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food production: past, present and future

Agriculture without fertilizers

In the early Middle Ages the fifteen monks and some servants at the monastery of a Saint Symphorien in Antver in France just managed to live on the excess produce from 100 families. These family farms did not produce more than 800 kg of grain per hectare and, because of bad seed quality and the presence of weeds, about 200 kg of this yield was required for seed the next year. Roughly half the net yield of 600 kg per hectare was needed for the draught animals and for beer (after all, the quality of the water was poor and the meat was salt), so that the remaining 300 kg per hectare was just sufficient to feed the person who did the work.

The low yields in Western Europe were due not so much to shortage of water or an adverse climate, but to a lack of plant nutrients. We know now that, expressed in traditional units ($N+K_2O+P_2O_5$), only 25 kg of nutrients per hectare were available each year for the growth of the crop and that these small amounts enabled the production of only about 1500 kg of dry matter per hectare. Since all plants need leaves, and cereals also need a stem to carry the ear, only about 50 percent of this plant material was recovered in the form of seeds.

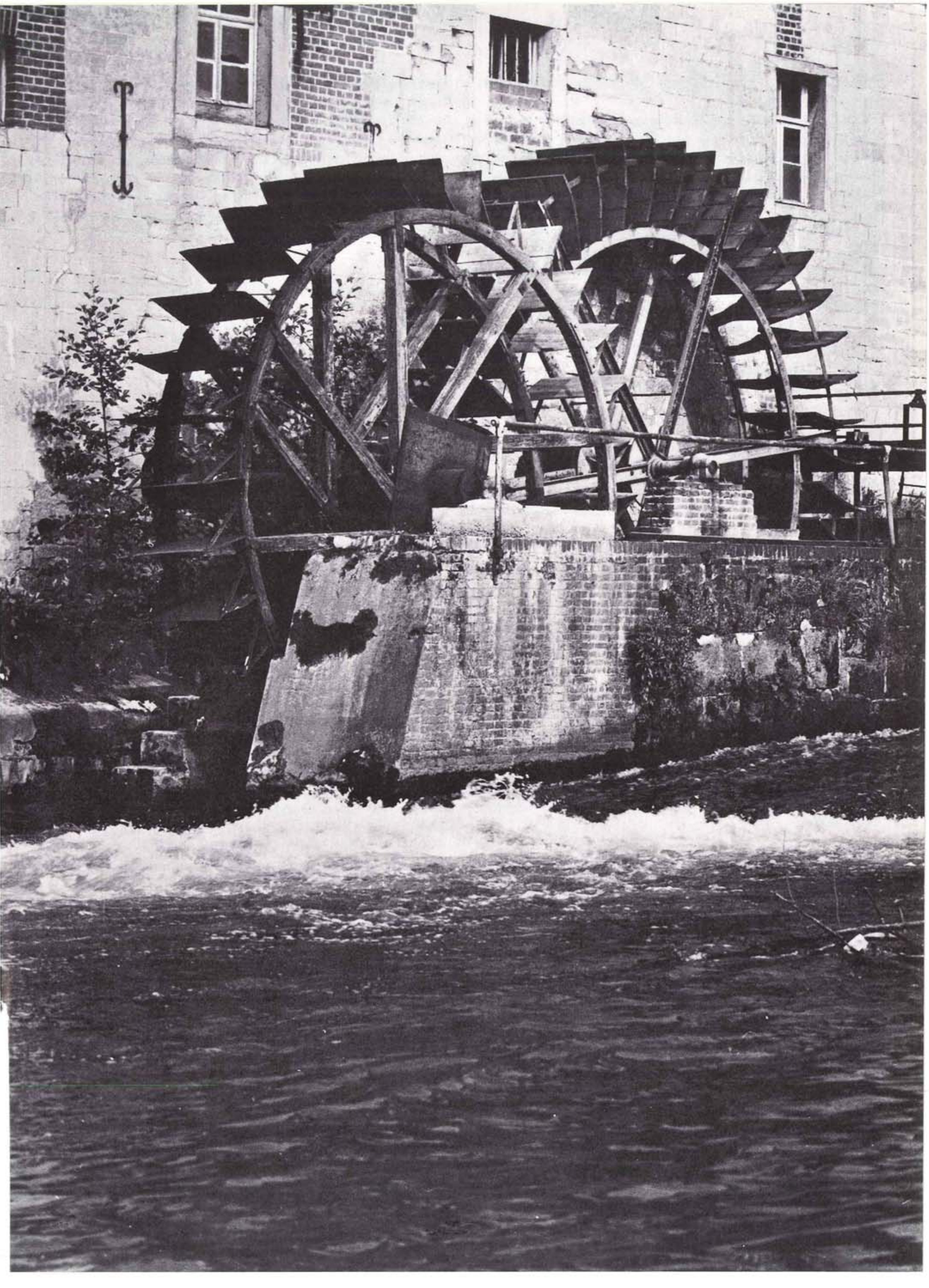
The main source of additional nutrients was manure: the small price difference between meat and grain and the relatively large meat consumption in the Middle Ages reflect that the animal herds were mainly maintained for their manure and that the meat was more or less a by-product.

In the course of centuries farmers succeeded in increasing the yield of grain to about 2000 kg per hectare by the application of a system in which cereals and other food crops were alternated with clovers, grasses and other crops for the feeding of animals, the marginal land was used for animal husbandry, all manure was carefully saved and much attention was given to the collection of refuse and night-soil out of the towns.

