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FOOD PRODUCTION AND FOOD SECURITY[1]

Foreword

This paper was written for the Dutch Open University. It examines the possibilities for and restrictions on food production and shows that the problems of food security can be ascribed to factors other than biotechnical ones. Political and economic restrictions have more effect on the production and distribution of food in the world than do technological limitations. This is demonstrated in this paper, which illustrates the basic principles of Theoretical Production Ecology.

1. INTRODUCTION

For centuries, food production was the primary occupation of the majority of the population. Until about a century ago (in the case of the Netherlands, until 1860), more than 50% of the working population in the industrialized countries was engaged in agriculture and even today a large proportion of the world's population are farmers or farm labourers. The decrease in the proportion of the population engaged in food production over the last 100 years has occurred at a particularly fast rate in the industrialized countries. In the Netherlands, some 5% of the working population are employed directly in the agricultural and horticultural sector, while in other industrialized countries, this percentage is even considerably lower. This is because non-soil-dependent agriculture and horticulture (greenhouses, mushroom cultivation, intensive livestock farming) are more developed in the Netherlands than elsewhere in Europe.

The enormous changes in the number of people employed in agriculture have been caused by a rise in soil and labour productivity. This has been made possible by the fact that this sector was able to make use of products developed by industry. Investments in land reclamation works, mechanization, improvement of soil fertility and crop protection are only possible if industry produces the machines, the artificial fertilizers and

1 This chapter has been adapted from a publication by De Wit (1971).

the crop protection technologies and agents required. This combination of inputs from several economic subsectors has led to the increase in soil and labour productivity. There is scope for this to continue in some 99% of the world's agricultural areas and, if these developments are managed properly, food production for the ever-increasing population can be guaranteed and the burden on the environment and natural habitats reduced, enabling the development of sustainable agricultural systems.

2. HISTORY OF AGRICULTURE

2.1 Agriculture in the middle ages

In the early middle ages, around 100 families were needed to maintain the fifteen monks and several servants living at a monastery situated close to the French town of Antver. These farming families produced just enough surplus food to feed a number of "white-collar workers". They were classic farming families, who only worked on the land. They produced some 800 kg of grain per hectare each year of which, because of its poor quality and competition with weeds, a relatively large amount of some 200 kg were needed as seed for the next year's crops. Of the remaining 600 kg, half went to the animals which worked the land and to beer production. The quality of the water was bad and the meat people ate was generally so salty that enormous amounts of beer were consumed. Only 300 kg of grain per hectare remained for food - just enough to provide one person a year with a meagre cereal diet. With the low level of mechanization in the middle ages, cultivating one hectare involved a great deal more labour than it does today. It took at least 500 hours to cultivate each hectare, so one person working full-time could farm no more than 2 to 3 hectares, since almost all the work had to be done in the growing season. At the moment, Northwestern Europe's highly productive agriculture produces around 7,500 kg of grain per hectare per year. No more than 150 kg of seed and some 15 hours of work go into each hectare. In short, the low yield per hectare per year and the large amount of labour needed to produce it explain why the vast majority of the population were forced to earn their living on the land by the sweat of their brows.

The cause of the low yields per hectare in early medieval times did not lie in climatic conditions. There was always sufficient water and, although some diseases flourished in the prevailing damp weather, this reduction in growth and yield was not the main cause. The most important reason for the low yields was the chronic shortage of nutrients for the plants. We now know that natural fertilization provides only 25 kg of nutrients to plants (nitrogen, phosphate and potassium). In combination with solar energy this is just enough to produce 1,500 kg of biomass. Since at least 50% of this is stems, leaves, etc., a maximum of only 700 kg of grain is actually produced.

