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CARBON BALANCE IN BIOREGENERATIVE LIFE SUPPORT SYSTEMS:

Some Effects of System Closure, Waste Management, and Crop Harvest Index

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ABSTRACT

In Advanced Life Support (ALS) systems with bioregenerative components, plant photosynthesis would be used to produce O_2 and food, while removing CO_2. Much of the plant biomass would be inedible and hence must be considered in waste management. This waste could be oxidized (e.g., incinerated or aerobically digested) to resupply CO_2 to the plants, but this would not be needed unless the system were highly closed with regard to food. For example, in a partially closed system where some of the food is grown and some is imported, CO_2 from oxidized waste when combined with crew and microbial respiration could exceed the CO_2 removal capability of the plants. Moreover, it would consume some O_2 produced from photosynthesis that could have been used by the crew. For partially closed systems it would be more appropriate to store or find other uses for the inedible biomass and excess carbon, such as generating soils or growing woody plants (e.g., dwarf fruit trees). Regardless of system closure, high harvest crops (i.e., crops with a high edible to total biomass ratio) would increase food production per unit area and O_2 yields for systems where waste biomass is oxidized to recycle CO_2. Such interlinking effects between the plants and waste treatment strategies point out the importance of oxidizing only that amount of waste needed to optimize system performance. Published by Elsevier Science Ltd on behalf of COSPAR.

INTRODUCTION

The use of plants for life support applications in space is appealing because of the multiple life support functions by the plants (Galston, 1992): Through photosynthesis, plants remove carbon dioxide (CO_2), while producing oxygen (O_2); and by choosing plant species with edible biomass, photosynthesis can also supply food. In addition, through the process of transpiration, plant-growing systems can be used for water purification, where wastewater is supplied to the roots and the transpired water vapor is condensed as clean water (Loader et al., 1999). If plants are included in a life support scheme, a certain portion of the biomass will be inedible and handling this "waste" biomass must be considered in terms of system mass balance. It is sometimes suggested that this waste plant biomass should be oxidized (e.g. through incineration) to resupply CO_2 to grow more plants. Yet this would only hold for highly closed systems where the area of cultivated plants is sufficient to produce all the required food (Taub, 1973 and references therein). Highly closed, autonomous systems would be appropriate for long-duration missions, but for shorter missions, where stowage and/or resupply are affordable options, plant production might be used to produce only a portion of the required food and life support in conjunction with physico-chemical technologies.

When one considers life support systems that include substantial amounts imported food (i.e., imported carbon), management approaches will differ from those used in more autonomous closed systems. In particular, strategies for waste treatment and resource recycling should be gauged to fit the degree of closure and optimize CO_2 and O_2 balance (Wheeler, 1996). I will explore this further using simple metabolic model of food, CO_2, and O_2 flow in a system that includes a crew (consumers), plants (producers), and a waste recycling system to deal with inedible biomass (Figure 1).

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DISCUSSION

Assumptions

To simplify the analyses, I will ignore the use of local resources, but clearly *in situ* resources will affect mission designs (e.g., availability of CO_2 on Mars). Second, I will assume that plant biomass is represented by the generic formula for carbohydrate, CH_2O. This formula suggests that carbon represents about ~ 40% of the plant dry mass (ignoring ash content), which is close to actual carbon analyses of several candidate crops (e.g., wheat, potato, and lettuce; Wheeler et al., 1996). Third, I will assume that both the assimilation quotient of the plants (CO_2 fixed / O_2 produced), and the respiration quotient (CO_2 released / O_2 consumed) of the humans equal 1.0. Typically, human respiration quotients are < 1.0 (Krall and Kok, 1960), but a diet low in fat could increase this value; likewise growing some fat-producing crops and manipulating the nitrogen form to the plants could lower the plant assimilation quotient (Krall and Kok, 1960; Eley and Myers, 1964; Tako et al, 2001). In practice, achieving complete balance of CO_2 and O_2 using only biological systems may be difficult (Eley and Myers, 1964), and physico-chemical systems will likely be required to fine tune the balance of the biological components.