These high yields were, however, restricted to the more or less urbanized regions of Western Europe. In other regions yields of about 1000 kg per hectare were the rule until the beginning of the 19th century. This holds for cereals. Higher yields were obtained by means of the potato, introduced on farms in the middle of the 18th century. These higher yields were due not so much to greater production of organic material, but to more advantageous distribution over the various parts of the plant. After all, the potato does not need a stem to carry the seed. In this crop about 80 percent of the organic material is laid down in the tuber and only about 20 percent is used for leaves and stems. The number of persons that could live off one hectare of land was therefore about two times larger with potatoes than with cereals and this explains, more than its taste, the popularity of this crop. The disadvantages of the potato were, and still are, its poor storage properties and its susceptibility to all kinds of diseases. Both factors contributed to the occurrence of famine in Western Europe during the last century and are currently still the cause of large price fluctuations.

Agriculture with fertilizers

The breakthrough came in 1840 when Liebig, a German chemist, collected conclusive evidence that the plant needs only water, minerals and nitrogen from the soil and that organic manures as such are not of importance for the nutrition of the plant. It became clear at this time that — as has been said — only 25 kg of plant nutrients were available for the crop without additional nutrition. By mineral fertilization, this



amount, and in consequence the yield, could be increased several-fold.
It still took several decades before the farmer became accustomed to the idea and the industrial production of fertilizer started. But from then on conditions changed rapidly, as can be seen from figure 1 which shows the yield of wheat in Germany and the Netherlands from the year 1800 onwards. The present average yields in the Netherlands are over 5000 kg per hectare, which compared with the net yields of about 600 years ago means a ten-fold increase. The present high yields are due to the application of more than 200 kg of plant nutrients over and above the large quantities of nutrients reaching arable land via farmyard manure obtained from catlle grown on conserved grass and imported food.
The increase in food production from the appilcation

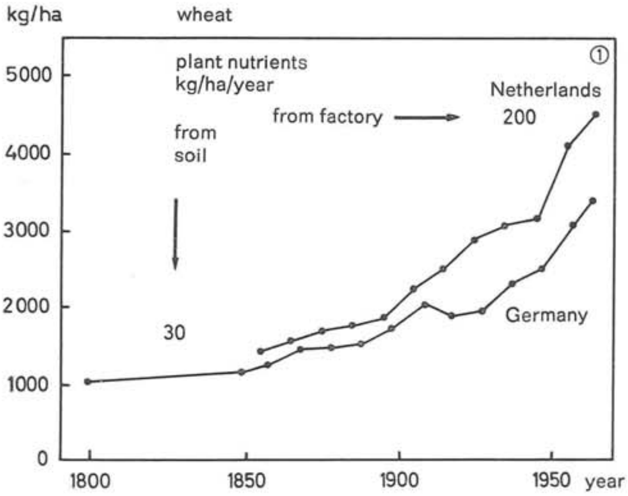


Figure 1. Yields of wheat in Germany and the Netherlands since 1800.

of fertilizers could only be brought about by the continuous adaptation of crops and crop varieties to the increase in the nutritional level. Some crops, like buckwheat, were not adapted and vanished, but among the temperate cereals the leafy, vigorous-tillering varieties were gradually replaced by more and more sturdy types. That this has been a gradual process is illustrated in figure 2 in which the index numbers of the grain yield and the straw yield of Dutch oat varieties are plotted against their year of introduction. It can in fact be shown that this process has been going on from at least 1840 onwards.
However, it should always be realized that the rate of yield increase during the last 100 years has been limited not so much by the technical possibilities, but by the need for food and the ability of the population to pay for food. Since the middle of the 19th century farmers have been able to produce all the food that was needed, but it is only during the last 20 years that the distribution of income has been such that everybody (in North-Western Europe) has been able to buy the food they wanted, which is — unfortunately — not always the food needed for well-being.

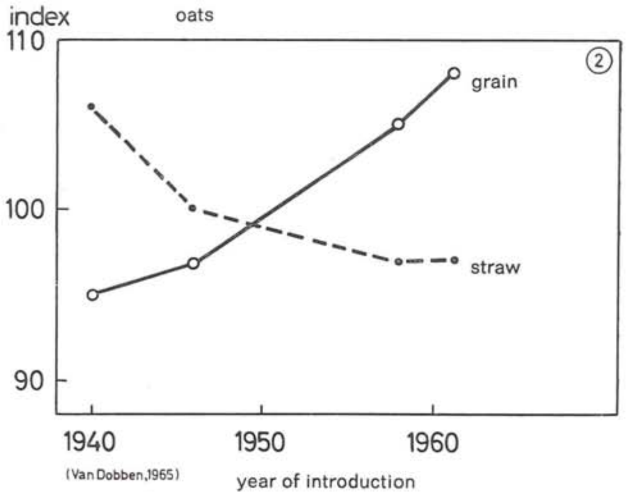


Figure 2. Index-numbers for the yield of grain and straw of varieties of oats, grown in the same year and at the same place, in relation to the year of introduction of the variety.

Potential production

As may be seen in figure 1, the yield of agricultural crops is still increasing rapidly despite the high level of 5000 kg per hectare for the yield of wheat which has been reached at present. This increase in yield cannot go on indefinitely and the question which arises is what are the maximum yields that can be reached by means of good varieties well supplied with minerals, nitrogen and water.
The total production of organic matter under such conditions depends on the velocity of the process of photosynthesis in the green leaves of the crop (figure 3). This is the process of capturing the energy from sunlight and subsequently transforming this energy plus carbon dioxide out of the air plus water into energy-rich sugar.
For a single leaf, the rate of photosynthesis is proportional to the light intensity at low intensities, but at high intensities a maximum value for photosynthesis is reached. The relationship between the rate of photosynthesis and light intensity for a leaf of sugar beet is presented in figure 4.

