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FEED AND FOOD FROM DESERT ENVIRONMENTS

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INTRODUCTION

The Bio-Saline Concept. The term "Bio-Saline Research" was originally designated by National Science Foundation scientists to describe a concept "that in time will lead to sustainable industries based specifically on plants selected to grow in salt water",[1] particularly in arid land areas of the Earth, where there is an abundance of solar radiation, sea water and dry climate.[2] A broader consideration of the possibilities of such areas indicates that it is also worthwhile to consider the potential of utilizing plants which are not salt-tolerant. The bio-saline concept has been extended to encompass "the elements of research, development, demonstration and utilization to apply modern bioligical sciences and technologies for deriving essential resource materials in an environmentally harmonious manner from marine and arid land mass systems".[3] Within this latter framework we can consider both the use of plants adapted to arid lands, and modification of the environment through controlled Environmental Agricultural Technology (CEA)[2] to allow a broad range of conventional and unconventional crops to be grown with a very limited supplies of fresh or brackish water. This water could be derived from the sea, from saline lakes, or from waste water treatment.

An Urgent Need. Aspects of both arid land plant utilization and of CEA have been subjects of research and development for many years, but there appears to be a relatively recent resurgence of interest which presages rapid growth in the future. This is a part of a general desire to increase production of all kinds of crops wherever possible. That this is so is a direct consequence of the awareness of the shortage of adequate food and proper nutrition in many parts of the world, and of the potential contributions that research can make to increasing food supplies.[4] It has been estimated that the developing countries need to increase food production by 3 to 4 percent each year until the end of the century.[4] At the same time there is a wide-spread realization during the past several years that supplies of fossil fuels, especially petroleum and natural gas are finite and are being fairly rapidly depleted. Along with the rapidly growing population of the Earth, and limitation of fossil fuel supplies and food production, there are the growing expectations of people everywhere for supplies of food, energy, and chemicals. All can be supplied to a greater extent than now by increased and more efficient use of agriculture.

The Green Revolution and its Limitations. Food production especially has increased greatly in yield per acre in areas of conventional agriculture through the application of plant breeding programs, increased fertilizer supply, irrigation, and other agronomic improvements. This "Green Revolution" has led to improved nutrition in some areas and has maintained minimal levels in others in the face of rapid population growth. No doubt further gains will be made through the application of these techniques to under-utilized land. There is a growing realization, however, that such increases may be limited in the future. Limitations include the amount of available good farm land, the increasing cost of fertilizer (especially fixed nitrogen produced by comsumption of fossil fuels), and possible susceptibility to disease of highly bred plant species, particularly when grown as a single crop over very large areas.

<u>The Limitation due to Lack of Water</u>. A serious limitation to crop productivity in large areas of the world with high solar radiation and long growing seasons (with respect to temperature) in the availability of water. This limitation is felt not only in clearly arid and semi-arid regions but also in areas where the rainfall is highly variable over a period of time. Such variability may occur over a short span of a few years or over a much longer span of centuries. What makes this kind of variation so frightening is the fact that the population of the Earth is now so much greater than during the past periods of history, when there was low rainfall in areas presently used for agriculture. Even if it is true, as some would claim, that areas of subnormal and normal rainfall tend to even out on a global basis, so that one area can supply another, economic and logistic limitations can and do create great hardships, including malnutrition and even starvation in areas dependent on rainfall which experience a period of drought.

<u>Desertification</u>. Another cause of problems in areas of variable rainfall is over grazing or in some cases over-cultivation of the land which accelerates the process of desertification--the conversion of land with plant cover to barren rocky or sandy desert. When subnormal rainfall is combined with such overuse, the results are particularly disastrous. Clearly, there is a pressing need to develop technologies to help those nations in arid and semi-arid regions whose principal energy resource is the sun.

<u>Interest of Desert Nations with Fossil Fuel Reserves</u>. Those nations in desert lands with other forms of wealth such as fossil fuel deposits also have an interest in developing local reliable and economic supplies of food and feed. Such locally produced supplies have many advantages

to the people of such nations: lessened dependence on imports, creation of new local industry, and stabilization of the economy and population. Fortunately, it seems likely that the diligent and intelligent application of a small amount of the resources of the wealthier nations with high solar energy and little water can serve both purposes: providing an abundance of food and feed from plants for themselves while developing the technology which will be transferable to those without large energy inputs other than solar energy. At the same time, these wealthier solar nations will be making an essential contribution to their future prosperity when their reserves of fossil fuel begin to be less abundant.

Future Developments. We are for many reasons fortunate that that time is still some decades in the future. One reason is that the research and development of some of the "Bio-Saline" or biosolar alternatives to a point of reliability and economic feasibility will require ten or twenty years or more. Other developments can occur sooner, for some research groundwork is already laid. In the discussions that follow, we should not be too constrained by either time or present economics, for the economics are certain to change with time. Some things can be done soon, and these can be used not only for the immediate benefit but also to provide a basis for evolution towards more sophisticated and more effective systems in the more distant future. Today's five hectare greenhouse producing tomatoes and cucumbers can be the forerunner of tomorrow's ten square kilometer CEA facility producing crops of staple foods and chemicals. The quayule plantation on semi-arid land can be the forerunner of a wide variety of dry-land crops producing liquid hydrocarbons from *Euphorbia* species, lubricating oils from *Jojoba*, etc.

Leguminous plants such as mesquite (Prosopis juliflora) which were once a food staple for American indians of the U.S. Southwest could become an important source of protein and carbohydrate once again. One of our objectives should be to recommend a program of research and development that will permit us to build on today's knowledge and technology towards both short range and long range future goals.

SIGNIFICANCE OF RESEARCH AREA

Dry Lands with High Solar Energy. The arid and semi-arid lands of the world constitute about 36 percent of the land area,[5] and the sea water volume is 97.3 percent of tht total water volume of the Earth.[2] Although some dry lands are found in the arctic regions, the arid and semi-arid lands with high annual solar energy lie mostly in the regions between 15° and 40° north and south of the equator.

Areas with the most abundant solar energy, averaging more than 200 $Kcal/cm^2 \cdot yr.$, include the Arabian Penninsula, the south coast of Iran, much of northern Africa (The Sahara, Egypt, and adjacent areas), parts of the United States southwest and northern Mexico, and parts of South Africa and Southwest Africa (Fig. 1).[6] Other areas of high solar energy, averaging over 160 $Kcal/cm^2 \cdot yr$, include nearly all of Australia, the rest of Africa north and south of 20° latitude as well as the tropical zone of east Africa, most of southern Asia and southern North America, and extensive regions of South America.

Not surprisingly, since cloud cover along with latitude determines the total incidence of solar energy at ground level, some of the world's great deserts are found in the areas of highest solar energy input. These include the Sahara, the Arabian Desert, the Kalihari Desert in

South Africa, and the Sonoran and Mojave Deserts in North America.[5] The coincidence is far from exact, however, as mountain ranges, cold adjacent oceans, and other factors can reduce the land precipitation to very low levels even where the total solar incidence is less. More detailed maps[5] of the world's deserts are required to show the locations of all the important deserts including some of the most arid. The Takla Makan desert, classified as extremely arid, lies in western China, in the rain shadow of the Tibetin Plateau. The Namid Desert lies along the coast of Southwest Africa, while its counterparts, the Peruvian Desert and the Atacama Desert lie along the west coasts of Peru and northern Chile. There are many other important deserts in the world, classified as arid and semi-arid including the Australian Desert which occupies the greater part of Australia, the North American, Great Basin, and Chihuahuan Deserts in North America, the Patagonian and Monte Deserts in Argentina, and the Turkestan, Thar, and Gobi Deserts in Asia. The arid, and especially the semi-arid deserts are particularly interesting with respect to possibilities for production of crops of plants adapted to dry environments.

Dry Lands Bordering Seas. There are very extensive lengths of coastlines with seas bordering arid lands with high annual incidence of solar energy. Such lands border the South Coast of the Mediterranean Sea, the Red Sea, the Arabian Sea and the Gulf of Omar and the Persian Gulf, the Atlantic coast of Africa north of about 15° N and south of 10° S latitude, much of the Indian Ocean coast of Western Australia, the Pacific coast of Peru and Chile from 5° S to 30° S latitude, and the Gulf of California and Pacific Ocean coast of Baja California in Mexico. This proximity makes it possible to obtain water from the sea, either for use with salt-tolerant plants, or following desalination, for use with plants requiring fresh-water. Also, temperature control of land installations such as greenhouses may be possible by using the lower temperature of the sea in the summer.

In a few cases, saline to brackish water lakes are found in desert areas, for example, Lake Chad in Africa. Moreover, there have been proposals to admit sea water to certain below sea level areas in the deserts, such as the 20,000 Km^2 Qattara Depression in Egypt. A few other such projects are possible if deemed advisable. Conceivably, salt water canals could be employed to bring sea water to interior areas, if an agricultural industry based on salt water were to evolve.