The analyses are based on a total biomass productivity of 32 g dry mass m^{-2} d^{-1}, which is taken from findings from NASA's Biomass Production Chamber (BPC) using a photosynthetic photon flux of 50 to 60 mol m^{-2} d^{-1} (Wheeler et al., 1996). Assuming a harvest index of 50%, which is reasonable for a mix of species (Wheeler et al., 1996; Salisbury et al., 1997), edible biomass productivity would then equal 16 g m^{-2} d^{-1}. Numerous studies have shown that productivities can be increased or decreased depending on the light provided to the plants (Bugbee and Salisbury, 1988; Wheeler et al., 1996), but a level of 50 to 60 mol m^{-2} d^{-1} is representative of relatively high light input and equal to that measured on a clear summer day. For calculating plant growing area to supply dietary needs, an energy requirement of 2500 kcal $person^{-1}$ d^{-1} and an average energy content of 4 kcal g^{-1} plant food were used. Finally, systems wastes (inedible biomass and human wastes) are assumed to be converted completely to CO_2 and H_2O. Clearly these assumptions oversimplify the many complex interaction of carbon and oxygen in a closed life support system, but they allow the following general comparisons:

Comparisons of Different Bioregenerative Scenarios

Closed System; 50% Harvest Index

In a fully closed system with a crop harvest index of 0.5, two units of CH_2O must be produced to supply 1.0 unit of food and 1.0 unit of O_2 needed to sustain each human (Figure 1). To maintain system closure, the one unit of

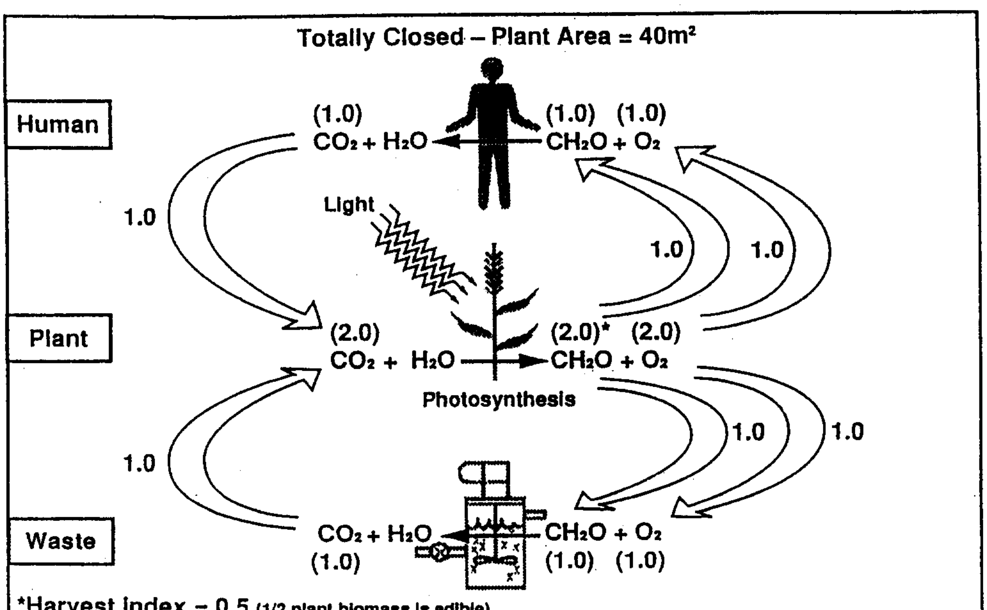

Fig. 1. Comparison of O_2, CO_2, and biomass (CH_2O) fluxes in a bioregenerative life support system that supplies all the gas exchange and dietary energy needs for one person. In this case, the system is closed, half the biomass is edible (i.e., harvest index = 0.5), and all waste biomass is oxidized to retrieve CO_2 and H_2O.

inedible CH_2O is then degraded (oxidized) using 1.0 unit of O_2. With a productivity of 16 g m^{-2} d^{-1} edible dry mass this would require about 40 m^2 of continuously cropped area to provide 2500 kcal $person^{-1}$ day^{-1} of dietary energy. This is slightly greater than the area requirements per person reported in the BIOS-3 tests (Gitelson et al.,1989), but higher photosynthetic photon fluxes (80 to 90 mol m^{-2} d^{-1}) were used in the BIOS-3 studies (Salisbury et al., 1997). Such closed system would be relatively autonomous (e.g., for future colonies), but these systems have been the focus of much of the bioregenerative research to date.

