Canadian peat moss and 15% compost.

Nutrients were returned to the soil through the recycling of dried plant wastes and through the water recycling system as irrigation water. Waste-water from the human habitat and the animal bay was first held in tanks where anaerobic bacteria began to break it down. It was then circulated in aquatic lagoons where water plants and their associated microbiota continued the digestion /10/. Treated water from the lagoons was then mixed with the sub-soil drainage water and condensate water to maintain a total dissolved salt level below 1000 ppm before it was returned to the soil as irrigation water. Most of the non-human edible plant material was fed to the animals. All the solid waste from the animal bay and any plant material that could not be fed to the animals, was shredded, dried, and dug back into the soil in between plantings. A small proportion was composted or fed to the worm beds. As a portion of the animal fodder had come from pruned materials from the wilderness ecosystems, a portion of the dried shredded material was also returned to the wilderness ecosystems as mulch.

Integrated Pest Management

Pest management techniques included use of a polycultural agriculture rather than a monocultural one, use of resistant cultivars, introduction of beneficial insects, environmental manipulations, manual intervention and use of non-toxic sprays. The main pest and disease problems were: two-spotted spider mite, broad mite, thrip, mealy-bug aphid, powdery mildew, root knot nematode, pill bug, and cockroach. A variety of predatory insects were introduced into the system before closure /11/, the most successful one being *Cryptoaemus montouzieri,* which remained present throughout the two-year experiment and appeared to maintain the mealy bug population at manageable levels. Aphids were controlled mostly by mechanical methods such as pruning, washing with water and spraying with soap and sulfur sprays. Two spotted spider mite was also reduced in population by washing with water or increasing humidity levels. Pill bugs and cockroaches were trapped and fed to the chickens, although Australian cockroaches, *Periplaneta australasiae,* which had originally entered the system on tropical plants in the rain forest, remained an increasing problem throughout the experiment. In the second year a cockroach parasite, *Aprostocetus hagenowii*, a small wasp which lays its eggs in the cockroach oothecae, were introduced both into the IAB and the kitchen area, but these did not prove effective. With the powdery mildew, sulfur spray, lowering humidity levels, and using the more resistant cultivars, gave some measure of control, but for cucurbits it was necessary also to maintain heavy pruning and rapid turnover of crops, as the disease increased rapidly in the early fruiting stage. Cabbage looper worms were effectively controlled on rice and vegetable crops using *Bacillus thuringiensis.*

The major pest problem during the first two years was broad mite. Although not usually a pest of field crops, the green-house conditions of the Biosphere 2 agriculture system seemed to be the ideal breeding ground for these microscopic mites, which severely attacked white potato, sweet potato, beans, peppers, and eggplants.Various strategies were used against the mites. The use of vegetable oils against such insect pests is a growing area of research in Integrated Pest Management (I.P.M) /12/. Vegetable oil spray was tried on potatoes beans and peppers. The spray gave some measure of control, but it only seemed to be effective on contact, because the mite larvae are carried by the adult male into the new leaf buds, and the eggs are laid on the underside of the leaves. It became apparent that a mite predator would be a more affective. (It was also observed that spraying the leaves with oil attracted cockroaches to the plants, and they would then eat holes in the leaves which they would not normally do with unsprayed leaves.)
During the mission the following predatory mites were introduced to try to combat the broad mite problem: *Euseius stipulatus, Typhlodromus porresi, Typhlodromus rickeri, Galendromus annectens, Amblyseus cucumeris, and Amblyseus barkerii*. Although initially these introductions reduced the pest population, the predator populations were not able to sustain large enough numbers over time. During the second year, signs of possible damage by soil pathogens were seen on grain crops. Tests were performed on root samples, and *Pithium graminicloa* was found to be present. Toward the end of the experiment a program was set up with the University of Arizona to find biological controls for this pathogen (see section on transition work).

Increasing amounts of root infection with root knot nematode were also seen on certain crops. Crop rotation was the only method of control used during the first two years, but during the transition phase experiments were initiated to explore the control of nematode with predatory nematodes and chitin preparations.

