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SPACE ECOSYNTHESIS:
AN APPROACH TO THE DESIGN OF CLOSED ECOSYSTEMS FOR USE IN SPACE

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1. Introduction

Support of man in space for extended periods of time will require that food, atmosphere, and water be regenerated in situ. Either carrying most or all of these materials at launch, or resupplying them during a mission, will become prohibitively expensive as both the number of men and the mission duration increase. Closed ecosystems intended for total human support have only recently begun to be investigated experimentally (Gitel'son et al., 1975) and theoretical considerations are sparse (Verhoff and Smith, 1971; Ulanowicz, 1972). For a review of closed ecosystems, see Taub (1974).

With the identification of the requirements for human life support, and of the overwhelming importance of "buffering capacity" in such an anthropocentric system, the long-term support of humans in space becomes a problem removed from the concepts of classical ecology. A solution to the problem appears to rely on a mixture of mechanical (or physico-chemical) and biological "devices," treated as machines, which can be turned on or off at will. Such a treatment of the biological components, other than man, is much more related to traditional farming practices than it is to observations

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of the behavior of self-regulating ecological systems. Yet, ecological approaches will be essential to the understanding of the biological systems that will be farmed, and such preliminary data must be amassed before an ecosystem can be developed.

Paradoxically, considerations of such closed systems, and the consequent forcing of naturally self-regulating ecological systems into agricultural constraints, appears to offer the promise of even greater understanding of natural ecosystems. To a large extent this understanding will come through the quantitative estimates of buffering capacity, and through better estimates of the significance of nonbiological energy trapping; for example, the role of lightning in the atmosphere in "fixing" nitrogen for biological purposes, or the role of atmospheric photochemistry in eliminating organic toxins.

It is the intent of this paper to provide a preliminary outline of an approach to supporting humans in space, and to discuss methods of treating the problems involved. As a preliminary exposition, its intent must be considered as an incomplete catalogue of the complexities of the final system, and as offering a flexible approach to modeling the system. The authors feel that a working understanding of the full operation of any proposed system can come about only through the use of models, and that mathematical representation of the dynamics of the system, plus specific model aspects, can permit simulation of system operation. We do not consider that such simulations can take the place of a physically simulated system, but rather that the insights gained from mathematical simulation will be invaluable in identifying areas of biological and physical science in which experimental information must be actively sought.

2. Life support in space

2.1 Shuttle capabilities and promise

The space Shuttle will lift between 13,000 and 29,000 kg into near-earth orbit with the mass of the payload dependent on the height and inclination of the orbit. After its journey into space the craft is designed to descend to earth and to land more or less as a conventional aircraft. This feature of re-usability dramatically reduces the cost of movement into and out of space. There is no doubt that such a craft will promote a more thorough utilization of space in the very near future.

The immediate uses for the Shuttle are now being considered. Scheduled for payloads are scientific experiments and a number of exploratory programs intended to identify ways in which space can be exploited for manufacturing purposes. Many of the scientific experiments are intended to examine the responses of animals and plants to the zero g force or to artificially created forces. The major use of the Shuttle may be in the emplacement, recovery, and repair of the various satellites on which mankind has come to depend.

The dimensions of the Shuttle are such that a separable payload, 18.4 m long, 4.6 m in diameter, and weighing 6.5 metric tons can be put in orbit. While structures of this size are limited compared to those man usually inhabits, clustering of units to form increasingly larger habitable spaces is envisioned. With the advent of the Shuttle program, man is well on his way to establishing modest space settlements. Larger

settlements are predictable, and future generations of the Shuttle will accommodate larger payload thus permitting even more massive settlements to be built.

Whether the assembly of stations as massive as those predicted by O'Neill (1977) will be accomplished is a moot point, but the most crucial element of the entire program, in fact the central point of the program, will be the support of man in space. The Shuttle Program projects the image of man, ordinary man, in space, supported in some comfort and with safety, and allowed to practice his characteristic role as observer, experimentor, and builder.

To the degree that Shuttle promotes almost exclusively the role of man in space, it is a biological mission. It is aimed, in its early stages, at identifying situations that may be dangerous to human habitation in space, and if such situations do exist, to overcome them. As a biological program its future advances are to be seen in terms of man's adaptability to new, quite different, but potentially useful, environments.

2.2 Human needs

For the immediate future the needs of human beings in space for food, water, and a breathable atmosphere will be met by resupply. Essentially, this involves carrying all food and water from earth, and collecting wastes for subsequent disposal. Atmosphere purification in spacecraft has been utilized, although regeneration of materials has not. Reliable and fast-acting water and gas conservation devices will be employed as

they are developed. Waste disposition, through techniques such as wet oxidation, will permit partial reuse even of some elements of solid wastes.

As space stations are enlarged, and as greater numbers of men must be supported, the cost of transporting food, oxygen, and water to them will become more significant. Similarly, for manned missions into deep space the cost of including food as a very large fraction of the initial payload will become prohibitive. Settlements on the moon or on other planets will have to function with a maximum of regeneration because resupply to such distant settlements would be a major expense.

Increasingly, physico-chemical and mechanical devices capable of regenerating oxygen from water, of capturing and possibly reutilizing the oxygen in carbon dioxide, and of purifying water will be developed. Removal of toxins and unpleasant gases from the atmosphere is becoming simpler, but recycling of all wastes to allow chemical resynthesis of food presents a problem without a foreseeable solution. To be sure, significant advances have been made in producing carbohydrates from CO_2 (Lerman and Murashige, 1973) and the formation of amino acids from gases such as CO, H_2, HCN, CO_2, O_2, and N_2, or some other easily generated form of these compounds (see Gabel, 1977, for a recent review of abiogenic syntheses of amino acids), but in all cases, the products potentially useful as food are extensively contaminated by toxic materials co-produced in the same syntheses. Many substances required by man are exceedingly complex organic entities which have only recently been synthesized in the laboratory, and then only after great effort.

2.3 Bioregeneration

Biological solutions to the regeneration problem have been investigated for a number of years. In essence, these approaches have involved the fermentor-style growth of organisms which could be eaten by man. Two of the most extensively investigated potential food sources have been algae, which grow on some nitrogenous human waste products, carbon dioxide, and light (Benemann et al., 1977), and hydrogen bacteria, which utilize hydrogen and oxygen, and carbon dioxide (Calloway, 1975). Feeding experiments have been conducted with the algal or bacterial products harvested from such "fermentations" and these trials have been partially successful. However, the organisms employed have sometimes been recognizably deficient in some of the compounds required in human nutrition, often containing endotoxins or nucleic acid concentrations too high for direct human consumption (Waslein et al., 1969).

Techniques for fractionation of bacterial or algal cells, and manufacture of nutritious food from parts of the cell material, although in their infancy, are promising solutions to some specific problems, such as supplying protein to humans, not only in space, but on earth as well (see Kihlberg, 1972, for review). It can be expected that such work will proceed with reasonable dispatch since it is potentially profitable. However, if it is to be used directly by man, microbial food will probably have to be supplemented with food from other sources. Indirect use of cheaply produced single cell food, for example, through feeding algal or bacterial food to animals which may then be used as human food, is also a promising approach.

2.4 Nutritional requirements

Human food requirements are imperfectly known. Certainly the major dietary components have been identified, and the relative proportions of protein, fat, and carbohydrate are well categorized. The "minimum daily requirement" of many vitamins and minerals has been established, although controversy still exists over the optimal intake of these substances. Yet the balance of nutrients required for sustained human health is not known nor is the relative importance of such things as fibre, collagen, pectin, and other substances generally considered "indigestible." What is known is that man has evolved over millions of years to subsist on a diet consisting of both plant and animal material and that eating more or less of one component among the many sustains health, but that exclusive use of a single component results in problems, some of which are minor, some major. The relationship of cancer and heart disease to diet, for example, are hotly contested subjects. Some are the consequences to humans of food additives—nitrite, coloring agents, and preservatives.

