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James A. Bassham

Photosynthesis in green plants is the ultimate source of all organic compounds including cellulose and food. Even the fossil fuels used by man for energy and synthesis of organic chemicals is the product of photosynthesis in past geologic eras. The combustion of cellulosic products of photosynthesis such as wood and straw by fire is one of the oldest forms of energy used by man. For stationary power sources, the direct combustion of cellulosic fuels, followed by conversion of the resulting heat to electrical energy via conventional power plants may be the most economic process for utilization of such fuels. Another possibility is to obtain efficient conversion of cellulosic waste to higher value organic products to be used for food, for the chemical industry or as portable, clean fuels.

Whether or not cellulose can be used for these purposes will depend not only on conversion costs but also on the cost of the cellulose. The industrial conversion of cellulose will therefore be based on utilization of readily available free or very inexpensive waste products from municipal trash collections, forest products and agriculture. Not only the cost, but also the quality and cellulose content of these sources will be important in determining the economics of processing. There are already competing uses, occurring or projected, for much of the most available cellulosic wastes. For example, paper wastes may be recycled for use as paper or shredded and fed to ruminants for biological conversion to protein. There is a well established industry for the conversion of sawdust and other wastes from lumber production into commercially valuable products. To a lesser extent use is made, or is planned, for agricultural wastes such as rice hulls.

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This being the case, we might give some consideration to agricultural production of fast growing plants for the production of cellulose and other organic compounds.

The special raising of crops for their cellulose is one aspect of "energy farming". The feasibility of such an agriculture is the subject of later papers in this session, and I will mention only some basic considerations. It is an unfortunate but not wholly coincidental fact that mankind is entering into an era of decreasing fossil fuel energy supply at the same time as there is an impending worldwide food shortage of frightening proportions. Available land suitable for agriculture is going to be sorely needed for food production. The techniques for increasing the productivity of such land often rely heavily on high energy consumption. An example is the use of chemical fertilizer which requires fossil fuel consumption for its manufacture. While it is true that much of the energy costs of food in a technologically advanced country are related to food processing, distribution and home preparation,[1] it is also true that in countries with chronic food shortages, the increased cost of fossil fuels needed for fertilizer production and other agricultural energy costs threatens some of the increased productivity that has been achieved by the "green revolution". At the same time, if we are to believe long range meteorological forcasts, the global climatic pattern during the next decade or longer may be more unfavorable for food production in some of the areas already most pressed by food shortages. When coupled with the ever increasing population in those countries, this means that hungry people will more than ever have to turn to those very few countries like the United States which have traditionally been able to produce agricultural surpluses. Unfortunately, this comes at a time when such surpluses are rapidly disappearing, due to increased internal and worldwide commercial demand. The export of agricultural surpluses in trade appears in fact to be one way the U.S. might keep its trade in balance, given the increased cost of fossil fuel imports.

What all this means in the context of energy farming is that most of the land suitable for conventional agriculture seems likely to be needed for food production. If cellulosic wastes can be obtained as byproducts from such food production, good; but we should not plan on using agricultural land solely for energy farming. There is another alternative, however, and that is to make use of areas not suitable for conventional agriculture or forest crops. To support the expense of using such areas, we must optimize photosynthetic productivity and perhaps should produce not only cellulose, but some other high value product such as protein at the same time.

As a necessary background for evaluating such projects we need to consider the essential points of photosynthetic energy conversion and productivity. Photosynthesis on earth results in 155 billion tons dry weight of primary productivity per year (Table I). Of this, about two-thirds is on land, and one-third in the oceans, which constitute 70% of the earth's surface. In the open ocean, the primary productivity is so diffuse that there is very little production useful to man. This is because nutrients, especially phosphate, are limiting. Fisheries are located in reefs and estuaries, upwelling zones and continental shelves. In any event, most natural ocean productivity appears to be a poor source of cellulose. However, with techniques of ocean farming that we will hear described in a later paper, it may be possible to utilize some ocean areas.

Of the 64.5% of total productivity on land, by far the larger part is in forests and woodlands. Some of these forests are of course the traditional sources of cellulose in the form of lumber and wood pulp for paper.

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.

The removal of substantial amounts of timber from these forests causes varying degrees of ecological damage, depending on the removal practices, nature of the forest and land, and other factors. Thus, while waste products from the forest industries presently established may be useful as cellulose sources, it is questionable whether any greatly increased harvesting of forest lands for energy would be a wise practice. The tropical rain forests, which have 22% of the primary productivity on only 3.3% of the area, are particularly vulnerable to ecological damage when trees are removed.