Labor

Approximately 45% of crew time was taken up with agricultural or food-related work, including the rough and fine processing, animal care and cooking. There was a slight reduction in the time taken during the second year due to the fact that increasingly more efficient ways were found to do various tasks, and the clay loam soil became easier to work as more crops were rotated through the plots.

Atmospheric Management

As with all areas of Biosphere 2, not only did the requirements of the agriculture system have to be taken into consideration, but also the requirements of the total atmospheric management of the Biosphere. This became particularly important during winter months when atmospheric levels of carbon dioxide were rising due to low light levels. Composting had to be minimized, which led to the system of returning plant waste to the soil in the form of dry shredded material. For the same reason efforts were also made to minimize soil disturbance and to maintain actively growing biomass in the plots at all times. Concern with the potential for trace-gas build up within the tightly sealed structure led to the design of the Biosphere 2 soil as an air cleaning device /13/. This involved pumping air through the planted active soil, thus exposing technogenic

TABLE 2 Food production during two year mission

BIOSPHERE 2 INTENSIVE AGRICULTURE PRODUCTION FOR 8 BIOSPHERIANS
SEPTEMBER 1991 TO SEPTEMBER 1993

CROP	YIELDS Kg/sq.meter Year 1	YIELDS Kg/sq.meter Year 2	TOTAL 2 YR YIELD Kg	g. per person per day	PROTEIN (g.)/ PERSON/ DAY	FAT (g.)/ PERSON/ DAY	Kcal/ PERSON/ DAY
GRAINS							
RICE	0.29	0.20	276.47	46.76	3.52	0.85	167.82
SORGHUM	0.24	0.17	189.83	32.10	4.24	0.64	106.63
WHEAT	0.22	0.14	191.87	32.45	4.29	0.65	107.78
STARCHY VEG							
WHITE POTATO	0.63	1.42	240.41	40.66	0.86	0.48	31.22
SWEET POTATO	2.25	1.95	2765.13	467.64	6.68	1.34	494.36
MALANGA	n/a	n/a	101.61	17.18	0.41	0.03	18.04
YAM	n/a	n/a	19.50	3.30	0.07	0.00	4.36
HIGH FAT LEGUMES							
PEANUT	0.10	0.15	147.42	24.93	6.59	12.20	146.03
SOY BEAN	0.15	0.34	21.41	3.62	1.32	0.66	14.56
LOW FAT LEGUMES							
LAB LAB BEAN	n/a	n/a	143.79	24.32	3.88	0.33	84.33
PEA	0.05		14.52	2.45	0.61	0.02	8.42
PINTO BEAN		0.20	27.49	4.65	1.15	0.04	15.94
SUBTOTAL			4111.95	695.41	32.47	17.20	1183.55
VEGETABLES							
BEANS GREEN	1.22	1.03	24.95	4.22	0.08	0.00	1.36
BEET GREENS	2.64	0.63	432.28	73.11	1.33	0.37	15.38
BEET ROOTS	2.83	2.20	760.23	128.57	1.88	0.18	56.94
BELL PEPPER			65.73	11.12	0.10	0.05	2.67
CARROTS	2.25	4.39	224.76	38.01	0.34	0.07	16.70
CHILLI			125.19	21.17	0.42	0.04	8.47
CABBAGE	3.42	2.78	152.82	25.84	0.30	0.04	5.91
CUCUMBER			48.13	8.14	0.04	0.01	0.04
EGGPLANT			244.94	41.42	0.44	0.03	11.10
KALE	8.30		11.29	1.91	0.06	0.01	0.93
LETTUCE	5.37	2.44	150.59	25.47	0.24	0.04	3.37
ONION			139.23	23.55	0.28	0.06	7.99
PAK CHOI	3.91	3.47	45.29	7.66	0.11	0.01	0.98
SNOW PEA	0.29		0.91	0.15	0.01	0.00	0.12
SQUASH SEED			10.43	1.76	0.51	0.82	9.70
SUMMER SQUASH	4.88	4.39	512.56	86.68	0.93	0.19	16.72
SWISS CHARD	12.69	14.65	141.52	23.93	0.43	0.05	3.93
S.POT. GREENS			64.41	10.89	0.31	0.03	2.72
TOMATO			352.90	59.68	0.53	0.11	11.72
WINTER SQUASH	4.15	4.05	342.47	57.96	1.05	0.10	36.82
SUBTOTAL			3850.63	651.22	9.40	2.20	213.57
FRUIT							
APPLE			0.57	0.10	0.00	0.00	0.06
BANANA			2170.92	367.15	2.36	10.49	220.29
FIG			54.34	9.19	0.07	0.03	6.70
GUAVA			53.50	9.05	0.06	0.04	3.64
KUMQUATS			4.17	0.71	0.00	0.00	0.42
LEMON			10.12	1.71	0.01	0.00	0.34
LIME			3.63	0.61	0.00	0.00	0.16
ORANGE			5.65	0.96	0.01	0.00	0.33
PAPAYA			1215.64	205.59	0.81	0.15	52.87
SUBTOTAL			3518.53		3.31	10.71	284.79
ANIMAL PRODUCTS							
GOAT MILK			841.84	142.37	4.58	5.59	99.05
GOAT MEAT			16.96	2.87	1.02	0.48	7.54
PORK			58.74	9.93	1.70	2.06	26.11
FISH			10.21	1.73	0.32	0.07	2.03
EGGS 257			14.29	2.42	0.29	0.27	3.86
CHICKEN MEAT			8.07	1.37	0.25	0.20	2.92
SUBTOTAL					8.17	8.68	141.50
TOTAL PRODUCED					53.35	38.80	1823.41