It will probably not be possible, in the immediate future, to resolve the existing claims and counterclaims regarding human nutrition, nor will the definitive human diet be completely described in terms of specific organic molecules. For this reason the diet of humans who remain in space for extended periods of time will probably consist of "normal" biologically produced food. It is because of these uncertainties hat man may want to produce food in space, a possibility reinforced by the difficulty of the resupply problem. It should be restated, however,

that growth of food in space will become necessary and cost-effective only for relatively large human settlements or for extended deep-space journeys. Small human colonies or short-term flights would seem now more easily supported via resupply or by taking along sufficient food at launch.

2.5 Biological recycling

An obvious advantage of growing food in space is that plants, in particular, are also capable of atmosphere regeneration. Specifically, autotrophs such as plants, take up the carbon dioxide expelled by heterotrophs, including man, and produce the oxygen such organisms consume. It is tempting to envision a space station in which human wastes are used by photosynthetic organisms, which are in turn used as food by man. The creation of such a system will be very difficult for many reasons, but it is apparently possible provided that careful preparations are made.

A human habitat in space, on the moon, or on another planet, will be a closed system. To a significant extent, although not totally, materials entering and leaving the system will be controlled. The uncontrolled entrance and exit of mass will be of major concern: for example, the transport of unwanted or dangerous microorganisms will be difficult to control, as will the leakage of gases into space or into a planetary atmosphere. Except for such considerations, an isolated system capable of supporting human life is a "closed, regenerative, ecological system"

and as such bears a resemblance to the whole terrestrial ecosystem. What requirements must be met to establish an isolated ecosystem in space?

Since man will be the central component of a space colony, all functional requirements must be established, basically, by human needs. Thus, man needs a continuous supply of oxygen at partial pressures that can vary between 1.6×10^5 and 2.0×10^5 dynes/cm^2. He needs food, composed of protein, fats, carbohydrates, a variety of minerals, and vitamins. He needs water for both internal and external use. The list of conditions that man cannot tolerate is even more extensive. The limits imposed would include water with a minimum of mineral and bacteriological contamination; air with well controlled and very low levels of volitile contaminants, but with reasonably controlled water vapor concentration; food composed of a proper balance of protein, fats, and carbohydrates and uncontaminated by either toxic chemicals or harmful bacteria. In designing optimal conditions for man, the requirements for human life support are defined. It is then necessary to define the functions that must be met by the life support system and to implement them.

With the assumption that physico-chemical techniques will be able to supply many, but not all, of the required functions, the establishment of biological food sources requires special consideration. A biological food producing and recycling system in space will be isolated, and to the greatest extent possible, "closed."

2.6 Ecosystem closure and buffers

The simple closure of a biological system, even if it is exposed to the same amount of light and heat as an open system, results in the eventual death of the system. The reasons that the system dies are complex, and not fully known, but even a cursory examination suggests many causes.

A fundamental reason concerns "buffering capacity," which is partially provided by the sheer size of the terrestrial ecosystem. For comparison, consider the buffering capacity available to one square meter of land on earth. In addition to the contents and the dynamics of the soil to a depth of about 1 m, there exists 2.42 m^2 of ocean surface. The average depth of the ocean is roughly 3400 m, so that the volume of ocean water corresponding to 1 m^2 of land is about 8300 m^3. The atmosphere above 3.42 m^2 of land and ocean extends to 60 km or more, but if the atmospheric gases were compressed to standard pressure, they would occupy about 1260 m^3. Figure 1 provides some indication of dimensions involved, and Figs. 2a and 2b suggest the relative sizes of the volume of ocean and atmosphere that can act as buffers to 1 m^2 of land. Considering for the moment only oxygen and carbon dioxide utilization and production, the photosynthetic autotrophs in any ecological system utilize light only when it is available, during the day. Consequently, oxygen is produced by plants cyclically. Heterotrophs, or oxygen users similarly undergo cyclic uses of that gas. As a result, CO_2 is produced by each organism in a cyclic fashion depending on its state of maturity, its momentary rate of metabolism, or its supply of food. In a small closed system these cycles, which are not

linked, do not necessarily correspond. Most importantly, the atmospheric volume enclosed in a small system would not be sufficiently large to maintain a steady-state concentration of oxygen, or to absorb CO_2 at a rate fast enough to maintain a steady-state concentration of that gas. The volume of the terrestrial atmosphere alone appears sufficient to dampen the cyclic consumption and production of oxygen and nitrogen.

In addition to large volume buffering the whole earth ecosystem utilizes the physical solubility of CO_2 and O_2 in the oceans as well as chemical equilibria to maintain average concentrations of CO_2 and O_2 all over the Earth. The chemical equilibria governing the capacity of the oceans to absorb CO_2 are complex. Physically dissolved CO_2 is in equilibrium with bicarbonate and carbonate ions. These soluble ions are, in turn, in equilibrium with insoluble Ca or Mg carbonates, and all equilibria are greatly influenced by, and affect, pH.

Both the oceans and the atmosphere perform an additional function that of distribution. Some areas of the earth (the deserts and polar regions) produce little O_2, while tropical rain forests produce large amounts. The atmosphere, acting as a transport medium, homogenizes the noncondensing gases so that only very slight variations in O_2, N_2, and CO_2 concentrations exist worldwide. Condensable gases, such as water vapor, are less homogeneously distributed; nevertheless, water distribution is vital for the survival of the terrestrial ecosystem.

While sheer size, physical solubility, and chemical equilibria are major factors in the buffering action available to the terrestrial ecosystem, another factor is system energetics. Energy is required to operate the "distribution device," the atmosphere. Solar energy, in the form of

heat, creates the winds that distribute the gases, and moves the water that dilutes volatile toxins and removes toxic gases. Solar energy is responsible for the destruction of many toxins, even the natural, toxic, organic compounds produced by plants. Ultimately, solar energy is also responsible for the formation of some nutrients, such as the nitrates formed by lightning discharge, as well as for the distribution of some materials, for example, in flowing water.

Thus, while not intuitively obvious, the energy requirements of a plant are not, and cannot be, totally met only by the light energy used by its leaves. Similarly, the energy used by heterotrophs depends on the "unseen" energy inputs which maintain some semblance of a steady-state system. Thus far, these energy requirements have been difficult or even impossible to measure. Isolating a portion of a terrestrial ecosystem deprives it of a significant fraction of the energy it requires to exist. The consequence is its eventual death.

2.7 Establishing closed ecosystems: ecosynthesis

It is a moot point whether an artificial ecosystem, totally closed to entry or exit of mass, fully recycling, and completely regulated by its biological components can be constructed. Theoretically, one could, through careful selection of ecosystem components, construct such a system, but to do so would require firstly, complete knowledge of the behavior of all the component organisms under all possible conditions, and secondly, matching them as to species and numbers of individuals in a volume large enough to provide sufficient buffering capacity. The creation of ecosystems

for practical use in space cannot wait until all of the required information is accumulated. Furthermore, any biologically balanced artificial ecosystem which included man could not be controlled sufficiently well to prevent the accidental introduction of unwanted species. Such organisms, even though innocuous to man, could have devastating consequences for the balance of a designed naturally controlled ecosystem.

In brief, extraterrestrial ecosynthesis (Averner and MacElroy, 1976) will require a closed system capable of supporting man by supplying food, and will function in a manner that it will recycle wastes, including CO_2, and generate oxygen. It is extremely doubtful that it could be self-regulating because of its relatively small size. Size will also tightly limit the amount of buffering capacity available. It will be essential that artificial buffers be created, and that regulation of the system be done through human intervention. In many ways such a system would resemble a typical farm, in that crops must be selected, noncrop plants eliminated, water and nutrients supplied when needed, and food harvested when mature.

