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ASPECTS OF AGRICULTURAL RESOURCES

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SUMMARY

This paper describes recent research on resources for the production of food.

At first, constraints imposed by plant properties and by the radiation of the sun are considered. Superimposed are constraints related to the availability of water and the quality of the soil. It appears that the production that may be achieved by means of existing crop species and by using existing amelioration, fertilizer and crop husbandry techniques and in the absence of pests and diseases, is about 30 times the present world production. This implies that the inability of men to organise resources of food production rather than a low level of potential resources is the core of the world food problem.

The existence of subsistence farming shows that it is possible to grow sufficient agricultural commodities without any other input besides the labour of the user of the products. However, an increasing urban population can only be sustained when yield improving and labour replacing means of production are made available to the agricultural population.

An analysis of the MOIRA-team (Linneman et al., 1976b) relates the agricultural production per country to its potential and the input of labour, of labour replacing techniques (tractors) and yield increasing means (fertilizers). The need for labour and labour replacing inputs increases more than proportionally upon the approach of the potential yield level of a country, be it only because more and more unsuitable soils are taken into production. However, the need for fertilizers increases practically proportionally with the yield level, a phenomenon that is confirmed by agricultural practice in countries with a high production per hectare.

As for the main fertilizers, it is concluded that potassium is available in unexhaustable amounts and that in the foreseeable future

only a fraction of the phosphate resources that are exploitable at present day prices, will be exhausted.

The availability of nitrogen is closely linked with the energy situation, which is discussed in relation to the mutual substitution of the energy from the sun, from fossile resources, and from human resources in agricultural production. It appears that the energy efficiency of arable farming has remained the same during the past 20 years, in spite of the fact that the labour productivity has increased more than two-fold.

PHOTOSYNTHESIS AND YIELD

Agriculture is the human activity that transforms solar energy at the earth's surface into useful (edible) chemical energy by means of plants and animals. The basic photosynthesis process takes place in the leaves where 8 quanta of light (400-700 nm) are minimally necessary to accomplish the reduction of CO_2 in CH_2O. The theoretical efficiency of the reaction is about 25 percent or 15.10^{-6} CO_2 per joule light, absorbed by the green chlorophyll. Due to unavoidable losses, the maximal measured efficiency is 8-12 10^{-6} g CO_2 joule^{-1}. The maximal light intensity is about 3 joule cm^{-2} min^{-1} so that a photosynthesis of 200 kg CH_2O ha^{-1} (100x100 m^2) hour^{-1} seems feasible. However, maximal efficiency is only reached at low light intensities. At high light intensities the transport of CO_2 from the air through the leaf surface towards the place where the reaction takes place is a limiting factor and the maximum photosynthesis for leaves of many crop species is therefore only 20 kg CH_2O ha^{-1} hr^{-1}, which is reached at a light intensity of about 1 Joule cm^{-2} min^{-1}. Due to physiological adaptation, the photosynthesis is not too much temperature dependent and proceeds often at a normal rate when the average daily temperature is above 10^{o}C. Some crop species of tropical origin (e.g. maize) may have a two times higher maximum photosynthesis. But even then much light energy is not efficiently used at high light intensities.

However, a crop is not a green cloth on a billiard table, but consists out of leaves that are more or less randomly distributed and with a total surface that is about 4 times larger than the soil surface. The light is therefore distributed over a total leaf surface which is considerable larger than the soil surface, so that the average light intensity is smaller. Maximal photosynthesis of a crop may amount then to 60 kg CH_2O $ha.^{-1}$ (100x100 m^2) hr^{-1} which is considerable higher than the 20 kg of the individual leaves. Good evaluated models of light distribution and subsequent gross photosynthesis have been developed during the last 12 years (De Wit, 1965; Goudriaan, 1976), which form the basis for the computation of photosynthesis.

The "sugar" that is produced in this photosynthesis process is not bagged as such, but used by the crop for growth and maintenance. This requires energy and calculations based on knowledge of the bio-chemical processes involved have shown that with a good growing crop 35 percent of the photosynthesis products are used in respiratory processes that provide this energy (Penning de Vries, 1972).

The quantitative knowledge of photosynthesis and respiration is advantaged to such an extent that it appears possible to simulate even the daily course of net CO_2-assimilation with reasonable accuracy (Van Keulen and Louwerse, 1973; Van Keulen, 1975). It appears thus in theory, but also in the field that the daily growth rate of a closed crop surface, well supplied with water and nutrients is somewhat over 200 kg dry matter ha^{-1} day^{-1} during the growing season in the Netherlands. The growth rate of algae cultures is of the same magnitude, but requires technical constructions that are even more expensive to build and to operate than greenhouses in which highly appreciated vegetables and flowers are grown. For a crop like wheat, this growth manifests itself at first in the formation of roots, leaves and stems, but after flowering seed formation is predominant. The seed filling stage may have a duration of about 50 days in a disease free environment and under these conditions the seed yield may amount to 10000-11000 kg per ha, as shown in table 1.