Environmental Constraints. At this point, it must be mentioned that alterations of the environment by man for his own benefit have a way of producing environmental consequences, often unforseen and frequently undesirable. Thus, desertification of once productive semi-arid lands resulting from overuse or unwise use for agriculture and grazing is one of the most serious problems in some of the areas. In other areas irrigation, even with nominally fresh water has resulted in great gains in productivity for extensive periods of time, only to be followed eventually by salt-buildup, siltation, and water-logging in the land, leading to crop failure and decline of human population in the region. Although some techniques such as flushing and draining of the land can sometimes be employed, it would be advisable in planning any irrigation system to develop strategies for the long range survival of good productivity.

Productivity of Dry Lands. Without irrigation, the photosynthetic productivity of dry lands is naturally extremely low. Desert Scrub, Dry Desert, and Chaparral lands constitute 19% of the continental area (Table I),[7] but only 2.3% of the primary photosynthetic productivity is found there. Most of the continental productivity is in forests, grasslands, woodlands, wet-lands and lakes, and in cultivated fields. Very little of the lands in arid regions are cultivated, but where irrigation is possible, as in the Nile Valley of Egypt, or the Imperial Valley of the United States, crop productivity is very high, even though the problem of salt-buildup can become serious in time. In such areas, further extension of agriculture is usually limited by the availability of good land, water, or both. Some lands, initially unsuited to conventional agriculture because they are too sandy, salty, or lack humus, can be improved with appropriate treatment. Water is therefore often the limiting factor. While irrigation projects can be used in some cases to convert desert areas into regions of high productivity, such projects obviously are limited by proximity to and abundance of fresh water in rivers or underground water reachable with wells. In some areas such supplies are nonexistent or prohibitively costly due to distance to rivers, depth of water tables or other factors. These are strong reasons to use whatever fresh water is available for crop production as efficiently as possible.

Efficient Use of Water. Efficient utilization of water can be accomplished in several ways. Plants capable of growing in dry lands can be exploited, application of water to the plants can be made more economically as by trickle irrigation, waste water from municipal and industrial uses can be reclaimed, purified and reused for agriculture, and evaporative losses can be greatly reduced by utilization of CEA, provided the system is sealed to prevent water loss, or sea water evaporation is employed to saturate the air over the plants with water vapor.

The use of marine plants, and of higher plants capable of growing in salt water and in brackish water are possibilities discussed in other papers in this Workshop, as is the possibility of growing algal biomass, particularly in conjunction with waste water reclamation. This paper will concentrate on two subjects: the possible use of plants tolerant to low water, high temperature, and high light intensities, and the use of special techniques such as CEA to increase the effectiveness of water utilization and efficiency of solar energy conversion.

Benefits of Increased Productivity. The economic and sociological implications of increased crop productivity in the dry-land countries is enormous. There is great diversity among the countries with arid lands and high solar energy input. They vary in population density and growth rate, per capita income, types of land and water resources that might be developed, and many others. The need for more feed and food, as well as for chemicals and materials from plants varies in both kind and amount from one country to another. Most or all would welcome increased crop production, even though the reasons may vary. The technology to be employed in achieving such improvements ultimately must be tailored to the specific opportunities and needs of each country. Later in this paper, some examples of specific possibilities will be given, but first we should consider some universal constraints on productivity in plants in general as well as in some dry land environments. Then we can consider strategies for approaching the maximum production permitted by these constraints. Finally, a program of research and development leading to the successful implementation of these strategies can be suggested.

The objectives and rewards of a successful program of this kind may be enumerated:

1. The development of new and improved agricultural, agrochemical, and agromaterial industries, which in the case of countries rich in petroleum resources can augment industry based on fossil fuels as these become less abundant.

2. The improvement of nutrition and health in all dry land countries, but especially those with presently inadequate access to agricultural products, or subject to threat of famine during periods of drought, or attacks of plant disease or insects, or due to desertification.

3. The alleviation of costly imports of food and chemicals through improved agriculture.

4. The possibility of environmental benefits to land and watersheds by growing of more plants tolerant to local conditions, and by relieving fragile grasslands of excessive grazing pressure by growing more forage crops in smaller irrigated areas.

Research and Costs. These important benefits must be kept in mind when assessing the cost of the research and development program needed to bring them about. This program will involve the disciplines of not only plant physiology and agronomy, but also of genetics, chemistry, physics, and several kinds of engineering, applied to a very diversified group of objectives. Some demonstration projects may of necessity have to be rather large in scale to be meaningful, and economic feasibility may be achievable only when highly complex systems are fully integrated. Some simpler concepts may also prove to be feasible, but the benefits may be more limited.

A reasonable view to take would be that mankind has reached an extremely critical stage in history, where population, technology, education, science, and political systems all are changing at an accelerating rate. If we are to gain any kind of control of this situation, it is imperative that we make full use of the advanced state of science to design systems for the future when present day economic parameters will no longer be valid. We must ask the economists not what is feasible now but what will be feasible in 10 to 50 years, and we must supply them with accurate projections of science and technology to use with their projections of supply and demand. We should not consider this to be an impossible task, but rather should do the best we can now, and constantly update the projections as new data are gained from an intensive program of research and development.

PRESENT STATE OF SCIENCE AND TECHNOLOGY

<u>Desert Science</u>. As indicated earlier, agriculture in the desert without abundant sources of fresh water for irrigation or the use of salt tolerant plants would appear to be limited to two possibilities. The first is exploitation and perhaps cultivation of plants native to arid environments. The second is to use CEA systems in which a small amount of fresh water obtained from salt water or limited sources such as springs, wells, or waste water reclamation can be used very efficiently by preventing its loss to the dry atmosphere or into the ground.

There appears to be an excellent scientific background of knowledge about the dry lands and the plants that inhabit them, and the dangers resulting from misuse of these lands. The reader who is unacquainted with the qualities and the problems of the desert and its agriculture will find an excellent introduction to this complex subject in the January/February issue of Mosaic, a publication of the National Science Foundation. It seems clear that although there is much knowledge about the ecology of dry lands, there is much to be done by way of applying this knowledge to develop suitable technologies and agriculture which would permit the utilization of the desert as a resource without degrading its qualities to a point where it is no longer productive.

Controlled Environment Agriculture (CEA). Similarly, with respect to Controlled Environment Agriculture (CEA), a very substantial start has already been made. The Environmental Research Laboratory (ERL) of the University of Arizona has been a pioneer in the development of CEA for desert environments. Because such environments often contain populations that can otherwise only obtain fresh fruit and vegetables by having them brought in by air at considerable expense, crops grown in CEA can have a high local value, contributing to the cost effectiveness of the installation. The four hectare Environmental Farms, Inc, near Tuscon, Arizona, in the U.S. produces more than one million kilograms of tomatoes annually, with the produce being sold at off season times in the U.S. In Abu Dhabi, nearly a ton of vegetables per day is harvested from five acres of CEA.

Desert greenhouses may be built of air-inflated plastic or combinations of plastic and glass. Sea water can be used for evaporative cooling, and sea water can be distilled to provide for irrigation. Problems of salt disposal in the greenhouses can be controlled because the soils are sandy and can be flushed with fresh water.

Given this promising growth in CEA technology, what is needed for the future? Can the application of CEA, now limited to relatively high value crops, and to construction requiring rather high investment of capital, be applied to staple crops such as grains and fodder, and can this technology ever be constructed by developing nations not favored by the possession of large deposits of fossil fuel wealth? Finally, can those inputs of energy from fossil fuels, such as the fuel to drive sea water pumps, distillation units, and the hydrocarbons required for the synthesis of plastic be replaced by solar energy? I believe that there is an affirmative answer to these questions.

Efficiency of Plants as Solar Energy Converters. If we are to develop CEA for widespread application to food and perhaps energy and chemicals production as well, it will be vitally important to maximize the efficiency of the systems. One efficiency with which we start is the efficiency of the photosynthetic process itself, which determines just how much of the sun's energy can be captured and stored by the plants. Such efficiency is also very important for desert plants, which must capture and store the sun's energy while at the same time conserving water. To prevent loss of water to the low humidity sink of the desert in the daytime, but still be able to take up carbon dioxide is a major accomplishment of desert plants. There are four aspects of the plant physiology of green plants that are especially important in this respect: the primary process of photosynthesis and its efficiency,[9] photorespiration, C-4 metabolism, and Crassulacean Acid Metabolism (CAM).

<u>The Mechanism of Photosynthesis and its Efficiency</u>. Total dry mass of organic material produced by a land plant, and to lesser extent the yield of the harvested organ (seed, root, fruit, etc.) are related to the efficiency with which the plant uses the energy of sunlight to drive the conversion of carbon dioxide, water and minerals to oxygen and organic compounds [10,12]--the process of photosynthesis.

Increased photosynthesis is helpful in most cases in increasing the yield of harvested organs (seeds, etc.), but an increase in photosynthesis does not necessarily translate linearly into increased crops in such cases. When the crop is the whole plant, however, and that plant is harvested while still growing rapidly (before senescence sets in) there should be such a relationship. If the crop is alfalfa, for example, and it is harvested repeatedly so that the plants are always growing at high rates, yield will depend on rate of photosynthesis.

