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CHAPTER 3

ENERGETICS OF WORLD FOOD PRODUCTION[1]

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Introduction

The problem of world food production and the population explosion is one of system design. How do we develop a network of food chains with as much stability as those which evolved earlier in some natural systems or in some of man's more primitive agricultural regimes now being displaced by war, competition, and overpopulation? How are the new energies now available to man's civilization to be best introduced? Which of the various kinds of possible new designs for systems of food production and consumption will lead to the survival of man in affluence, stability, and justice?

In recent years, studies of the energetics of ecological systems have provided points of view and means of dealing with complex food networks that combine the basic laws of physics and chemistry with the complex aspects of living systems such as self maintenance, self design, self control, self switching, self reproduction, and other properties that characterize forests, seas, anthropological systems, and modern societies. An energy network language is used to organize quantitative data on the parts and their exchanges with each other. Just as the parts of a radio are related to each other and to the whole system in a circuit diagram showing the flow of electric current, so an energy diagram can be constructed that illustrates the flow of energy among the populations using symbols for each component that are mathematically defined and have numerically measured magnitudes. Because energy is a common denominator for all processes, all forces and influences in the world system of food flows can be drawn and measured. When an energy network diagram is prepared, it can be simulated with electronic computing devices so that the consequences of one design feature or one external feature may be tested before some action program is attempted with a nation's food reserves.

When the relationships of world food production, consumption, and internation transfer are clarified with simple diagrams, some principles

[1] Abbreviated from a book manuscript, *Power and Survival*.

systems are found to be at the heart of the present world problems of food and population. Some action programs of food giveaway, for example, turn out to be competitive to closed-loop-reward flows that are required for stability. Understanding the world's food production system is essentially the same problem for the whole biosphere as understanding the natural systems that formerly predominated on the earth. Although the study of man's system in this way is new and the details worked out in only a few cases, let us consider from energy flow analysis what kinds of limitations there are on man and his programs of feeding the world.

Energy Network Diagram for a Native Cattle Keeping System

To illustrate the principles of the energy network diagram, consider in Figure 1 the pattern of food flow to man in a section of Uganda as described by Deshler (3). The parts of the system are grouped into logical compartments that contain populations of similar function and similar input-output flows of energy. The main pathways of energy flow are drawn, and their magnitudes are indicated in kilocalories per area of land per year. The storage of potential energy in each compartment is also indicated in kilocalories per area of land.

Energy flow starts with the allocation of light energy from the sun to a square meter of earth in Uganda which supplies energy for plant growth. The plants are grouped into two compartments, the natural range of mixed plants and cultivated crops. The photosynthetic conversions of food from these two groups pass next to consumers; the range production goes partly to wild consumers and partly to the cattle of the Dodo tribe, while crop production goes directly to storage for tribal man. The cattle provide protein supplement to man through meat, blood, and milk.

As required by the energy laws of the universe, a large fraction of the potential energy disperses into heat at each step as shown in Figure 1 by a heat sink symbol at each process indicating energy that is no longer available to the system. The work that is done by the sun in bringing rain, by the wild consumers, by cattle, and by man is indicated by a work symbol in another energy flow at the point where that work controls or predisposes necessary action. Note that many work actions result in small flows of energy from downstream back upstream providing the means by which downstream agents such as man and cattle can, with small but highly focused energies, stimulate flows in the main power stream that will lead to their own support. These are *reward loops* that are the key controls that permit evolution and self design of successful systems that have survival stability.

duction. Thus the diversity of animals, plants and microorganisms in the natural range system provides man a stable system of which man is a part. All net crop yields go to man. Any replacement of this system by one that used more of the natural range would (1) require the substitution of a control system at great energy cost, (2) raise the prospect of overgrazing the photosynthetic surfaces, and (3) upset the soil bases.

Small work expenditures of about three calories by man control and augment flows of much larger magnitude for grain prouction thus serving as gates so that their own work is amplified by the natural system.

The yield of protein to man is 0.06 percent of the range intake of the cattle which includes all the many stage processes of collecting sparse vegetation, putting it through the ruminant microbe systems of the stomach, and making not just organic matter, but high quality diversified proteins while refertilizing the range to further stimulate the system.

The input of rain involves a huge energy subsidy from outside the system, but its input is very irregular. In electrical networks, variable input is stabilized by introducing storage units (called pulse filters) that smooth out the energy flow. The cattle also serve as pulse filters as well as doing loopback work on the range through fertilization.

Basic Energetics and the Energy Flow Network Diagram

Let us interrupt our discussion of man's food support systems to indicate a few of the basic laws of energetics and force and illustrate the way they are represented in an energy network diagram. The basic symbols are given in Figure 2.

Everything that takes place on earth involves a flow of potential energy into dispersed heat through pathways driven by directed forces that originate from the energy storages. The essence of cause, Newtonian physics, and the laws of energetics are irrefutable on these principles. It is only recently that these laws, which were developed for simple physical systems, have been applied to the complex levels of nature's ecological system or the even more complex system of man's activities in the biosphere. The flows of energy through complex food chain pathways and through cultural economic systems follow the basic laws, and may be expressed quantitatively with the understanding that the flows in the large scale world are primarily populations of

A useful way of representing the networks of energy flows to include the limitations and requirements of the laws of energetics is through the energy network language illustrated in Figure 1. Here a pathway of potential energy flow is represented by a line; if it is inherently unidirectional and incapable of reversal, it is marked with an arrow symbol. The potential energy storages are marked with the tank symbol which indicates a source of causal force along the pathway lines. The mathematical equation that describes the relation of potential energy to storage varies and must be specified in each case. The force is in linear proportion to the storage quantity whenever the storage function is one of stacking up units of similar caloric content, a property common in ecological and large scale systems involving man.

One adheres to the second principle of energetics by drawing the network to illustrate that any process has some potential energy diverted into dispersed random motion of molecules (heat). The necessary heat flows are indicated by a downward flow into the heat sink which is symbolized with an arrow into the ground. The first law of energetics is adhered to by having all inflows balance outflows either into storages, into the heat ground, or into exports. The many kinds of work which are done against frictional forces are illustrated by arrows that flow from the potential energy storage tanks into the heat sink.

Where a work process is necessary to facilitate a second flow, the arrow crosses the second flow representing the work done on it. For example, the work of people on a farm facilitates the flow of light energy into food storage, although the energy of the workers' food went into metabolic heat during the time of work. A work flow which facilitates a second flow in proportion to its activity is mathematically a product function and thus is indicated with a box containing an "X." Such a box indicates a limiting factor process and the work is identifiable as a control gate on the flow. Many of these secondary flows derive their driving potential energies from a point downstream and are thus multiplicative reward feedbacks.

Odum and Pinkerton (11) showed that whenever an energy flow is transformed and restored into a tank at the optimum rate for maximum energy storage, 50 percent of it must go into the heat drain. Whenever a flow must cross an energy barrier, the energy carrier must increase in potential energy temporarily and hence must lose 50 percent to the heat sink (Figure 2D).

Each symbol used has a mathematical definition and for each symbol, there is a graph of functional response of output with input variation. These response graphs are known in various branches of science under different names so that individuals using the relationship in one branch of science may be unaware that the same law is in independent usage in another branch. For example, the hyperbolic curve of limiting factor control, where there is a loop of necessary material being cycled and reused, is given different names in systems used in biochemistry, photosynthetic kinetics, photometry, economics, and chemical engineering. In Figure 1, each of the loopbacks of necessary work, if isolated, constitutes one of these hyperbolic responses.

Since each symbol represents something definite mathematically, the network diagram is also a statement of the computer program that has to be written for simulation in digital computers.

When the response of the groups of connected parts is to be studied, one may also model the system with electrical units on the passive principle where the flow of the electrical current simulates the flow of carbon, and heat energy losses in the real system are simulated by heat losses in the electrical system. The voltage simulates potential energy. There is an electrical unit for each of the symbols which are shown in Figure 2. For example, if the system in Figure 1 is constructed in electrical hardware, one may vary the input energy pulse and determine the pattern of arrival of energy to man in the course of the year. If something is omitted in drawing the circuit, the response will differ from that of the real system so that one may add features, gradually developing the model until it does indeed simulate the real system. Then one may use it for predicting responses to new situations. The importance of considering whole system functions together may be illustrated by the controversy over the utility and requirements of the sacred cow in India.