THE WORLD FOOD RESOURCE

The simulation models may be used with some confidence to compute the possible food production on the world in dependence of radiation and temperature. If it is assumed that all the land surface is optimally supplied with nutrients and water, the sum total would be sufficient to satisfy the needs of 1000.10^9 persons, but these poor people could then only live from the land, but not on the land at the same time.

There are, however, many other restrictions on yield and those related with the availability of water and the suitability of the soil are being considered by Buringh, Van Heemst and Staringh (1974). For this purpose, 222 broad soil regions were distinguished on basis of the FAO-international soil maps, of which those in Africa are presented in Fig. 1.

The amount of land that may be reclaimed by making use of existing technologies is estimated for each soil region. This amount is presented for each soil region on the map by the surface of the shaded squares of the grid, the unshaded squares presenting the land that is considered unsuitable for agriculture, but of which still some may be used extensively, e.g. as grazing land. The potential production of the land in each soil region is calculated on basis of radiation and temperature data and expressed in kg grain equivalents per hectare per year. In addition, humidity and wind data are used to estimate the potential evaporation by means of the well known Penman method (Penman, 1948). However, the potential yield is in general not achieved because of water shortage and restrictions due to soil properties.

The amount of water available is calculated from rainfall, soil physical properties and potential evaporation on a monthly basis and a reduction factor on yield is directly related to the ratio of available water and potential evaporation, according to fairly established quantitative methods Makkink and Van Heemst, 1975; Van Keulen, 1975). Further, the possibilities of irrigation for each region are evaluated on basis of present plus projected, irrigated areas and the availability of irrigation water and soil topography (H.J. Moen and K.J. Beek, 1974). There is no straightforward approach to estimate reduction factors on yield due to adverse soil conditions, which cannot be overcome by present fertilization, amelioration and crop husbandry techniques, but estimates are made by Buringh et al. (1974) in close cooperation with other soil scientists with world wide experience. The smallest of the reduction factors for water or soil is then used to calculate the maximum possible production from the potential production. This maximum production is presented in the map of Fig. 1 in 6 classes, ranging from 25000-30000 to 0-5000 kg grain equivalents per hectare.

About 24 percent of the African continent is potential agricultural land, but only 20 percent of this land is at present cultivated and the yield of this cultivated land is only a fraction of the maximum possible yield, the order of magnitude being 1000 kg grain equivalents/hectare.

For the world as a whole, it appears that 25 percent of the land area or 3420 million hectare is potentially arable, of which 470 million hectare may be irrigated. At present 1400 million hectare is cultivated and 200 million hectare irrigated. The maximum production is 50 milliard (10^9) tons of grain equivalents, which is almost 40 times the present cereal production of 1.3 milliard tons or almost 30 times the present total production in grain equivalents, 65 percent of the arable land being cultivated with grains. This amount would satisfy the caloric needs of 100 milliard persons, but taking into account sufficiently diversity of diet and the use of meat, 40 milliard would seem a better estimate. With the present doubling interval for the world population of about 30 years, this leaves us a period of grace until doomsday of a little over 100 years, which is not very long taking the magnitude of the problem into account.

The calculated production refers to the yield that may be achieved by means of existing crop species, by using existing amelioration-, fertilizer- and crop husbandry techniques, but in the absence of pests, diseases and other disasters. It is not implied that it is easy to overcome the experimental and feasibility gap, i.e. the differences in yields on experimental stations and on well managed farms and in yields on the latter and the average yields (ORAM, 1976). It is also not implied that it is desirable that the world population grows to its limits, but it does signify that the inability of man to organize the exploitation of the food production resources rather than a low level of resources is a core of the present problem.

THE PRODUCTION PATTERN

The existence of subsistence farming shows that it is possible to grow sufficient food and other basic agricultural commodities with no other input than the labour of the user of the products. Economic development implies that the agricultural population has also to provide agricultural commodities in increasing amounts to an increasing urban population. Therefore, the productivity per unit agricultural labour has to increase continuously and this is only possible when yield improving and labour replacing means of production are made available to the agricultural population.

During the development of a model on the international relations in agriculture "MOIRA", Linneman et al. (1976b) needed some quantitative insight in this matter and for this purpose a country-wise cross sectional analysis was made to link the demand for food with yield and yield potential of a country and the means of production.