and biogenic trace gases to microbial metabolism (14,15,16). However, it did not prove necessary to use the system during the first two-year mission.

PRODUCTIVITY

Overall the agriculture biome produced approximately 80% of the food for the eight-man crew during the first two-year mission The production for the two years is summarized in Table 2. Production in different crops was affected by a variety of different factors, but the main factor affecting all crops was light level (Table 3). The glass and space frame structure of the IAB eliminated 50- 60% of the ambient light. The experiment was also affected by an El Niño Southern Oscillation, which produced unusually cloudy autumn and winter weather patterns in the southwestern United States for the two year period. The second winter had somewhat lower light levels than the first year. January and February 1993 light levels being down by 20% from those of 1992. Artificial light was deliberetely not put in for the first two years, so that the amount actually needed could be added during transition one, thus avoiding excess capital costs and giving a direct seasonal correlation for the first two years.

TABLE 3 Production comparisons at different light levels in wheat and sweet potato

CROP	Total light received by crop in mol m^{-2}	Average light per day in mol m^{-2} d^{-1}	Yield Kg m^{-2}
Wheat 1	679	6.4	0.04
Wheat 2	1534	10.5	0.09
Wheat 3	2022	16.4	0.24
Sweet potato 1	1258	7	1.26
Sweet potato 2	3047	14.6	1.8
Sweet potato 3	3419	22.7	2.88

Grains

Of the grain crops the rice was by far the most productive overall giving a yield of 0.29 Kg m^2 over the first year and 0.19 Kg m^2 over the second year. Two cultivars raised by the California Rice Research Institute were used. The lower production during the second year was due partly to lower light levels and partly due to the build up of toxic gases in the paddy water as the fields were left continually flooded. At the end of the second year the fields were allowed to dry out completely for three months and the subsequent crop was very successful. Wheat production varied greatly from crop to crop. Care had to be taken to keep maximum temperatures below 29.5°C during the wheat production period to avoid early tillering. During the second year the crop also suffered from pithium damage. Sorghum production also varied. The most successful cultivar was a short stemmed one called Dorado. In the second year the Sorghum also showed signs of pithium damage and the ripening grains were attacked by cockroaches.