Sacred Cattle and Rice Production in Monsoon Climates

Another example of a primitive agricultural system of man and nature is provided by the system of rice and cattle in India and in other monsoon climates where the severity of the dry season essentially forces all systems of vegetation, whether controlled by man or not, to recommence each year. As shown in Figure 3, there is a flow of energy through rice and some grass, man, and the sacred cattle (work animals) with the loopback circuits of work control similar to those described in the Uganda example in Figure 1. Harris (7) opposes

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[illegible] serve as a source of critical protein, and especially facilitate mineral cycling and work on the plots necessary for a fast start on crop production when the wet monsoon begins. The energy network diagram (Figure 3) supports these contentions by showing the necessary reward loops, the work diversity in building protein and the storage function required where rain is irregular. Those who advocate removal of the sacred cows needed under the present agricultural system refer to the simple principle of shortening the food chain to save energy. In this case, a little knowledge about one process without understanding the complete system may be producing recommendations that endanger millions by upsetting a self-supporting system. Harris (7) cites Gandhi's comment that cows are sacred because they are necessary. The more general principle may be that religion is the program of energy control necessary for survival encoded in behavioral language.

Comparison of the Energetics of Primitive and Modern Food Production Systems

In elementary school textbooks, the expanding role of man on earth is often presented in terms of the evolution of his food producing systems and how they increased the number of people that it was possible to feed on a given area of land. First, man obtained food by hunting, fishing, and gathering fruits of the natural forests. Then came primitive agriculture in which man's labors, domestic animals, and crops are substituted for part of the natural environmental system of plants and animals. Finally, industrial man's agriculture is largely accomplished with aid of machines, chemicals, special varieties of plants and livestock and various kinds of industrial aids. The bulk of the persons who work to support the farming process are in cities far away from the farm but they are just as necessary to the farm as the man riding the tractor. Consider the network diagram for these three levels of complexity of food producing systems.

In Figure 4A is an energy diagram of the populations of a complex natural system in which man is supported by many converging food flows. Examples are the pigmy in the rain forest of the Congo and the Amazon Indian in the American Rain Forest. Many species at the various stages of photosynethetic production and consumption form one of nature's complex networks of loops, controls, and interactions most of which are still only slightly understood. The population density of man was about one person per square mile. The energy [illegible] presence may have been important in the stability mechanisms because his effort was focused on specific components of the system. The complex of populations suggested in Figure 4A performed many work functions necessary for survival of man and the whole system. This situation is summarized in Figure 4B which emphasizes that all the necessary services such as receiving energy, cycling minerals, preventing epidemics, developing soil structure, controlling microclimate and light levels were done with feedback of small energies from the system's own resources. Man was the child under an umbrella of the stable forest system. Remnants of such systems still exist in the tropical forest belts.

The second level of complexity is the agriculture that is based largely on solar energy which was described in the examples from Uganda in Figure 1 and India in Figure 3. In these systems, man controlled a larger part of the energy budget by acting as a control gate on crops and cattle. The sharp fluctuations of rainfall required and permitted man to have a larger influence in comparison to his role in the forest from where his culture may have spread. In both systems, however, he was supported entirely from solar energy; the necessary work processes being performed directly or indirectly from energy from the sun. Man's role was limited by the amount of potential energy he could divert without weakening the system and permitting competing alternatives to displace the system or man himself. His activities were limited to those which would guide, reinforce, and improve the total power flows. Man's inputs in these semi-arid regions provided a measure of stability for him in an environment in which there were large seasonal variations in plant production.

The third level of complexity is illustrated in Figure 5. This is an entirely new system in which vast new flows of potential energy are made available from fossil fuels so that all the things that once had to be done as drains from the central budget may now be done with outside fuel. The original flow may produce vastly increased yields because the necessary work is being done on a different budget. This diagram shows how increases in agricultural yields have been achieved in modern times. Ninety-seven percent of farm production in the United States is exported from the farms for consumption in the cities by urban workers who are really farm workers but don't know it. Special new varieties of plants and animals have been developed which allow much of the food to be routed into net food storage rather than into disease prevention, protection, and other aspects of self work in the old system.

when in fact the apparent improvement has been due to use of an energy subsidy. There is little wonder that improved varieties sent to underdeveloped countries fail without the accompanying network of energy subsidies. One might as well send television tubes to a culture that has only crystal radios. *One must export whole systems, not a few parts.*

Energy Cost of High Quality Nutrition

One of the highest work costs in terms of energy is involved in diversifying food flows from a simple fuel to a variety of nutritional components sufficient to support man; a diet complete with amino acids, vitamins, and other necessary chemical compounds. The cost of 10 qualitatively different flows is much greater than the cost of the same organic mass produced in one form since all the specialized machinery and enzyme systems must be supported in each flow and many of the special molecules are produced through long chains of biochemical action. The advantages of mass production are lost. The diversity of species in nature's original habitats provided man with a broad nutritional base when he was a small part of the system. Later, when his agriculture concentrated on a few plants and replaced the natural system with a greater net yield of food, his population density increased but some of the energy was converted to increased yield at the expense of the former system's diversification. Special components were developed to supply the nutritional diversity either through transportation of products produced elsewhere or through local diversification systems such as the cattle in Figures 1 and 3.

A vegetarian may have a good nutrition provided he goes to the extra work and expense of gathering and combining enough kinds of plant foods to satisfy his dietary requirements. As an alternative he can eat more expensive meat products that provide a nutrition that is closer to his need. In meat, the combining has already been achieved by the integrating action of the animals and their systems of work and sustenance.

In natural communities, there is a convergance of separate food chains, each of which begins with a different plant, so that many higher animals are concentrations of the diversified nutritive composition required by man. The energy cost of such concentrating and combining may be inferred from the maximum yields of meat observed in some systems of food flow from plants to dependent larger animals (Figures 1 and 4). Those who claim that a calorie of diversified protein supplement can be made as cheaply as can a calorie of car-

subsidies of collection, combination and industrial aids from fossil fuel.

The Carrying Capacity for Man

In wildlife management, one sometimes uses the phrase "carrying capacity" to describe the ability of a grassland range to support a population of animals or birds. The carrying capacity is that population level which is compatible with the entire network of supporting plants, the mineral cycles, and especially the maintenance of the essential elements for effective support such as soil, water levels, diversity, and reserves that protect all parts against fluctuations. It is a population level for long-range survival.

The essence of the problem of food production for the world is in the question: "What is the carrying capacity of the earth's surface for man?" The same question arises in the discussions of man in space. What is the area of plant surface necessary to support man on solar energy? How much area is needed when solar energy is supplemented by some fuel energy from earth? The biosphere is really an overgrown space capsule and the questions about carrying capacity are similar. For projected levels of energy supplement from coal, oil, and nuclear power what is the carrying capacity of the earth?

This has been a much confused subject. Several years ago some extreme estimates of carrying capacities were made by those attempting to develop algal systems for man in space. The carrying capacity for a man was said to be half of one square meter. This was based not only on erroneous figures of photosynthetic efficiency but also on yields of laboratory algal systems which were heavily supported by fossil fuel energies through research appropriations, but the efficiencies were computed without the work of the researchers and industrial support even being mentioned.

Figure 6A and Figure 6B are network diagrams for an algal production system of pilot plant size. In Figure 6A all of the energy inputs are drawn including the sun and the work flows drawn from the industrial culture. As much fuel energy is apparently required as is produced as food. In Figure 6B, the energy subsidies are omitted and only the sun's energy is shown. This was the approach taken by the proponents of the extreme efficiency of algal culture and is very misleading. Often intensified agriculture is presented in the same way without adding the energy inputs of the many subsidies of city work and industrial inputs.

Calculations of carrying capacity for man must include all the work flows that provide stability, reserves, protection, organization, yield, special nutrition, recycling, and the controls necessary to the complex systems in which he was imbedded (Figure 4A). Because of his original specialization as a mobile control unit and because his genetic inheritance of nutritional requirements has remained relatively stable, he still requires the food contributions of many chemical systems. He may live at the apex of a natural network of hundreds of species of plants and animals; he may keep a symbiotic nutrition factory such as cattle which utilize the ruminant stomachs containing many species of microorganisms to develop the complex nutritive convergence; or he may set up an economic system for convergence of a complex farm and grocery distribution system. Our modern system is based on the latter two alternatives. Disastrous consequences follow when workable systems of the first two types are discarded before an adequate system of the latter type is developed.

Summarizing, we conclude that the carrying capacity of man is determined by the energy source utilized to do the work necessary for the system to survive. When energy inputs are limited to those provided by the sun, the carrying capacity of men is apparently on the order of one individual per acre as in the rice-cattle system (Figure 3). Much greater densities are possible where the energy inputs are concentrated flows as when fossil fuels are used.