The initial slope of the photosynthetic curve does not seem to vary much with species and is in the neighbourhood of 3.6 kg sugar per hectare per hour for each 0.01 cal per cm^2 per minute absorbed by the leaves. However, maximum photosynthesis at high light intensity may vary considerably from species to species. For individual leaves of many agriculturally important species it may be assumed for discussion purposes that the average maximum photosynthesis is about 20 kg of sugars per hectare per hour, although it should be realized that for several tropical grasses, including maize and sorghum, maximum values at least twice as high as this are observed at favourable temperatures.
Thus, at an absorbed light intensity of about 0.2 cal per cm^2 per minute, the leaves are already operating close to their maximum. This light intensity occurs on an overcast day with the sun at the zenith. Light intensities on a clear day may amount to 0.8 cal per cm^2 per minute so that (cf. figure 4) a large proportion of the light must go to waste for crops with large horizontally arranged leaves. However, crops consist of small leaves held in many directions (Fig. 3), so that the light is more evenly distributed over the leaves, and the photosynthesis of a canopy of leaves is accordingly higher than the maximum photosynthesis of a horizontal leaf.
Calculating crop photosynthesis is thus primarily a geometrical problem that can be tackled by means of a computer. The factors which must be taken into consideration are the photosynthetic curve, the light-scattering coefficient of the leaves, the amount of leaf surface per unit area of soil, the crop architecture, the light intensity, and the direction of the incoming light.

Figure 3. A crop of maize, photographed from an unusual direction.

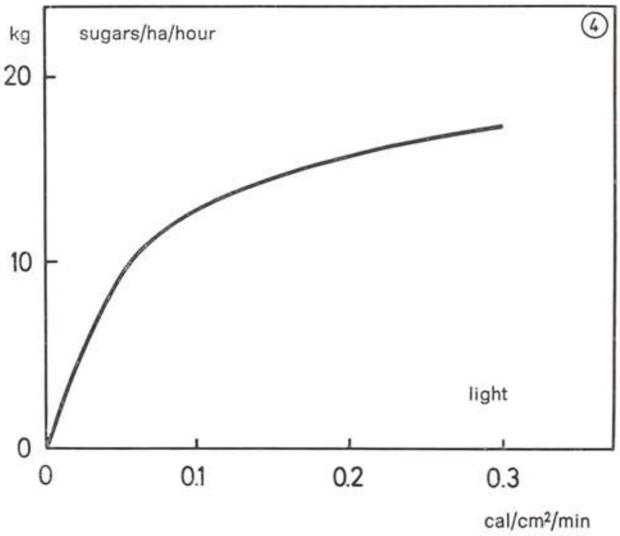


Figure 4. The photosynthetic curve of a leaf of sugar beet.

This latter factor depends on the state of the sky and the height of the sun.
It has been calculated that for a closed crop consisting of leaves with a maximum photosynthetic rate of 20 kg sugars per hectare per hour and a crop architecture like that of temperate cereals, the rate of Photsynthesis on a perfectly clear day is 35, 50 and 55 kg sugars per hectare per hour with the sun at a height of 30, 60 and 90 degrees, respectively. These rates are certainly higher than the maximum rate of 20 kg for a single leaf. This important increase in photosynthesis is a result of the better light distribution. With overcast skies, the light intensity is about $^1/_5$ of the light intensity with perfectly clear skies,

but photosynthesis is reduced only by half because the light on overcast days is very evenly distributed. The daily photosynthetic rate of a crop for a specific geographic location depends on the state of the sky, the latitude and the date. It appears that in the Netherlands this potential photosynthesis equals about 400 kg of sugars per hectare per day in summer and about 60 kg in winter. These totals, calculated on the basis of the light climate, can only be reached when the average temperature is reasonable. This is presumed to be the case when the 24-hour average temperature is 10° C or higher. In the Netherlands these temperature conditions prevail from mid-April to mid-October. Summing the daily totals for this period, the potential photosynthesis of a healthy crop surface in the Netherlands maintained throughout the entire growing season appears to be about 50,000 kg of sugars per hectare.

This sugar is not stored as such, but used by the plant to synthesize its roots, its stem, its leaves, its flowers and its fruit. Preliminary calculations have shown that for the production of one gram of protein, fat and cellulose and for the uptake of 1 gram of salt about 2.35, 2.94, 1.15 and 0.1 gram of sugar, respectively, is needed. Hence, for one gram of tissue consisting of 25% protein, 6% fat, 60% cellulose and 10% of minerals about 1.45 gram of sugar is necessary. Accordingly, a photosynthetic input of 400 kg sugar per hectare per day or 50,000 kg of sugar per hectare per season amounts to a growth rate of the plant of about 275 kg organic material per hectare per day or 35,000 kg per hectare per season. Roughly one-quarter of this organic material is produced in the form of roots or other material which is very difficult to harvest or is respired for the maintainance of the living tissue which has been formed, so that in po-