As already suggested, the 2.7% cultivated land which accounts for 5.9% of primary productivity, mostly food and fiber, is going to be needed mostly for agriculture, although cellulosic byproducts can be used. Some of the temperate grassland in the U.S. might be suitable for energy farming in view of the high yields of certain grasses, but much of this land is already used for grazing of animals in agriculture, and is thus a source of protein. Where there is adequate rainfall, or the land can be irrigated, it is likely to become cultivated land.

Considering other areas of the U.S. receiving high annual solar irradiation (Table II), we come to the Dry Desert and Desert Scrub. In fact, the U.S. Southwest (Arizona, Nevada, New Mexico, Southern California, Southern Utah, and

TABLE II

SOLAR ENERGY AT EARTH'S SURFACE IN U.S.

	$B.t.u./ft^2 \cdot day$	$cal/cm^2 \cdot day$	$Kcal/m^2 \cdot day$	$watts/m^2$
U.S. Average (annual basis)	1,450	393	3,930	190
U.S. Southwest (annual basis)	1,700	461	4,610	223
U.S. Southwest (summer)	2,500	678	6,775	329

West Texas) which contains much of such land has by far the highest sunlight, averaging about 1,700 B.t.u./$ft^2 \cdot day$, 461 cal/$cm^2 \cdot day$, or 223 watts. When land in this area can be irrigated, as in the Imperial and Central valleys of California, the agricultural productivity is very great. Some of the high yields shown in Table III were obtained in such areas. However, the high surface irradiance is related not only to latitude but also to lack of cloud cover, and water is a scarce commodity in much of this area. Thus if the desert is to be farmed, beyond the forseeable limited increase in irrigated area, it must be done in a closed system to conserve water. I will return to this point later.

Given the amount of solar energy available at the earth's surface, the maximum yield of expected photosynthetic product may be calculated (Table II). Using essentially the estimates of Loomis _et al_.,[2] we find that for land plants, we can expect a theoretical maximum efficiency of about 5.3% conversion of total solar irradiance to energy stored in the chemical form of cellulose. While this low figure may seem disappointing, it is much greater than the 0.1 to 0.2% commonly seen in agricultural products. This is, of course, partly because it is based on total dry weight (arbitrarily considered equivalent to cellulose) rather than the stored energy of seeds or roots.

The 5.3% figure results from a combination of several factors. First, photosynthetically active radiation (P.A.R.) constitutes only 43% of the total radiation (T.R.) reaching the earth's surface. Most of the remaining radiation is of wavelengths too long to be used by green plants. Only about 80% of P.A.R. can be absorbed by an optimal leaf canopy.

The energy of the photosynthetically active radiation ranges from about 70 Kcal per einstein (an einstein is one mole or 6×10^{23} photons) for violet light (λ = 400 nm) to about 40 Kcal for red light (λ = 700 nm); the mean

TABLE III

MAXIMUM EFFICIENCY OF LAND PLANTS

1. P.A.R. / T.R. = 0.43
2. Maximum Leaf Absorption = 0.8
3. Efficiency of Absorbed Light Conversion = 0.23
4. (Photosynthesis-Respiration)/Photosynthesis = 0.667

Overall Efficiency = (0.43)(0.8)(0.23)(0.667) = 0.053

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1. P.A.R. = photosynthetically active radiation

   T.R. = total solar irradiance at earth's surface

2. Optimal leaf canopy can absorb about 80% of P.A.R.

3. For the reaction,

$$CO_2 + H_2O \longrightarrow \underset{\text{1/6 glucose}}{\{CH_2O\}} + O_2 \qquad \Delta G = +115 \text{ Kcal}$$

about 10 einsteins are required. P.A.R. is from 400 nm (violet) to 700 nm (red); mean λ = 575 nm.