A Diagram for Classification of Countries, Takeoff

Industrialized civilizations support dense populations because their larger carrying capacity is based on the continued flow of concentrated potential energy derived from fossil fuels. Other sources such as nuclear energy may become important in the future. The present uneven distribution of wealth is really an uneven distribution in the application of fossil fuels. Primitive areas with rich oil deopsits can only sell the fuel since they have no network of advanced technology capable of accepting the subsidy directly.

For consideration of problems of world food suply, the diagram in Figure 7 may be used to scale countries ranging from those rich in in power to those that still survive on primitive food gathering systems. The vertical axis of the graph shows the net yield of food to man; the horizontal axis marks the rate of subsidy of concentrated potential energy from non-solar energy sources. The horizontal line at the top of the figure marks a production of 50,000 K cal/m²/year, which represents the maximum gross photosynthetic rates of natural systems. The gross fixation of solar energy in photosynthesis (before one subtracts nature's use of its production in self-sustaining work processes) describes an upper limit which agricultural production approaches but fuel supplementation, production never exceeds the maximum gro photosynthesis rate where light energy is the only limiting fact Man may improve gross production with fossil fuels only by ove coming limitations other than light energy availability such as wat or mineral shortages (see Figure 5). In Figure 7, we may draw the li corresponding to maximum gross photosynthesis in the unlimit natural system, or in the best agricultural system at about 150 K c of organic matter fixed/m²/day in growing seasons. Several leve of energy subsidy are indicated in Figure 7. The system of man in t deep forest described in Figure 4 is plotted in the lower left corn Just above this is the farming system of man and nature without fos fuel support as in Figures 1 and 3. Passing upward to the right, o finds present patterns of modern grain agriculture with considerat fossil fuel subsidy that serves to remove limiting factors and subs tute for some of the self-controlling functions. These increases yields that have been obtained by modern agriculture have been d scribed as a yield takeoff by Brown (2) and are proportional to t auxiliary fossil fuel energy. The algal pilot plant (Figure 6) is fou in the uper right of the diagram where the subsidy of concentrat energy is much higher than for agriculture.

The diagram shows the role of auxiliary fossil fuels and that m is eating potatoes indirectly made from oil. The progress made providing food for the world's population results mainly from i provements in conversion of existing concentrated fuels into edit form by substituting outside work for self-maintenance in the so agricultural systems.

If one locates the position of a country on this diagram, one is loca ing its degree of commercial complexity. One thus establishes t amount of auxiliary energy subsidy that can be utilized and the ki of system that can be immediately recommended.

Food Direct From Fuel

If highly concentrated, fuel-rich agriculture is really providing potatoes where main system-support energies come from oil, one na urally asks the question if direct conversion of oil to food in chemic or microbiologically mediated industries would not provide the san or better yields. Since fuel-enriched agriculture is subsidized by natur light, it may continue to out-complete food production only from o Figure 8 is the results of an attempt to draw an energy diagram f direct conversion of fuel to food by microbial and chemical mean The energy source is petroleum and the control system is also from t fossil fuel-based industry. As physical laws require, energy transfo in nature generally convert around 10 percent of their food input to protoplasm. Where system work is being subsidized as in egg, milk, and meat production, efficiencies approach the theoretical 50 percent at which maximum power delivery occurs. Where the organic substrate requires more energy for processing, efficiencies may be less. The diagram in Figure 8 reflects low yields in which energy input is approximately ten times output. Compare this with the increased yields obtained by using fossil fuel to overcome various limiting factors in agricultural systems (Figure 7) in which output is equivalent to energy input at the higher production levels. So long as areas of the world have agriculture with limiting factors that can be attacked with fossil fuel work supplements, one may achieve such a one to one conversion of fuels to food by substituting fuel based work for the loopback work in the solar-based food producing systems.

Loop Selection Principle and Food Give-Away

One of the principles emerging from ecological energy studies is the positive feedback loop by which a downstream recipient of potential energy rewards its source through the passage of a neccessary material, currency, or work back upstream. Thus the animals in a balanced system feed the phosphates, nitrates, and other requirements for plant growth back to plants in reward loops so that a plant which is in a food chain that regenerates nutrients in the form it needs is reinforced and the system continues. Species whose work efforts are not reinforced are quickly eliminated since they run out of raw materials or energy. They must be connected to input-output flows to survive.

Man's pollution production problem is related to his food production problem since there is an energy block when the wastes of civilization's metabolism do not get back into the fertilization of agriculture.

In man's complex system, he has arranged a feedback currency that is even more flexible than the geochemical recycling systems of natural ecosystems. He has invented money which is fed back in reward for work done. The action of money moving in opposite direction from the energy flows is indicated with the economic transactor symbol (Figure 2). The money flow of each population is thus looped to at least one other population, and by interconnecting loops the economic system provides rewards for each and a means by which productive circuit designs are rewarded by reuse. Reinforced and reused loops inforced. The "design" of systems in nature has occurred through this evolutionary mechanism. The networks of man are doing the same thing. An understanding of the role of closed loop selection allows us to use the principle to develop systems of feeding the world. Failure to understand the closed loop principle has been responsible for many failures where some system of food production was started but not continued.

Examples of the work loops that form reward controls in long-surviving successful systems of man and nature were cited in Figures 1, 3 and 4. Similar loops are required for system stability where the food systems of two or more countries are being joined. The serious problems of how to send food to India and Vietnam are examples. The food chains must have loops of work to be stable and surviving. Several ways of sending food from a food-rich country like the United States to an underdeveloped country are diagrammed in Figure 9 energy circuits. The give-away of food is indicated at B without a work loop, a system which will be eliminated either by decision or by loss of the effectiveness of participating agriculture of both countries.

Even the sale of food at market price by an industrialized country destroys old workable systems. The rise in standard of living that goes with fuel injections into an economy produces a lower standard of living among subsistence farmers and forces them to join the complex developing system. As standards rise, the amount paid to individuals for work increases. As a result, the cost of products including service work goes up. So long as an individual's work is part of the main system, payments increase with costs. However, the subsistence farmer who produces his own food and needs to purchase a few things with his small surplus cannot get them because prices have increased disproportionately to his production, principally because food is being produced at less cost elsewhere using fossil fuels. Unless a farmer produces a considerable cash crop surplus, there is no way for him to take advantage of the enriched main culture. His relative position is reduced. The cheaper food becomes anywhere in the world, the more the subsistence farmer loses.

Energetics of Cash Crop Monoculture Versus Fuel Subsidized Agriculture

The production of highly-specialized cash crops by developing countries presents a special problem in their relationships with developed nations. The rich countries, if they cannot or have not learned to manu-

... may be smarter economy for developing countries to produce the complex product such as coffee, tea, chocolate, and spices for export and use the funds obtained to buy less exotic foodstuffs from countries that have fossil fuel subsidized agriculture. This is the relationship between many tropical countries and the United States at the present time. The energy diagram for such a system resembles part D in Figure 9 and has a reward loop.

The hazard inherent in a national economy based on monocultural production of a specialized commodity is its collapse if too much production is arranged. With the tropical countries disorganized and competing for markets for specialized products from plantations which require long-term capital investments, over-production has produced disastrous results. As world-wide food storages develop and cheap food exports from mass producing countries dwindle, the pressure on all nations to produce large quantities of basic foodstuffs will return. A lower standard of living will result unless food production everywhere receives some fossil fuel injection. The sooner notice goes out that food subsidies from rich mass production lines cannot be permanent, the sooner the change in plantings will be made. Will there be enough know-how remaining in specialty crop-producing countries to reinstitute basic food-producing agriculture?

Presently, the exportation of cheap food by developed nations is causing severe poverty among the non-industrial producers of food which further reduces the world food production capacity. As the rewards for farming decline, there is little incentive for farmers to make the kind of investments necessary for injecting fossil fuels into the network. The more low cost or free food that flows out from the fossil fuel rich centers, the more the developing countries are driven to drop subsistence farming and substitute specialty cash products or work services desired by the industrialized system. Little wonder that economic curtains of all kinds are put up to prevent lesser developed economies from becoming slave systems in which food producing capabilities are permanently lost (Figure 9A). Because the people in the towns can buy cheap food from abroad, they desert their own market production systems and become permanently dependent on foreign food. If domestic production is eliminated in this fashion and world food shortages develop, the resulting increase in prices will cause a sharp drop in living standards in towns whose progress was based on fossil fuel expenditures in rich countries far away.

for the world network of rich countries and do it just as cheaply as those countries can. If it enjoys no advantage due to location, climate, or resources, it must import a full-fledged fossil-fuel based activity if it is to compete, perhaps gaining some aid from cheap labor. Since the injection of fossil fuels into tropical agricultural systems has not been worked out for many food crops, these countries find it easier to become specialized industrial arms of the rich countries than to develop a food production economy. The patterns of tropical development so far have been of this nature.