The yield potential of a country is for this purpose expressed in the total area of potential arable land (PAL), in hectares and the maximum production (Y_m) per hectare of PAL. The actual performance is also expressed per hectare of PAL, so that the quotient (Y/Y_m) is a direct measure for the degree of exploitation of the available production resource. The production is for this purpose expressed in kg consumable protein rather than grain equivalents or calories. Not so much to take a stand in the rather futile argument whether calories or proteins are limiting, but to have a somewhat more direct link with nitrogen turnover

The amount of consumable protein is the amount of plant protein that is suitable for human consumption plus the animal protein produced from plant protein that is unsuitable for human consumption, both being primary protein sources. A part of the production capability for consumable protein is sacrified for non-food products and lost in processing, especially the production of meat on grain basis. The amount of consumable protein is therefore larger than the amount of consumed protein, but the difference depends to a large extent on the income-class of the consumer, as is illustrated in table 2.

Because of the limited data base input of agricultural labour was considered proportional to agricultural population (A), the input of labour replacing means of production proportional to the number of tractors (T) and of yield increasing means of production proportional to the kilogram use of fertilizers (F). All means of production are also expressed per hectare PAL.

The data for 106 countries were subjected to a statistical analysis on basis of the labour equivalence equation:

$$L = A + K_1 . (\sqrt{(T+K_2)} - \sqrt{K_2}) \qquad (1)$$

and the yield equation:

$$Y = \frac{E.L}{E.L + Y_m} \; . \; Y_m \qquad (2)$$

Other power terms in the substitution equation of labour and tractors proved not to be significant. The numerical values of K_1 appeared to be

22 and K_2, a correction term for low tractor densities, was set at .0004. The substitution equation for labour and tractors is vizualized in Fig. 2a, for an equivalent amount of labour of 2 and 4 units per hectare. It appears that the mechanisation level increases more than proportionally with the replacement of the agricultural population. The equation suggests also that agricultural production may be achieved either without the input of tractors or without the input of labour. The first is true, but automation has not proceeded that far that the latter extrapolation must be taken too literally.

The yield equation approaches to:

$Y = E.L$

with L approaching to zero. E is therefore the initial efficiency of the use of equivalent labour. Its numerical value was found to be 51 kg consumable protein per unit L or per caput of the agricultural population (per year), in situations where no tractors are used. This is about 2 times the need for food and signifies that in any country a scarce population may subsist by living in those areas that are most suitable. The relation between yield and equivalent labour is further vizualized in Fig. 2b for the yield and labour range that is of practical significance and the accuracy of the whole statistical exercise is presented in Fig. 3a as the relation between measured and estimated yield. The remaining deviations are considerable, but for econometrists, the coefficient of determination of over 0.8. is sufficient to characterize the main trend. And the crop scientist may be satisfied because the least unacceptable treatments were those that take potential resources into consideration.

The analysis implies that in each country the used crop husbandry methods are appropriate for the rational use of the equivalent labour. One measurable treatment is the use of fertilizers for the production of consumable plant protein which is presented in Fig. 3b in relation to the yield expressed per unit of potentially arable land. The scattering of the data is again considerable, but the relations vizualize to what extent fertilizers are needed when the yield level is above a base level of about 80 kg consumable protein per hectare actually cultivated land.

Let us now consider a country X with a total population of 5 caput per hectare potentially arable land (PAL) and with a diet of 50 kg consumable protein per caput per year. The use of consumable protein per hectare is then 250 kg per hectare PAL, and with a maximum production of 2000 kg consumable protein per hectare PAL, an equivalent labour per hectare of 5.7 is necessary. If then the agricultural population is 20 percent, or 1 person per hectare PAL, it follows from the substitution equation, that the mechanisation level is characterized by .005 tractors per hectare PAL, and from figure 3b that the fertilizer needs are about 125 kg per hectare PAL. If, on the other hand, the potential food resource is decreased to 500 kg consumable protein per hectare PAL, the density of equivalent labour is increased to 10 units and the mechanisation level to .084 tractors, all per hectare of PAL. Likewise the consequences of changes in population pressure, diet, fraction of agricultural population are in first instance quantified in an overall manner.