Atmospheric buffering capacity for a particular gas will have to be supplied by mechanical means. Such mechanical mechanisms must be capable of removing certain atmospheric constituents and supplying others. The energy necessary for operating both the mechanical and biological systems presumably will come from sunlight, but could also be supplied by other means, such as nuclear reactors. Control of the system would no longer be dependent on natural self-regulatory mechanisms, but rather on constant monitoring by sensing devices and periodic analyses. The behavior of the system would have to conform to an established but variable model of the function of the system.

3. Ecosynthesis

3.1 Physical description

Although not essential in this very early phase of modeling a closed ecosystem for space, a physical description of a possible ecosystem enclosure has been found helpful both in developing a mathematical model of the system and in postulating essential experimental verifications. The description of the "standard" system that follows is quite general, and is recognizably deficient in detail. It is also completely open to modification since the subsequent mathematical description can be altered at will. Thus, the physical description should not be considered as the center of design, but rather as an aid in conceptualizing the mathematical model.

The physical dimensions of the space habitat are set essentially by human food requirements. In this model it is assumed that man can be sustained on a daily diet of 120 g of protein, 50 g of fat, and 400 g of carbohydrate per 70 kg body weight, and that these nutrients can be supplied by selected combinations of corn, wheat, and soybeans. Food for one 70-kg man for 1 day would require an amount of these grains that would be produced by crops occupying 2.2 m^2 with light of intensity and quality identical to sunlight at the earth's surface. Assuming three crops per year rather than daily harvest of grain, and crop production equal to maximum reported yields, the area required for these crops can be roughly calculated to be 820 m^2.

It must be stressed that the area values calculated in this manner are subject to very large variation and could be affected by such factors as the use of genetically engineered high-yield crops, error margins derived from estimates of crop failure, the inclusion of animals other than man in the ecosystem to serve as secondary food sources, or the choice of single-cell organisms as a partial food source. It should also be noted that growth of such crops at less than 1 g force may have profound effects on crop yield as well as growth rate. This particular point is stressed because of our implicit assumption that a force of 0.5 g or more may be required for the habitat.

This concept of a space station with a synthetic ecosystem then envisions a total volume of 8000 m^3, a crop area of 6400 m^2, a human living and working area of 1200 m^2, and a support system area of 500 m^2. The structure is conceived as supporting up to seven people, and consisting of many shuttle packages, assembled and linked in two locations, both rotating around a common center to allow a force of about 0.5 g. It is further assumed that the light energy necessary to sustain crops is provided by electricity which is generated separately by a large assemblage of solar panels. Throughout, it is assumed that power requirements will not be limiting for any portion of the operation of the system.

3.2 Model systems

Since the space station will be a closed system, and since it will be necessary to monitor all portions of the system, the technique of mass balance appears best to describe the functional aspects of the

station. For the purposes of describing such a model, eight compartments will be considered initially: man or heterotrophs, plants or autotrophs, food, waste material, atmosphere, water, storage or buffer, and a chemical-physical (mechanical) processing center.

Initially the flows of the following elements, all common to biological systems, will be monitored: carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), and phosphorous (P). For the most part, methods of rapid and accurate analysis of these elements are available, and flows among the compartments can be followed relatively easily. The dynamics of element flow will be derived from models of metabolic activity and growth that employ previously obtained experimental data to identify not only steady-state levels of elements, but future requirements as well. Much information about the growth development and chemical composition of organisms is already available; models of this kind will identify many other organisms from which such information must be gathered in the future.

Through the use of such models of individual metabolic and developmental needs, instantaneous requirements for the elements CHOPNS can be calculated and the movement of the elements in and out of a compartment can be predicted. The three biological compartments of heterotrophs, autotrophs, and waste will thus be described in terms of existing models of such activity. Similar but more accurate models can be derived for the nonbiological compartments: atmosphere, water, storage buffer, and processing system.

3.3 Ecosystem Concepts

Before discussing the specifics of a closed system model, it would be advantageous first to consider the concept of ecosystems and the methods that have been developed to study them. The term ecosystem generally refers to some specific volume of space occupied by organisms as well as their physical and chemical environment. However, a catalog of the kinds and numbers of organisms, of the geological, meteorological, climatological, and other inanimate parameters of a volume of space is not a sufficient description of an ecosystem, because it does not include the dynamic behaviour of the components, particularly the living components. The interactions of organisms with one another must also be described and related to the physical reality of other system components in order to obtain the physical and functional description of an ecosystem.

Observational ecology has resulted in the collection of data, such as numbers or types of organisms. Time-dependent data collection has allowed assessment of perturbations arising during the time interval, and mathematical expressions have related the observed changes. The result is a model which can often relate the extent of the change to the extent of the perturbation.

With the aid of computers to simulate the events—the magnitude of the perturbation and the change in numbers or types of organisms—one can numerically mimic observed changes as well as predict future changes. While computer models and event simulations do not identify causes, they are often useful in suggesting the reasons for the observed results and permit further experimental testing. It is precisely this aspect of

computer modeling of ecosystems that is of interest in examining the behavior of closed ecosystems through the use of computer modeling.

3.4 Mathematical descriptions

A model of an ecosystem can be considered as representation of a system of living and nonliving components occupying a defined space, through which energy, mass, and information flows. Since a space ecosystem will be a closed one, a mass-balance technique appears best suited to describe it (Quinlan, 1975; Quinlan and Paynter, 1975). At a gross level, such a model might be illustrated as in Fig. 3.

The photosynthetic properties of autotrophs, such as plants, allow them to use the radiant energy of sunlight to synthesize complex polymers, carbohydrates, lipids, proteins, and nucleic acids from CO_2, NO_3, PO_4 and other minerals and gases. As these nutrients become less available the growth rate of the autotroph will be curtailed. If the autotrophs continue to act as a sink to such minerals, the environment would eventually be depleted. However, heterotrophs, such as animals incapable of using solar energy directly, feed upon the carbon compounds formed by plants. They are able to oxidize the compounds, and in so doing extract and trap energy; they are also able to use the compounds either directly or by rearranging them, for their own growth purposes. The oxidation reactions of heterotrophs ultimately release CO_2 and the other minerals required by autotrophs.

This cycle of mineral fixation and release is the aspect of an ecosystem that can be simulated using models, because the rates of flow

of each mineral constituent in and out of the living organisms can be mathematically described. For example, Fig. 4 is a more general description of the reservoirs and flows suggested in Fig. 3, but also includes a more sophisticated view of the controls that can be exerted on the flows. This approach to the construction of mathematical models of ecosystems follows the technique of Quinlan (1975) and Quinlan and Paynter (1975).