Closed System, 50% Harvest Index, Some Food From Waste Biomass

If some food were generated from the inedible biomass, this would increase the system efficiency and reduce the required area of plants for each person. For example, by retrieving 0.1 units of food from the inedible biomass, the total biomass production and crop growing area could then be reduced to 36 m^2 $person^{-1}$ to provide the required dietary energy and O_2 (Figure 2). Various methods of converting waste biomass to food have been proposed, including the use of edible fungi, fish or single-cell organisms (Taub, 1973; Strayer, 1993). But as with any life support components, the mass, energy, and labor requirements for such subsystems must be considered in terms of the overall system costs and benefits (Drysdale, 2001).

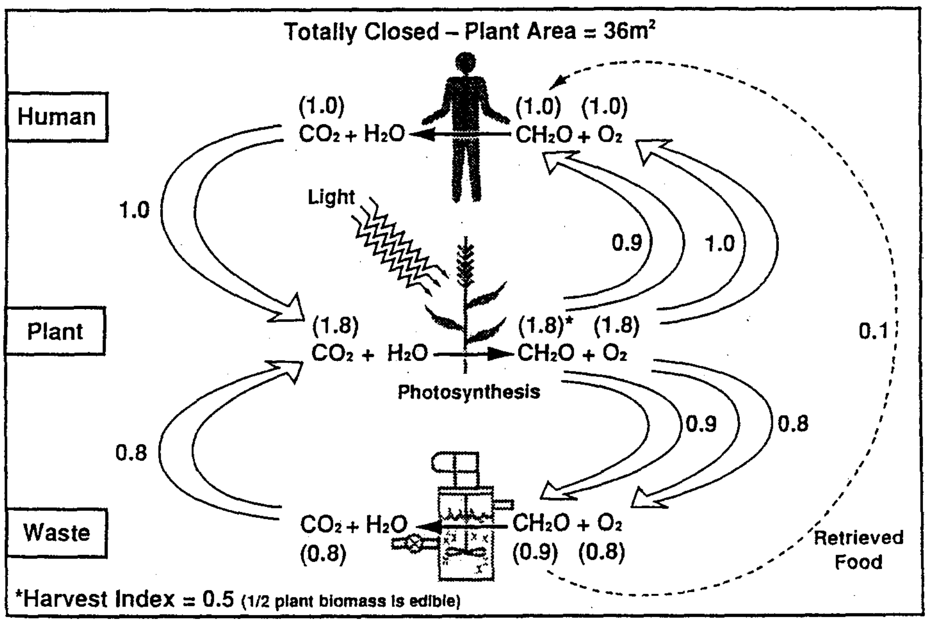

Fig. 2. Comparison of O_2, CO_2, and biomass (CH_2O) fluxes in a bioregenerative life support system that supplies all the gas exchange and dietary energy needs for one person. In this case, the system is closed, 50% of the plant biomass is edible, and 0.1 units of food are retrieved from the waste biomass.

Closed System, 70% Harvest Index

An alternative approach to reducing required crop area to support food production and gas balance would be to increase the harvest index of the plants. For example, if the harvest index is increased from 50 to 70%, the crop area needed to support one person in a closed system can be reduced from 40 to 28 m^2 (Figure 3). In this case, the edible biomass productivity would be 22 g m^{-2} d^{-1} (i.e., 0.7 x 32 g m^{-2} d^{-1} total biomass). Note that the effects of a higher harvest index are twofold: the edible yield per unit area increases, regardless of system closure, and the amount of biomass going to waste treatment system is reduced, thereby saving O_2 produced from photosynthesis.