$E = 10 \cdot Nhc/\lambda = 10 \cdot 28{,}600/\lambda_{nm}$ Kcal — $N = 6 \times 10^{23}$

$E = 10 \cdot 28{,}600/575 = 10 \cdot 49.74 = 497.4$ Kcal — c = velocity of light

Eff = 115/497.4 = 0.2374 — h = plank's constant

4. Respiration (at night, low light) ranges from about 0.2 to 0.4 of photosynthesis, depending on species and environment. Here we used 0.333, so net photosynthesis is reduced to 0.667.

energy for light used by green plants is about 49.74 Kcal, corresponding to λ = 575 nm. About 10 einsteins must be absorbed for each mole of CO_2 reduced to sugar according to the equation

$$CO_2 + H_2O \xrightarrow{\text{10 einsteins}} \underset{\text{1/6 glucose}}{\{CH_2O\}} + O_2 \qquad \Delta G = +115 \text{ Kcal}$$

which results in an energy storage of 115 Kcal. Thus the efficiency of the actual photosynthetic process is about 115/10(49.74) = 23.1%.

At night plants respire, undoing the work of photosynthesis, so that there is a net storage of only 66.7%. Multiplying these factors together, (0.43)(0.231)(0.80)(0.667), we get 0.053, or 5.3%.

The dry weight of a plant is, of course, a complex mixture, containing varying amounts of cellulose, sugars, proteins, fats, etc. For our present purpose we make the calculation as if all the dry weight were cellulose. For the kind of fast-growing, woody plants and grasses often considered for energy farms this is probably not too misleading an assumption.

Each mole of CO_2 reduced produces 1/6 glucose moiety. The molecular weight of glucose is 180, but in cellulose one water molecule is removed per glucose added to the chain, so the molecular weight of cellulose per CO_2 reduced is 162/6 = 27. For each Kcalorie of total radiation, 0.053(1000) = 53 Cal are stored, enough for 53/115 = $0.461 \cdot 10^{-3}$ moles. This corresponds to $0.46 \cdot 10^{-3} \cdot 27$ = 12.4 mg of cellulose. Thus, for the U.S. Southwest annual average, 4610 Kcal/m^2·day, a dry weight yield of about 57.4 g/m^2·day could be expected.

How close can plants in the field come to this maximum rate of productivity? A selection from scattered reports (the sources are not given here; these are intended only as indicative of maximum reported yields) shows that

TABLE IV

MAXIMUM PHOTOSYNTHETIC PRODUCTIVITY AND MEASURED MAXIMUM YIELDS IN SELECTED PLANTS

	$g/m^2 \cdot day$	tons/acre·yr.	metric tons/hectare·yr.
Theoretical max. at 12.5 μg/cal (Table II)			
U.S. Average annual	49	80	179
U.S. Southwest ave. ann.	57	94	210
U.S. Southwest, summer	85	138	309
Maximum Measured			
C-4 plants			
Sugar cane	38	(62)	(138)
Napier grass	39	(64)	(139)
Sudan grass (Sorghum)	51	(83)	(186)
Corn (Zea mays)	52	(85)	(190)
Non C-4 plants			
Sugar beet	31	(51)	(113)
Alfalfa	23	(37)	(84)
Chlorella	28	(46)	(102)
Annual Yield			
C-4 plants			
Sugar cane	31	50	112
Sudan grass	10	16	36
Corn (Zea mays)	4	6	13
Non C-4 plants			
Alfalfa	8	13	29
Eucalyptus	15	24	54
Sugar beet	9	15	33
Algae	24	39	87

a substantial fraction of the expected maximum yield has been achieved under certain optimal conditions. For example, the reported annual growth rate of 50 tons/acre·year dry weight of sugar cane in Texas corresponds to an energy conversion efficiency of about 2.8% of total incident irradiation. This appears to be about the highest growth rate and efficiency to have been achieved on an annual basis in the U.S., but higher rates and comparable efficiencies have been reported for other plants during their periods of maximum growth.

Frequently, but not always, the highest growth rates are achieved with C-4 plants, such as sugar cane. The term "C-4 plant" has been used to designate certain plants of tropical origin which have an extra, preliminary CO_2 fixing pathway in addition to the reductive pentose phosphate cycle, or Calvin Cycle. This pathway functions to pump CO_2 into the vascular bundle chloroplasts of the cell where the Calvin Cycle enzymes are located.

With non-C-4 plants, in air which contains only 0.03% CO_2, as light intensity and photosynthesis rate increases, the CO_2 level inside the chloroplasts drops until the process of photorespiration becomes significant. Eventually, with increasing light intensity, a point is reached where any further increase in photosynthesis rate which might result from a higher rate of fixation of CO_2 is offset by the CO_2 being liberated by photorespiration.