Imperatives in Design of World Food Systems

If fossil fuels are the real means for feeding the world above the present and primitive carrying capacities, then the principal political issue is how to introduce a stable fossil fuel subsidy into the food networks of underdeveloped regions. There are several possibilities.

1. Suppose fossil fuels and nuclear power are first passed through the advanced cultures for food manufacture, the food being exported as a gift (Figure 9B). Such a system seems to leave control of the energies with the advanced cultures, but it is not a closed loop system and does not receive the reward reinforcement necessary to form a permanent structure. The donation of food without provision for loop-back reward has a negative effect on the producing system, and the receiving system develops larger and larger populations whose unchanneled energies must go either into random and hence destructive activities, or be focused on some group action, that may have further negative effect on the donor or itself. To make such a food donation flow work, the circuit must be closed with a loopback of work, currency, or materials sufficient to make that a more stable loop than alternative ones (Figure 9D). The closing of such economic loops from rich countries to underdeveloped ones was the raw materials-manufactured goods production system of the colonial era. Unfortunately, inequities in distribution of wealth and other issues made that system unpopular and curtailed its further use.

2. An alternative way to develop food production based on oil is to design whole closed loop systems in the rich countries and export the whole loop process (Figure 9C). No food is exported, but the initial equipment and educational investments to start the loop within the less developed countries are exported along with arrangements for fossil fuel imports. A closed self-completing loop within a nation would

... in the loop, food goes into feeding the persons responsible for the work of the food augmenting process.

Such a development is not without hazard to the altruistic donor country since it involves setting up a fuel competitor which in effect dilutes the relative power of the donor in the world.

3. The third alternative is to do nothing, leaving the less developed countries and their burgeoning populations to their own fates (Figure 9A). Confronted with starvation and desperation, some form of totalitarianism could evolve which would set up its crash programs without the essence of democracy and peaceful development. Military ambitions may take the helm at considerable hazard to present democracies.

4. A fourth alternative involves a single, fuel-based economic system of food production, closed loops, and a one-world economy. No part is in competition if it is locked with direct and indirect reinforcing and stable currency loops. Since larger systems tend to dominate smaller ones, there is a tendency toward evolution of a one-world system. This solution may evolve, but cannot be initiated through the unilateral action of rich countries that control only limited parts of the earth's populations.

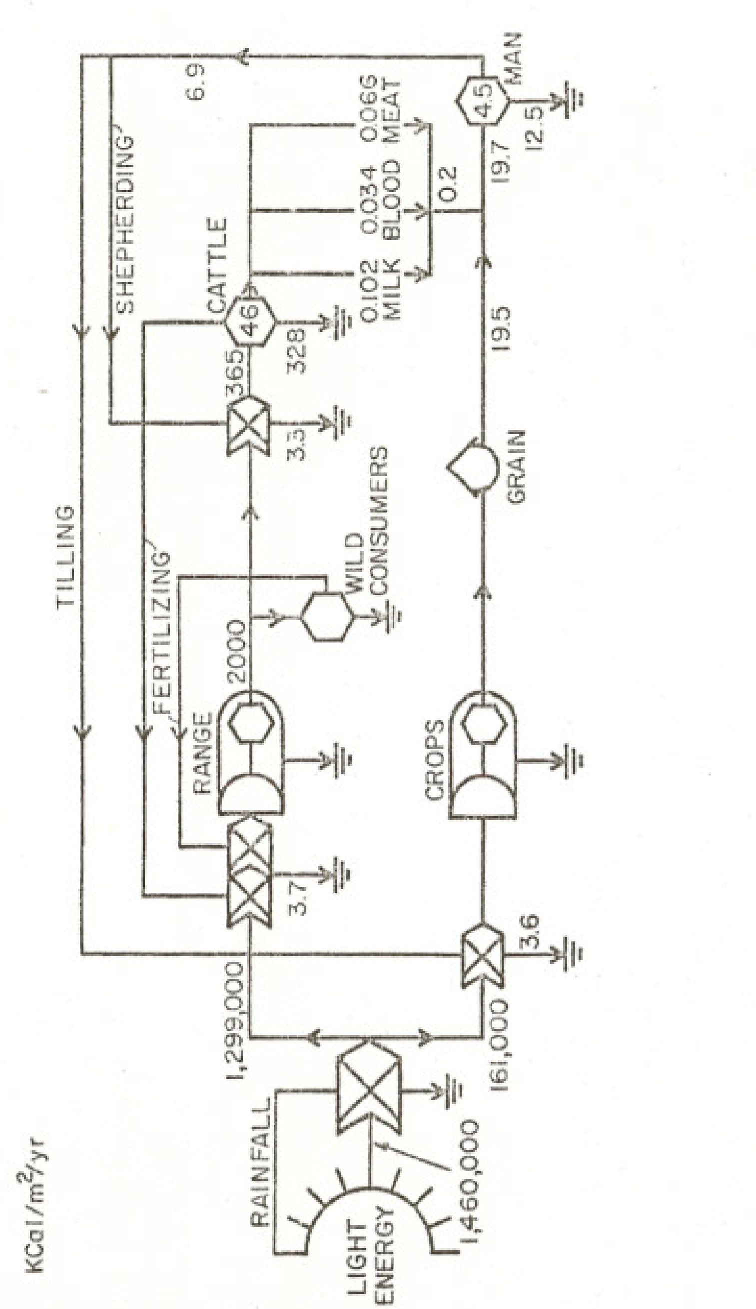
Summary

The design of a system of world food production and consumption can be aided by consideration of energy flow networks that show some hidden bases for man's progress and point up some delusions regarding the capacity of science to develop means for feeding growing populations.

For the future contingency of continuing increase of energy flows from fossil and nuclear fuels, maximum food production may be expected if our auxiliary energies are used as controls to overcome limiting factors wherever they exist in solar energy based agriculture rather than as direct substitutions for agriculture. To be effective, aid to new areas must introduce whole, self-contained systems that permit the effective use of auxiliary energies.

For the future contingency of failing energy flows from fossil and nuclear sources, a national program of research is needed now to plan for survival of man within simpler systems that will be induced by the reduction of our energy base. If we gain knowledge now of the operation of networks of nature and man that will support him in lesser systems to provide yields for man. For future need, conservation of some of the workable primitive systems of man and nature is essential.

For either contingency, the ability of a nation to hold leadership will depend upon its ability to control flows of food and fuel.



in Uganda. Food is derived from grains, meat, blood, and milk. Animals serve as a storage filter smoothing the pulse and as a nutrition convergence. (Based on an account by Deshler, 1965 (3).) Numbers are Kilo calories per square meter per year. There are 70 people per square mile. Dry weights were converted to kilo calories using 4.5 K-cal/gm.

The basic net production of plant material for dry regions is given by Walter, 1954 (reproduced in Odum, E. P., p. 403(10)) as a function of rainfall. Using 21 inches of rainfall and Walter's diagram, one is able to determine that 500 g. of dry plant material matter are produced per square meter of land each year. As 1 acre is cultivated per person and there are 70 persons per square mile, one finds that 11 percent of the natural yield area is pre-empted by crops.

At 4.5 cattle per person and 560 pounds per cow, 33 percent of which is dry weight excluding ash and water, one is able to determine that 10.2 g of animal weight is produced per square meter.

Seventy people per square mile at 150 pounds per person of which 25 percent is dry matter is equivalent to 1.0 grams per square meter.