3.5 Mathematical model

Figure 4 describes the transport of element X between three storage compartments, an inorganic nutrient storage (X_1), an autotrophic storage (X_2), and a heterotrophic storage (X_3). The autotrophs take up and incorporate the inorganic nutrient into their biomass at a characteristic rate (TX_{12}), which is ingested by the heterotrophs (TX_{23}) and remineralized back into inorganic nutrients (TX_{31}). Thus, in this simple closed-loop, the laws of mass conservation dictate that the rate of change of mass in each compartment is a function of the rate of flow of mass into the compartment minus the rate of flow of mass out of the compartment, or:

$$\dot{X}_1 = T_{X31} - T_{X12}$$

$$\dot{X}_2 = T_{X12} - T_{X23}$$

$$\dot{X}_3 = T_{X23} - T_{X31}.$$

The sum of the rates of change of mass in each compartment must equal zero:

$$\sum \dot{X}_1 = 0$$

and since mass is neither gained nor lost, it is a constant:

$$X_1 + X_2 + X_3 = M \equiv \text{constant}.$$

The rates of elemental mass flow between the compartments are a function of the state of the compartments. This is indicated in Fig. 4 by the rates modulation signal flow. Thus, for this closed elemental cycle, the following functional dependencies can be written:

$$T_{X12} = k_{X12}\left(\frac{X_1}{a_1 + X_1}\right)X_2$$

which describes the observation that the nutrient uptake matter flows go to zero if either the nutrient pool (X_1) or the autotroph population (X_2) goes to zero and saturates in X, as X increases to some value. Similarly,

$$T_{X23} = k_{X23}\left(\frac{X_2}{a_2 + X_2}\right)X_3 \quad .$$

Since the rate of predatory matter flow, (T_{X23}) will fall to zero if either the predator (X_3) or prey (X_2) population goes to zero, and becomes saturated in X_2 as X_2 increases to some level. Finally, the rate of mineralization can be described by

$$T_{X31} = k_{X31}\ (X_3)$$

since the rate of mineralization (T_{X31}) will fall to zero when the heterotroph population (X_3) goes to zero, and is independent of the size of the nutrient pool (X_1) and does not saturate as X_3 increases

The parameters k_{X12}, k_{X23}, k_{X31} (rate constants), and a_1, a_2, a_3 (saturation constants) are determined by a number of variables, for example, variations in temperature, pressure, biological species, spatial distribution of elements, and light intensity.

These equations then define the behavior in time of a simple closed element cycle model. The major elements in an ecosystem (C, H, N, O, S, P)

are all modeled separately, however, and a realistic representation of the flow of elements in any ecosystem must allow for functional couplings such that all the individual element cycles are integrated into a single dynamic system. This can be done by cross-coupling individual element cycles by single-flow linkages. These linkages transmit information from one cycle to another such that the behavior of the latter is modulated by the behavior of the former. For example, Fig. 5 depicts the manner in which the flow of one element (e.g., carbon) might modulate the flow of another (e.g., phosphorus) and vice versa in our simple three-compartment closed ecosystem.

This model depicts the functional coupling of the C and P element cycles through intercycle rate modulations directed at nutrient uptake flows. Thus the state of autotrophic storage of carbon (C_2) regulates the nutrient flow of phosphorus into the autotrophic compartment (P_2) by means of the cross-coupling parameter KPC12, and the state of the autotrophic storage of phophorus (P_2) regulates the flow of inorganic carbon into the autotroph compartment (C_2) through the cross-coupling parameter KPC12. Thus the rate of change of carbon storage in the autotroph compartment would modulate the rate of phosphorus uptake into the same compartment and vice versa. This is but one example of how elemental cycles can be linked so that perturbations in the behavior of one cycle can be transmitted to other cycles and thereby modulate their behavior.

Real ecosystems are of course vastly more complex than the simple three-compartment, two-element cycle model depicted in Fig. 5. Nevertheless, this simple model does represent a number of features of many closed ecosystems that might be designed for extraterrestrial situations, and as

such represents a strategy of modeling that will shed light on the behavior of such systems.

3.6 Using a model: an example

One of the mathematical models of the flow of carbon within a closed system has been used to suggest the magnitude of the problem of buffering capacity. The closed system consists of an atmosphere large enough to support about 50 men and their supporting crops (about 62,000 m^3). However, only one man is functioning in the system, together with support crops of soybean, corn, and wheat. The model, with eight compartments (Fig. 3), was perturbed by replanting only 91% of the crop that is harvested daily. Therefore, the mass of the crop is continually decreasing and, because the system is closed, this mass must appear in another compartment. In this model, the mass of the atmosphere compartment increases due to metabolic oxidation of food and oxidation of nonedible plant materials. Figure 6 is a plot of carbon in the atmosphere (CO_2) versus time. Case D represents a mechanically buffered situation in which the initial concentration of atmospheric CO_2 is maintained at 0.03%; other cases are unbuffered and include Case A, with a food crop large enough to support one man 'indefinitely'; case B, a food crop 50% greater than case A; and case C, a crop size that has been reduced to 85% of that in case A, and that can be assumed to be fully exhausted in some finite time. As can be seen, the relatively minor perturbation of slowly decreasing crop size markedly increases the atmospheric CO_2 concentration, even in a very large volume.

The brief description of the mathematical model above includes several assumptions that are open to alteration in the future. The most fundamental

of these is that the best method of modeling a closed ecosystem is through a mass-balance technique, employing individual elements, such as carbon or phosphorous. There is no doubt that the complexity of this approach may be initially time-consuming, and that the methods of coupling the flows of different elements will involve the invocation of molecular, rather than atomic, representations. However, we feel that these disadvantages are out-weighed by the potential advantage, namely, that following individual element flows will permit more sophisticated probing of ecosystem behavior. In fact, the potential contributions to terrestrial ecological sciences will be magnified specifically because element flow can be evaluated in studies of closed ecological systems.

4. Scientific Utility of Studying Closed Biological Systems

4.1 Ecological Concepts and Experiments in Space

Both the physical concept of closed ecosystems in space and the method of modeling can be utilized in designing some of the specific experiments that will be necessary before physical construction of such a system. As presented here, an in-space ecosystem would consist of a closed volume containing plants and animals sufficient to support man, and also containing physico-chemical devices operating to overcome certain inefficiencies of biological components. The system would be operated as a farm to produce a variety of products, among them food, oxygen, carbon dioxide, water, nitrogen and other materials as may be necessary. Operation of the ecosystem as a farm implies control of all significant organisms and of their requirements and products. Thus, control through timely and precise

allocation of materials, becomes a predominant function of a state model of the farm ecosystem.

In preparation for a control model, experimental investigation of individual biological and physical components becomes of interest. In this regard, interspecies interaction and its effect on the behavior of biological components looms to major importance, and it is in this area that experimental research must be conducted if believable models of ecosystems are to be developed.

Present knowledge of ecosystem behavior is primarily at the gross level of large animal or plant interactions. The most fruitful past approaches to the study of interspecific interaction have been descriptions of predator-prey relationships, or of competition for a mutual requirement, such as food. Numerous examples exist of evolved characteristics which alter direct predator-prey relationship, for example, the chemical component of certain butterflies that make them distasteful to birds, or the more sophisticated selection of mimicry, described by Bateson, that allows some species of butterflies to pretend that they are distasteful. Examples of evolved competitive advantages exist as well.

However, at the microbial level, interspecific relationships are much less well understood, yet microbial metabolism comprises a significant fraction of the total metabolic activity of the earth, and will doubtless function similarly in space. Knowledge of the role of microorganisms in processes such as nitrification and denitrification will be essential to the design of closed ecosystems, as will knowledge of the interactions among certain groups of microbes.

Among plants, competitive relationships must be described in sufficient detail to prevent disruption of food-growing. Similarly,

plant production of volatile organics which have been observed to be toxic to other organisms (Gitel'son et al., 1975) must be evaluated. Other aspects of plant growth, such as metabolic or structural changes at less than 1-g force, must be investigated.

The introduction of Shuttle launches may include opportunities to fly sizeable closed system experiments in space. It can be anticipated that, in addition to investigating the growth and metabolic characteristics of various organisms at various g forces, flight opportunities could be utilized to test small farm ecosystems. Such an experiment might be envisioned as containing plant, microbial or animal components, or all of these, in a container in which sensing and monitoring functions have been included. Attempts might be made to maintain water, atmospheric, and light energy homeostasis by reference to a small computer model of the system, which would, as needed, perform certain control functions. Such functions might be the introduction or removal of oxygen or CO_2 as required, or the physico-chemical recycling of certain wastes; for example, wet oxidation of selected organics, or of the maintenance of an appropriate reduced versus oxidized state of nitrogen.