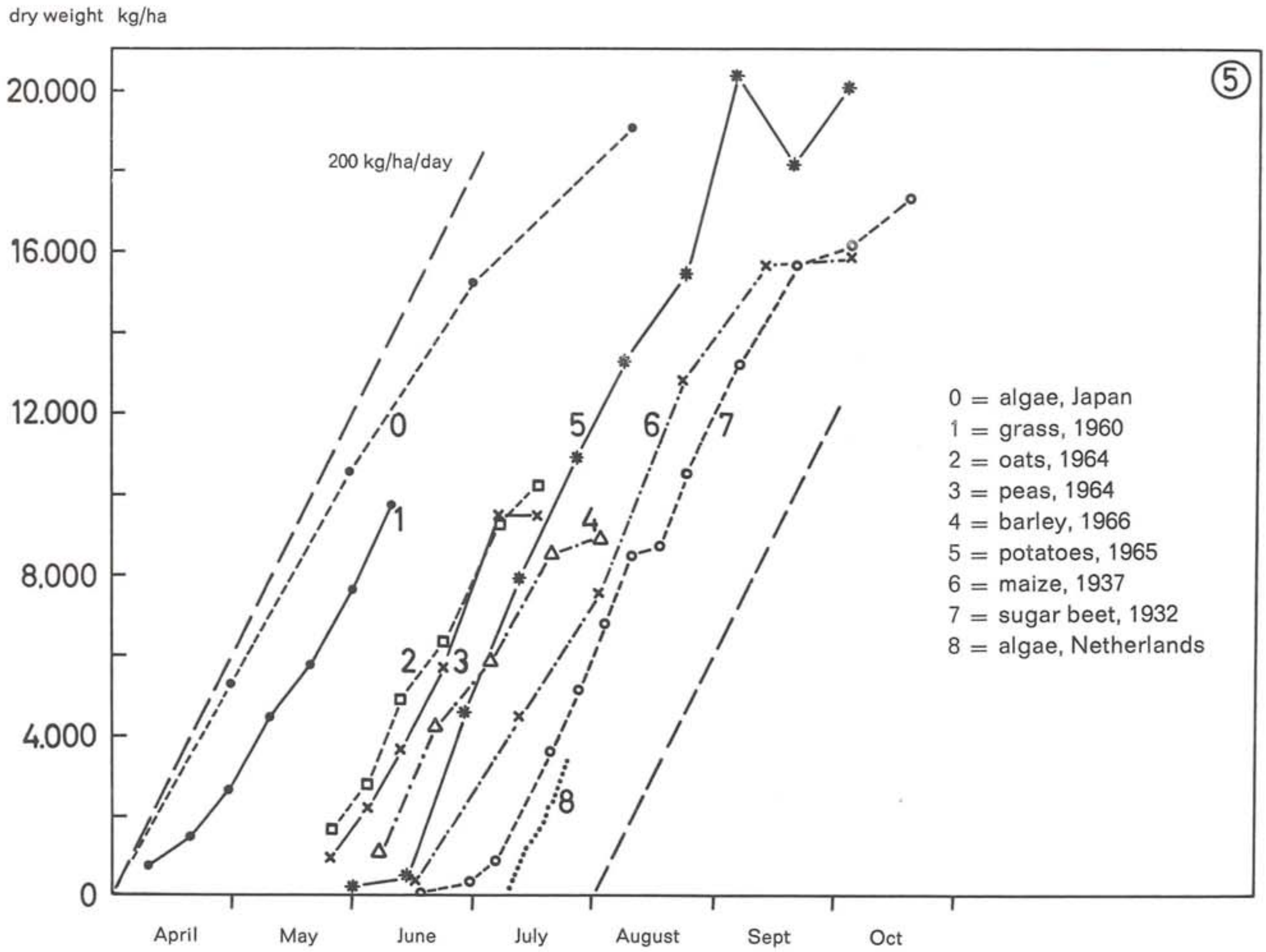
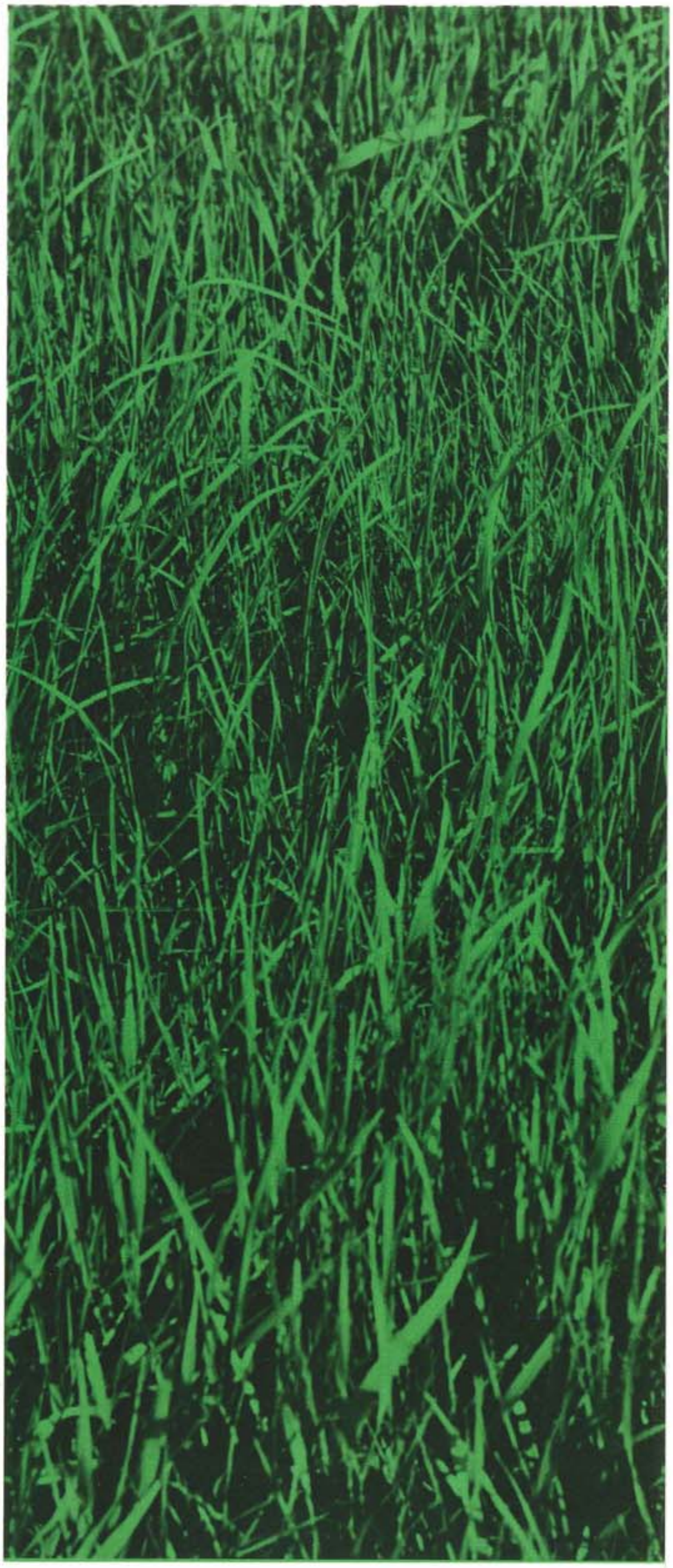