The photosynthetic process takes place entirely in the chloroplasts of green cells. Chloroplasts have an outer double membrane. Inside the chloroplasts is a complex organization of membranes and soluble enzymes. These inner membranes contain the light-absorbing pigments, chlorophylls a and b, and carotenes, and various electron carriers, membrane-bound enzymes, etc. All these components are required for the conversion of light energy to chemical energy. The membranes are formed into very thin hollow discs (thylakoids).

As a result of the photochemistry in the membranes, water is oxidized inside the thylakoids, releasing protons and molecular oxygen, O_2. The electrons pass through the membranes and bring about the reduction of a soluble, low molecular weight protein called ferredoxin, which contains iron bound to sulfhydryl groups of the protein. The oxidation of two water molecules takes four electrons from water and these are transferred to four ferredoxin molecules. Each electron following this course must be transferred through a number of steps. In each of two of these steps, a photon of light is used with a quantum efficiency of 1.0. The light requirement for the transfer of four electrons is thus two times four, or eight photons.

$$2\ H_2O + 4\ Fd^{+3} \xrightarrow{\text{eight photons}} 4\ H^+ + O_2 + 4\ Fd^{+2}$$

This equation does not give the entire result of what happens in the thylakoids. Concurrent with the electron transfer, there is a conversion of adenosine diphosphate (ADP) and inorganic phosphate (P_i) to the biological acid anhydride, adenosine triphosphate (ATP).

$$ADP^{-3} + P_i^{-2} \longrightarrow ATP^{-4}$$

It appears that about three ATP molecules are formed for each four electrons transferred, so the approximate complete equation becomes:

$$2\ H_2O + 4\ Fd^{+3} + 3\ ADP^{-3} + 3\ P_i^{-2} \xrightarrow{8\ h\nu} H^+ + 3\ ATP^{-4} + 4\ Fd^{+2} + O_2$$

With the utilization of eight einsteins (moles of photons), the thylakoid photochemical apparatus produces four moles of reduced ferredoxin and about three moles of ATP. These amounts of reduced ferredoxin and ATP are needed to bring about the reduction of one mole of carbon dioxide to sugar in the dark reactions that follow. This occurs in the stroma region of the chloroplasts, outside the thylakoids. The early reactions of photosynthesis are complete when carbon dioxide has been converted to the glucose moiety of starch, a major storage product in chloroplasts. By considering only a sixth of a mole of such a glucose moiety, one can write a simplified equation for the entire process of photosynthesis:

$$CO_2 + H_2O \xrightarrow{\text{8+ photons}} \underset{\text{1/6 glucose moiety}}{(CH_2O)} + O_2$$

The free energy stored by this reaction is about 114 Kcal per mole of CO_2 reduced to starch. (There is a bit more energy stored per carbon in starch than in free glucose.)

Green plants use only light with wave lengths from 400 nm to 700 nm. This photosynthetically active radiation (P.A.R.) constitutes only about 0.43 of the total solar radiation at the earth's surface at latitudes common to dry lands. All this light is used no more efficiently by the green plant cells than if it were 700 nm light. The integrated solar energy input between 400 and 700 nm at the earth's surface is equivalent in energy to monochromatic light at 575 nm. An einstein of light has an energy content given by Avogadro's number times $h\nu$, where h is Planck's constant and ν is the frequency of the light. With the appropriate units, E (Kcal/einstein) = $28{,}600/\lambda$, where λ = wavelength = c/ν, in nm. An einstein of 575 nm light contains 49.74 Kcal. At least eight photons of light are required per molecule of CO_2 reduced; eight einsteins of light are required per mole of CO_2. Probably the actual efficiency is somewhat less, but measurements of quantum requirements under optimal conditions in the laboratory have given quantum requirements in the range of 8 to 10 einsteins required per O_2 molecule evolved.[13]

The maximum efficiency of 0.286 is for conversion of P.A.R. The efficiency based on total solar radiation incident on the plants with total absorption of P.A.R. is 0.43 x .286 = 0.123. This is the basis for the statement sometimes made that the maximum efficiency for solar energy conversion by photosynthesis is about 12%.

The maximum net efficiency, over a 24 hr period, and under field or aquatic conditions, depends on two other factors: The amount of incident light actually absorbed in the green tissue, and the cost of energy used in respiration and biosynthesis. For land plants it has been estimated that the maximum absorption to be expected from an optimal leaf canopy may be 0.80.[11] This is due to some light being reflected, and some reaching the ground or falling on nonphotosynthetic parts of the plant (such as the bark of trees). With aquatic plants such as unicellular algae that are totally immersed there may be less reflection and with sufficient density of algae, absorption could be essentially complete in green tissues.

A major loss in stored chemical energy results from respiration which occurs in all tissue not actively photosynthesizing. This includes green cells at night or in dim light, and roots, trunks and other organs that are not green or only a little green. The energy derived from respiration is used for various physiological needs of the plant, transport and translocation, conversion of photosynthate to protein, lipids (including hydrocarbons in some plants), cellulose for structures such as stalks and trunks, and so forth. In the green cells during photosynthesis, some energy from the photosynthetic process itself may be used for such purposes, as mentioned earlier. Like the light absorption factor, the factor for respiration/biosynthesis is extremely variable, depending on the physiological conditons and needs of the plant, but it is estimated that in a typical case respiration and biosynthesis use up one third of the energy stored by photosynthesis.[11] The factor would thus be 0.67.

It may be argued that both the absorption factor and the respiration factor are not true maximum values, since there may be cases where each is exceeded. The product of these two factors, 0.80 x 0.67 = 0.53 probably is close to the maximum, since there is some trade-off between the two factors. For example, for a land plant to have all brightly illuminated leaves and hence lower respiration compared to photosynthesis would mean that its leaf canopy was probably less perfect than required for 0.8 absorption. At the other extreme, when there is dense foliage, little light may reach the ground, but the respiration in the shaded leaves may nearly equal photosynthesis. Similarly, an algae pond may be nearly totally absorbing, but the average light intensity for the cells would then be so low as to allow a high rate of respiration.

If we combine the photosynthetic efficiency, 0.123, with the product of the absorption and respiration/biosynthesis factors, 0.534, we obtain an overall maximum efficiency for photosynthetic/biosynthetic energy storage by green plants of 0.066. This calculated maximum efficiency can be compared with various reported high yield figures from agriculture. Before doing this it is useful to convert the efficiency to expected yield of dry matter.

From the equation and discussion given earlier, the reduction of a mole of CO_2 to the glucose moiety of starch or cellulose stores about 114 Kcal and results in an organic molecular weight of 27. Each Kcal of stored energy thus results in the formation of 27/114 = 0.237 grams of biomass (dry weight), if the biomass were entirely cellulose and starch. Of course, this is not the actual case, but the assumption provides a reasonable approximation.

Calculated Maximum Biomass Production and Reported High Yields. From the foregoing discussion, the upper limit for biomass production can be calculated by multiplying the efficiency, 0.066 times the daily total energy times 0.237. For high solar energy areas with 200 Kcal/ $cm^2 \cdot yr$, or $2 \cdot 10^6$ $Kcal/m^2 \cdot yr$, the maximum energy stored would be 0.066 x $2 \cdot 10^6 = 1.32 \cdot 10^5$ $Kcal/m^2 \cdot yr$. The biomass, if all starch and cellulose, would be $1.32 \cdot 10^5 \times 0.237 = 3.1284 \cdot 10^4$ $grams/yr \cdot m^2$, 85.7 $grams/day \cdot m^2$ or 313 metric tons/hectare yr. This, of course is the total dry biomass that could be produced, with continuous optimal growth.

Since optimal conditions of temperature, light absorption, etc. are never found during all times for crops grown under conventional agriculture, it is obvious that reported crop yields will not approach closely to this maximum on an annual yield basis. Also, crops in the temperate zone are usually grown under lower annual energy imputs. Nevertheless, it is instructive to compare reported high yields and maximum growth rates with the calculated values.

What are the actual rates measured? The figures in parentheses (Table II)[14] are rates during the active growing season, not annual rates. For C-4 plants, these maximum rates range from 138 up to 190 metric tons per hectare per year. The highest (190) is about half the calculated maximum. Similarly, the highest reported annual yield, with sugar cane in Texas, is 112 metric tons per hectare--again about 1/2 the calculated maximum (263) for the U.S. Southwest. The energy storage efficiency for these reported yields suggests that 3.3% to perhaps 5% with CEA as the best we can hope for with land plants in the future.

The Photosynthetic Carbon Reduction Pathway (Reductive Pentose Phosphate Pathway). The terms "C-4" plants and "C-3" plants encountered in Table II refer to important characteristics of photosynthetic carbon metabolism that require some discussion. All known green plants and algae capable of oxidation of water to O_2 employ the reductive pentose phosphate cycle (RPP cycle),[15,16] This RPP cycle begins with the carboxylation of a five-carbon sugar diphosphate (RuDP, Figure 2). The six-carbon proposed intermediate is not seen, but is hydrolytically split with internal oxidation-reduction, giving two molecules of the three-carbon product, 3-phosphoglycerate (PGA). With ATP from the light reactions, PGA is converted to phosphoryl PGA, which in turn is reduced by NADPH to the three-carbon sugar phosphate, 3-phosphoglyceraldehyde (Gal3P). The reduced two-electron carrier, NADPH, is regenerated by the reaction of the oxidized form, $NADP^+$, with two molecules of reduced ferredoxin, also produced by the light reactions in the thylakoid membranes. Five molecules of triose phosphate are converted to three molecules of the pentose monophosphate, ribulose 5-phosphate (Ru5P) by a series of condensations, isomerizations, and chain length dismutations. Finally, the Ru5P molecules are converted with ATP to the carbon dioxide acceptor, RuDP, completing the cycle.