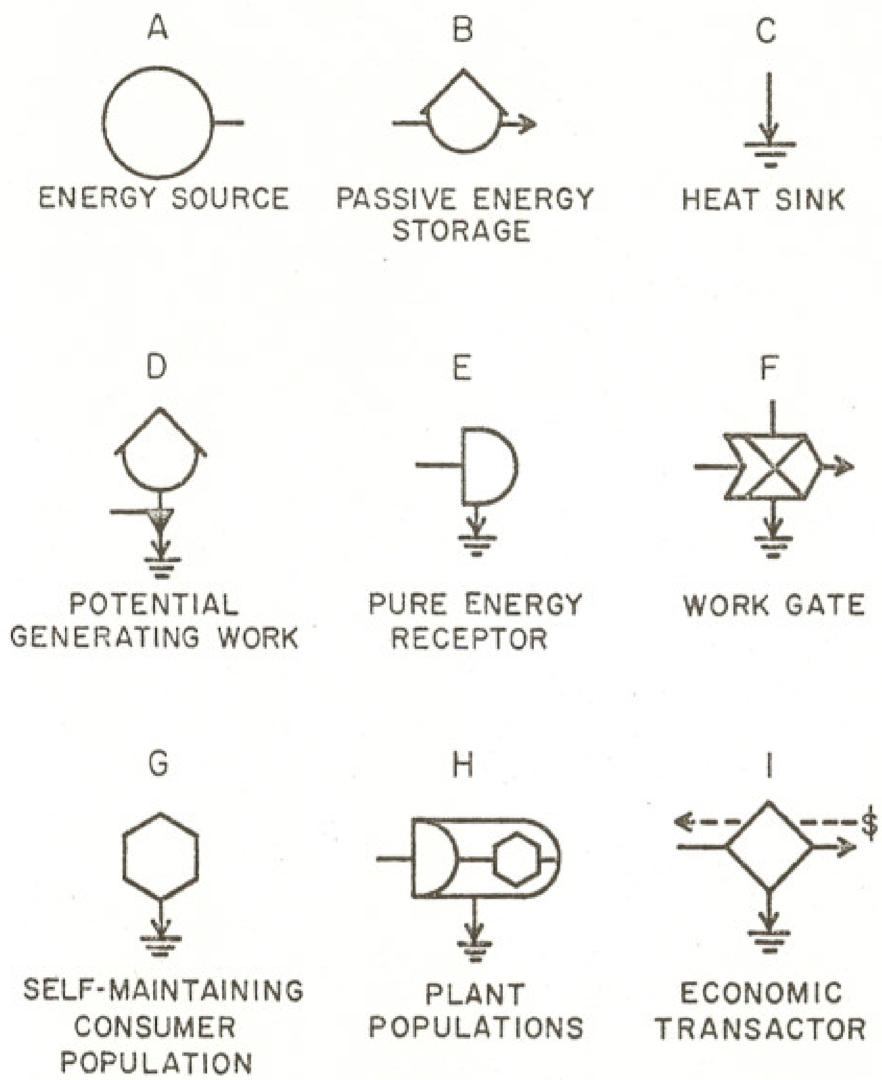
By integrating the area under curves given for monthly consumption of milk, blood, and meat, one obtains an annual caloric yield per person from the cattle of 3800 cal of milk, 2450 cal of meat, and 1265 cal of blood which provides the per area data in the figure. Calorie requirement per person is given as 2000 cal/person/day or 19.7 cal per square meter per year. The milk, meat, and blood supply only 0.2 of this requirement so crop intake is the remaining 19.5, a net yield much less than the net yield of vegetation of the natural range.

Total insolation in this area just above the equator is about 4000-cal/cm²/day based on solar radiation maps for winter and summer for Africa given by Drummond (4).

The work of men in tending the crops and cattle can be taken as a percent of their time involved in this activity (primarily the daylight hours). As the culture is intimately involved with the cattle, one may assume that ⅙ of the daily metabolism of man is devoted to management of the cattle and the same amount is used for production of crops. The rationale for this procedure is that the maintenance requirements of man during his work are necessary to that work. The metabolic activities of 650 pound steers estimated from Kleiber (8) require 8000 Kcal per day or 365 Kcal/m²/yr.

Some fraction of the cow's time and metabolism goes into refertilizing the range on which it grazes thus reinforcing and maintaining its loop. Part of a cow's day is spent on the move, and parts of its organ systems are involved in the nutrient regeneration system. One-tenth of its metabolism was taken as its work contribution to vegetation stimulation.

This system does not involve money and the economic transactor symbol does not appear.



... requires that one specify the energ type and whether the source is constant force, constant flux, or follows som other delivery function.

B. When potential energy is stored without transformation and then remove the simple tank symbol is used. For example moving grain into a warehouse an out involves no transformation of the chemical potential energy of the grai although some work must be done in the process utilizing energy from other flows

C. This symbol shows the dispersion of potential energy into heat no longe usable for work processes by the system. This heat dispersal is required fo any spontaneous process and irreversible entropy increases result.

D. When potential energy is stored with a transformation, the second energ law requires dispersal of part of it into heat. At optimum rates of potentia energy storage, 50 percent is dispersed.

E. When incoming pure energy in the form of light or wave trains withou matter flow is received and transformed into the potential energy associate with matter as in photosynthesis or in conversion of tidal energy, the recepto symbol is used. Heat energy is dispersed as in symbol D.

F. The work-gate symbol shows the work done by one flow against friction or in acceleration and deceleration of work at rates that aid a second energy flow to cross an energy barrier. Work done in this manner has mass actior kinetics, serves as a limiting factor, is a hyperbolic gate, and makes possible loops and hidden energy subsidies capable of system control. Work which induces a secondary energy flow increases the conductivity of the second circuit, and thus is mathematically a multiplier.

G. The hexagonal shaped symbol with heat sink drain is used for consumer populations which have the combined properties of symbol D for self storage and one or more work gates as part of their self maintenance system, including at least one work gate looped to an upstream circuit facilitation the introduction of fuel energy. This symbol mathematically has a logistic (autocatalytic) input-output function.

H. Plant populations are a combination of the functions of the energy receptor symbol E and the self-maintaining consumer symbol G.

I. The economic transactor symbol is used in human systems where economic transactions provide a low energy flow of symbols (money) in a direction opposite to the energy flow and in proportion to the work or potential energy flow. The economic transactor is one of the system control devices. The dashed line shows the flow of money according to the price-energy flow ratio. In energy diagramming, the dashed line can be omitted.

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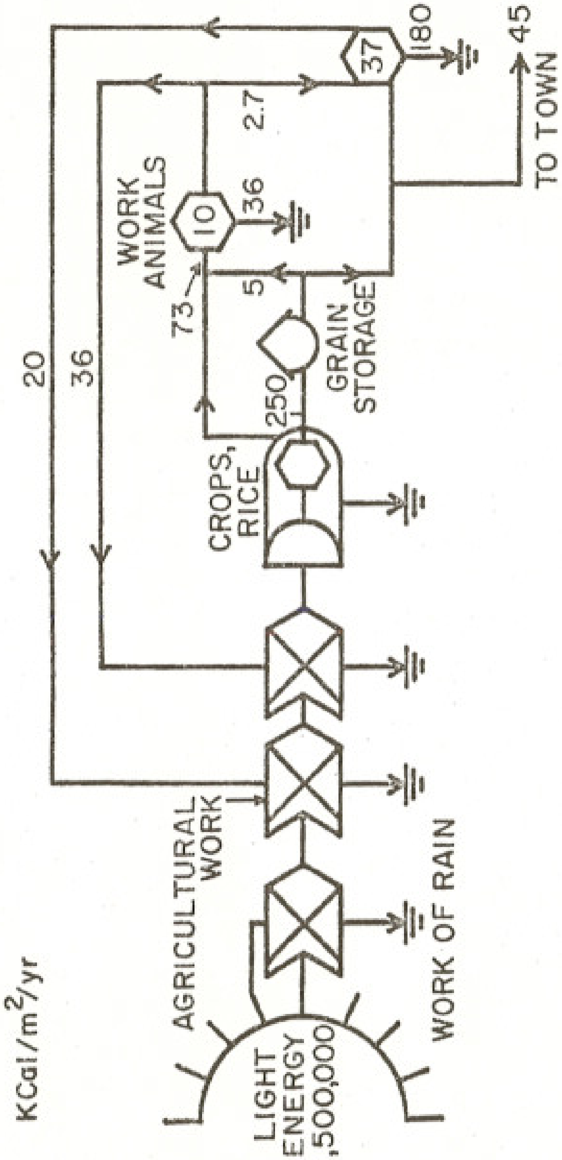
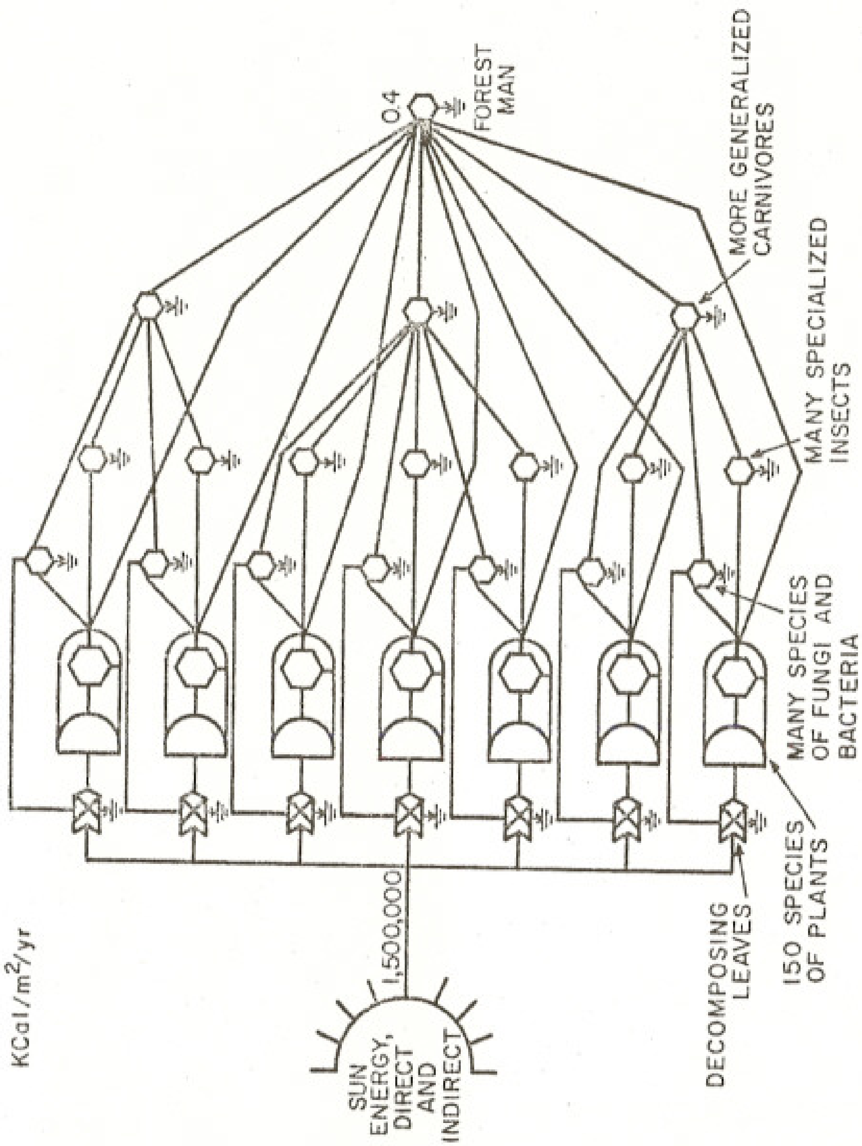
Monsoon agriculture in India



