Major achievements of material circulation – closed habitation experiments using Closed Ecology Experiment Facilities

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Abstract: The Closed Ecology Experiment Facilities (CEEF), which consisted of the Closed Plant Experiment Facility (CPEF), the Closed Animal and Human habitation Experiment Facility (CAHEF) and other, were installed in Institute for Environmental Sciences for studying behavior of radionuclides in an ecosystem isolated from the outside. The CPEF had a Plant Cultivation Module (PCM), which comprised of three plant chambers illuminated solely by artificial lighting and one plant chamber illuminated by both natural and artificial lighting. The CAHEF had an Animal keeping and Human habitation Module (AHM), which comprised of an animal room for two goats and a habitation room for two crews. Both modules had each physical/chemical material circulation system and connected through a closed corridor and an airlock. Material circulation experiments including circulation of air, water and waste materials were carried out from 2005 till 2007 with two crews staying in the CEEF. In the experiments, 23 crops including rice, soybean and peanut were cultivated in the PCM, and two goats were kept in the AHM. Almost all of the food consumed by the crew and the feed to the goats (e.g. rice straw and leaf and stem of rice, soybean and peanut) were produced from crops cultivated in the PCM. The oxygen produced in the PCM by photosynthesis of crops was separated and supplied to the air in the AHM. Increased carbon dioxide in the AHM atmosphere by respiration of crew and goats was separated and supplied back to the air in the PCM. The crew habitation experiments were carried out with stepwise increasing materials circulated in the system. The experiments for 1 week were started with only food production and circulation of air in 2005. In 2006, 2-week habitation experiments adding water circulation were conducted three times changing the crew by week. Finally, 1-week, 2-week (two times) and 4-week habitation further adding waste materials circulation were conducted in 2007, and the carbon flow in the system was clarified.

Key words; closed habitation, air tight facilities, crop cultivation in a closed system, air revitalization, water circulation, circulation of CO_2 from waste processing

1. INTRODUCTION

The Closed Ecology Experiment Facilities (CEEF) were installed in Institute for Environmental Sciences for studying behavior of radionuclides in an ecosystem isolated from the outside. The first target among the radionuclides was ^{14}C, and stable carbon behavior was studied in the CEEF. In order to simulate essential parts and their function of the ecosystem including humans, the CEEF was composed of the Closed Plant Experiment Facility (CPEF) for plant cultivation, the Closed Animal keeping and Human habitation Experiment Facility (CAHEF) for two crews and two goats, and the other. For environmental control and material circulation, each facility had a material circulation system using physical/chemical processes. The experiments with two crews and two goats in the CEEF were carried out with stepwise increase of materials circulated. Food production and circulation of air in the facilities were started in 2005, water circulation was introduced in 2006, and finally waste materials were also circulated in 2007.

In this paper, we outline the material circulation experiments conducted using the CEEF.

2. OUTLINE OF AN EXPERIMENTAL SYSTEM

The CPEF had a Plant Cultivation Module (PCM), which comprised of three plant chambers (each cultivation area of 30 m^2) illuminated solely by artificial lighting and one plant chamber (cultivation area of 60

m^2) illuminated by both natural and artificial lighting. The CAHEF had an Animal keeping and Human habitation Module (AHM), which comprised of an animal room for two goats and a habitation room for two crews. Both modules had each physical/chemical material circulation system and were connected through a closed corridor and an airlock, as shown in Fig. 1.

In the experiments with two crews staying in the CEEF, 23 crops including rice, soybean and peanut were sequentially cultivated in the PCM (Table 1), and two goats stayed in the AHM (Table 2). Almost all of the food consumed by the crews (82% on fresh weight base in 2005 but more than 90% later) and the feed to the goats (e.g. rice straw and leaf and stem of rice, soybean and peanut) were produced from crops cultivated in the PCM.

