SEVENTH SESSION

Photosynthetic Limits on Crop Yields

Photosynthesis: its Relationship to Overpopulation

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At this symposium we are discussing photosynthesis in all its various aspects —from its energy requirements to its maximum efficiency in converting carbon dioxide and water to food. Up to this point in man's history, photosynthesis is the only source of food on earth and its capacity may ultimately determine the number of people who can live on this planet without starvation.

How many people can live on earth if photosynthesis is the limiting process? To answer this question, the potential photosynthetic capability of green crop surfaces has to be estimated and related to the energy requirements of man.

In calculating the potential rate of photosynthesis, we must assume that neither water nor minerals are limiting. In previous talks during this meeting

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the relationship of light intensity to photosynthesis has been discussed. At low light intensities photosynthesis of leaves is proportional to light intensity, but at higher light intensities a maximum value is reached. The initial slope of the photosynthesis function does not seem to vary much with species and is in the neighborhood of 3.6 kg carbohydrate/ha · hr* for each 0.01 cal/cm^2 · min absorbed by the leaves. From species to species maximum photosynthesis at high light intensities may vary considerably. However, for individual leaves of agriculturally important species, we can use for discussion purposes an average value of about 20 kg carbohydrate/ha · hr.

Leaves that absorb a light intensity of 0.2 cal/cm^2 · min already operate close to this maximum. This light intensity occurs on an overcast day with the sun in the zenith. The light intensity on a clear day may amount to 0.8 cal/cm^2 · min so that a large proportion of the light must go to waste for crops with large, horizontally displayed leaves. However, crops consist of small leaves displayed in many directions so that the light is more evenly distributed over the leaves and photosynthesis is accordingly higher.

Calculating crop photosynthesis is primarily a geometrical problem and can be tackled by means of a computer (1). The factors which must be taken into consideration are the photosynthesis function, the scattering coefficient, the leaf area index, the leaf display, the light intensity, and the direction of the incoming light. This latter factor depends on the condition of the sky and the height of the sun.

In a crop consisting of leaves with a scattering coefficient of 0.3, a photosynthesis function with a maximum rate of 20 kg carbohydrate/ha · hr, a leaf area index of 5, and a leaf display for small grains or young grass, photosynthesis on a perfectly clear day is 35, 50, and 55 kg carbohydrate/ha · hr with the sun at a height of 30, 60 and 90 degrees, respectively. Now these rates are certainly higher than the maximum for a single leaf. This important increase in photosynthesis is a result of light distribution. With overcast skies, the light intensity is about one-fifth the light intensity of a clear sky, but photosynthesis is reduced only by one-half because the light is very evenly distributed.

Returning to the problem of the daily photosynthetic productivity for a specific geographical location, this total depends also on sky conditions, latitude, and date. Under our conditions in the Netherlands (52° north latitude), crop photosynthesis is described by the model as 75, 190, 350, and 210 kg carbohydrate/ha · day on the 15th of December, March, June, and September. These totals, however, depend on temperature and can only be reached

*All calculations are in the metric system.

1 kilogram (kg) = 2.21 pound (lb)
1 hectare (ha) = 2.47 acre
1 kg/ha = .891 lbs/acre

This latter conversion factor is so close to 1 that one may read lbs/acre for kg/ha.

when the average 24-hour temperature is about 50°F or higher. In the Netherlands, these temperature conditions prevail from mid-April to mid-October. Adding daily totals for this period, the potential photosynthesis of a crop surface in the Netherlands is 50,000 kg carbohydrate/ha. This figure is too high because losses due to respiration are not taken into account and due to the fact that the crop surface is not always closed. To correct for these factors, we can assume half this value. Now there is one other factor which affects the validity of the 25,000 kg organic material/ha figure if we are thinking in terms of the number of individuals which can be fed per hectare. Not all of the 25,000 kg carbohydrate are usable for human consumption. This figure must again be halved – giving 12,500 kg organic material/ha as suitable food. This corresponds to nearly 300 bushels of corn or 70,000 pounds of potatoes per acre – high, but achievable, yields.

What does this mean in terms of population? Twelve thousand five hundred kilograms of carbohydrate contain about 50 million kilocalories of energy. Each human requires about 1 million kilocalories per year as food. Theoretically, therefore, one hectare in the Netherlands can support about 50 persons. On this basis, a rule might be established that the number of persons who can exist on one hectare is equal to the potential photosynthesis of that hectare expressed in tons. Should the necessity of apportioning people to

TABLE I

The Potential Productivity of Earth and the Population it Could Support

				m²/man to support life				
				No allowance for urban and recreational needs		750 m²/man for urban and recreational needs		
North Latitude (degrees)	Land Surface in ha ($x10^8$)	Number Months above 10°C	Carbohydrate/ha · yr in kg ($x10^3$)	m²/man	no. men ($x10^9$)	m²/man	no. men ($x10^9$)	Percentage Agricultural Land
Column 1	2	3	4	5	6	7	8	9
70	8	1	12	806	10	1556	5	52
60	14	2	21	469	30	1219	11	38
50	16	6	59	169	95	919	17	18
40	15	9	91	110	136	860	18	13
30	17	11	113	89	151	839	20	11
20	13	12	124	81	105	831	16	10
10	10	12	124	81	77	831	11	10
0	14	12	116	86	121	836	17	10
−10	7	12	117	85	87	835	9	10
−20	9	12	123	81	112	831	11	10
−30	7	12	121	83	88	833	9	10
−40	1	8	89	113	9	863	1	14
−50	1	1	12	833	1	1583	1	53
Total	131				1022		146	

land area become a reality, this formula would not permit the growing of protein-rich food or the conversion of carbohydrates to meat, but this problem will be discussed later.