When the three RuDP molecules are carboxylated to give six PGA molecules, and these are in turn reduced to six Gal3P molecules, there is a net gain of one triose phosphate molecule, equivalent to the three CO_2 molecules taken up. This net Gal3P molecule can either be converted to glucose 6-phosphate (G6P) and then to starch, or it can be exported from the chloroplasts to the cytoplasm. Once there, it is reoxidized to PGA, yielding in addition ATP and NADH, which thus become available to the non-photosynthetic part of the cell for biosynthesis. Some of this exported carbon and reducing power may be converted to sucrose, a sugar which can then be translocated from the photosynthetic cell into the vascular system of high plants through which it can move to other parts of the plant such as the growing tip, seeds, roots, or other sinks. Alternatively, in an expanding leaf, the material exported from the chloroplasts may stay in the cell and be used in the synthesis of new cellular material leading to cell division.

The C-4 Pathway. Plants which have only the RPP cycle for CO_2 fixation and reduction are termed "C-3" plants, since the primary carboxylation product is a three-carbon acid. Certain plants of supposed tropical origin including but not restricted to a number of "tropical grasses" such as sugar cane, corn, crabgrass, sorgum, itc. have, in addition to the RPP cycle, another CO_2 fixation cycle.[17-19] In this cycle, CO_2 is first fixed by carboxylation of phosphoenolpyruvate, (PEPA) to give a four carbon acid, oxalacetate (OAA), which is then reduced with NADPH to give malate (or in some cases the amino acid aspartate) (Figure 3).

The malic or aspartic acids are believed to be translocated into the chloroplasts in cells near the vascular system of the leaf which contain the enzymes and compounds of the RPP cycle. There these acids are oxidatively decarboxylated, yielding CO_2, NADPH, and pyruvate, which is translocated back out of the chloroplasts containing the RPP cycle. In another variant, not shown in Figure 3, the malic acid is converted once again to oxalacetic acid in the vascular bundle chloroplasts, and this acid is decarboxylated to give PEPA which is then converted to pyruvate. Finally, the pyruvate is converted by reactions which use up two ATP molecules to reform the PEPA. Since the first compounds into which CO_2 is incorporated in this cycle are four-carbon acids, plants with this cycle are called C-4 plants. The site of the conversion of pyruvate back to PEPA appears to be in specialized mesophyll cells whose chloroplasts do not contain a complete RPP cycle (RuDP carboxylase is missing). The exact locations of the sites of various reactions of the C-4 cycle and the possible intracellular transport of metabolites remain the subject of some controversy.

The net result of the C-4 cycle appears to be the fixation of CO_2 at sites removed from the RPP cycle chloroplasts, the translocation of the C-4 acid products into these chloroplasts, and the release of CO_2 close to RuDP carboxylase. The cost is two ATP's per CO_2 molecule transported. While at first glance this complex mechanism may appear to be hardly worth the trouble (after all, C-3 plants do without it), it turns out that the C-4 cycle performs an extremely valuable function. One reflection of its value is the higher productivity of C-4 plants seen in Table II. C-4 plants are in general capable of higher rates of net photosynthesis in air under bright sunlight than the most active C-3 plants. The C-4 plants are believed to have evolved in the very regions we are interested in: the semi-arid lands with high solar energy incidence.

Photorespiration.[20] The reason for the difference lies in the virtual abolition of the effects of photorespiration in C-4 plants. In C-3 plants, in air under bright sunlight, and especially on a warm day where growing conditions should be very favorable, a certain part of the sugar phosphates formed in the chloroplasts by photosynthetic fixation are reoxidized, and are in part converted back to CO_2. Apparently, the energy and reducing power liberated by this oxidation are not conserved and the process is energetically wasteful. As light intensity and temperature increase, any increase in photosynthetic CO_2 uptake is negated by increased photorespiration. Net photosynthesis, the difference between the two processes, cannot increase beyond a certain point. The limiting effect on C-3 plants can be removed by reduction of the level of O_2 in the atmosphere to 2% or by elevating the CO_2 pressure, but in the field plants must live with the natural atmosphere which contains 0.033% CO_2 and 20% O_2.[20]

There is still some controversy surrounding the detailed mechanism of photorespiration, but much evidence supports the role of glycolic acid as the key intermediate compound.[20] It is produced in the chloroplasts by oxidation of sugar phosphate to phosphoglycolate and glycolate which is then oxidized outside the chloroplasts to give photorespiratory CO_2. The production of glycolate is favored in C-3 plants by high light, atmospheric or higher O_2, low CO_2 pressures, and elevated temperatures. Its formation is inhibited by elevated CO_2, although there is reported to be some glycolate formation insensitive to CO_2 pressure inside the chloroplasts where the C-3 cycle is operating, it is thought that glycolate formation from sugar phosphates is minimized in C-4 plants.[20] Some glycolate is produced even in C-4 plants, so that a further effect of the C-4 cycle may be due to the ability of the PEPA carboxylation in the other parts of the leaf to recapture CO_2 before it can escape from the leaf. C-4 metabolism is of great importance to many plants growing in desert environments. C-4 plants are able to continue net photosynthetic CO_2 uptake at much lower effective internal CO_2 pressures than C-3 plants, due to the virtual absence of photorespiratory loss of CO_2 from the leaves. This is an advantage when water stress dictates partial or complete closing of stomata, and at other times permits higher rates of photosynthesis in bright light so that the C-4 plants can grow faster when favorable conditions exist. The importance of _Zea mays_ (corn) to Amerindians of the U.S. Southwest and Mexico stemmed from the ability of this C-4 plant to grow in semi-arid environments.

Crassulacena Acid Metabolism. It is of particular interest to consider plants native to semi-arid areas and deserts which do not require irrigation. Not surprisingly, many such plants have evolved very long root systems for collecting water from considerable depth and over large areas. They have also developed physiological mechanisms for avoiding water loss. Such mechanisms can conserve water but sometimes at the cost of limited photosynthetic productivity. For example, plants with thick waxy cuticles and with stomata that can be closed during the heat of the day are not able to take in carbon dioxide rapidly; thus photosynthesis is limited. Many desert plants exhibit Crassulacean Acid Metabolism (CAM) in which CO_2 is taken in through stomata open at night and incorporated by a carboxylation of PEPA to give dicarboxylic acids with four carbon atoms (for reviews see Osmond,[21] Ting.[22]) During the night this PEPA is made from sugars stored in the plant. In the daytime, the stomata are closed, limiting water loss but also CO_2 ingress. The four carbon acids are decarboxylated, the CO_2 released is reduced to sugars by photosynthesis, and the PEPA is also reduced back to sugars. In the morning and again in the late afternoon there can be intermediate stages when the stomata are open and CO_2 fixation by carboxylation of both ribulose diphosphate (RPP cycle) and PEPA occurs at the same time.

Plants with CAM also exhibit photorespiration in the heat of the day when the stomata are closed. The recycling of CO_2 within the leaf that occurs in such plants is reminiscent of internal CO_2 recycling in C-4 plants.[21]

There are some 18 flowering plant families with CAM metabolism including the Crassulaceae, the Cactaceae, Alzoaceae, and Succulent Euphorbiaceae.[22] All cacti probably have CAM. Although very important to desert ecology, there are also many CAM plants found in areas of high rainfall. In desert CAM plants the cycling of carbon through the CAM pathway can persist for long periods of time in the absence of any external water with the stomata closed. In one experiment Opuntia bigelovii plants were severed at the base and mounted in stands in the desert where cycling of carbon through CAM on a daily basis persisted for three years.[22] These plants can therefore derive energy from photosynthesis for very long periods in the desert without opening of stomata in either night or day. When plants in the desert are watered, the tissue rehydrates, and the stomata open at night, permitting CO_2 uptake to resume. After watering by rainfall, the stomatal opening may persist for a longer time in the morning and more C-3 (reductive pentose phosphate pathway) metabolism can occur.

Other Physiological Adaptations. The ability to conserve water is obviously important to desert plants, but there are other requirements as well. In very hot areas, tolerance of high temperature is required. Desert plants employ a great variety of physical shapes, reflectances, insulation, etc. to protect themselves from heat. Since water is a limiting factor, few species can afford the luxury of extensive cooling by transpiration, as employed by plants accustomed to plentiful water. One studied species, which does grow in very hot locations with abundant fresh water demonstrate the adaptation of enzyme systems to high temperatures. Tidestroma oblongifola, a C-4 species grows in Death Valley, U.S., at fresh water springs. Its maximum growth is reached at 45°C, a temperature at which some temperate zone species greatly decline in growth rate, even if well watered.[23] Although accustomed to growth in atmospheres at very low humidity, this plant does very well in chambers maintained at high temperature and high humidity. Plants with such characteristics could prove to be very useful in desert greenhouses when maximum growth rates and minimal cooling are desirable. I will return later to the question of how food and feed might be obtained from such plants.