systems in a climate such as India's has a sharp seasonal pulse that prevents more diverse systems from exc the simple one by competitive invasion. Data are based on tropical populations of 610 persons per square mile. Indian grain yields averag Kg/acre/yr. [Brown, (2)]. One farm animal is shown for each 10 pe One-third of the food calories of the cattle remain in feces. One-half of a metabolism is considered to be used for work and faecal fertilization animal protein intake for India is about six grams/person per day. [Brown, From FAO data, 2 percent of the food crop is fed to animals. Animal metab is 8000 K cal/day [Kleiber, (8)]. Farm work occupies 0.1 of the total man- of the population.

... the rain forest system



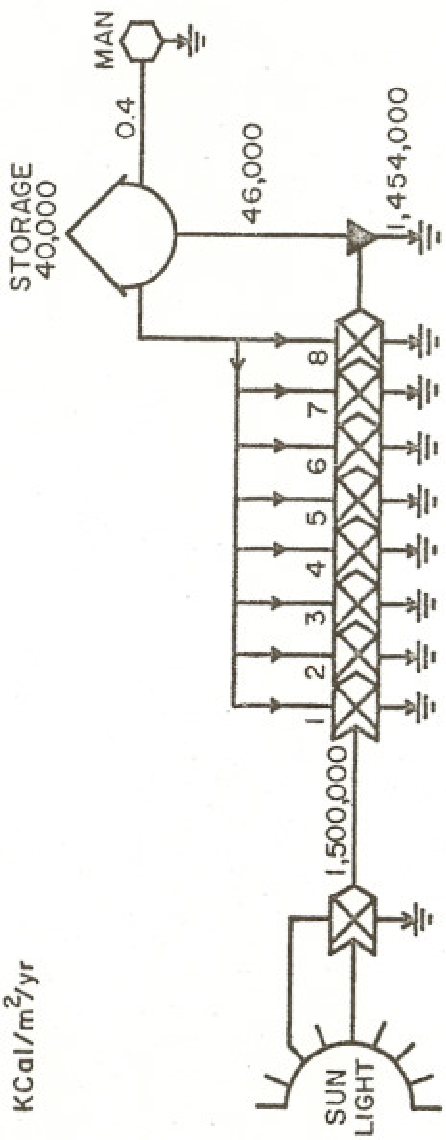
This is the kind of network one has with a complex natural ecological sy with many species. Such systems are found where the climate does not ha sharp pulse in drought, temperature, or other factors that force the syste start over each year. Man is found in low densities of about one per square in many such systems; examples are the Indian in the rain forest of the Ama the rain forest pigmy of the Congo, and the aboriginal peoples of Austr Hagen (6) gives a population in 1940 of 1.4 persons per square mile for the Am basin, including the towns.

Turnbull (12) gives a population of 40,000 pigmies for a rain forest are 50,000 square miles, or 0.8 person/square miles.

Birdsell (1) finds aboriginal populations in Australia range in dens from 550 persons per 600 square miles in villages in high rainfall areas (to 550 persons per 40,000 square miles in dry central areas.

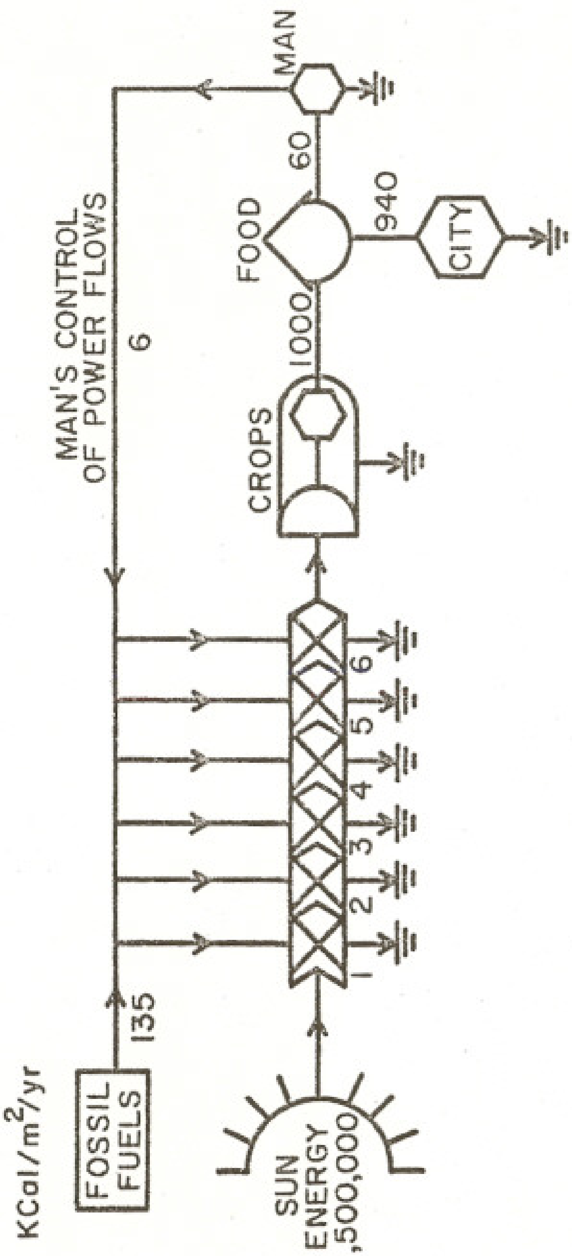
Rain forest gross photosynthesis at El Verde, Puerto Rico is 32 grams of matter/m²/day.

Rain forest system with components grouped



See Figure 3A for the type of network for which all the details are rarely known. The multiple species network of food chains and mineral regeneration routes accomplish the following work flows: (1) Regenerate plant materials; (2) provide epidemic protection with special biochemical substances in each plant species; (3) provide limit on any one microorganism or insect species by generalized carnivores and omnivores; (4) provide continuous chlorophyll receptors for maximum use of light; (5) provide stable programs of fruiting and other reproduction; (6) gather and converge specialized plant nutrition into organic constitution of higher organism meat; (7) provide shade to control ground invasion; (8) maintain soil structure with organic matter, burrowing animals, roots and microbes; (9) provide auxiliary energies from action of winds, rain, and other flows of the biosphere contributing to system function.