Toward the end of the first mission work was underway to find better adapted grain cultivars for the system. This included experimenting with millet production and with new rice varieties imported from areas of the Philippines that had overall light levels and temperature ranges similar to those found in the IAB.

Starches

Sweet potato was the most productive starch crop, producing on average 1.9 Kg m^2. As well as supplying the main starch source for the humans, the greens provided the main protein source for the goats. During the two years, experiments were performed with different watering regimes, and it was found that dry shocking the crops periodically helped to induce potato production. The broad-mite pest attacked the sweet-potato crop but only during the dry-shock periods. Taro, white potato, green banana, small plantings of yam, and plantain were also sources of starch. The white potato was the most popular with the crew, but severe broad mite damage prevented it from becoming a major part of the diet. Taro did well even under shady conditions, but several members of the crew found it totally unpalatable.

During the transition phase, new cultivars of tropical starchy root crops were introduced for trial, including yam cultivars known to do well under shade in the Philippines, and Cassava. New taro varieties were also introduced in an attempt to find some that were more acceptable for consumption.

Legumes

Various types of beans were tried in the system both before and during the experiment; for example, kidney beans, pinto beans and soy beans. However, it was found in all cases that the plants were very badly damaged by mites and in some cases by powdery mildew. The most successful bean was the hyacinth bean, *Lablab purpureus,* which seemed to be immune to the pests and produced abundantly in the summer months but had a winter dormancy period. Inquiries in India where the plant is used commonly for human and animal food, produced a cultivar from the Tamil Nadu Agricultural University that fruited all year round. During the second year, successful soy and pinto crops were grown as techniques for controlling the mite had improved. Peanut was the main source of vegetable fat in the diet. Peanuts produced well in the second year as they were planted in May and June after the worst of the cloudy weather was over. Several different cultivars were tried, but a small Spanish cultivar was the most successful. The peanut crop did not seem to be affected by pests or diseases, but care had to be taken with the moisture content of the soil, to avoid drying out during pegging. Bean greens and peanut greens were also a source of high protein animal fodder.

Vegetables

One of the 18 field plots was devoted to fresh vegetables, and this plot was rotated annually. A supply of fresh vegetables was maintained all year although the type varied from season to season. Fresh green leafy vegetables were available all year. Carrots, chard, cabbages and beets did well through the winter months, and summer and winter squashes, tomatoes, cucumbers, eggplants, and peppers were grown through the spring, summer and fall. The Australian guada bean, a large vining plant producing squash-like fruit, produced well all year round. The main pest affecting the vegetables was powdery mildew on the cucurbits (see IPM section) and cockroach damage on the cabbages.

Fruits

By far the most productive fruit was the banana. The trees in the orchard and along the north wall of the IAB produced 2.4 tons of bananas, which were the main source of sweetener in the diet. The bananas were also eaten green as a starchy vegetable. Papaya also produced very well and was also used both as a fruit and green as a vegetable. Figs and guavas in the orchard and in the lower IAB. were the next best producers, the citrus producing very little, probably due to low light levels, now supplemented by artificial light.

The Animal System

Domestic animals were included in the system for several reasons. They consume portions of the plant material produced in the agriculture system that the human beings could not consume and would break it down into compostable material. The goat milk, goat meat, and the chicken meat and eggs would also provide a small addition to the diet and some variety.

For the first year, two adult pigs were also kept in the system and they produced a litter of 7 piglets. The Pigs selected for the system were Ossabaw Feral Swine, a small pig known to do well on a diet high in leafy vegetable material; however they did not maintain weight well, and after the first litter the sow did not become pregnant again. The decision was made to eliminate the pigs from the system.

The African pigmy goats proved very successful. Four does and one buck were maintained on a diet of approximately 4 Kg of high protein fodder and 4 Kg of roughage per goat per day. The goats produced on average 1.14 Kg of milk per day, and six kids were raised for meat.

The chickens were a cross between the Asian jungle fowl and the Japanese silky hen. The aim was to get a laying hen, both hardy and docile, that took care of its young. The egg production was far lower than anticipated. The chickens were fed largely azolla, trapped insects (i.e. pill bugs and cockroaches), and a small amount of table scraps consisting mostly of vegetable peels. This diet did not seem to be high enough in calories and fats to promote egg production.