Another problem concerns the yearly rate of yield increase, which depends at first sight on a somewhat surprizing way on the yield level. This is illustrated in Fig. 4, where the grain yields in kg per actually cultivated hectare for the main regions from 1954-1973 are arranged along a continuous scale. Below a yield level of 1700 kg/ha, the rate of yield increase is only 17 kg/ha/year, but above this yield level, this rate jumps to 78 kg/ha/year. Obviously, this breaking point presents the yield level at which the transition from traditional agriculture with little outside inputs to modern agriculture with considerable input of outside resources occurs. Just below this yield level, the relative yearly increase is only 1 percent, and this is far too low to keep up with the population increase. Emphasis is then on increase of the acreage of land under cultivation and prevention of hunger. Just above this point, the relative yearly increase is 4.5 percent which is larger than the population increase in the countries concerned; emphasis shifts then to taking marginal land out of production, to conversion of primary products and production of luxury commodities.

The transition from the more traditional situation to modern high input agriculture has been attempted at a yield level of 1100 kg/ha in the USSR, but not too successfully as appears from the scattering of the yield data. China appears to be at present just at the breaking point of 1700 kg/ha and this makes clear why so much attention is given to the use of fertilizers in the present 5 year plan.

FERTILIZERS

A statistical analysis (Fig. 3b) suggests a more or less linear relation between fertilizer use and yield level. This seems contradictory to the common notion diminishing returns. However, other crop husbandry practices, like choice of variety, methods of soil cultivation, regulation of the water supply, and weed and disease control are adapted at the same time and this leads indeed to a situation where the use of fertilizers increases not more than proportionally with the yield level.

This is illustrated in Fig. 5 for the nitrogen effect on the growth of wheat in the Netherlands under circumstances that permit different maximum yield levels. Irrespective of the yield level, the efficiency of fertilizer use is the same, at least up to a yield level of 80 percent of the potential. Around this level or higher, the yield is mainly increased by extension of the growth season through disease control. The same nitrogen is then used for a longer period and for a larger proportion accumulated in the seeds, as is illustrated in table 1 by data of De Vos (1976). Grassland experiments (Alberda, 1971) showed that applied nitrogen is recovered fully when potential yields are approached, whereas 50 percent recovery is more usual at lower yield levels where the growth of the crop is less controlled.

As for phosphate, it is well established that at relatively low yield levels on soils with a relatively low phosphate status, only a small portion of the applied phosphate is taken up and that by far the largest portion is fixed in iron and alluminium compounds in a for the plant unavailable form. Prolonged use of the land with increasing yield levels leads to a situation where a large part of the alluminium and iron compounds become more or less saturated. Under Dutch conditions, this phenomenon has lead to the advice of phosphate application at a rate comparable with the rate of removal by the harvested material. Liming is done to control the pH of the soil. But a near-natural pH is also sufficient for potential yielding crops so that from moderate yield onwards, the lime requirement does not increase with increasing yields.

All this leads to the important conclusion that the need of fertilizers does relative decrease in the range from medium to high yield levels, so that a straight line relation as suggested by the economist's analysis (Fig. 3b) may be extrapolated to higher yield levels without much danger of underestimating fertilizer needs.

Of course, the world use of fertilizers has been increasing rapidly with increasing production during recent decades (Fig. 6), and it should be questioned whether there are sufficient resources. An analysis by the "MOIRA" team was reassuring. With an annual growth rate in phosphate use of 5 percent, 1500 Mtons of phosphate is necessary for the period of about 35 years in which a doubling of the world population is expected. This is only 10 percent of the amount of phosphate rock which is assumed to be exploitable with present techniques and at present prices. Moreover, it appears that a doubling of the price would lead to a five-fold increase of the commercial interesting reserves and this would reduce the needed amount only to 2 percent of the available resource. The cumulative demand of potassium appears to be only 0.1 percent of the commercially interesting resource which is negligible for all practical purposes. Nitrogen in its elementary form is available in unexhaustable quantities in the air, but its transformation into ammonia, suitable for use by the plant, requires energy whether it is done industrially or by biological means, and its supply is therefore closely linked with the energy situation.

ENERGY

Agriculture has been defined in the beginning of this article as the human activity that transforms solar energy into useful chemical energy by means of animal and plants. In addition, fossile energy and human energy are necessary to run the farm and to manufacture all material inputs: rather than one energy flow, three energy flows are involved during farm production and optimizing the productivity of one of these does not necessarily imply the optimization of the others.

To judge the energy and labour productivity of farming systems, it does not suffice to consider only the direct fuel use (for tractors, etc.) and the direct labour use on the farm itself, but also the indirect fuel and labour which is used during the manufacture of the inputs from its raw materials and its transportation to the farm. The sum of direct and indirect fuel use during manufacture of a product is referred to as added energy, added labour being the analogeous sum of direct and indirect labour.