Desert Agriculture for Food and Chemicals. Many types of utilization of plants growing in the desert might be imagined, from the already widespread (and often excessive) grazing of desert or dryland grasses by livestock to proposals to harvest hydrocarbon-containing plants growing in dry land as a source of liquid fuels and chemical feedstocks, proposed by Calvin.[24] A principal problem with using the desert fringes for grazing livestock is the tendency to over graze, resulting in the conversion of desert fringe to desert (desertification). Educational programs for the people living in these environments might help, but only if alternative sources of food and wealth from the desert can be developed. Even so, population control would seem to be a necessity, once a stable base for agriculture and industry adequate to the planned population were developed. This may sound utopian, but the only alternative would appear to be cyclic drought, desertification and population decrease through famine and disease, to be followed by repopulation during periods of greater rainfall, _if_ the land recovers during those periods. At least this is the impression received by the newcomer to the field of desert utilization by people. (It is expected that this subject will receive considerable augmentation from Dr. McGinnies at the Bio-Saline Workshop.)

One dry-land plant which has been suggested as a useful source of food and materials is the common Mesquite (_Prosopis_ species), found growing wild in many parts of the U.S. Southwest.[25] The pods of this plant have a high food value as protein and carbohydrate and were used by American Indians as an important dietary supplement. Possibly this plant could be used to supply both fuel and food. The plants are legumes and do not require nitrogen fertilization. An annual yield of 43 Kg dry weight of pods was harvested from one large tree in Southern California. The protein has high nutritional value.[26]

Several types of plants well adapted to semi-arid environments and capable of producing useful chemicals appear to have considerable potential. Guayule has been raised in Mexico, and at times in the U.S. for many years as a source of natural rubber.[27] From 1910 to 1946, the U.S. imported more than 150 million pounds of guayule rubber from Mexico. Much of this came from wild stands, which eventually could not support such sustained harvesting. During the 1920's, large plantations were planted in the U.S., and rubber from these plantations competed with Hevea rubber from Indonesia. Such developments stopped during the 1930's, and later when the supply of Indonesian rubber was interrupted, it was necessary to launch a massive new project in guayule production in the U.S. and in Mexico. Over three million pounds of resinous rubber were produced. By 1943, synthetic rubbers were being produced from fossil fuels, and at the end of World War II these synthetics plus large supplies of Hevea rubber which became available from Indonesia again removed the necessity for producing Guayule rubber.

In Mexico, however, guayule development has continued, and agencies of the Mexican government are embarking on rubber production from guayule plants growing wild over about 4 million hectares. There is considerable technology available for the production of Guayule, harvesting, extraction and deresination. From work done in Manzinar, California in 1942-44, it is clear that good yields of Guayule can be grown in semi-arid regions without irrigation. Thus, Guayule production may serve as a model for the production of other dry land plants capable of supplying useful chemicals. Yokayama[28] has been able to increase the rubber content of harvested guayule by a factor of 2 to 3 by treating the 4-week old seedlings with 5000 ppm each of 2-(3,4-dichlorophenoxy)-triethylamine and 2-diethylamino-ethanol plus a wetting agent, and harvesting three weeks later.

The direct production of hydrocarbons as liquid fuels and chemical feedstocks by the extraction of latex bearing plants of the Euphorbia family has been proposed and is being studied by Calvin.[24,29] Test plots of several species are now being grown in southern California. Preliminary yield figures suggest that the hydrocarbon content of the biomass produced could supply as much as 5 to 10 barrels of oil per acre per year. These species can grow on semi-arid lands in the U.S. Southwest. Such direct production of liquid fuels is very attractive since it bypasses the conversion of biomass to heat and then to electricity, with the resulting losses in efficiency. Moreover, the time will come when supplies of petroleum will be exhausted, and it may well be necessary to obtain chemical feedstocks from plants as a replacement. Even if that time is 50 years or more in the future, it is hardly too soon to begin to develop the technology to guarantee continued supplies so vital to modern civilization. Preliminary analyses of the hydrocarbon and lipid materials in the latex of plants suggest a wealth of useful chemicals may become available.[29]

Another example of a specialty dry land plant is Jojoba. This plant is now being grown on Indian reservations and in other areas in Arizona as a source of a valuable lubricant with properties which allow it to replace oil obtained from whales.

Present CEA Installations in Desert Areas. The status of controlled environment agriculture around the world has been reviewed in 1973 by Dalrymple,[30] and further discussion of CEA with examples of advanced CEA systems has been provided in 1977 by the extensive report by de Bivort.[31] In the latter report it was concluded that CEA could substantially alleviate the agro-food problems of environmental degradation regional shortages of arable land, water, and fertilizers, and unreliability of production. The costs of present types of CEA systems were found to be prohibitive for agronomic crops, but acceptable for some high value fresh vegetables, but new types of CEA systems can be conceived for growing crops at considerably lower costs and much less total energy consumption than present CEA. Finally, CEA would appear most attractive if integrated with solar energy and water management systems for community units of several thousand people. It was recognized that CEA benefits are of interest to all concerned with food, energy and water resources and new opportunities for local self-sufficiency.[31]

In reevaluating the possibilities for low-cost CEA, de Bivort and his associates proposed a system with a double plastic cover, a cable suspension, and a solar chimney to pull air over the plants for CO_2 supply and heat removal. This passive, solar powered system would have dramatically lowered capital and operating costs, with capital costs estimated to be from 10 to 20 dollars per square meter. There are many other novel ideas in the proposals, providing an example of the kind of new thinking that will be required to go from conventional greenhouse raising of very high value plant crops to the use of CEA for larger scale agriculture.

The system proposed seems designed more for areas with cold winters, however, than for some of the desert lands we are considering. In the desert it may be important to <u>lose</u> as much heat at night as possible rather than retaining it by providing a layer of foam insulation.

At the present time, by far the greatest application of covered agriculture is in countries other than semi-arid and desert lands. For example, Japan is by far the largest user of covered agriculture, with over 10,000 hectares under cultivation in 1973.[30] Other leading countries, in terms of area under cover include The Netherlands, Italy, Belgium, France, the United Kingdom, USSR, Romania, Greece and South Korea.

Some of the most advanced CEA systems are to be found in arid lands. Although relatively small in area, these facilities are often very productive. Such facilities are located in Abu Dhabi, Kuwait, Iran, in Arizona in the U.S., and Puerto Pinasco in Sonora, Mexico. One example of yield obtainable from such facilities is 538 metric tons (fresh weight) per hectare of cucumbers from the one in Abu Dhabi.[31] This facility includes both an air inflated polyethylene structure covering 2.5 hectares, and structured greenhouses covering one hectare. Cooling is by evaporation of seawater, with fans forcing air through the cooler and the greenhouses. Freshwater is obtained by desalting sea water, and considerable care is taken to use this costly water as efficiently as possible. The water vapor from the evaporative cooling by seawater is thus extremely important in preventing excessive water loss to the air from transpiration. Many other important details of engineering and horticulture have been worked out in such installations,[31] and this experience will be a most valuable resource for the development of larger or more advanced systems. Further details of CEA, present and proposed, are discussed by de Bivort, in this workshop.

Can such systems be applied on a large scale to agriculture in arid or semi-arid lands? The author[9,32-34] has proposed covering large areas in dry lands with high greenhouses made from tough, sun-resistant plastic. The structures might by 1 Km^2 in area and 300 meters high (at maximum extension), perhaps with a capacity to go up and down daily. A requirement would be to maintain growing temperatures year round. Under this canopy would be grown high-protein forage legumes such as alfalfa. They would be harvested periodically during the year, leaving after each harvest enough of the plant to produce quickly a good leaf canopy. Growth would be year round. The atmosphere would be enriched in CO_2 and neither water vapor nor CO_2 would be allowed to escape, although some CO_2 would diffuse through the plastic canopy (Figure 4).

While there are serious problems to be overcome with this system (economic, engineering, and physiological), there are a number of important advantages.

1. With year round growth and CO_2 enrichment (photorespiration eliminated), maximum photosynthetic efficiency should be possible. At a 5% conversion efficiency the yield would be about 200 metric tons (dry weight)/hectare-year. The whole plant except for roots would be harvested and used.

2. Most or perhaps all of the nitrogen requirements in legumes would be met by N_2 fixation, due to stimulation at these high photosynthetic rates. Enrichment with CO_2 can result in a five-fold increase or more in N_2 fixation in the root nodules of legumes.[35]

3. Alfalfa grown under optimal conditions has as high as 24% protein content based on dry weight. It is feasible and economic to remove a part of this protein as a high value product using the methods developed at the Western Regional Research Laboratory of the U.S. Department of Agriculture at Albany, California.[36] The residue is a feed for ruminants. Most of the feeding of expensive cereal grains to cattle could be replaced by this alfalfa, and the cereal grains could be sold for human nutrition in the U.S.A. and abroad where there is a rapidly growing market. The protein extract of the alfalfa has a high value as animal (poultry, for example) feed. An interesting alternative is to convert part of it to a protein product for human consumption.[37] Nutritionally it is as good as milk protein[38] and far superior to soy protein. From the 15 metric tons of dry matter removed as juice from the leaves, it might be possible to recover 5 tons of protein, worth $5,000 at $1 per Kg.