Harvest indices of crops vary widely depending on what parts of the plants are consumed, and the biochemical nature of the edible structures (Figure 4). The highest harvest index crops are typically obtained from leafy species, where entire portions of the shoot are consumed (e.g. lettuce and spinach; Wheeler et al., 1994; Salisbury et al., 1997). But leafy crops are usually inadequate for meeting a wide-range of human nutritional needs (e.g., quantities carbohydrate). On the other hand, tuber and storage root crops can be good sources of carbohydrate and can have high harvest indices (Tibbitts and Wheeler, 1987; Bonsi et al., 1992; Salisbury et al., 1997). Harvest indices of seed crops vary depending o ıe species and the genotypes (see Bugbee et al., 1994; Bugbee, 1995; Ohler and Mitchell, 1996), and species with oil storing seeds typically have a lower harvest index than species with carbohydrate storing seeds. However, oil crop seeds are more energy dense and thus have a high caloric value per unit mass (Frick et al., 1994).

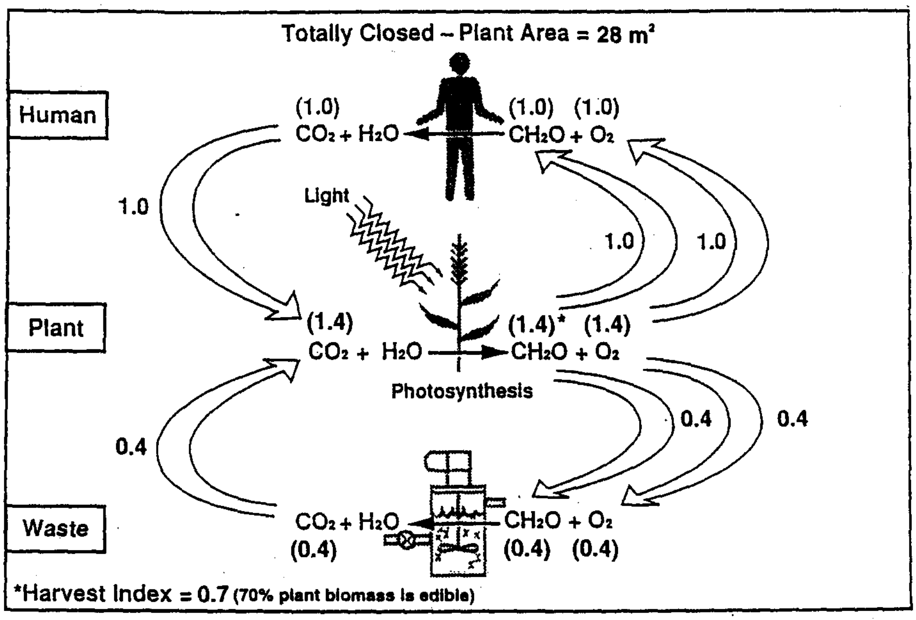

Fig. 3. Comparison of O_2, CO_2, and biomass (CH_2O) fluxes in a bioregenerative life support system that supplies all the gas exchange and dietary energy needs for one person. In this case, the system is closed, 70% of the plant biomass is edible, and all waste biomass is oxidized to resupply CO_2 and H_2O.