FOOD PROCESSING

Rough Processing

The rough processing of the harvested food took place in the basement area below the IAB. Access was by stair or elevator, and the harvested crops were generally moved in large plastic bins for drying, processing, and storage. Two large drying ovens were used to dry crops and the processing equipment included a threshing machine, a winnower, a rice dehuller, and a large electric flour mill. One of the main problems with the processing machinery had been to find equipment on the right scale for the needs of the IAB Laboratory equipment was generally too small and equipment designed for the agriculture industry was too large. On the whole, the largest available Laboratory equipment was used.

Grains were dried in the ovens and then threshed and winnowed. The dry clean grain was stored in air-tight containers, the straw was shredded for return to the soil or used as animal bedding, and the winnowed hulls were given to the chickens to scratch through for the occasional grain that had been left behind. Beans were dried and then dehulled, usually by hand; putting the beans in a sack and crushing the hull with a mallet proved to be the fastest way. They were then winnowed and the clean seed stored in air-tight containers or in the refrigerator. The dried crushed hulls were a favorite snack for the goats and were often used to feed them during milking. Peanuts were washed, oven dried in their shells, and stored in air-tight containers. The peanut greens were dried and kept for winter high protein fodder.

Potatoes were washed thoroughly and left to cure for two or three days on open shelving before being placed in cold storage. They would not keep longer than two months in cold storage, and care had to be taken to eat the smaller ones first as they would not last more than a few weeks. This did not matter during the first two years since the potatoes would be quickly consumed after harvest. During transition, experiments were performed with pulping and freezing and drying and freezing the potatoes; both methods worked well.

The fruits and vegetables were generally harvested fresh daily. The bananas often had to be stored as whole bunches would ripen at one time. They were either pulped, or broken into small pieces and frozen.

Fine Processing

The crew took it in turn to cook once every eight days. Sally Silverstone, the Food-systems manager, would weigh and record the total daily allotment of food and give it to the cook to prepare in what ever way they wanted. A typical day's food would consists of a breakfast of porridge made with grains, goats milk, banana, and a small bowl of beans, or some potato pancakes. Lunch would normally consist of a large soup, either bread, potatoes, or rice for starch and a vegetable dish and salad. Dinner would be more elaborate with a main course consisting of a starch, beans, or occasionally meat served with several vegetable dishes, a salad, and a dessert. The food was divided out equally amongst the eight crew members regardless of size or gender. The kitchen was well equipped with electrical processing equipment (i.e. blender food processor, mixer, microwave oven, etc.) In addition to the daily cooking, there were other fine processing activities performed by the food-systems manager. These included bread making, cheese making, yogurt making, wine making, jam making and freezing of fruits and vegetables.

HUMAN ADAPTATION TO THE DIET

Nutrition

The average daily nutritional intake of the crew is summarized in Table 4 and 5. On average over the two years, the crew ate 2200 calories, 73 g. of protein, and 32 g. of fat per person per day. The nutritional values of the foods were compiled using standard figures from nutritional almanacs and from Dr. Roy Walford's diet planning computer program. Dr. Walford was the medical officer for the crew. As the food was divided equally, and the daily allotments of total food were carefully weighed and recorded, it was possible to have an accurate record of each persons dietary intake. As far as micro nutrients are concerned, the only ones showing deficiency according to government RDA standards were vitamin D and vitamin B_{12} A supplementary vitamin supply was made available to the crew to cover these deficiencies. Vitamin B_{12} is found in the diet almost exclusively in animal protein and was therefore low in the biospherian diet. However, recent studies into the effect of a purely vegan diet on health have shown that even though vegans have serum B_{12} levels well below average, they are mostly free of neurological or hematological symptoms /17/. In an enclosed system such as Biosphere 2, the ability of the body to produce vitamin D by irradiation is limited by the glass barrier. The diet also did not contain much fish liver oil, the main dietary source of vitamin D.