The determination of the added energy and labour content of the main products may become a valuable tool to anticipate the result of rizing prices of energy and scarcity situations. The effort is a common task of economists and technicians with various backgrounds, but as long as the needed interdisciplinary attempt is not matured, all results can only be rough guesses.

Keeping this in mind, it may be estimated on basis of the most recent information for Dutch agriculture (Oskam, 1975; Lange, 1975; De Wit, 1975 a, b) that the added energy on arable farms in the Netherlands is about 35 GJ/ha of which about half is used directly on the farm (mainly in the form of fuel) and somewhat less than half indirectly, mainly for the manufacture of fertilizers. For instance the manufacture of NH_4NO_3 ready for farm use may require according to Schuffelen (1975) 100 MJ/kg, or 10 GJ/ha at an application rate of 100 kg N/ha/year. Surprisingly enough, it appears that, irrespective of the per capita national income of a country, the energy use for nitrogen manufacture amounts to about 1.4 % of the total energy use (Schuffelen, 1975), whereas the energy use for agricultural purposes is roughly about 5 percent of the total in more developed countries. This amount is small enough to conclude that mankind should not go hungry because of lack of energy, but large enough to contribute its share to a more efficient use.

The added labour use on arable farms in the Netherlands appears to be about 0.084 man/ha/year (Oskam, 1975) of which the greater part, 0.067 man/ha/year, is used on the farm. The added energy use of 35 GJ/ha plus the added labour use of 0.084 man/ha results in a yield of 50 percent of the potential or about 5000 kg/ha in terms of wheat.

Agriculture is a human activity as old as mankind and like all other ancient activities as building of roads and houses, transport or weaving, it may be executed at the expense of much labour and little energy or the other way round. The knowledge that in 1970 about 35 GJ/ha added energy and 0.084 man/ha added labour was needed for the production of 5000 kg wheat per hectare presents therefore only one point in the iso-yield diagram with added energy and added labour along the axes; this is the full point in Fig. 7. If attempts would be made to produce 5000 kg wheat/ha with as less energy as possible, the spade, the hoe and the sickle instead of tractor, plow and combine would be used. A historical analysis shows (De Wit, 1975) that this required roughly about 0.4 man/ha at the 5000 kg/ha yield level. But still the energy needed to manufacture fertilizers and other yield improving inputs would be needed for the latter level and this amounts to about 15 GJ/ha (see above). The open point in Fig. 7 at 15 GJ/ha and 0.4 man/ha presents therefore another point of the 5000 kg/ha iso-yield curve.

Interpolation is done now by assuming that the square root of added energy above 15 GJ/ha and added labour are linearly related. This is suggested by the form of the substitution relation between tractors and agricultural population (eq. 1), it being implicitely assumed that the use of labour replacing energy is mainly governed by the level of mechanisation. The iso-yield function for the 5000 kg/ha yield level is then:

$$0.071 \sqrt{(AE-15)} + AL = 0.4 \text{ man/ha}$$

in which AE is added energy in GJ/ha and AL is added labour in man/ha. The resulting function is given in the diagram.

Extrapolation below the added amount of labour of 0.084 man/ha shows that further elimination of labour seems to require little energy compared to the amount already used; this would anyhow be achieved by automation and scale enlargement. The function suggests that at the most 47 GJ/ha would be necessary, but this is an unrealistic extreme. This amount is, nevertheless, considerably less than the heat of combustion of 80 GJ/ha which is harvested in the form of grain. Obviously more energy is produced than used in modern agriculture, but this is of small importance since fuel cannot be eaten and grain is not used for fuel. On the other hand, the 4000 kg/ha straw and stubble that is produced at the same time contains also energy, and it is suggested that this energy may be transferred with 80 percent efficiency to methane by fermentative processes, and this could cover in principle all energy needs of farm production.

The added labour use in the fifties was two times higher than in the seventies (Oskam, 1975), whereas the added energy use was about 30 percent lower (Lange, 1975). This combination of added energy and labour use is presented in the iso-yield diagram by a square, which happens to be located near the 5000 kg/ha iso-yield function. However, wheat yields in the fifties were only 3500 kg/ha, so that this difference in yield characterizes quantitatively the increase in efficiency of production. Otherwise formulated, the added labour use decreased in about 25 years to the half, but in spite of this the yield per unit amount of added energy remained the same. Surprizingly enough, the energy productivity of modern agriculture does not seem to have decreased in the Netherlands (Lange, 1975). Because of lack of information, it is in general assumed that the energy efficiency of industrial processes did not increase. This is of course not true, as is illustrated by the large increase of the efficiency of ammonia production (Quartulli and Wagener, 1973). Speculations about future developments should take into account further efficiency improvements, characterized by a shift of the iso-yield function towards the origin and by increasing yields per hectare.