The oxygen (O_2) added to the air in the PCM by photosynthesis of crops was separated and supplied to the air in the AHM. Increased carbon dioxide (CO_2) in the AHM atmosphere by respiration of crew and goats was separated and supplied back to the air in the PCM. In addition to food production and circulation of air, water circulation was also carried out in 2006 and 2007. Finally, waste processing and circulation of materials in waste were also introduced in 2007.

The crops in the PCM was pre-cultivated before habitation experiment for 20 weeks to make steady state of plant biomass in the module. Part of crops, such as rice, harvested in the PCM was processed outside (e.g. threshing and hulling) and returned to the CEEF.

Table 1 Crops cultivated sequentially in the CEEF in 2006. Area for growing seedlings before transplanting was 10.3 m^2.

Crop	AAP [m^2]	PBP [day]	PAP [day]
Rice	60.00	24	95
Soybean	30.00	14	63
Peanut	30.00	0	140
Sugar beet	5.00	14	126
White radish	0.55	7	42
Turnip	0.30	7	42
Cabbage	0.30	21	70
Pea	0.55	7	70
French bean	0.55	0	70
Onion	0.55	49	91
Carrot	1.30	21	63
Chinese cabbage	0.85	7	84
Tomato (cv. Mini-carol)	1.50	21	84
Cucumber (cv. Mini-sala)	0.50	14	70
Sweet pepper	0.50	14	112
Shiso (*Pellira ocymoides* L.)	0.50	28	70
Spinach	2.50	0	35
Green onion	0.30	14	56
Shungiku (*Chrysanthemum coronarium* L.)	1.75	0	42
Komatsuna (*Brassica campestris* L.)	0.50	0	28
Lettuce	0.50	7	28
Mitsuba (*Cryptotaenia japonica* Hassk.)	0.70	7	35
Leek	0.50	21	84

AAP, cultivation area after planting; PBP, cultivation period before planting; PAP, cultivation period after planting.

3. MAJOR RESULTS

(1) Major results of 2005 experiments

One-week closed habitation experiments were conducted three times in 2005 to study circulation of O_2 and CO_2, and supply of food from crops cultivated in the CEEF. On a fresh weight basis, 82% of food for crew and all feed to the goats were supplied from harvested crops in the 2nd and 3rd experiments.

Environmental conditions in the AHM during the experiments and carbon flows are shown in Table 3 and Fig. 2(a), respectively.

Table 2 Period, crews (A, B, C and D) and number of goats for each material circulation experiment.

Experimental period in 2005	Sep 6-13	Sep 27- Oct 4	Oct 18-25
Crew	A&B	A&B	A&B
Number of goats	2	2	2

Experimental period in 2006	Sep 5-12	Sep 12-19	Oct 10-17	Oct 17-24	Nov 7-14	Nov 14-21
Crew	A&C	B&D	A&D	B&C	A&B	C&D
Number of goats	2	2	2	2	2	2

Experimental period in 2007	Aug 28 - Sep 4	Sep 18 - Oct 2	Oct 16 - Oct 30	Oct 30- Nov 13	Nov 13- Dec 11
Crew	C&D	A&D	C&D	Absent	A&C
Number of goats	2	0	2	2	2

The AHM supplied 43-56% of CO_2 demand in the PCM, while 46-51% of O_2 synthesized in the PCM was used in the AHM. Almost all of the CO_2 shortage and the O_2 surplus came from un-processed waste. The carbon taken up and excreted by crews and the goats was estimated as 64-92% of that in the edible part of the harvested crops and 36-53% of that in the inedible part, respectively.

(2) Major results of 2006 experiments

Crops in the PCM covered 92-95% of the food consumed by the crews and 79% of the feed to the goats.

The average assimilation quotients ($AQ = CO_2/O_2$) of rice, soybean and all crops, calculated from amounts [mol d^{-1}] of CO_2 injected to and O_2 separated from each plant chamber, were 0.95, 0.87 and 0.90, respectively. The AQs for rice and soybean were similar to the values calculated by following equation using the data of edible and inedible part production and nutritional content of these parts, assuming that AQs for carbohydrate and fiber, protein, and lipid are 1.0, 0.8, and 0.7, respectively.