Figure 5. The growth of several agricultural crops and algae in the Netherlands, compared with the calculated growth rate of 200 kg per hectare per day, algae (0,8), grass (1), oats (2), peas (3), barley (4), potatoes (5), maize (6), sugar beet (7).

tential yield experiments growth rates of about 200 kg per hectare per day should be measured.
These growth rates are actually reached in the Netherlands under good conditions, as is shown in figure 5. In this figure, the month of the year is given along the horizontal axis and the harvestable material of these crops at different times along the vertical axis. The slope of these experimentally determined growth curves are in reasonable agreement with the slope of 200 kg per hectare per day, based on theoretical considerations. The large differences in total production of agricultural crops are due not so much to differences in rate of growth, but to the length of the periods during which a closed, green, healthy crop surface can be maintained.
For winter cereals, this period is not longer than about three months, so that the total production is not more than 18,000 kg organic material per growing season. In spring cereals, the growth period is still shorter, and therefore the total production still lower. As has been said, about 50 percent of the organic material is used for the production of leaves and stems, so that the production of seed, taking account of its water content, is estimated at 10,000 kg per hectare. The average production in the Netherlands is 5000 kg per hectare, but good and lucky farmers may reach up to 8000 kg, and on experimental fields yields of over 9000 kg per hectare have been obtained. In some parts of the world the daily radiation during the growing season is higher than in the Netherlands and the growing season is also somewhat longer; in these regions yields of 12,000 kg wheat per hectare have been reached.
With potatoes it is possible to maintain a green, closed, healthy crop surface for four months, so that a total production of 24,000 kg organic matter per hectare may be obtained of which 80 percent is recovered in the tubers. The tuber production then amounts to about 20,000 kg of dry matter per hectare or 100 tons of potatoes per hectare. This potential yield has in fact been obtained in experiments. In practice the yield is close to 40 tons and on good farms 60-70 tons are obtained at present. Contrary to what is often claimed, it appears both from experiments and theoretical considerations that the growth rate of algae is not appreciable higher than that of normal agricultural crops.

The potential production on a world scale

As has been said, potential photosynthesis in the Netherlands amounts to about 50,000 kg per year, and it is not unreasonable to suppose that with our present knowledge and our present crops it is possible to obtain ¼ of this or 12,500 kg organic material per hectare per year in a form suitable for human consumption. This amounts to a quantity of energy



of 50 million kilocalories per hectare per year, and because a human being needs about 1 million kilocalories to live, this means that in the Netherlands about 50 persons can be fed from one hectare, provided that they are satisfied with a vegetable diet and do not waste much.

In other parts of the world the potential production is higher or lower depending on the length of the growing season and the amount of sunlight received. With a good supply of nutrients and water it is possible to grow crops throughout the entire year in the tropics, and the potential photosynthesis then amounts to 120,000 kg per hectare per year or a crop production of about 24,000 kg edible organic material per hectare, so that it would be possible for 120 persons to live from the produce of one hectare. It has been shown that these yields are obtainable with crops like sugarcane and rice. This means that the present human population of 3 billion (3.10^9) persons could obtain their calories from an area which is no larger than 500 x 500 km^2. Indeed, the possibilities for food production cannot be imagined.

Area by area calculation, of which the result is given in table 1, shows that the number of persons that may live from the produce of the total land surface of the earth (the sea excluded) amounts to more than 1000 billion (1000.10^9), that is more than 300 times the present population of the world. These persons would then live *from* the earth but would not have any space to live *on* the earth. On the average this amounts to less than 150 m^2 per person for food production only. Estimates of the surface needed to live, to work and to relax depend to a large extent on the cultural background of the estimator. I have some experience of living on the bank of the river Rhine in one of the most industrialized areas of the Western world. My estimate is that we need about 750 m^2 per person to live, to work and to relax and to maintain something of nature around us.