It is also worthwhile to consider the marginal substitution ratio of added energy with respect to added labour and the energy use per man. The former is defined as the slope of the iso-yield function (dAE/dAL) and the latter is the ratio AE/AL. In the present situation (black dot) the energy use is 420 GJ/man and the marginal substitution ratio 125 GJ/man. The latter value means that flow of energy to agriculture and its supporting industries has to increase with 125 GJ/year or 6 KW (thermal) for each man that is replaced by further automation and mechanization which amounts to less than 10 guilders per day. The upward movement along the iso-yield function could proceed in the past because the price of labour continued to increase with respect to the price of energy using means of production. Be it only because the suppliers of energy are determined to put their monopoly position to fair use and to keep up inflation, this favourable situation may be changing. In that case governments should attempt to direct future growth by aiming at a marginal substitution ratio of energy and labour which is considered optimal and maintainable for society as a whole, through prices or otherwise.

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Table 1. Yield and crop characteristics of winter wheat treated with and without fungicides (De Vos, 1976).

	FUNGICIDES	
	WITH	WITHOUT
SEED YIELD KG/HA	10100	7630
TOTAL YIELD KG/HA	21780	17460
N-UPTAKE KG/HA	213	211
PROTEIN CONTENT SEED %	11.7	12.3
LEAF AREA DURATION M^2 LEAF X DAYS/M^2 SOIL	26.4	18.4
LEAF AREA INDEX AT ANTHESIS M^2 LEAF/M^2 SOIL	5.7	5.7

Table 2. Consumable protein and consumed protein in dependence of income (1965 base) per person per year (model MOIRA).

INCOME CLASS $	CONSUMABLE PROTEIN KG	CONSUMED PROTEIN KG	RATIO
< 100	24	19	0.80
100-200	27	20	0.73
200-400	32	22	0.69
400-800	49	29	0.59
800-1600	70	33	0.47
1600	98	35	0.35

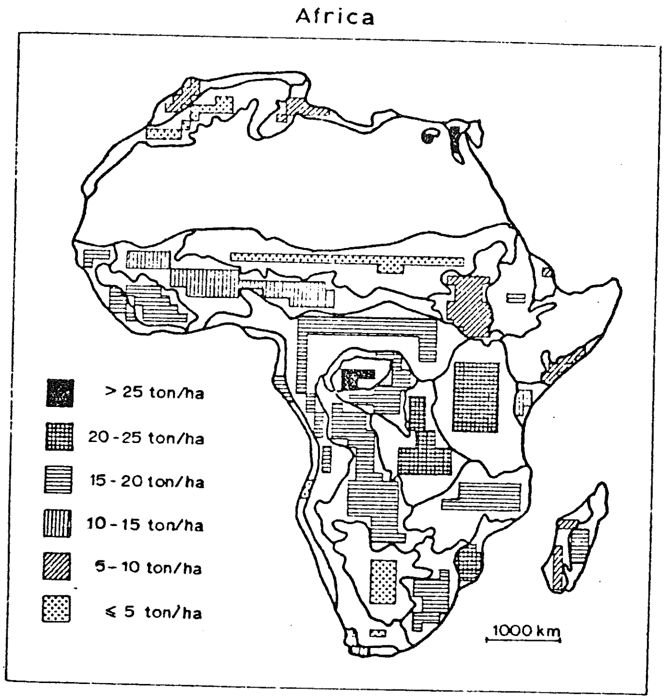

Fig 1

Broad soil regions in Africa with their area of potentially arable land and its average potential yield, in kg grain eq./ha/year, taking water and soil constraints into account.