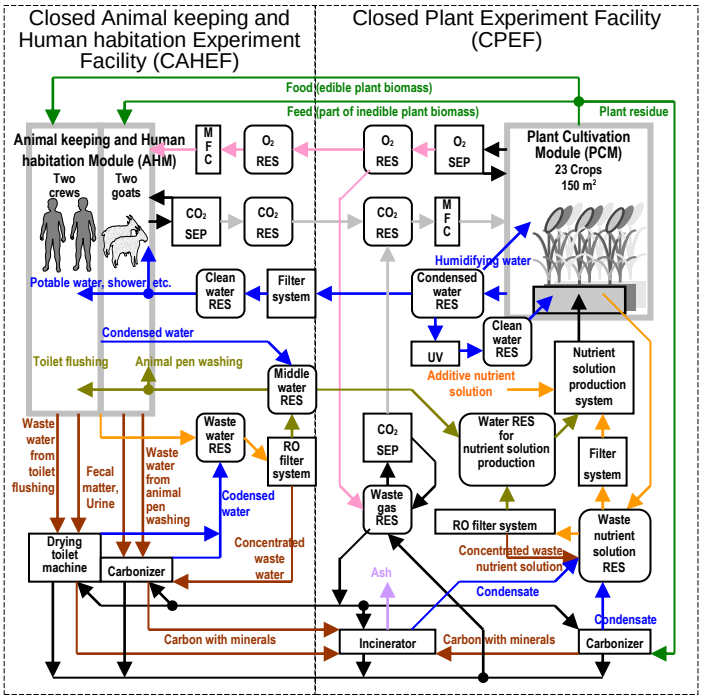

Fig. 1 Material flows in the CEEF in 2007. Food and feed were transferred from the CPEF to the CAHEF by two crews. Area and volume: Plant cultivation module (total, ~194 m^2; cultivation area, 150 m^2; ~677 m^3); Space for preparation (~141 m^2, ~332 m^3); Airlocks (~7 m^2, ~16 m^3); Animal keeping room (~23 m^2, ~54 m^3); Human habitation room (~52 m^2, ~123 m^3); Corridor (~69 m^2, ~163 m^3). MFC, mass flow controller; RES, reservoir; RO, reverse osmosis; SEP, separator; UV, ultraviolet sterilization system.

$$AQ = \{Y_E \cdot (F_{EC} + 0.8 \cdot F_{EP} + 0.7 \cdot F_{EL}) + Y_I \cdot (F_{IC} + 0.8 \cdot F_{IP} + 0.7 \cdot F_{IL})\} / \{Y_E \cdot (1 - F_{EA}) + Y_I \cdot (1 - F_{IA})\}$$

where, Y_E, dry edible biomass yield (g); F_{EC}, fraction of carbohydrate and fiber in Y_E; F_{EP}, fraction of protein in Y_E; F_{EL}, fraction of lipid in Y_E; F_{EA}, fraction of ash in Y_E; Y_I, dry inedible biomass yield (g); F_{IC}, fraction of carbohydrate and fiber in Y_I; F_{IP}, fraction of protein in Y_I; F_{IL}, fraction of lipid in Y_I; F_{IA}, fraction of ash in Y_I.

The AQs calculated from the above equation were 0.98 and 0.91 for rice and soybean, respectively. The average respiratory quotient (RQ = CO_2 /O_2) of crew + goats was obtained from balance of CO_2 and O_2 in the AHM as 0.86.

Water was also circulated in the CEEF in 2006, and the water balance in the PCM is shown in Table 4. The water loss from the PCM was less than 0.5% of the input, and was comparable to water lost from crops processed outside of CEEF. In addition, 500 L of nutrient solution was withdrawn as waste from the CEEF in a whole plant cultivation period including the pre-cultivation period. The water balance in the AHM was approximately -9% of the input (Table 5). Since waste of crew and goats was processed using outside air in 2006, water in those waste was lost from the system.