On basis of this 750 m^2 and an average of 150 m^2 for food production, it follows that about 900 m^2 per person is needed for all his activities and this amounts to a maximum world population of 145 million (145.10^9). This population would then need about 19 percent of the land surface for food production. This amount of land surface suitable for modern agriculture is available. However, a human being does not live only on potatoes, and to obtain a diet with a reasonable amount of meat about two times more land surface is necessary for agriculture. This brings the number of persons who may live on earth back to about

$$\frac{150+750}{2 \times 150+750} \times 145 = 125 \text{ billion } (125.10^9);$$

still a considerable number of human beings.

However, persons adjusted to living in rural areas and not like myself in industrial areas may estimate that 1500 m^2 is needed instead of 750 m^2 to live, to work, to relax and to conserve nature. The maximum number of persons who may then live on earth falls to

$$\frac{150+750}{150+2 \times 750} \times 145 = 80 \text{ billion } (80.10^9)$$

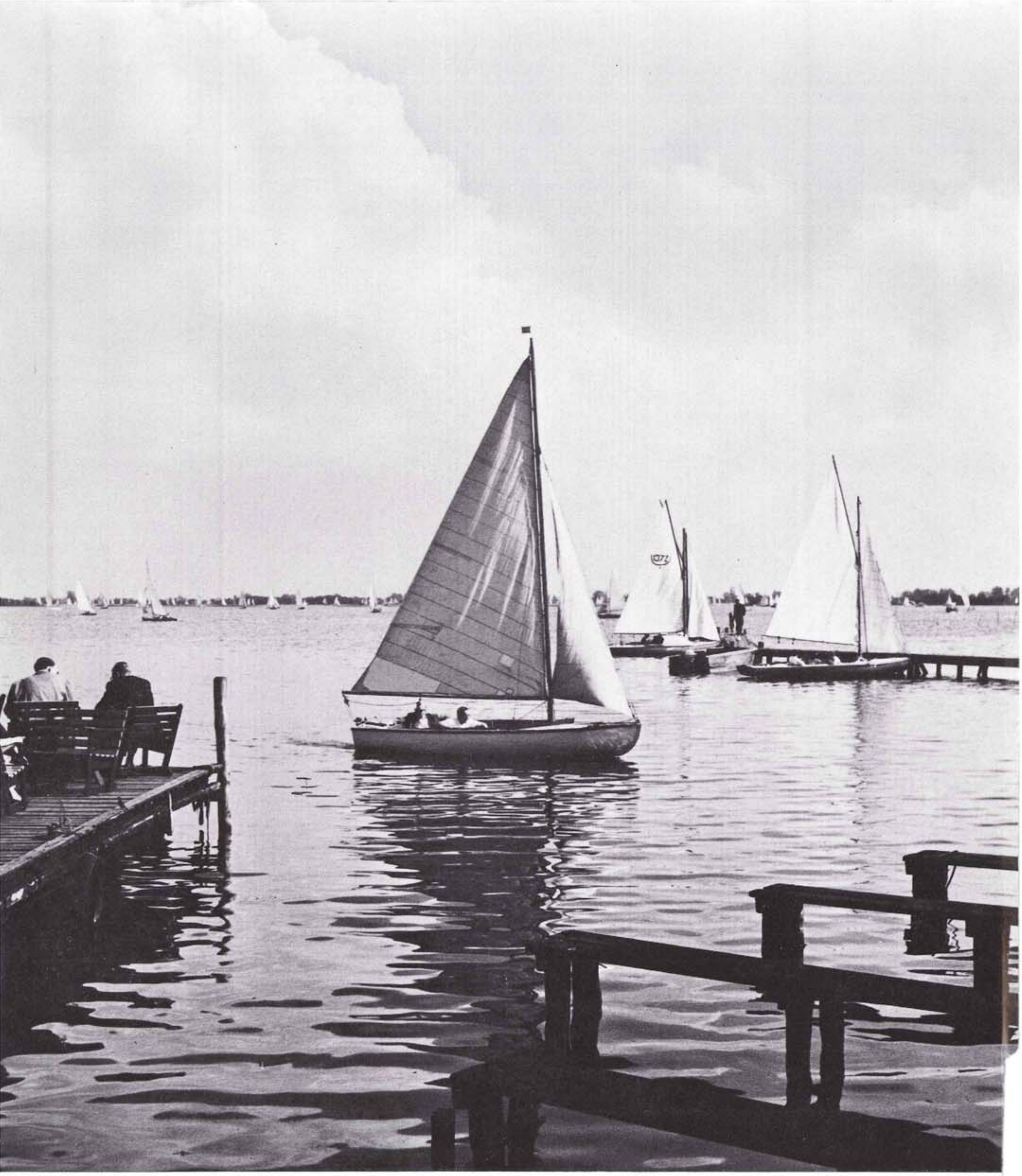
or to about half of the previous estimate. If two times 150 m^2 are needed for food production and two times 750 m^2 for other needs, the possible world population is still 73 billion (73.10^9).

A comparison of the above figures shows that the size of the world population does not depend so much on the area of the land that is needed for agricultural production, but much more on the land surface which is needed for other purposes, so that the supply of food is not the limiting factor. More likely, the limiting factor will be mutual irritation and could be the impossibility of getting rid of our waste products.