4. Land with relatively low value at present because of lack of water could be used because of water recycling. With water vapor containment, only a few percent of the present irrigation requirements for desert land would have to be met.

5. The modular nature of the system would help in the prevention, containment, and elimination of plant diseases.

Since this scheme is envisaged as applicable to areas far removed from the sea, the use of evaporative cooling with sea water was not assumed. Instead, it was proposed to include a high enough canopy to enclose a sufficient volume of air so that the daytime temperature excursion would not be excessive. This might work in the higher cooler desert areas, especially where nighttime temperatures are very low, and sufficient loss of heat through the plastic at night occurs to bring the internal temperature down by morning. Even so, additional cooling powered by solar energy collectors outside the enclosure might be required.

The advantages of a completely closed system over the air flow-through system would be complete retention of water vapor and more effective enrichment with added CO_2.

Of course, there are many problems; some very serious. The greenhouse effect would have to be controlled, perhaps by allowing daily expansion of the canopy. Contraction of the canopy at night would tend to maintain a greater temperature gradient across the plastic between inside and outside, allowing faster heat transfer out through the plastic. Expansion by day would reduce the daytime temperature excursion. The plastic would have to be tough, sun-resistant, not too permeable to CO_2, perhaps capable of synthesis from materials grown under the canopy, and inexpensive. In fact, use of fossil fuels to synthesize the plastic could be avoided by making the plastic from some of the solid biomass residue, after protein extraction. Cellulose could be converted to glucose by treatment with enzymes from the fungi[39] and the resulting glucose could be fermented to give ethanol. Ethanol in turn could be converted to ethylene and thence to polyethylene or other suitable plastic. The insoluble material of plants also contains polymers of xylose. After acid hydrolysis, the xylose can be converted to furfural,[40] a possible starting material for other plastics.

There are other problems, but they may all be solvable. These very serious engineering and economic problems are not to be lightly dismissed, but a discussion of possible solutions will require considerable engineering study to be meaningful.

FUTURE RESEARCH NEEDS

Many areas requiring research and engineering will be evident from the foregoing discussion. some are extensions of already abundant knowledge, such as the identification and characterization of desert plants. Other areas require the development of relatively new research and engineering areas.

Botany and Taxonomy. Identification and listing of abundance of various species of plants in dry lands seems to be very complete in some areas. For example, there is a very detailed study of the plants of the Central-Southern Nevada Area.[41] Probably there are large areas of dry lands where such detailed studies are not yet available, but would be useful both for evaluation of the potential of native plants, and for assessing environmental costs of proposed developments.

Plant Physiology. As indicated earlier, the biochemistry of plant photosynthesis including that of desert plants is widely studied and appears to be well understood. Other areas of plant physiology relating to water and mineral use and conservation may be much less well studied or understood.

Potential of Native Plants to Provide Useful Food, Feed, and Materials. While there may be much historical and cultural knowledge about plants from dry lands as sources of food and feed, there appears to be a need for extensive analysis of plants to determine the amounts and identity of useful constituents. A few examples were given earlier of some plants that are only recently being recognized as sources of valuable substances. Also, there is little information about the potential of crops from native plants if they were systematically cultivated.

Plant Improvement and Adaptation. Experience with temperate zone plants requiring moderate to heavy water application shows that very great increases in productivity, quality of product, resistance to disease, and other desirable properties can be achieved through breeding and other agronomic techniques. Although some plants such as *Zea mays*, capable of growing under semi-arid conditions have been extensively bred and improved, there may be many other plants from arid regions that could also benefit from such programs, particularly if the search is extended to plants useful for chemicals and materials.

Desert Ecology and Management. Although much has been learned, much more remains to be done, particularly with respect to educational programs to help inhabitants of dry lands to make better use of these resources without degradation of the land. The problem of desertification of desert fringe land deserves much attention.

Controlled Environment Agriculture. Although use of greenhouses goes far back in man's history, advanced CEA is in its infancy. The promising starts made by several countries around the Persian Gulf and in the U.S. and Mexico should serve as a beginning for more extensive and sophisticated projects. In particular, systems should eventually be powered entirely by solar energy. There are complex problems of mechanical, chemical, and civil engineering involved.

At the same time, CEA can create new conditions for plant growth for which no plants growing in natural environments are fully adapted. The possibilities are very great for plant breeding to produce plants capable of improved properties suitable for CEA. Among these may be mentioned:

1) High temperature tolerance
2) High growth rates at high temperatures and humidity
3) Maximum use of CO_2 enrichment and ability to tolerate substantial levels of sulfur dioxide
4) Resistance to mildew
5) For legumes, high rates of N_2 fixation under CEA conditions.

No doubt many more could be added to this list.

There is a need for a long range, stable (in terms of financial support) of research and development in CEA, in which engineers, agronomists, economists, plant physiologists, and chemists would interact and work together towards a really new kind of agriculture capable of highly efficient solar energy utilization to produce needed food, feed, and materials.

CURRENT AND FUTURE RESEARCH RESOURCES

Dr. William McGinnies, a discussant for this subject is himself an authority on desert lands management and ecology, and can supply a list of other experts on the various aspects of deserts and their plants mentioned in the preceeding section. Another discussant, Dr. Lawrence de Bivort, has recently compiled an extensive report on CEA and can supply a complete list of research and development resources for CEA. The third discussant, Dr. Bessel Kok, is an authority on photosynthetic energy capture and conversion and can provide names of the principal contributors in that field.

Plant physiologists in the U.S. working on various aspects of plant photosynthetic metabolism and its regulation include: Dr. Clanton Black, University of Georgia; Dr. Gerald Edwards, University of Wisconsin; Dr. Ollie Bjorkmann, Stanford University; Dr. N.E. Tolbert, Michigan State University; Dr. I. Ting, University of California, Riverside; the author; and many others. Dr. Bjorkmann and others at the Carnegie Institute of Washington, Stanford University, have done extensive mobile laboratory studies of desert plants in Death Valley, California, U.S., as well as at Stanford, and have accumulated much information about response to temperature and other environmental factors. Prof. O.H. Lange, University of Wurtzberg, Germany, is an authority on desert plants, including those near the Red Sea. Dr. R. Pearcy at the University of California, Davis, is another expert on physiology of desert plants.

Institutions devoted to the Desert and its resources in the U.S. include the International Center for Arid and Semi-Arid Land Studies at Texas Tech University, the Desert Research Institute in Reno and Boulder

City, Nevada; and The Environmental Research Laboratory (ERL) of the University of Arizona, Tuscon. ERL has designed many of the CEA systems presently in existence including the facilities in Abu Dhabi, Kharg Island, off the coast of Iran, the 4 hectare facility at Environmental Farms, near Tuscon, Arizona and others. The Directór of ERL is Carl Hodges.

The National Science Foundation has played a leading role in various aspects of desert research. Much of the CEA work by ERL is supported by NSF, and NSF funded a study on the Desert Biome for the International Biological Program.

Many more institutions and names could no doubt be added to this list. Given sustained, long range planning and funding in a well managed program with clear goals, there is little doubt that skilled scientists and engineers could be found to do the work. In a relatively short time they would produce a successful program for obtaining abundant supplies of food, feed, chemicals and materials from the desert lands bordering the oceans. This would be done using only the energy of the sun.

TABLE I

PRIMARY PHOTOSYNTHETIC PRODUCTIVITY OF THE EARTH

	Area (total = 510 million Km^2)			Net Productivity (total = 155.2 billion tons dry wt./yr.)		
Total Earth	100			100		
Continents		29.2			64.6	
Forests		9.8			41.6	
Tropical Rain			3.3			21.9
Raingreen			1.5			7.3
Summer Green			1.4			4.5
Chaparral			0.3			0.7
Warm Temperate Mixed			1.0			3.2
Boreal (Northern)			2.4			3.9
Woodland		1.4			2.7	
Dwarf and Scrub		5.1			1.5	
Tundra			1.6			0.7
Desert Scrub			3.5			0.8
Grassland		4.7			9.7	
Tropical			2.9			6.8
Temperate			1.8			2.9
Desert (Extreme)		4.7			0	
Dry			1.7			0
Ice			3.0			0
Cultivated Land		2.7			5.9	
Freshwater		0.8			3.2	
Swamp & Marsh			0.4			2.6
Lake & Stream			0.4			0.6
Oceans		70.8			35.4	
Reefs & Estuaries			0.4			2.6
Continental Shelf			5.1			6.0
Open Ocean			65.1			26.7
Upwelling Zones			0.08			0.1

Percentages based on data presented by H. Lieth at the Second National Biological Congress, 1971.[7]

TABLE II

MAXIMUM PHOTOSYNTHETIC PRODUCTIVITY AND MEASURED MAXIMUM YIELDS IN SELECTED PLANTS

	Assumed Radiation Kcal/cm^2·yr	gm/m^2·day	metric tons/ hectare yr.	eff. %
Theoretical max. (Table II)				
High Solar Desert ann.	200	86	313	6.6
U.S. Average annual	144	61	224	6.6
U.S. Southwest ave. ann.	168	72	263	6.6
U.S. Southwest, summer	247	106	387	6.6
Maximum Measured				
C-4 Plants				
Sugar cane	247	38	(138)*	2.4
Napier grass	247	39	(139)	2.4
Sudan grass (Sorghum)	247	51	(186)	3.2
Corn (Zea mays)	247	52	(190)	3.2
C-3 Plants				
Sugar beet	247	31	(113)	1.9
Alfalfa	247	23	(84)	1.4
Chlorella	247	28	(102)	1.7
Annual Yield				
C-4 Plants				
Sugar cane	168	31	112	2.8
Sudan grass (Sorghum)	168	10	36	0.9
Corn (Zea mays)	168	4	13	0.4
C-3 plants				
Alfalfa	168	8	29	0.7
Eucalyptus	168	15	54	1.3
Sugar beet	168	9	33	0.8
Algae	168	24	87	2.2

*Parentheses indicate maximum rates. Since these are not sustained over a whole year, they are much higher than annual yields.