Experiments such as these could be designed to explore simultaneously organism physiology, the effect of varying gravitational forces, the accuracy of the models which had been developed to describe the system, the control model, and the sensing, monitoring, and control devices.

4.2 Ecological Analysis

In addition to the practical applications to which studies on closed ecological systems may be put, other benefits may accrue, particularly in the field of basic ecological sciences. A system closed to mass exit or entry, but open to energy input and with controlled energy loss, mimics a "test tube environment" and [for the first time] will permit study of all parameters of ecological systems. To be sure the enclosed system will not be a "natural" one, but it is this very aspect that will allow new ways of evaluating interactions between species, of studying the true metabolic and energy requirements of groups of organisms, of investigating environmental triggers of metabolic and behavioral changes, and of re-examining classical predator-prey and competition interactions. The advantages of closed system studies lie primarily in the realm of easily established control experiments, and of permitting specific and regulated variables to affect the system. It is anticipated that such approaches will add important insights to and new interpretations of the voluminous data already collected on ecological system behavior.

Among the parameters of ecology which have not been well evaluated are the roles of buffers and the quantitation of buffering capacity. In closed systems, buffers would be specifically defined, either as "naturally" occurring absorbers or storage depots, or as mechanical or physico-chemical devices. In exploring buffers, the true energy requirements of species would become apparent, thus enlightening the relationship between organisms and the inanimate world, as well as identifying what are now obscure energetic relationships among organisms. An example of the last-mentioned

relationship is the energetic role of nitrogen fixers in relationship to fixed-nitrogen users, and to denitrifiers. Examples of animate-inanimate interactions have been mentioned previously.

The true value of the study of closed, controlled ecological systems may be as much in its effect on terrestrial ecological science, as in its ultimate use to support man in space. The controlled closed system we have defined here differs significantly from the usually described "closure" experiments. Rather than observing a system as it declines in its productivity and species diversity, the controlled system allows specification of what keeps the system alive, and in doing so, quantitates the factors necessary to do so. In addition, the technique allows an evaluation of the real costs and advantages of ecosynthesis, and could have a major impact effect on improving agricultural productivity on earth.

5. Conclusions

Support of men in space for significant periods of time will benefit by an ability to recycle wastes into food and to regenerate the atmosphere and water. In the absence of physico-chemical methods of food manufacture, living sources of food must become a central part of any long-term missions once resupply becomes impractical. Abundant light energy favors the growth of plants or other photo-synthetic organisms. These organisms also have the advantage of consuming CO_2 and generating oxygen, two functions advantageous to man in a closed habitat in space.

The temptation to develop a closed ecosystem mimicking man's terrestrial environment becomes very strong. However some generally unappreciated

aspects of the real world become obvious when closure is attempted: because of lack of sufficient buffering capacity and the absence of certain energy requiring functions, such as atmospheric circulation and rainfall, closed systems over long or short time periods become sterile. Recognition of this fact strongly suggests that mechanical or physicochemical methods must be used to maintain an ecological system in a desired state.

Since a specific function—support of man—is desired of a closed ecosystem in space, an isolated man-supporting ecological system would be run as a farm, and would be controlled as such. The limited size of the enclosure, the susceptibility of biological systems to environmental perturbation, and the need for control and predictability all suggest that monitoring, sensing and control within an in-space ecosystem be directed through the use of a computerized mathematical model of the system. Such a model, while operating a farm consisting of the entire environment of the space station could, through simulation, perform a predictive function. Moreover, such a model developed even before a physical system was constructed, would serve the function of simulating the behavior of a system and could aid in identifying parameters that must be evaluated before a physical system is constructed.

The technique of modeling a closed ecological system through mathematical representation of mass flow appears to offer many advantages for understanding closed ecological systems. Such models, incorporating presently available information on biological behavior, capable of alteration as new information becomes available, and containing information on the characteristics of the mechanical devices necessary in the system,

will significantly aid the development of physical design, as well as serving to extend the body of information on terrestrial ecological systems. Ultimately, these predictive models, and subsequently derived state models, will permit the development of reliable, man-supporting ecosystems in space.

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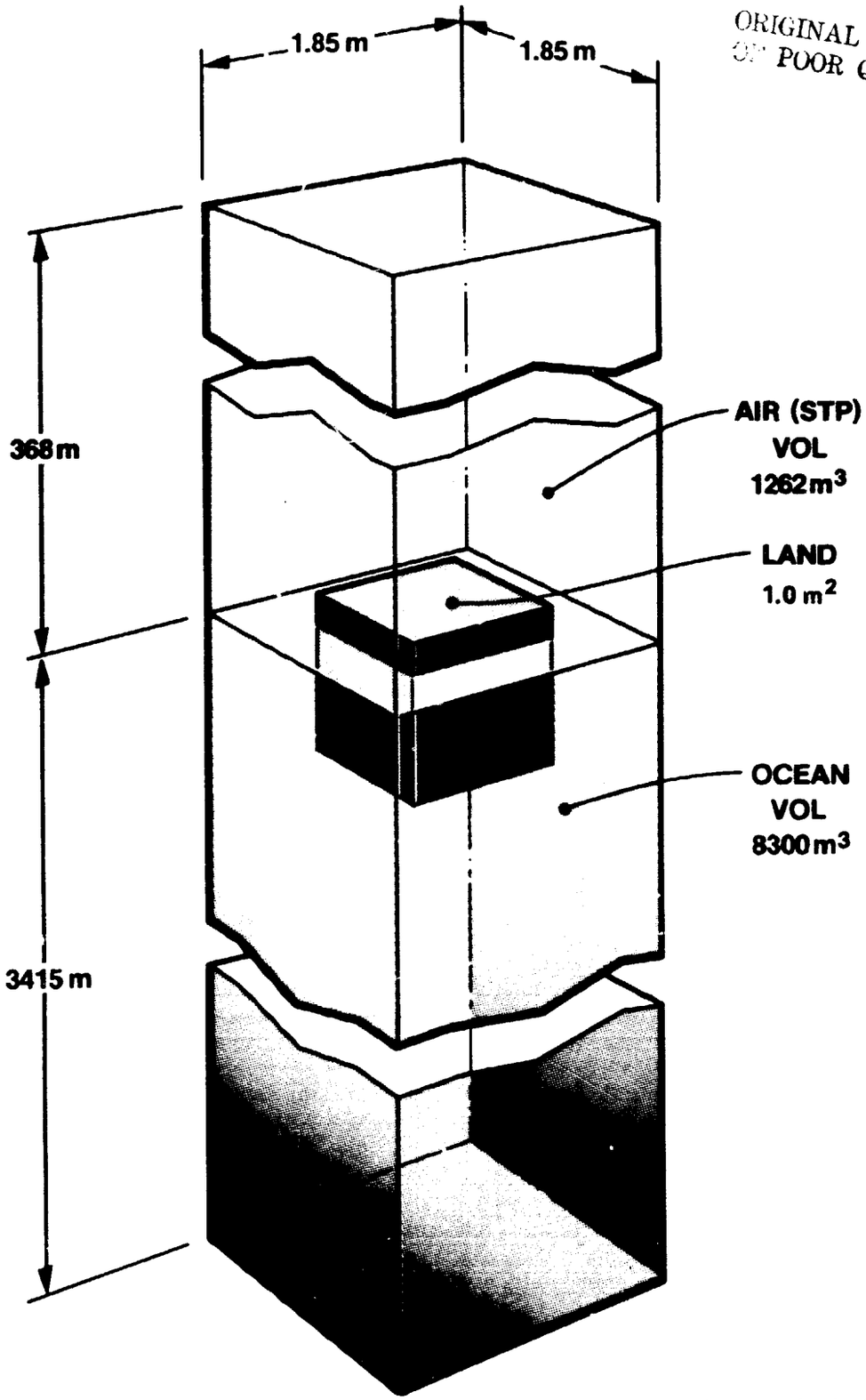

Fig. 1. Relative dimensions of the size of atmospheric and oceanic buffers available to 1 m^2 of terrestrial land.