One may wonder how much food may be obtained from the sea. This should not be overestimated. It must be taken into account that there is so much water in the sea that it is impossible to supply the mineral nutrients and the nitrogen which are necessary to maintain the potential production of the green plankton (primitive plants). Without fertilization, the organic matter production is in general no higher than

Tabel 1. **The area of land, the number of months with average temperatures above 10°C, the potential production, the area of land needed per person and the number of persons that can obtain sufficient food when all land is potentially cultivated, for latitudes ranging from + 70 degrees in the Northern to — 50 degrees in the Southern hemisphere.**

North Latitude degrees	Land Surface 10^8 ha	Number of months above 10°C	Carbohydrate per ha per year 1000 kg	Land area per person m^2	Number of persons in billions (10^9)
70	8	1	12	806	10
60	14	2	21	469	30
50	16	6	59	169	95
40	15	9	91	110	136
30	17	11	113	89	151
20	13	12	124	81	105
10	10	12	124	81	77
0	14	12	116	86	121
— 10	7	12	117	85	87
— 20	9	12	123	81	112
— 30	7	12	121	83	88
— 40	1	8	89	113	9
— 50	1	1	12	833	1
Total	131				1022



the production of unfertilized land surfaces, i.e. 2000 kg per hectare per year. This organic material is eaten by small animals, these small animals are eaten by bigger animals and only later on in the food chain do fishes appear which are suitable for human consumption. Since at each conversion step $^7/_8$ of the energy is lost, only one percent of the organic material can be harvested for human use. The food production of the sea is thus only 1/500 of the calculated food production of the same land surface. In spite of the 5000 m^2 of sea which is available per person by the time the world population is 100 billion (100.10^9), this sea food is negligible as a source of energy. Of course the sea will always remain a source of good and delicious food and fisheries will therefore remain important.

The above considerations must not be taken as an argument for an unlimited growth of the world population. The present population of 3 billion (3.10^9) is at the present birth and death rate doubling about every thirty years. Hence, it will take only about 150 years to reach the maximum calculated number of 100 billion (100.10^9) if we go on reproducing at the present rate.

Industrialized agriculture

Much of the labour and capital costs in highly productive, industrialized agriculture for ploughing, sowing, harvesting, herbicides and insecticides, water management and fertilizer application depend mainly on the surface which is under agriculture and increase only slightly with increasing production per surface unit. Taking into account that there is still much scope for increase in production it is always more profitable to increase the production per unit of land than to keep marginal soils in production. It may even be that the rate of increase in production on the good agricultural land may be larger than the increase in demand, and it is therefore likely that in the coming years all over the world marginal lands will be taken out of production. These lands will be partly used for extension of the industrial centres, but the greater part will be replanted with forests or used for extensive grazing, and also for recreational purposes. This development leads to a much more hygienic way of food production with much less destruction and contamination of the environment, as may be illustrated with a few examples.

Phosphate is indispensable for a high yield level. It appears in the many potential yield experiments that have been done during the last ten years that the present phosphate level and phosphate fertilization rates are more than sufficient to achieve the highest possible yields. Obviously an increase in yield per unit area does not necessarily lead to an increase in the use of phosphate.

For nitrogen, it has been shown in grassland experiments at Wageningen that unbalanced mineral composition of the forage may be avoided by applying the nitrogen only at the time and in the amounts it is needed for potential growth. When this is done, however, it is found that most of this nitrogen is taken up by the plant and that only a very small proportion is lost, and according to Kolenbrander this loss is due rather to denitrification than to leaching. For arable land it is equally true that high yields can only be obtained with a more careful use of fertilizer nitrogen than is practised at the present moderate yield levels. Improvements in growing conditions (for example better drainage) can lead to higher production per unit of minerals absorbed. High yields also lead to the use of less nitrogen fertilizer per unit of product.

The yield per unit of water used is also the highest in high yielding situations. This is partly due to relatively lower losses from deep percolation, direct evaporation (in canals and waterworks) and partly due to a favourable ration between the rate of photosynthesis and the rate of transpiration by well fertilized green crop surfaces.

Lastly it should be realized that the present yield level can only be maintained by the use of biocides to control diseases, pests, insects and weeds. Here again, there is no indication that the amounts of biocides needed per hectare are higher in situations where the yield level is higher. At least as far as the use of herbicides is concerned there is considerable evidence to the contrary. Hence, the amount of biocides used per unit of product also decreases in proportion to the increase in yields.

The situation may be summarized as follows. With moderate yield levels large amounts of agricultural land are needed to feed the millions and this leads to the use of considerable quantities of fertilizer, biocides and water per unit product, to the establishment of a huge industry for manufacturing, collecting and processing all these materials and to the practical impossibility of controlling their diffusion throughout the remnants of a more or less natural vegetation. On the other hand, with a high yield level far less agricultural land is needed and far less fertilizer, biocides and water are necessary per unit of product, a smaller industry suffices to cover these needs and it is at least less difficult to control the diffusion of contaminants throughout the much larger areas that are still covered with more or less natural vegetation. There are at present a considerable number of biologists and other persons who are concerned about modern developments and are of the opinion that it may be better to ban industrialized agriculture and to return to older closed systems of farming. It should be remembered, however, that this leads to yield levels which are, in terms of grain, of the order of 2000 kg/ha, as has been shown by experience at the