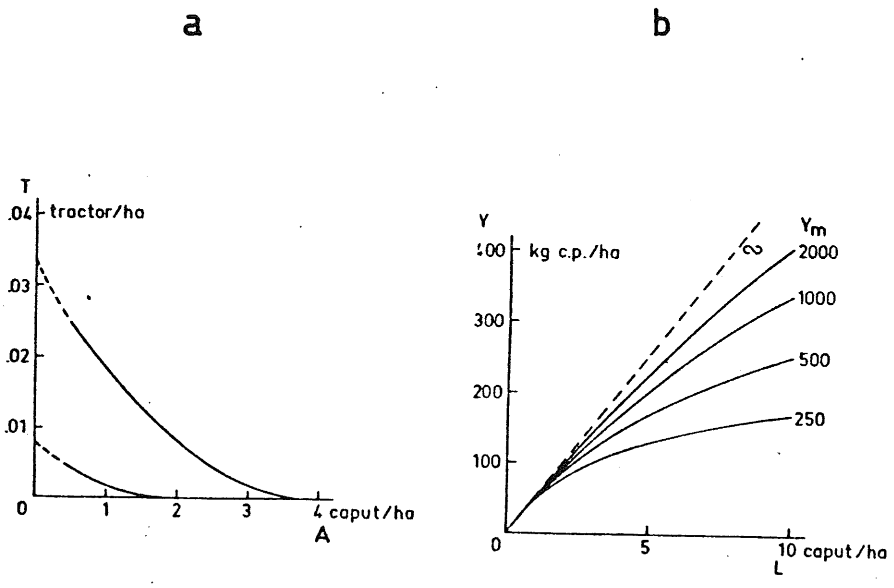

Fig. 2

A result of a cross-country analysis (model MOIRA, Linneman et al., 1976):

a. The substitution relation for labour (in caputs of agricultural population) and labour replacing capital (in number of tractors) per hectare potential arable land for two levels of equivalent labour.

b. The interrelation between yield (Y), maximum yield (Y_m) and equivalent labour use (L) per hectare.

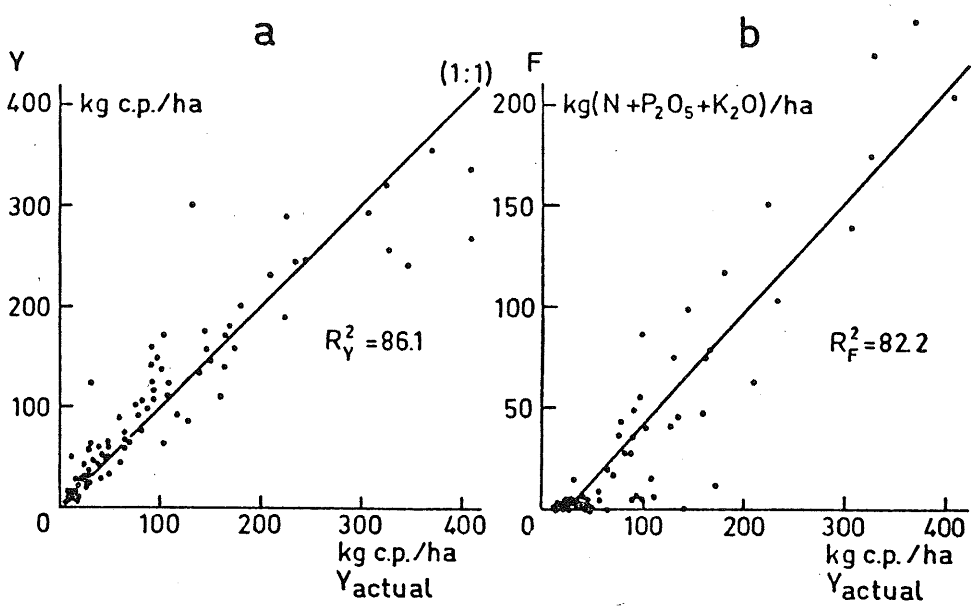

Fig. 3

Scatter diagrams (model MOIRA):

a. The relation between computed (Fig. 2) and actual yield per hectare potential land for over 100 countries.

b. The relation between yield in kg consumable protein and kg fertilizer use ($N+P_2O_5+K_2O$) per hectare potential arable land for 86 countries. The data for three countries, with high fertilizer use on land that is not used for arable crops, are omitted.