Fuel subsidized industrial agriculture



Man in a United States system of industrialized, high yield agriculture wh
energetic inputs include some of the vast flows of fossil fuels which replace
work formerly done by man, his animals, and the network of animals and pla
in which he was formerly nursed. Work flows include: (1) Mechanized
commercial preparation of seed and planting replacing natural dispers
systems; (2) fertilizer increments which replace mineral re-cycling syste
(3) chemical and power weeding replacing the woody maintenance of a shad
system; (4) soil preparation and treatment to replace the forest soil-build
processes; (5) insecticides and fungicides which replace the system of chemi
diversity and carnivores for preventing epidemic grazing or disease; (6) devel
ment of varieties which are capable of passing on the savings in work to
food storages; new varieties are developed as disease types appear, thus provid
the genetic selection formerly arranged by the forest evolution and che
selection system. One hundred seventy persons per square mile support 32 x t
number in cities. The level of United States grain production is about 1
Kcal/m²/yr. [Brown, (2).] The fuel subsidy is calculated using 10^4 Kcal/$.
production yields $60 per acre per year in United States production and if
costs were 90 percent of the gross, then $54 per acre was the measure of use
materials and services from the industrialized culture. This becomes 54 x
Kcal per acre or 135 Kcal/m²/yr.

Algal pilot plant with subsidies included

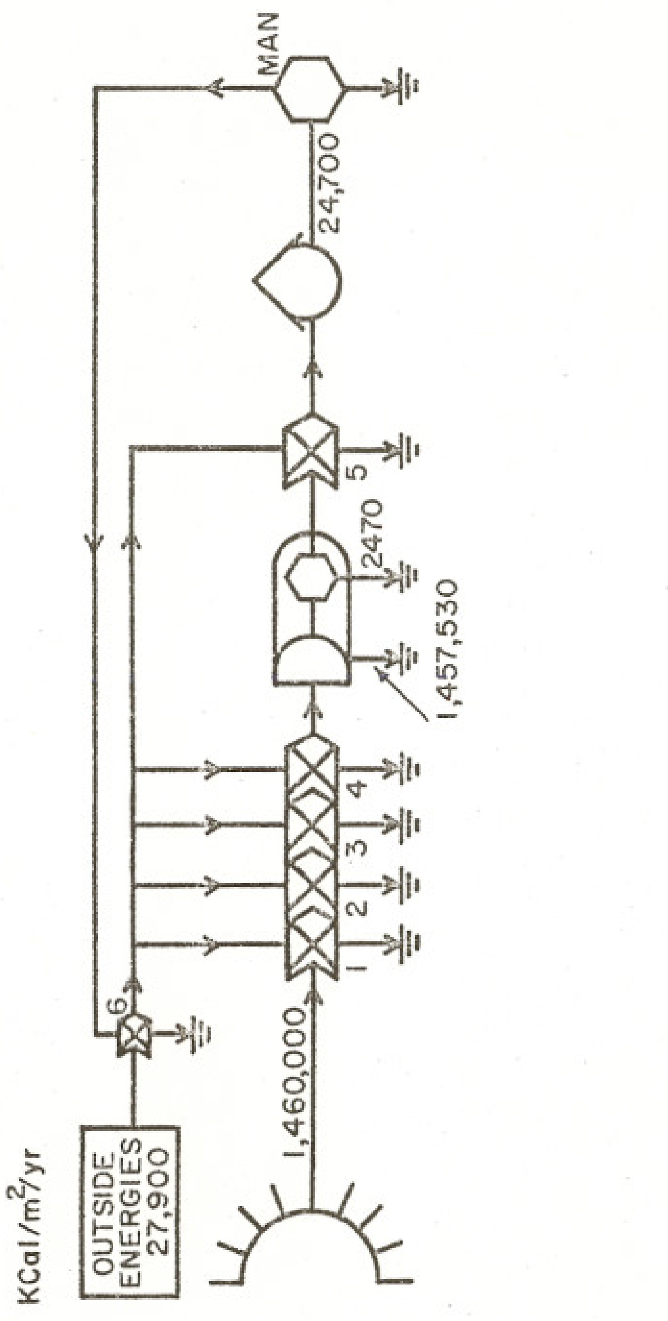


Diagram of the flows per square meter per year which were actually involved in algal pilot plants. Work processes: (1) Mineral input which replaces natural recycling systems; (2) structure of tanks and tubes that replaced natural mixing and adaptations for moving cells relative to medium; (3) energy for pumping and stirring replacing the natural wind, wave, and current systems; (4) carbon dioxide injections replacing the respiratory feedback system; (5) energy for concentrating and drying algae replacing the gatherers and concentrators of the natural food chains; (6) control valves operated by man replacing the built-in control network of the larger species.

Algal pilot plant without subsidies shown

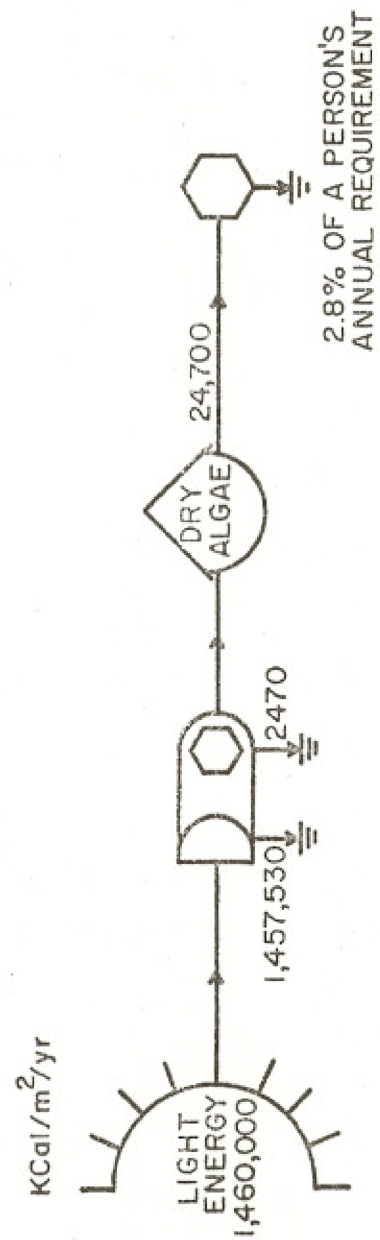
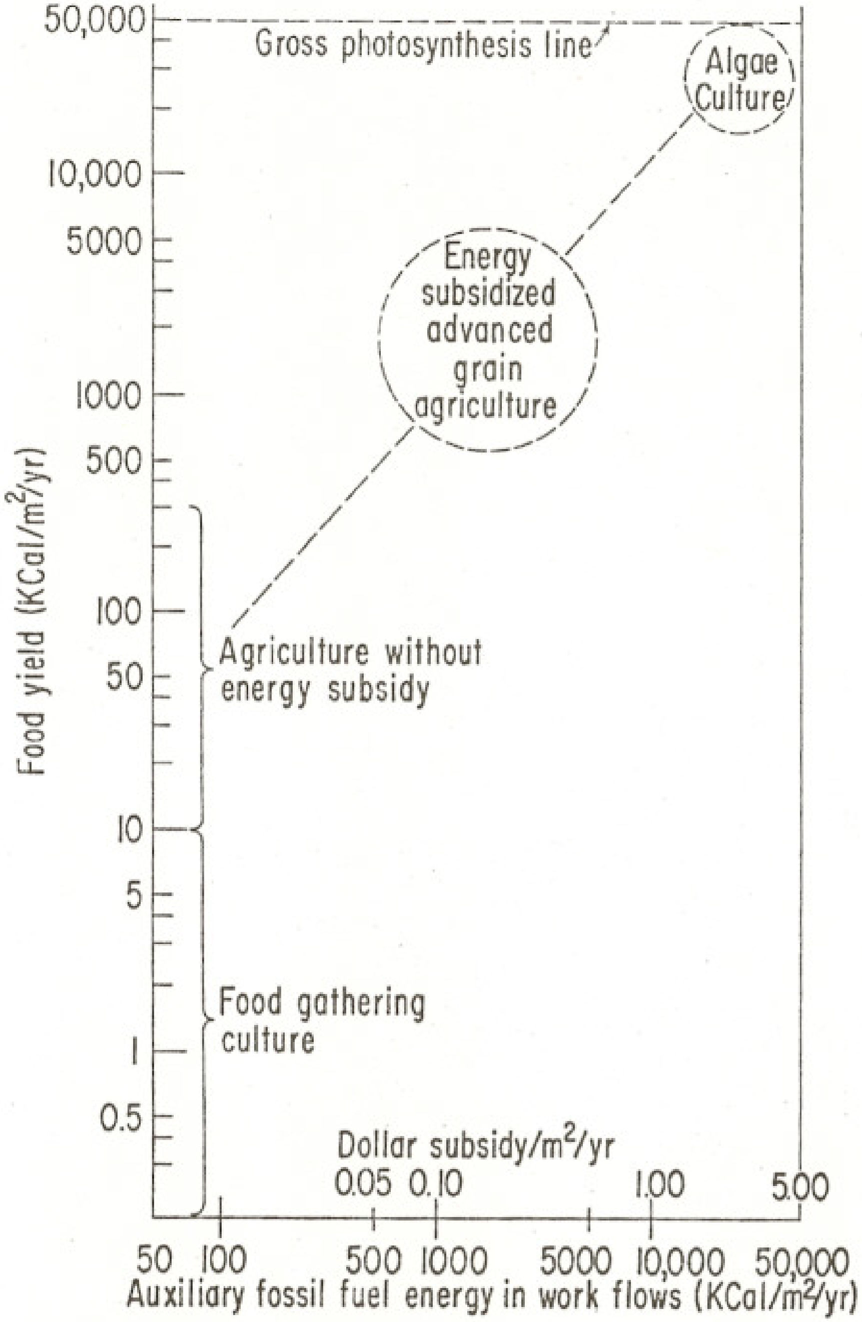