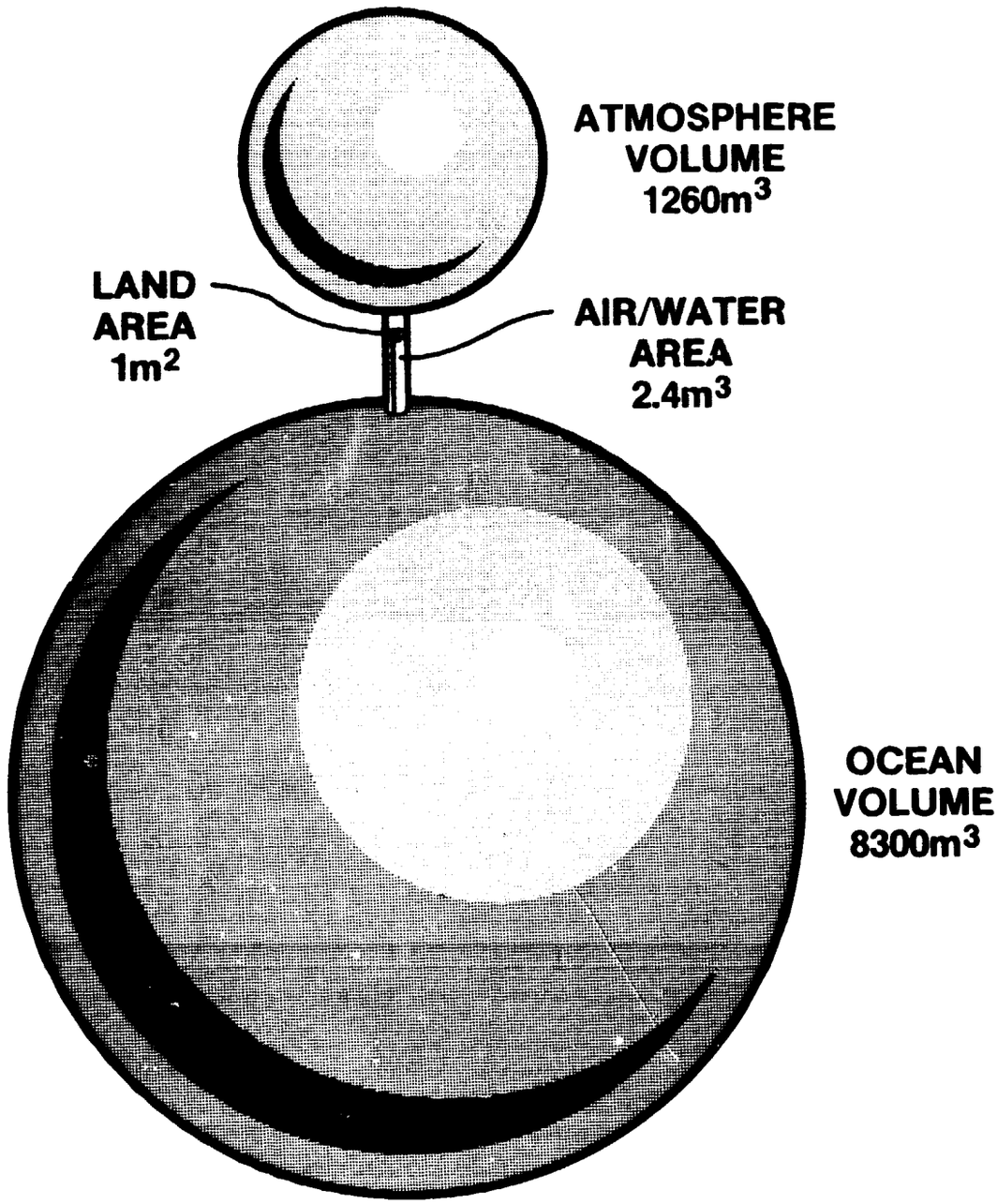

Fig. 2a. Relative volumes of atmosphere and ocean that act as buffers to 1 m^2 of land.

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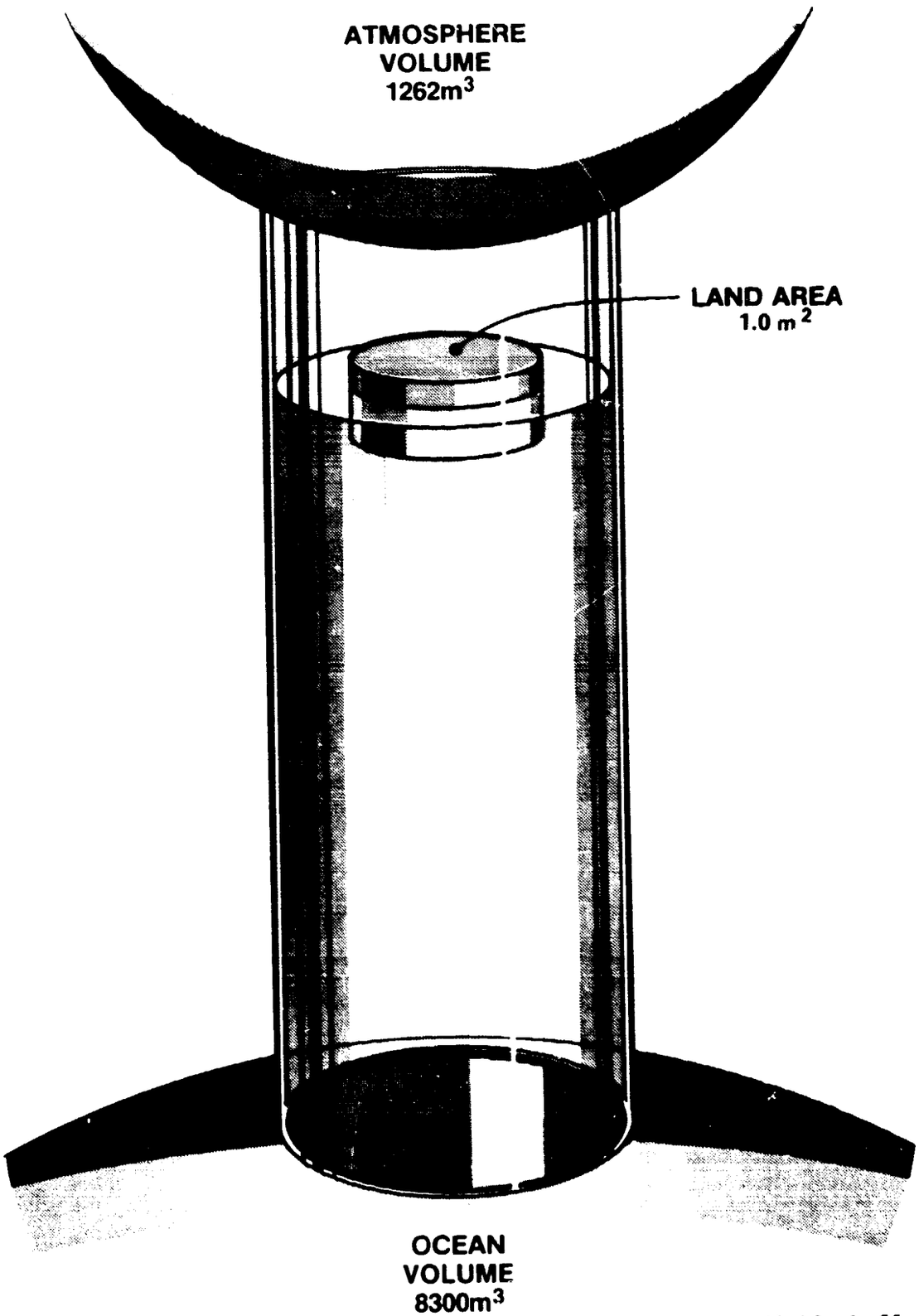


Fig. 2b. Enlarged view of land mass in relation to available buffering capacity.