In C-4 plants, the higher level of CO_2 in the vascular bundle chloroplasts apparently minimizes photorespiration. Moreover, if CO_2 is produced by this process it is recaptured, along with incoming CO_2 from the air, by the C-4 carboxylation mechanism, in which CO_2 is added to the three carbon compound, perhaps in the outer, mesophyll, cells (there is a current argument about this). The carboxylation product is reduced to another C-4 acid which is translocated into the vascular bundle chloroplasts where oxidative decarboxylation releases CO_2 and reduced NADP, plus the three carbon acid pyruvate, which is translocated back to the site of C-3 carboxylation. Finally, adenosine triphosphate (ATP) made by the light reactions is used to convert pyruvate and phosphate back to phosphoenolpyruvate, completing the C-4 cycle.

What this means is that plants with C-4 metabolism (first discovered by Kortschak, Hartt and Burr[3]) are able to function efficiently under conditions of high light intensity at air levels of CO_2 without paying the penalty of photorespiration. However, it means that photosynthetically active non-C-4 plants could perform just as efficiently if given a higher level of CO_2. In fact, this has been experimentally demonstrated, as shown in Table IV, from the excellent review on "Maximum Production Capacity of Food Crops" by S. H. Witwer.[4] It is noteworthy that the response to elevated CO_2 is generally greater for non-C-4 plants. Another significant finding from the studies with increased CO_2 is that there is a great increase in N_2 fixation by legumes.[5]

One conceivable solution to the problem of economic cellulose farming might be to raise some crop in the U.S. Southwest desert by employing a closed system (to recycle water). If such a closed system were used, CO_2 pressure could be elevated to perhaps 0.2%, permitting a choice of plants to be made without regard to whether or not they were C-4 plants. At the present time, covered or greenhouse agriculture is only considered economic for very high value crops, such as flowers and tomatoes in the winter. However, with new technology, including the use of transparent plastic instead of glass, the cost could drop.

TABLE IV

(Data from Witwer[5])

RATES OF PHOTOSYNTHESIS AT AIR LEVELS AND ELEVATED LEVELS OF CO_2

(milligrams $CO_2/dm^2 \cdot hr$)

Plant	Air	Elevated CO_2
Corn, Grain Sorghum, Sugar Cane	60-75	100
Rice	40-75	135
Sunflower	50-65	130
Soybean, Sugarbeet	30-40	56
Cotton	40-50	100

At the U.S.D.A. Western Regional Research Laboratory, scientists have developed methods of extracting protein from alfalfa in a form suitable for human nutrition.[6] This is interesting because very high yields of protein per acre can be obtained in the leaf protein of alfalfa, and this leaf protein has excellent nutritional properties--even better than soy protein. Present processes by no means extract all the leaf protein. Most is left in so that the alfalfa residue still is a protein-rich animal feed. However, altering the process to extract most of the protein and other soluble components, leaving only a cellulose residue seems a possibility.

Suppose that the yield of some leafy crop capable of many harvests per year could be boosted in the presence of 0.2% CO_2 to be equal to the dry weight yield of sugar cane in Texas to 40 tons/acre·year. Further, suppose that from this dry weight, 10 tons of vegetable protein and 25 tons of cellulose and sugars could be recovered. At 1 dollar a pound, the protein would be worth $20,000. This is an order of magnitude less than the value of greenhouse crops considered to be economic at present, but given the world food shortage and improved technology, there might be a crossing point at some future date. At the same time, the 25 tons of cellulose and sugars would represent about 1.5% energy efficiency, based on total irradiance. This is not very good, but the cost of the installation per mi^2 might be enough less than, say, silicon cells or heat pipes and optical systems to justify consideration.

There are, of course, other serious problems with such a proposal. For example, there would be severe problems of heat disposal, economic harvesting, planting, etc. Even if the temperature under the cover can be kept at a level where plant growth is possible, conditions would be hot and humid. Some other leafy plant with high growth rate and protein content would doubtless prove more suitable than alfalfa. A program of plant breeding might be required to produce plants with suitable characteristics.

The above suggestion is advanced mainly for discussion purposes at this time. It does bring together the elements previously discussed: (1) production of cellulose along with an economically valuable food product, (2) utilization of land not required for agriculture at present, but without destruction of ecologically important forests, (3) use of areas with high sunlight, but with a limited supply of water, and (4) use of CO_2 enrichment to obtain maximum production. Obviously, much research would have to go into the selection and utilization of the best crop and technology before such a scheme could even begin to approach practicality.

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