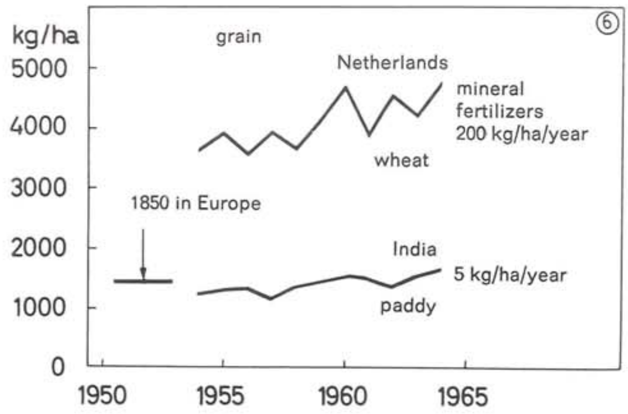


Figure 6. The yield of low land rice (paddy) in India and wheat in the Netherlands and the yield of wheat in Western Europe about 1850.

beginning of the 19th century, and that such yield levels necessitate to the impossible choice of either reclaiming much more land or the starvation of large segments of the world population.

Traditional agriculture

There are many parts of the world where agriculture is still carried on in traditional ways and where in spite of a good climate and in spite of the availability of water, yields of only about 1000 kg grain per hectare are obtained. This is for instance the case with lowland rice in India and other Asian countries. The yield of this crop during 1950-1965 is given in figure 6, together with wheat yields in the Netherlands and wheat yields in Western Europe in the middle of the 19th century. Yields of around 1000 kg per hectare, which are the same as in Western Europe before the introduction of fertilizer, show that the use of this fertilizer in India must be practically negligible. This is indeed the case; although on the increase, the total use is only in the region of 10 kg per hectare, which is less than 1/20th of the amount used in the Netherlands.

To increase production it is in the first place necessary to increase the use of fertilizer. It is even possible to increase yields without the introduction of new varieties, although high yield increases are only obtained by the combined use of fertilizer, new varieties and pest and disease control. It has been shown in several Asian countries that in this way yields of over 9000 kg of grain per hectare can be obtained from one rice crop.

A great difference between a country like India now and Europe in former times is that in India the population pressure has been so great for such a long time that in many regions no soil is available for animal husbandry. This is one of the reasons why no agricultural systems with production levels of about 2000 kg grain per hectare were developed and is also the reason for the lack of protein in the diet. However, we have to take into account that vegetable crops have a low protein content especially because the nitrogen fertilization level is low and not for physiological reasons. With the increase in yield due to fertilization the protein content of the food therefore increases considerably and the protein shortage accordingly decreases. This process is further accelerated by the circumstance that with the increase in production more space becomes available for the cultivation of forage for animal use and animal husbandry receives more attention, so that the quality of the diet improves.

The problems of the developing countries now and of the developed countries in former times run, technically speaking, to a large extent parallel except that the hundred years which were necessary to learn to grow high yielding crops free from pests and diseases are not necessary any more.

Bio-industry

In reading the present issue of this journal, it appears that the main uncontrolled contamination of the environment by agriculture originates from the bio-industrial complexes where meat production is centred.

Unlike many other sources of contamination in agriculture, these are point sources and the technical means for control are available. The cost of control amounts to about ten guilders per finished calf, which is small compared with the annual budget of the householder, but rather large compared with the net income of the feeding operations. At least in the Netherlands, the principle is adopted that the waste-maker pays. But agricultural policy being what it is, it seems likely that the problem may be solved by some kind of subsidy, with the bad side effect that bio-industrial complexes would be founded and maintained in sensitive environments where otherwise the costs of proper waste-handling would be prohibitive. Whatever the short-term policy, in due course the problem may fade away for humanitarian reasons. Since Napoleon III in the middle of the 19th century offered a prize for the discovery of a "substitute for butter, suitable for the marine", industry has worked on it and succeeded in making vegetable butter, which is much cheaper than the animal product and at least comparable in quality and taste. Likewise good leather and wool analogues are available and at the present time the stage has been reached where vegetable meat analogues of good nutritional quality may be marketed much cheaper than the classical product. It is often maintained that taste and eating habits are so conservative that the future of vegetable proteins as a substitute for meat is not very bright. However, artificial fur is not gaining on the natural product because it is so much better, but because it is being considered more and more unethical in modern society to hunt or breed and kill animals for the sole purpose of obtaining a product that can also be obtained in a far less repulsive way.

There is no doubt that bio-industry also makes a repulsive impressoin on practically anyone outside agriculture who is exposed to it. Television and other mass-communication channels will undoubtedly see to this exposure and this may very soon lead to a situation where reasonable meat analogues are preferred above meat obtained from bio-industry.

Development of society in this direction would not only lessen the waste problems originating from bio-

industrial complexes, but also allow for a considerable decrease in the acreage necessary for food production. After all, each 1000 kg of suitable plant produce can provide at least 200 kg of plant proteins, but each 1000 kg of suitable vegetable animal food provides at the most 100 kg of animal protein. This is not taking into account the feed needed for maintaining adequate breeding stock, let alone the large quantities of high value milk proteins used in animal feeding.

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Photographs:

Cover: *Haematococcus pluvialis* (an algal species) cultivated at a low nitrogen concentration during alternate drying and remoistening. Phase contrast microscopy (2500 x) by dr. J. W. Woldendorp and A. J. van Straeten.

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Woldendorp/v. Straeten p. 18-25.
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C. T. de Wit: p. 71.
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