(3) Major results of 2007 experiments

Material circulation experiments with 1-week, 2-week (two times) and 4-week habitation were conducted in 2007. For the 4-week experiment, crops in the PCM covered 90% of the food consumed by the crews and 98% of the feed to the goats.

For circulating all material in the system, waste materials were processed in the last experiment with 4-week habitation in 2007 by following processes using air in the system: carbonization and incineration of feces and urine of crew and goats and inedible part of crops excluding feed for goats. Since we had trouble in the carbonization system during November 13– 22 and on December 1, some waste materials were processed by using outside air. During December 2 – 11 after dealing with the troubles, all of the waste was processed using air in the system. In that period, the amounts of CO_2 separated from the AHM atmosphere, recovered from the waste decomposition processes and supplied to the PCM were 543 mol, 245 mol and 877 mol, respectively (Fig. 3). It indicated that approximately 90% of CO_2 consumed by the crops was recovered from the AHM and the waste processing systems. On December 6, 38 mol carbon were released out of the system during cleaning of the carbonization system for waste of crew and goats. This amount accounted to nearly half of the amount of above-mentioned missing carbon.

Table 3 Environmental conditions in human habitation room and animal holding room of the AHM during the habitation experiments conducted in 2005.

Room	Experiment	Light period/dark period [h d^{-1}]	Temperature [°C]	Relative humidity [%]	CO_2 concentration [μL L^{-1}]	O_2 concentration [% (v/v)]
Human habitation room	1st experiment	16/8	24.8-25.5	37-55	1,477-3,676	20.1-20.6
	2nd experiment	16/8	24.9-25.4	37-51	1,472-3,492	20.0-20.8
	3rd experiment	16/8	24.9-25.3	37-52	1,832-3,514	20.1-20.3
Animal holding room	1st experiment	12/12	19.9-25.3	44-60	1,610-4,002	20.1-20.6
	2nd experiment	12/12	19.8-22.0	45-53	1,496-4,214	20.2-21.0
	3rd experiment	12/12	19.8-22.4	45-54	1,921-3,656	20.2-20.6