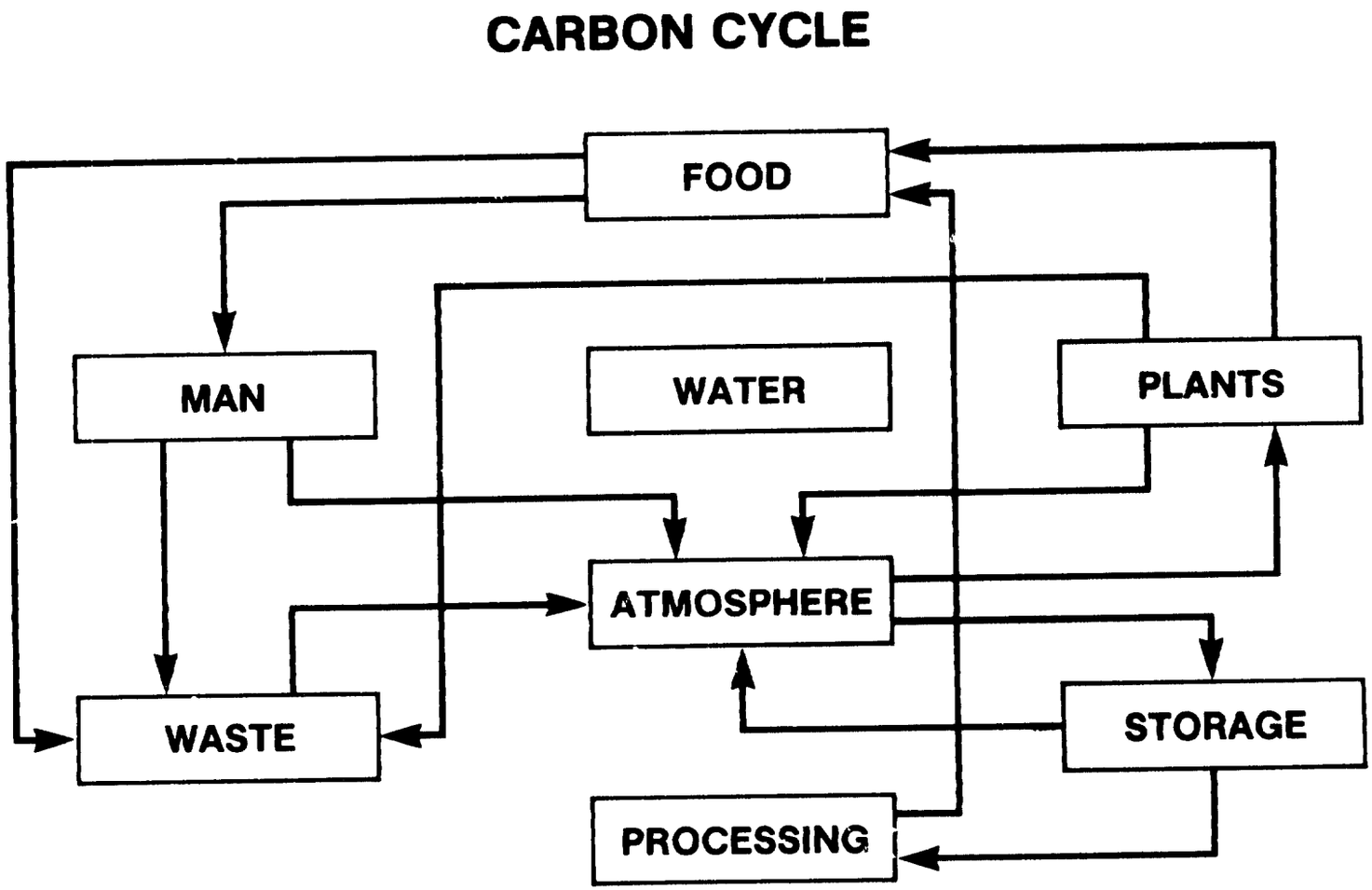
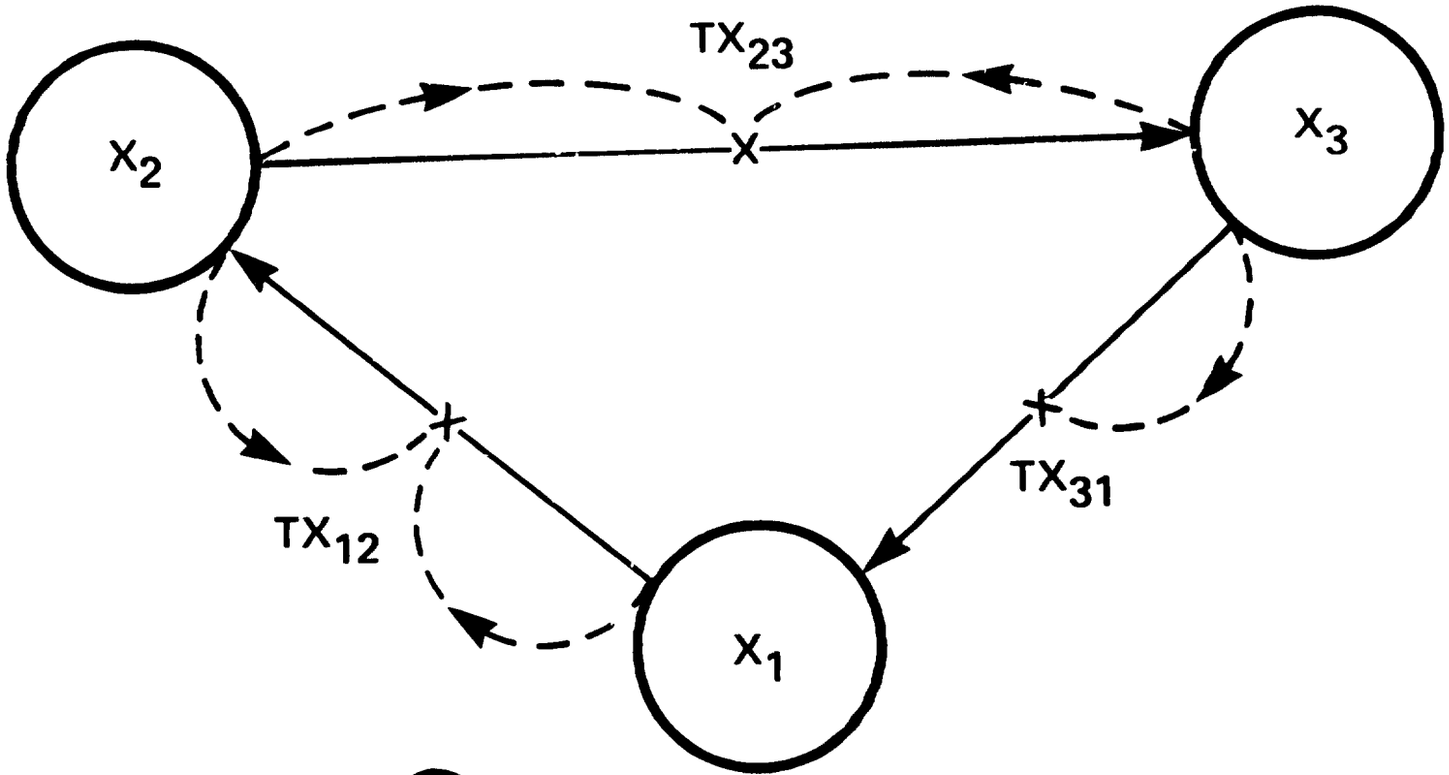


Fig. 3. The compartments representing the accumulation of specific elements in a closed ecological system. The flow of carbon, one of five elements to be considered in the initial model development, is indicated by lines; direction by arrows.