Certain agricultural practices, such as the spreading of animal manure or the use of green manure, increased production. The most important source of plant nutrients was animal manure. The main purpose of keeping large herds on uncultivated land was clearly to improve soil fertility. This is obvious, because the difference between the price of meat and the price of grain was very small and the demand for grain for the production of bread, beer and porridge was so great that the size of a herd was often determined by the need for manure. Decisions could be taken on such a basis in those days, since the land area per inhabitant was much larger than it is now. Up to the beginnning of this century, yield rose as a result of new agricultural practices to 2,000 kg per hectare per year. However, this only happened on well-managed land, to which large amounts of animal manure and/or green manure (such as clover) were applied. The size of the population enabled land to be used in this way. Enough rangeland was available on which cattle could be kept and thereby enhance soil fertility in concentrated areas where, for example, grain was grown. In contrast, in other parts of the world, such as China and India, the pressure on agricultural land was much greater. There, the level of production remained at around 1,000 kg of grain per harvest.

In industrializing Europe, population growth increased dramatically in the last century and it became impossible to feed everyone on the traditional diet of meat and grain. The introduction of the potato and the replacement of animal fats by vegetable fats meant that many more people could be fed. Crop rotation[2] was employed on a large scale and food crops were alternated with clovers, grasses and other crops used for animal feed. Manure was carefully stored and urban waste was composted and used to improve soil fertility. Higher yields were therefore only achieved in the industrialized areas of Northwestern Europe. In other parts of Europe, yields remained extremely low, at less than 1,000 kg of grain per hectare. The high yields achieved with potato, which was introduced in the mid-eighteenth century, were not the result of the production of more dry matter per unit area, but of a more favourable distribution of dry matter among the organs of the plant. Potato does not require a stem to carry seed and 80% of the dry matter formed therefore ends up in the tuber, while, in the case of grain, the figure is only 50%.

[2] Crop rotation is the cultivation of different crops on the same area of land each year in order to prevent supply of certain nutrients from becoming exhausted.

2.2 Agriculture with artificial fertilizers

Large-scale increases in yield only became possible after industry began to produce artificial fertilizers. In 1840 the German chemist Liebig showed that plants only require water, minerals and nitrogen from the soil and that organic matter in itself is of no nutritional significance. The role of organic matter in determining the structure and texture[3] of the soil does not strictly have any connection with plant nutrition. Liebig's experiments showed that only 25 kg of the nutrient nitrogen is available to the plant if no fertilizer is applied, thus restricting production. By applying minerals to the soil, the level of nutrients, and therefore also yield, could be multiplied. It was not until several decades after Liebig's discovery that farmers became aware of it and industry began to produce mineral fertilizers. Conditions changed rapidly after that. Up to the beginning of this century, productivity rose at a rate of some 3 to 4 kg of dry matter per hectare per year, after which the rate increased to 18 to 20 kg per hectare per year until, after the Second World War, productivity experienced a dramatic increase to some 80 kg per hectare per year (see Figure 1.1).

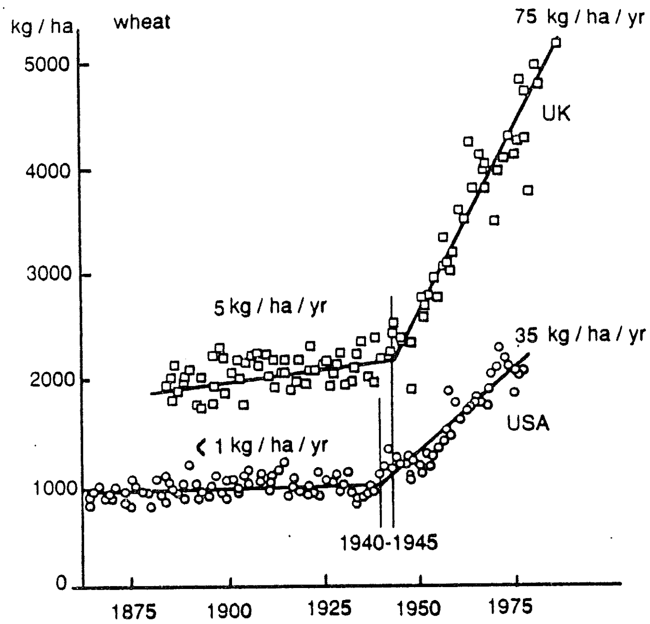

Figure 1.1. Wheat yields over more than 100 years in the United Kingdom (U.K.) and the United States of America (U.S.A.).