TABLE 4 Average protein, calories, and fats consumed per person per day

MONTH	PROTEIN (g)	Kcal	FATS (g)
Oct 91	67	1789	28
Nov 91	62	1925	21
Dec 91	74	2183	27
Jan 92	62	1948	23
Feb 92	74	2247	37
Mar 92	74	2206	32
Apr 92	72	2092	29
May 92	71	2043	28
Jun 92	72	2038	30
Jul 92	62	2227	32
Aug 92	66	2307	28
Sep 92	72	2491	34
Oct 92	68	2307	37
Nov 92	70	2304	34
Dec 92	88	2345	30
Jan 93	82	2225	30
Feb 93	74	2247	37
Mar 93	99	2282	34
Apr 93	79	2204	29
May 93	69	2190	30
Jun 93	72	2337	40
Jul 93	67	2252	32
Aug 93	75	2397	39
Sep 93	72	2609	38
Overall average	**73**	**2216**	**32**

The crew weights are summarized in Table 6. All the crew had initial weight losses over the first 6 months ranging from 9 to 22% of their body weight. (This seemed to be the main period of adaptation to the diet.) Dr. Walford's studies also showed significant drops in blood cholesterol and blood pressure during this period/18/. Weight response during the second six months shows a small further loss in six members and a small gain in two. During the second year, the weights of the crew became far more steady, showing a slight increase overall.

TABLE 5 Nutritional intake of crew

Nutritional element	Unit	Average amount per person per day	RDA	% RDA
Tyrosine	mg	2541	960	265
Phenylalanine	mg	4902	960	511
Valine	mg	3701	840	441
Tryptophane	mg	858	180	477
Isoleucine	mg	3154	720	438
Lysine	mg	3617	720	502
Leucine	mg	6835	960	712
Methio + Cystine	mg	1967	600	328
Threonine	mg	2562	480	534
Vit a	IU	59591	5000	1192
Vit d	IU	3	400	1
vit k	µg	159	70	227
Riboflavin	mg	2	2	99
B 6	mg	5	2	236
B 12	µg	1	3	19
Biotin	µg	71	100	71
Vitc	mg	489	60	814
Vit e	IU	38	15	250
Thiamine	mg	3	1	262
Niacine	mg	27	20	133
Folacine	µg	836	400	209
Pantothenic Acid	mg	10	4	238
Calcium	mg	750	800	94
Magnesium	mg	735	400	184
Sodium	mg	412	500	82
Copper	mg	2	2	107
Zinc	mg	11	15	73
Chromium	µg	176	50	351
Phosphorous	mg	1628	1200	136
Potassium	mg	6881	1875	367
Iron	mg	23	18	128
Manganese	mg	55	2	2735
Selenium	µg	70	50	140

TABLE 6 Weights of the eight Biospherians over 2 year period

	BODY WEIGHT IN kg				
Crew member	Sept 1991	Mar 1992	Sept 1992	Mar 1993	Sept 1993
Male 1	67.3	60.5	56.8	61.0	59.2
Male 2	68.2	59.1	54.5	58.0	57.0
Male 3	67.3	55.5	54.0	58.0	56.0
Male 4	94.5	73.6	67.5	71.0	72.5
Female 1	75.0	64.5	66.0	69.0	70.5
Female 2	55.9	50.9	49.5	52.0	52.2
Female 3	59.1	52.3	51.0	53.5	53.9
Female 4	52.7	42.8	44.0	48.0	46.8

General Adaptation

The crews ability to adapt comfortably to the diet differed greatly between members. Although all the crew initially missed sweet foods, coffee, and other personal favorites, some members felt far more hungry than others, especially during the first six months. After the first six months, the calorie and fat intake was increased slightly by adding more peanuts to the diet. All the crew members commented on the fact that after the first few months they found their taste buds were adapting to the diet and that foods that had initially tasted bland seemed more tasty and that natural sugars in foods such as fruit, sweet potato, and beet were far more detectable.