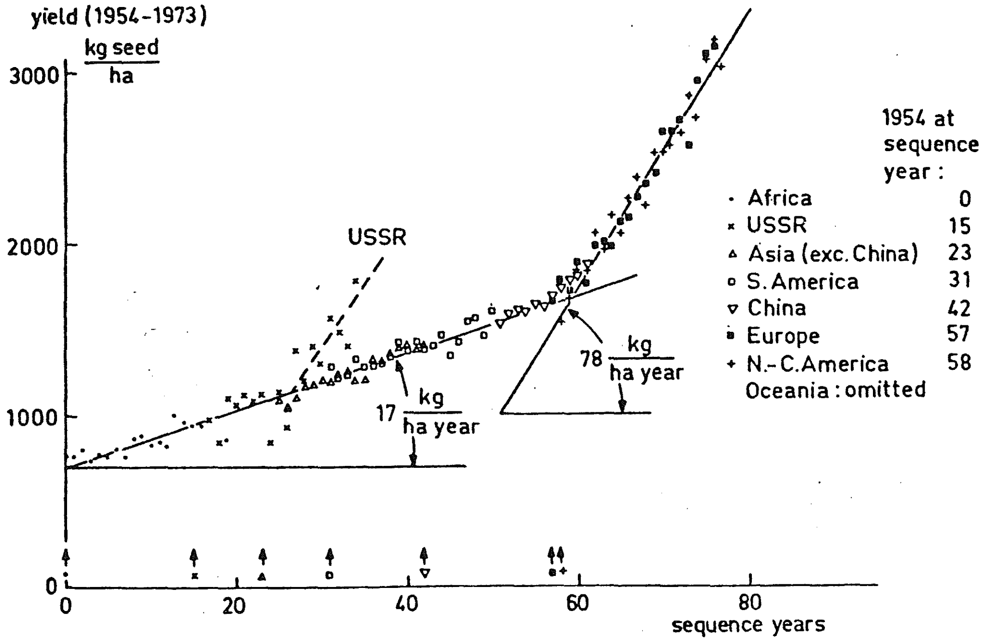

Fig. 4

Yields from 1954-1973 in the main regions distinguished by FAO, ordered along a continuous yearly time scale. The position of the year 1954 is marked by an arrow for each region. Oceania, with an average yield of 1200 kg/ha, is omitted because of the erratic fluctuations in the reported yield data.

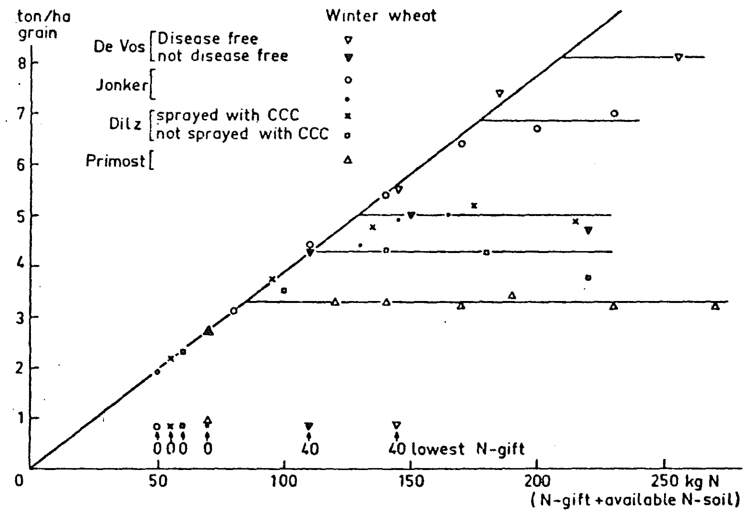

Fig. 5

The relation between yield of winter wheat and nitrogen application in experiments varying from 3000-8000 kg/ha. The curves are adjusted for the nitrogen available from the soil.

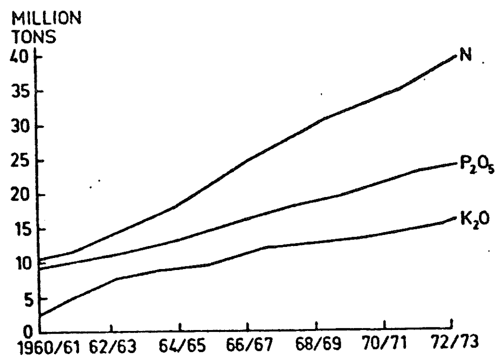

Fig. 6

World fertilizer use since 1960.

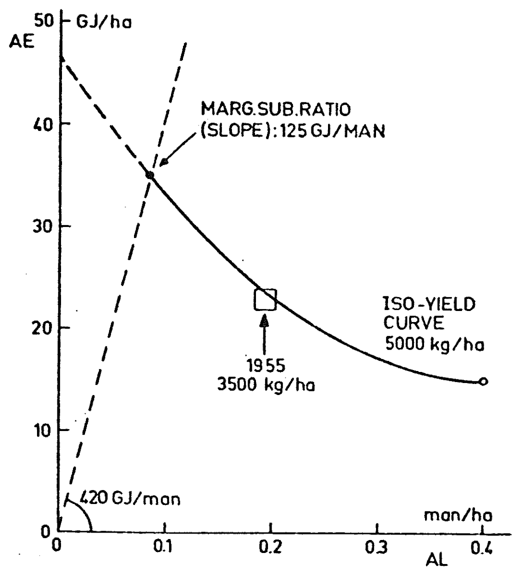

Fig. 7

A suggested iso-yield curve for wheat growth in the Netherlands at a yield level of 5000 kg/ha with added energy and added labour along the axis.