Figure Captions

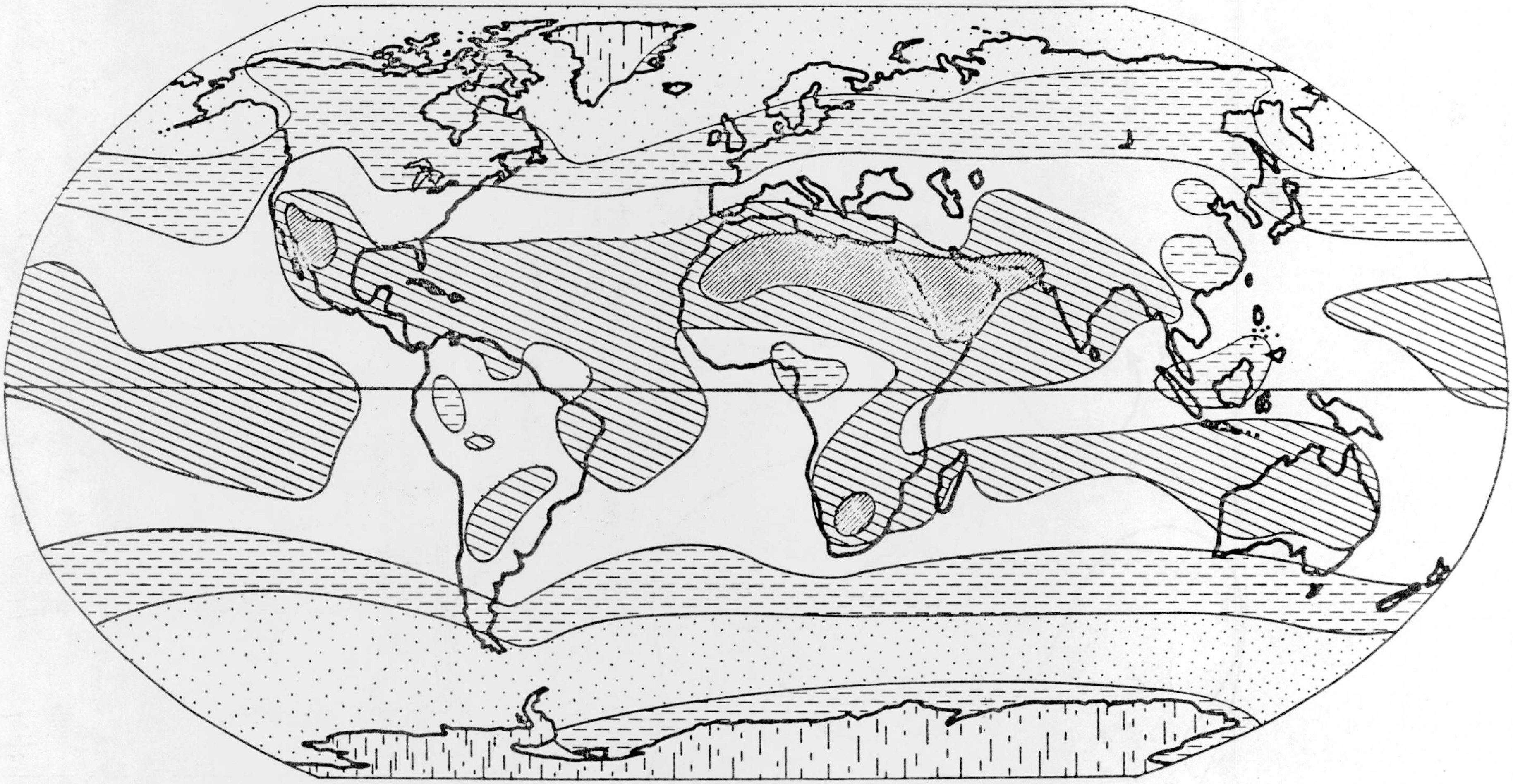
Figure 1. Mean Annual Insolation--Worldwide. Smaller area local variations are omitted in this global map in order to provide a general view of incidence of solar energy at the earth's surface. The figures are for total insolation over one year.

Figure 2. The reductive pentose phosphate cycle. The heavy lines indicate reactions of the RPP cycle; the faint lines indicate removal of intermediate compounds of the cycle for biosynthesis. The number of heavy lines in each arrow equals the number of times that step in the cycle occurs for one complete turn of the cycle, in which three molecules of CO_2 are converted to one molecule of GAl3P. Abbreviations: RuDP, Ribulose 1,5-diphosphate; PGA, 3-phosphoglycerate; DPGA, 1,3-diphosphoglycerate; NADPH and $NADP^+$, reduced and oxidized nicotinamide-adenine dinucleotide phosphate, respectively; GAl3P, 3-phosphoglyceraldehyde; DHAP, dihydroxyacetone phosphate; FDP, fructose 1,6-phosphate; G6P, glucose 6-phosphate; E4P, erythrose 4-phosphate; SDP, sedoheptulose 1,7-diphosphate; S7P, sedoheptulose 7-phosphate; Xu5P, xylulose 5-phosphate, R5P, ribose 5-phosphate; Ru5P, ribulose 5-phosphate; and TPP, thiamine pyrophosphate.

Figure 3. The C-4 cycle of photosynthesis. This is one version of the preliminary CO_2 fixing cycle which occurs in certain tropical grasses as well as in a scattering of other plant species. This cycle by itself does not result in any net fixation of CO_2 into

organic compounds, but rather serves as a vehicle to move CO_2 from cell cytoplasm and perhaps outer leaf cells into the chloroplasts of the vascular bundle cells in these plants. This CO_2 transport is thought to be responsible for the minimization of photorespiration in these cells (see text). In some plants, another version (not shown) of the C-4 cycle is found in which OAA is converted to aspartate rather than malate for transport. Abbreviations: PEPA, phosphorenolpyruvate; OAA, oxaloacetate.

Figure 4. Scheme for energy and protein production by covered agriculture. Alfalfa, grown under transparent cover year-round with CO_2 enrichment, would be harvested and processed to remove some protein as a valuable product. The residue would be used as animal fodder or, in the version shown here, as fuel for power plants. Combustion CO_2 and H_2O from this and fossil fuels would be returned to the greenhouses.