Using the calculations described above, the potential production of the earth has been estimated in 10-degree latitude intervals (Table I). The land surface in hectares and the number of months in which the average temperature is above 50°F is shown. Then the potential photosynthesis is shown and, derived therefrom, the land surface necessary to grow food for one person and the number of men that can live from the land area at that latitude (column 6). The values vary from 80 m^2 per person in the tropics to 800 m^2 per person in the higher latitudes. The staggering conclusion to be drawn from this table is that 1,000 billion people could live from the earth if photosynthesis is the limiting factor!

This is how many could live *from* the earth; not *on* the earth. A dense population can only be maintained in an affluent society and an affluent society has been estimated (2) to require at least 350 m^2 (0.087 acres) per person for urban use. Additional recreation areas may add another 350 m^2 per person to the total. This figure is probably underestimated since the region from Boston to Washington covers an area of 138,000 km^2 and includes metropolitan areas of 27,500 km^2 occupied by 37 million people. This amounts to about 750 m^2 (0.19 acre) per person for urban needs only.

To obtain an estimate of the total land use per person (column 7 in Table I), 750 m^2 is added to the values in column 5 which represent the land necessary to support life per person. Division of the amount of land available by the total land needed for each individual gives a figure of 146 billion people. This figure, 146 billion, may be somewhat too high since some land is not suitable for urban use, agriculture, or even recreation. On the other hand, the value may be increased by shifting a part of the population from highly productive areas in the tropics to more northern latitudes. The percentage of land that is necessary for agricultural purposes is shown in column 9. This amounts to not more than 15% of the land surface of the world. In an advanced technological age where parts of the deserts may be irrigated, this is probably available.

The number of persons who can live on the earth can be increased only a little by increasing the yields per unit surface because most of the land is necessary for other purposes than growing food. A yield increase of 30% leads only to an increase of the maximum number of people by 3%. Even if all the production could be obtained from the sea, the maximum number would increase only 20%, from 146 billion to 175 billion.

The sea can be neglected as a source of food because the amount of minerals that must be added to keep so much water in a reasonable nutritional status is prohibitive. The organic matter produced by plankton at the present nutritional status is only 5% of the potential photosynthesis of a comparable land area. Of this organic matter, only 1% can be harvested in the form of fish, so food production of the sea is only 1/500 of food production on land. With a population of 146 billion, 2,500 m^2 of sea surface is available per man. This is the equivalent of $2500/500 = 5$ m^2 of land.

Suppose that each person consumes an additional 200 g (0.4 lb) of meat per day. About 5,000 kcal in the form of vegetable fodder products is necessary to grow this amount of meat which contains, on an energy basis, 500 kcal. In that case, each man will need about two times more land for agricultural purposes. This amount is still so small compared to other needs that the maximum population totals 126 billion. However, if we estimate that the need for land for non-agricultural purposes will be 1500 m^2 rather than 750 m^2 per person, the 146 billion total population figure is reduced to nearly one-half, i.e. a population of 79 billion. The agricultural land required for

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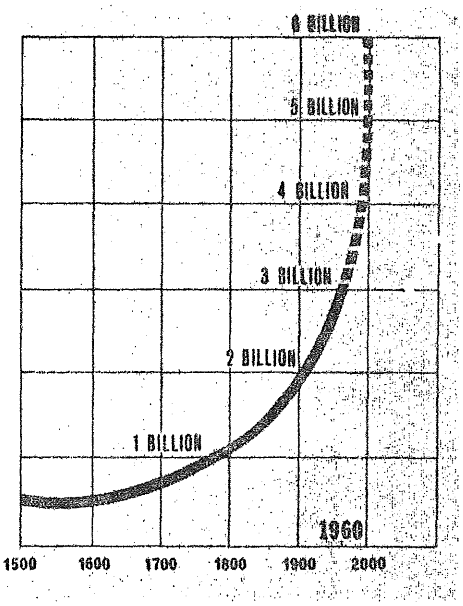

79 billion people would equal about 7% of the earth – an area which is readily available. The number of persons on earth is, therefore, ultimately limited by the amount of space a man needs to work and live in reasonable comfort and not by the production of food. In the long run a situation of over-population without starvation must be visualized.

At present there are about 3 billion men living on earth. The predictions are that there will be 6-7 billion around the year 2000. At this rate of increase, the number of 100 billion will be reached in 200 years. At that time starvation may be a bitter memory only, but today many, many persons go hungry in a world where the technical ways and means to prevent this are available.

REFERENCES

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2. L. H. J. Angenot, "Living Space". Symposium on men in dense packing, Amsterdam, Netherlands, 1966.