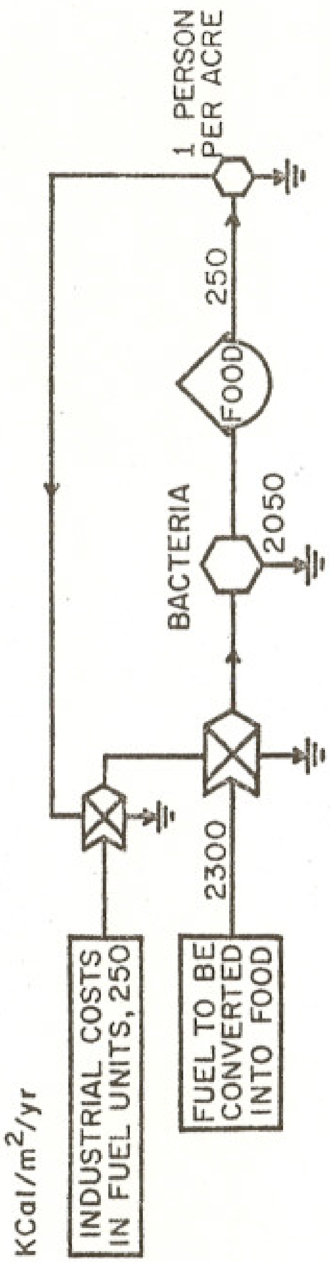
Diagram of the flows per square meter per year which the algal protagonists included in their calculations, finding 4.2 percent efficiency of visible light that is one-half of the solar input energy shown.

Calculations for Figure 6 were taken from data on an algal pilot plant operated by Arthur D. Little Company. [Fischer, (5).] A yield of 20 tons per acre was obtained. A year of isolation provides 1,460,000 Kcal/m² input (400 langleys per day). Gross production is taken as 10 percent greater due to respiration, which is small in rapidly growing and harvested cells since they are not maintaining their own system. Five Kcal per gram dry weight was used to convert algal weight to potential energy of yield.

The work costs were given by Fischer in dollars including a depreciation of the cost of the installations over a ten year period. The dollar costs of $2.80 per m²/yr. were converted to work energy values using the ratio of United States fuel consumption to United States dollar budget in 1960 of about 10,000 Kcal/dollar spent.



... photosynthetic systen a function of the auxiliary, fossil fuel energies being used to do work would otherwise have to be done from the yield. As favorable environme supplements and fossil fuel inputs become large, the net yield to man approa the maximum gross photosynthesis ceiling inherently limited by the t modynamics of photosynthetic cells. The ceilings for the gross photosynth of the best agriculture and the most productive natural communities are al the same, here written as around 150 kilo-calories per square meter per day rood from hydrocarbons

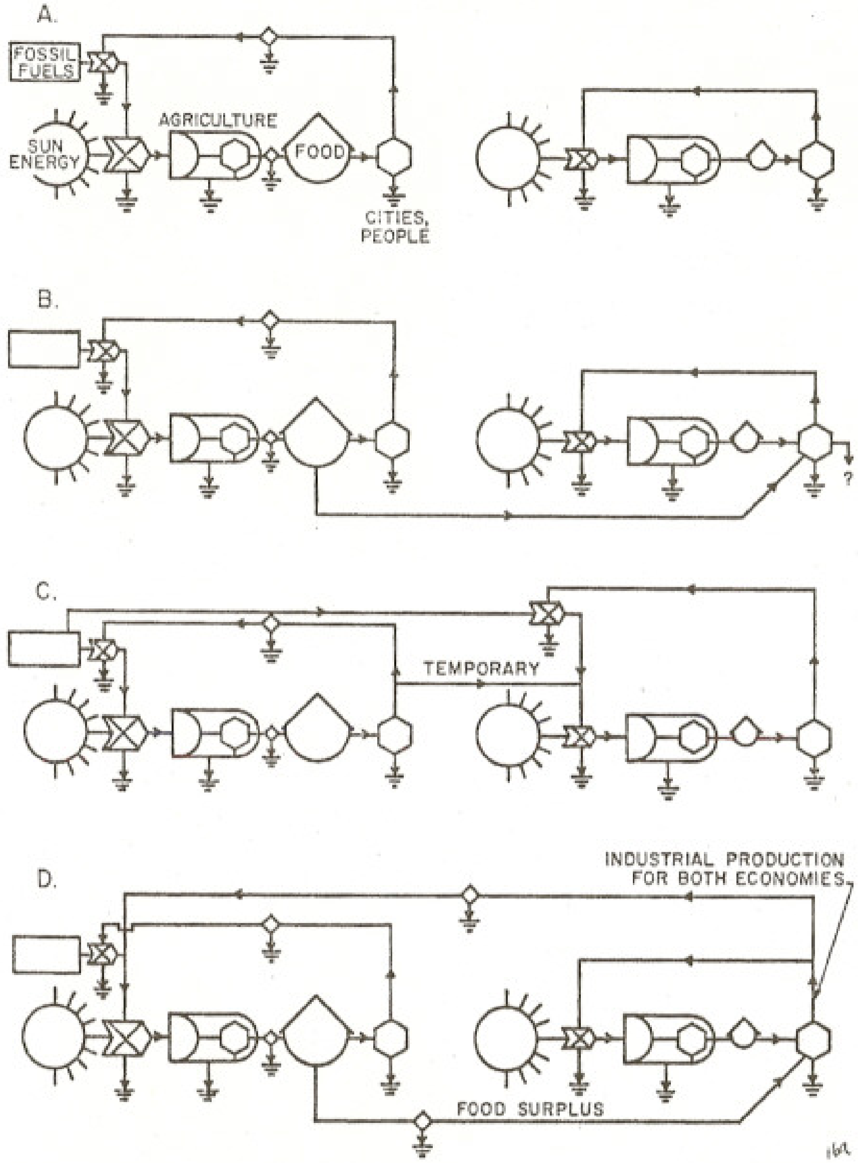


system of food production converting methane and/or petroleum to f
using industrial microbiological means of growing bacteria on hydrocarb
Calculations are prorated to indicate the amount of fuel required per a
to support 640 persons per square mile. Fuel cost of the industrial sub
is computed from the $0.55 per kilogram cost estimated by McPherson
Percent of fuel converted was obtained from a report on a Shell Co. pilot p
in which 10^7 g of food (50 percent protein) were produced from two mil
cubic feet of methane (4.6×10^8 kCalories) (J. van Overbeek, pers
communication [2]).

[2] Dr. van Overbeek was formerly with Shell Development Company, Modesto, Califo
He is now with Texas A&M University.

Figure 9

Systems connecting developed and developing countries



country to a less developed country.

A. Both systems with closed loops and separate.

B. Industrialized system donating food without loop back; system is r rewarding and unstable; temporary subsidy of energies does harm to und developed population.

C. Industrialized country aids second country to develop its own fossil f support as a separate loop system.

D. Industrialized country produces food but incorporates second country a closed work loop of its economic system.