= MATTER STORAGE

= MATTER FLOW

= RATE MODULATING SIGNAL FLOW

X = RATE MODULATION RELATIONSHIP

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Fig. 4. An illustration of the flow of carbon among compartments in a small closed system. The solid lines represent the flow of mass between compartments (circles); the discontinuous lines represent modulation effects which are flow regulations imposed by either the receiving or the producing compartment.

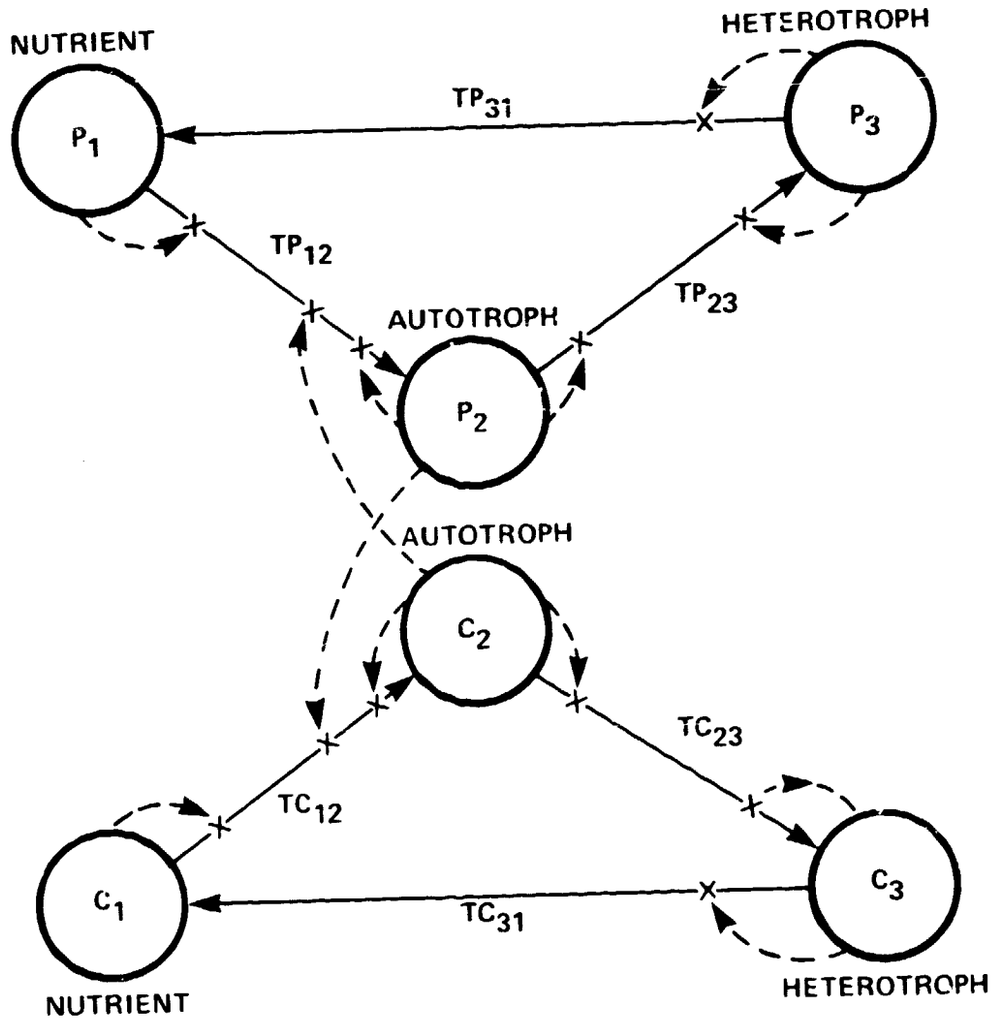

Fig. 5. A representation of the relations between the flows of two different elements, phosphorous and carbon in a closed system. The coupling of the flows, for example in molecules containing both elements, can be represented by modulation effects.

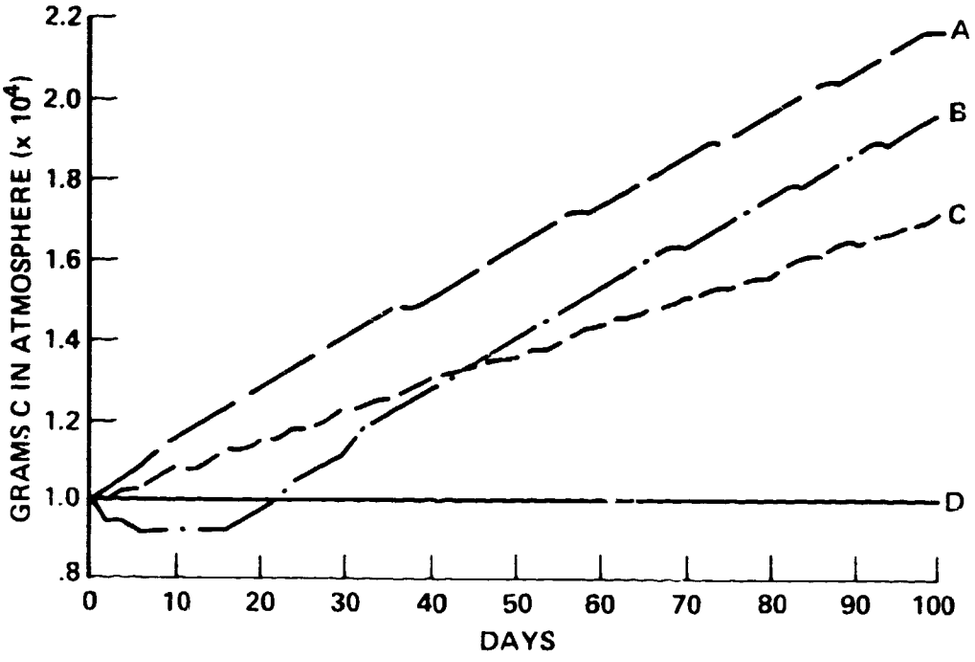

Fig. 6. The effect of crop-size perturbation on the concentration of atmospheric CO_2 in a large volume (62,000 m^3) closed system supporting one man. The initial crop size was varied: case A, crop size just sufficient to sustain one man "indefinitely" when complete replacement is made of all harvested plants; case B, crop size 150% of that in case A; case C, crop size 85% of that in A; case D, a mechanically buffered case in which initial CO_2 concentration is maintained at 0.03%. In each case, the perturbation consisted of replanting only 91% of the crop that was harvested each day.

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16. Abstract

The use of closed ecological systems for the regeneration of wastes, air, and water is discussed. It is concluded that such systems, if they are to be used for the support of humans in space, will require extensive mechanical and physico-chemical support. The reason for this is that the buffering capacity available in small systems is inadequate, and that natural biological and physical regulatory mechanisms rapidly become inoperative. It is proposed that mathematical models of the dynamics of a closed ecological system may provide the best means of studying the initial problems of ecosystem closure. A conceptual and mathematical model of a closed ecosystem is described which treats the biological components as a farm, calculates the rates of flow of elements through the system by mass-balance techniques and control theory postulates, and can evaluate the requirements for mechanical buffering activities. It is suggested that study of the closure of ecosystems can significantly aid in the establishment of general principles of ecological systems.

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