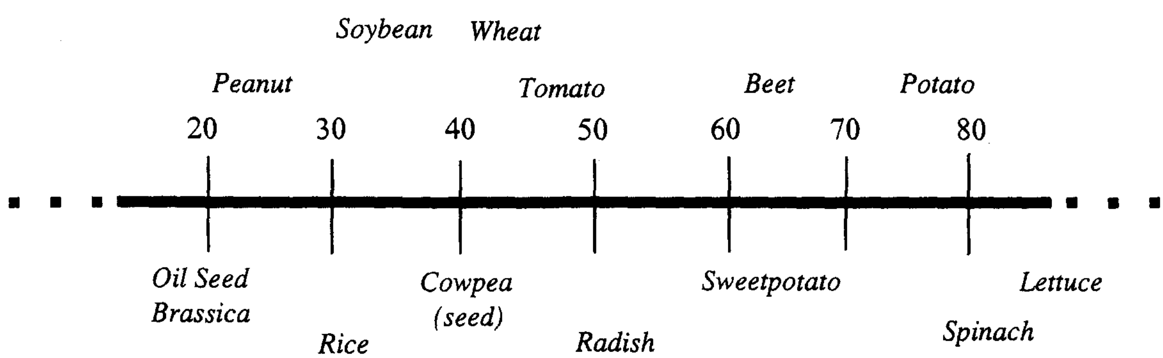

Fig. 4. Harvest index ranges (%) of some plants species grown under controlled environment conditions (see Wheeler et al., 1996; Salisbury et al., 1997). Value for beet assumes some leaves are edible.

<u>Partially Closed System; 50% Harvest Index.</u>

For each of the situations posed so far, the systems were assumed to be closed with regard to food and O_2. Yet most early applications of bioregenerative life support will likely involve only partially closed systems, where substantial amounts of food are imported to sustain the crew. If half of the food were stowed and half produced on site, then only 20 m^2 of plant area would be required instead of 40 m^2 in a fully closed system (Figure 5). Note that in this case, the CO_2 needs of the plants could be met by the crew respiration and human waste oxidation (Figure 5). Thus there would be no need to oxidize the inedible biomass, which could be stored, discarded, or used for some other purpose. This would then allow the 20 m^2 of plants to meet all of the O_2 requirement and CO_2 removal for one person (Figure 5).

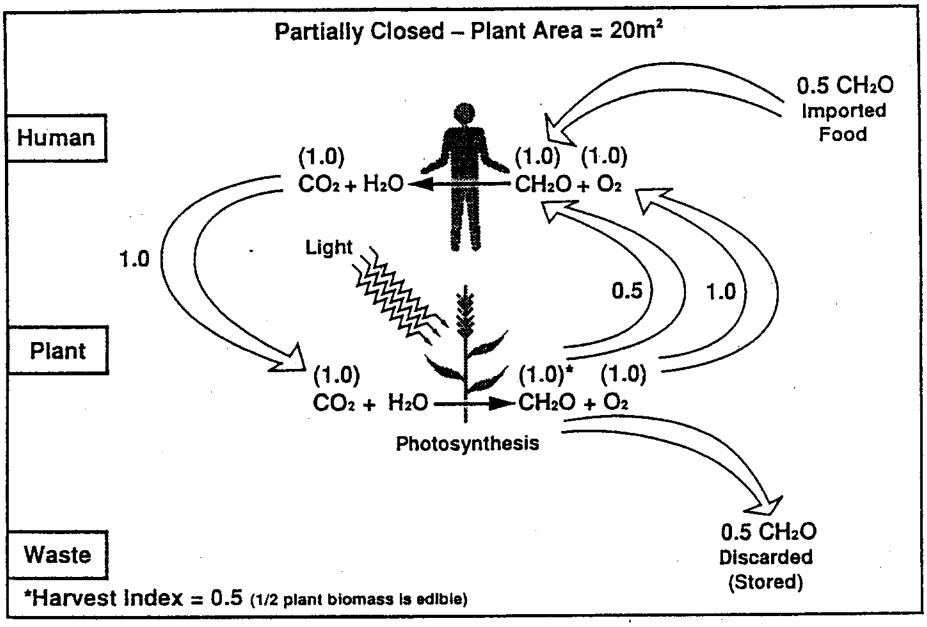

Fig. 5. Comparison of O_2, CO_2, and biomass (CH_2O) fluxes in a bioregenerative life support system that supplies all the gas exchange and half dietary energy needs for one person. In this case, the system is open to imported food, 50% of the plant biomass is edible, and no inedible plant biomass is oxidized.