The diet and cooking became an extremely important part of everyday life in the Biosphere. The standard of the cooking on a particular day would have an effect on the general spirits of the crew and it became almost a competitive issue amongst the crew to see who could produce the best meals.

Variety was extremely important. A new taste or a new dish became a real treat and every effort was made to enhance cuisine so as to avoid the monotony of the same foods. Much of the variety was provided with the various fruits, vegetables, herbs, and spices and the different milk products such as cheese and yogurt. Color and shape were also important and the crew appreciated a well presented meal.

Much of the crew's social life became centered around food. Holidays were celebrated with large feasts, and the food-systems manager would put by small stores of food that could be eaten on these occasions. On feast days all members of the crew would participate in cooking, each making their own specialties, and most of the day would be spent enjoying the feast. The diet was largely vegetarian, but after the first year two crew members found that they had become sensitive to eating even the small amount of meat that was in the diet and opted to stop eating meat altogether.

TRANSITION PHASE

Physical Changes

The five month period between the September 1993 opening and the second closure with the new crew in March 1994 was taken as an opportunity to make improvements in the system and gather key data without disturbing the integrity of the atmosphere of the Biosphere.

The major change made in the IAB was the addition of artificial light to promote crop growth over the winter months and during cloudy periods. These lights were concentrated in the areas of most heavy shading by the overall structure and provided between 6 and 10 $\mu mol\ m^{-2}\ s^{-1}$ light depending on the area. Additional planting space was added in the basement area and supplementary light was also added for the new planters. The original composting system was heavily modified to make it easier to shred, dry, and store material when this was necessary for atmospheric control.
Much effort was made to improve efficiency. This included importing a larger threshing machine to speed up rough processing, and work began on designing a larger electricly powered rototiller for working the field crop plots.

The data base used for collection of the food data was completely updated to make it more user friendly and interactive with other computer software.

Research Plans Initiated

Several experiments were initiated in the areas of pest control. A mite-breeding program was introduced in order to maintain a continuous supply of predatory mites to combat the broad mite. A complete study of the pest/predator situation was carried out by Dr. Jim Litsinger, the project consultant on IPM, and a program was outlined for future introductions of some specialist predators and many generalists to try and enhance the overall 'food web' of the agriculture biome. Marine toads and Toquay ghekos were introduced during the transition phase to control the cockroach population.

Dr. R. Harwood of Michigan State University worked with the research department to outline a program of soil and water nutrient monitoring over time so that the sustainability of the system could be monitored closely. Programs were also initiated with the University of Arizona Plant Pathology Department to look into Biological control of nematode and pithium. Several trial plots were set up during transition using fungii *Gliocladium virens* and *Trichoderma.* spp. treatments. A bacterium known to attack pithium, *Pseudomonas capacia*, was also used.

One of the main areas of work during transition was to import new plant cultivars for trial. Of particular importance were new sources of starch and grain and a wider variety of beans and vegetables. Overall some 60 new varieties of food crops were introduced for trial during the second closure period. It was planned that these would be tried out directly in the system during the 1994/1995 period and that continuous experimentation with new cultivars would be part of the planting system in the IAB.

CONCLUSION

The first two-year closure experiment of Biosphere 2 showed that the basis had been laid for a sustainable, chemical-free, 1.28-ha agriculture system, which with careful management could easily be enhanced to provide a full diet for at least eight and eventually ten people and their domestic animals. The restricted-calorie, low-fat, refined-sugar-free, high-fiber diet gave rise to physiological adaptations that in previous studies have been correlated with good health, retardation of aging, and potential life extension/18/.
The materially closed Biosphere 2 profferes a unique laboratory in the field of agriculture and food-systems for investigation into sustainable methods of pest control, continuous monitoring of nutrient cycling, very accurate studies of the effect of diet on human physiology, soils and crop management, waste-water treatment, and the integration of domestic animal systems. The crew response to diet on a long-term mission showed that a diet that was not only nutritionally adequate, but also varied and pleasing to taste was extremely important for crew morale.

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