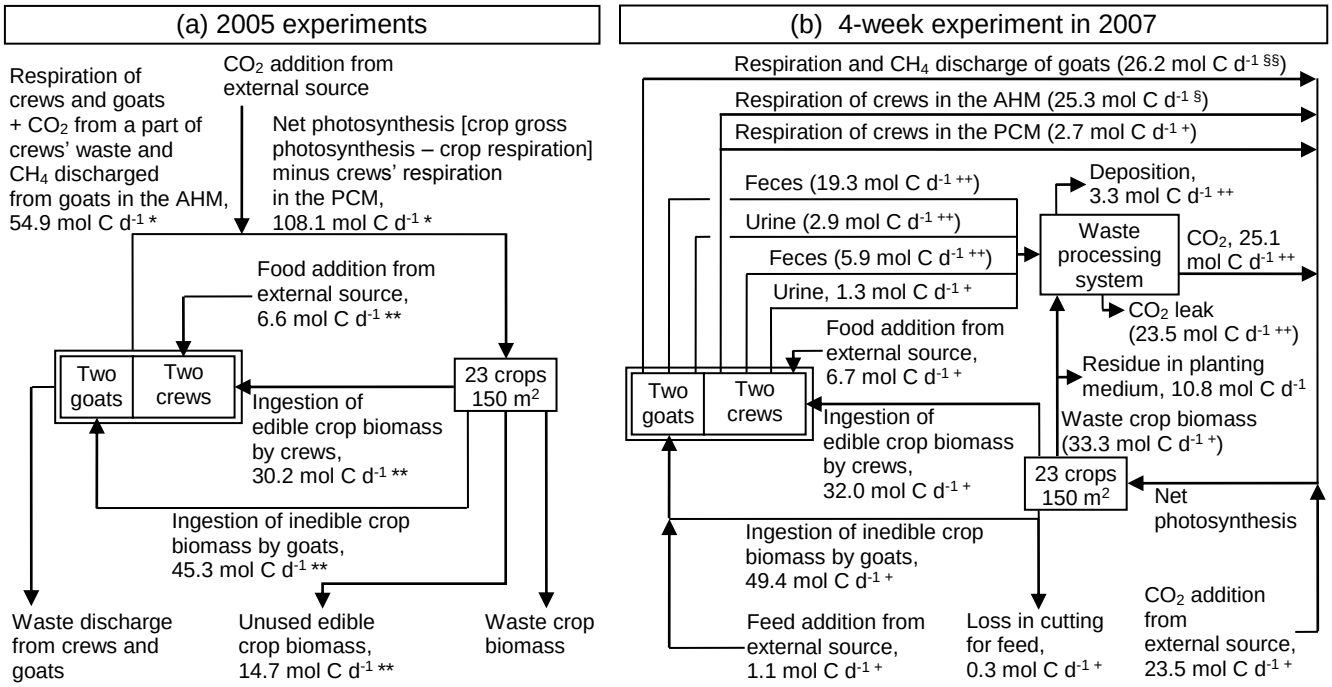

Fig. 2 A summary of carbon flows in 2005 experiments (a) and 4-week experiment in 2007 (b). *****: averages for three experiments in 2005, ******: averages for the last two experiments in 2005. $^{+}$: averages for the last experiment in 2007. $^{++}$: averages for days without troubleshooting on waste processing system in the last experiment. Values in parentheses: estimated values. §: data in experiment without goats. §§: difference between data in experiments with and without goats.

Fig. 2(b) summarizes carbon flows measured or estimated for the 4-week experiment. Estimated leak amount of CO_2 from the waste processing system was comparable to amount of CO_2 addition from external source. This result shows that CO_2 from external source will substantially decrease, if CO_2 leak from the waste processing system is suppressed.

Table 4 Water balance in the PCM in 2006 (Mean±SD for two weeks × three times).

Water supplied to the PCM	Amount [L d^{-1}]
Replenished clean water	737±93
Supplied nutrient solution	1350±750
Water discharges from the PCM	**Amount [L d^{-1}]**
Transpired water collected as condensate	679±22
Discharged nutrient solution	1400±720

Table 5 Water balance in the AHM in 2006 (Mean±SD for two weeks × three times).

Water supplied to the AHM	Amount [L d^{-1}]
Clean water	51.5±8.3
Middle water for toilet and pen washing	23.7±2.9
Water discharges from the AHM	**Amount [L d^{-1}]**
Reverse osmosis membrane processed water	56.3±17.8
Concentrated waste water	4.6±1.7
Condensed water	7.3±8.0

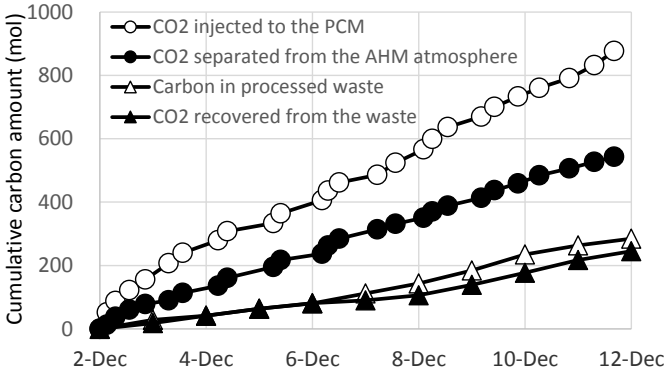

Fig. 3 Cumulative amount of carbon (mol) in CO_2 injected to the PCM, separated from the AHM atmosphere and recovered from the waste and carbon in processed waste from December 2 to December 11 in the last experiment conducted in 2007.

4. POSSIBLE CONTRIBUTION OF ACHIEVEMENTS IN CEEF EXPERIMENTS

Data obtained in these experiments conducted in 2005-2007 using the CEEF is valuable for examination and planning of human-in-loop systems necessary for independent long-term human living habitats such as lunar or Martian base.

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