Uses for Waste Biomass and Carbon Sinks

If the life support system is partially closed, where some food (edible CH_2O) is imported, then several options might be considered for dealing with waste biomass (inedible CH_2O):

Oxygen Yield

To minimize O_2 use in waste handling, inedible biomass might be stabilized for storage and / or removal from the system. This might involve some initial treatment to retrieve minerals to grow more crops (e.g., leaching; Mackowiak et al., 1996) followed by dehydration to retrieve water. This approach would minimize O_2 for waste processing, allowing most of the O_2 produced in photosynthesis to go to the crew. Alternatively, the inedible biomass might be degraded anaerobically and generate products that might have value for life support (Schwingel and Sager, 1996; Cornet and Albiol, 2000). Because there is O_2 in the waste biomass, the biomass might be chemically processed to release the oxygen from the CH_2O. For example, the biomass could be incinerated to generate CO_2 and H_2O, and the CO_2 then reduced to produce H_2O and CH_4 (this would require a source of H_2). All of the H_2O could then split electrolytically to generate O_2. This initially consumes some of the O_2 produced by photosynthesis in addition to requiring the physico-chemical system capacity for handling CO_2.

Consumable Products

The waste plant biomass might also be used to produce some consumable products. For example, the biomass might be processed in bioreactors to retrieve nutrients to grow more plants, after which the residual solids are pressed into cubes or blocks to support plant seedling growth (Mackowiak et al., 1996). Or, more complex products as particleboard or paper might be considered, but these would require substantial processing. In all cases, nutrients could be extracted from the waste biomass prior to using the residual solids; these nutrients could then be recycled to grow more plants thereby reducing import costs for fertilizer (Mackowiak et al., 1996).

Generating Soils

Another option might be to process or compost the waste biomass and then incorporate the residual with some local regolith to create a "soil" for future use. This soil could then serve as a carbon sink. Assuming up to 10% by mass of a soil might be organic matter and a bulk density near 1.2 g cm^{-3} (1200 kg m^{-3}) (Brady, 1991), a soil bed 0.25 m deep and covering 100 m^2 could hold up to 0.25 m x 100 m^2 x 1200 kg m^{-3} x 10%, or 3000 kg of organic matter. This soil could then be used for plant cultivation and act as a slow-rate bioreactor where some carbon is turning over while new compost (waste biomass) could be added. Generating soils in this option then provides a useful "sink" for the waste carbon accumulation in the systems as a consequence of imported food (carbon) for systems the only partially closed.

Woody Plants

Another potential sink for inedible CH_2O might be to grow plants that sequester carbon into wood, for example ultra dwarf fruit trees that might fit into small volume systems. Wood production rates up to 0.3 kg m^{-2} yr^{-1} have been reported from dwarf apple trees (Palmer, 1988), and if one assumes these productivities could be increased to ~1 kg m^{-2} yr^{-1} under controlled environment cultivation, then up to 100 kg or wood could be produced from a 100 m^2 area of dwarf fruit trees per year. Unlike using soils where carbon capacitance would reach a steady state, wood could be produced continually depending on physical constraints of the life support farm. Interestingly, trees are seldom discussed for bioregenerative applications because of their size and delayed production, yet ultra dwarf trees might be kept to heights of < 1 m, reach production in 2-3 years from planting (Rom and Carlson, 1987), in addition to yielding flavorful and colorful foods that would be difficult to supply from Earth. This initial requirement to generate woody architecture prior to producing fruits could be used in early missions that are carbon from large proportions of stored food.

CONCLUSIONS

Strategies for handling waste biomass from plant production systems will vary depending on the degree of system closure. In all cases, choosing plants with a high harvest index will be beneficial to maximize edible yield per unit area and minimize inedible biomass production. In addition, recovery of nutrients from waste biomass should be beneficial regardless of system closure constraints. If a large portion of the food is being produced in the life support system, much of the waste biomass would need to be recycled (oxidized) to supply CO_2 for subsequent plantings. If however, the system is open to a large portion of imported or stowed food, oxidizing the waste biomass may not be advisable because of the oxygen required for the reaction. In this case, it may be better to dispose of the waste biomass following nutrient and water retrieval or sequestering the carbon into reservoirs or cellulose containing products that add valuable constituents to the life support system as it matures and becomes more autonomous.

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