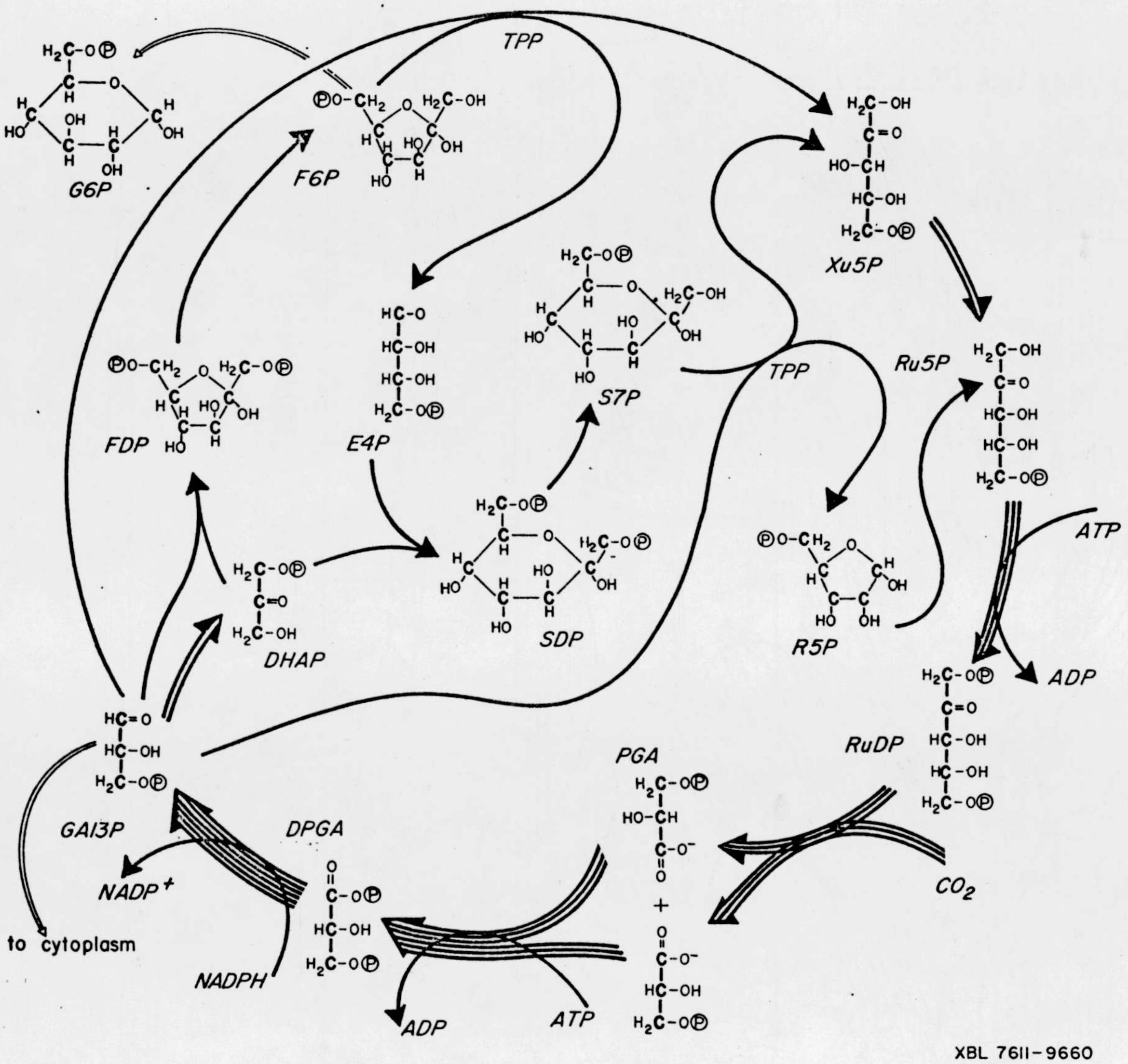


MEAN ANNUAL INSOLATION

kcal/cm²/yr. (1.33 W/m²)

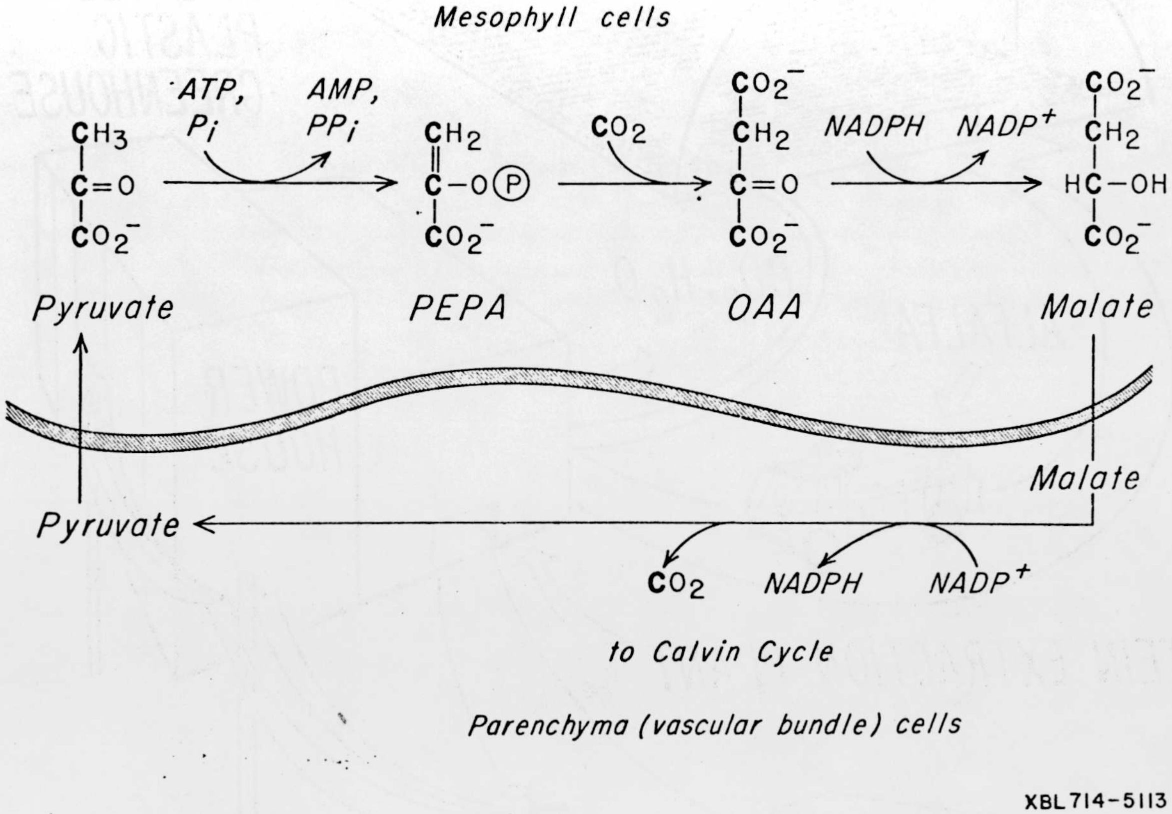
Bassham, J.A.

Fig. 1



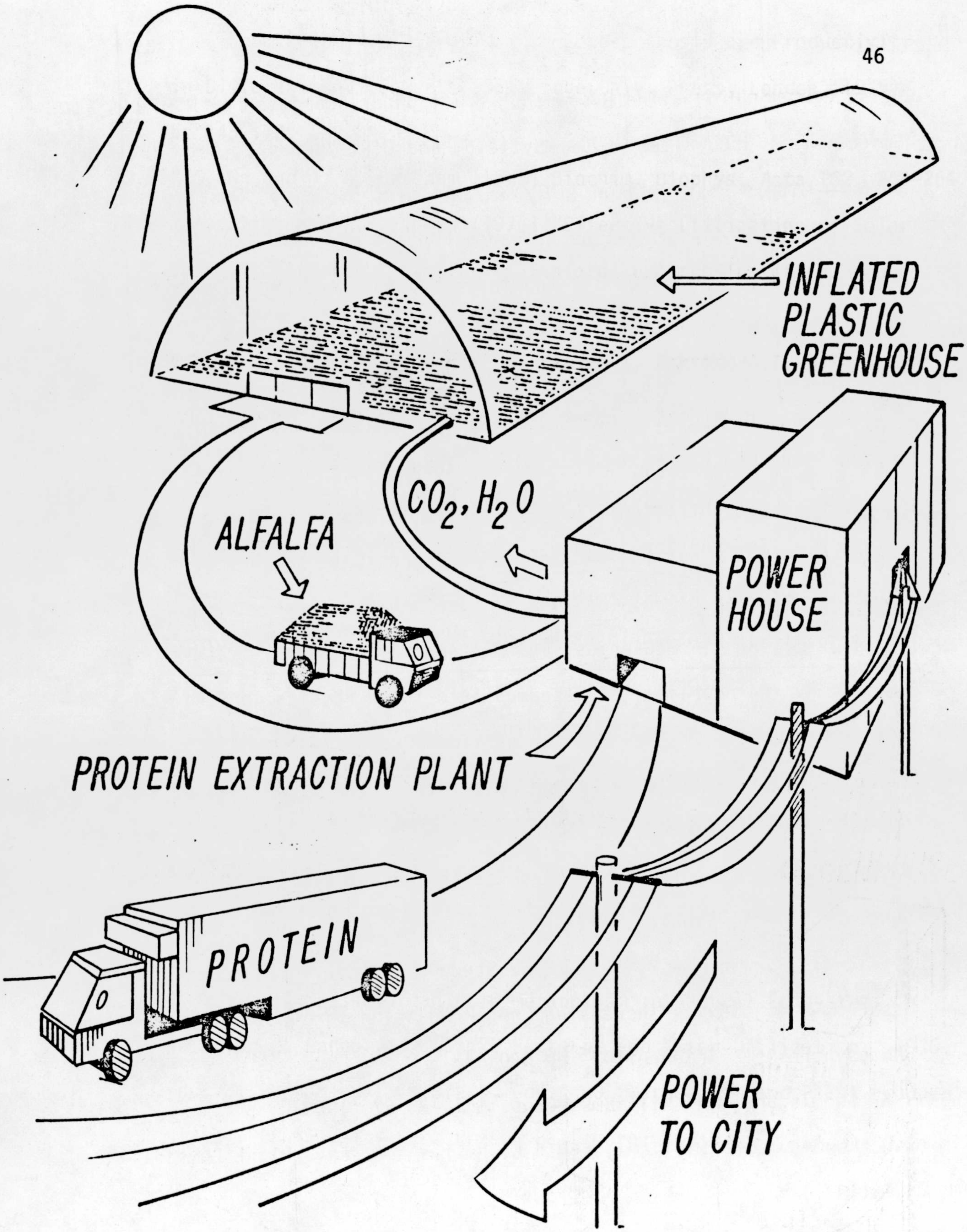
Bassham, J.A.

Fig. 2



Bassham, J. A.

Fig. 3



Bassham, J.A.

Fig. 4

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