[3] Structure and texture are properties determined by the distribution and proportion of soil particles of different sizes (e.g. coarse sand, clay). This, in turn, determines the physical properties of the soil.

Current wheat yields in the Netherlands are approximately 8,000 kg per hectare - five times the level at the beginning of this century and twelve times the level at the middle ages. These are the figures for productivity per unit area; even more striking are the figures for productivity per person, which are now 200 times higher than in the middle ages. In short, there has been a dramatic rise in productivity over a period of less than 80 years, which has enabled large numbers of workers to leave agriculture. This discontinuity was made possible partly because enough jobs were created in other sectors of the economy to absorb the displaced labour (see section 4.1). The current high yields are the result of the 200 kg of nutrients applied to each hectare every year, next to the nutrients available to plants from the livestock manure produced by animals which during the winter are fed on preserved grass and imported feed. This increase in yield through the use of mineral fertilizers was possible only thanks to new productive varieties. Some crops, such as buckwheat, were not adapted and therefore played no important role in food provision, a fact which eventually caused them to disappear. Among the cereal crops, the varieties which tiller readily were gradually replaced by varieties which produce stiff straw. The gradual nature of this process is illustrated in Table 1.1 and Figure 1.2, in which the index figures for grain and straw yield for Dutch varieties of oats are plotted against the year of introduction.

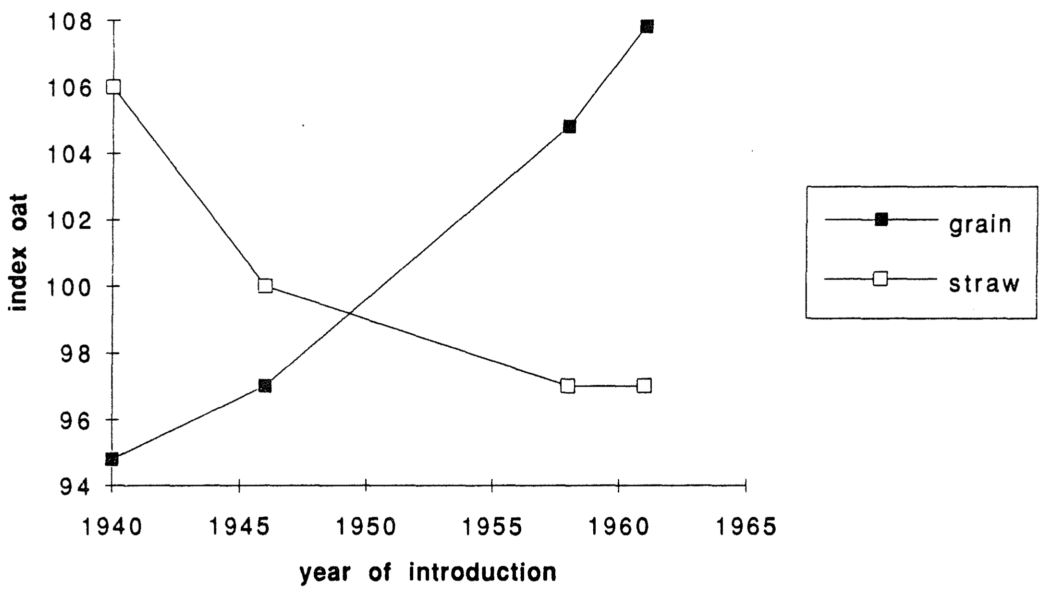

Figure 1.2. Index figures for the yield of grain and straw produced by different types of oats grown in the same place in the same year, in relation to the year in which they were introduced. After: De Wit (1971).

Table 1.1. Characteristics of old and new winter wheat varieties assessed under optimum growing conditions at Cambridge, United Kingdom, 1984-1986 (Austin *et al.*, 1989)

variety group	total above ground dry matter ($ton.ha^{-1}$)	grain yield (85% dry matter $ton.ha^{-1}$)	harvest index (on basis of above-ground dry matter)	stem length (cm)
very old	15.0	5.94	0.34	145
old	15.4	6.55	0.36	134
intermediate	14.8	7.87	0.45	96
modern	15.9	9.47	0.51	78

This process of adaptation had certainly got under way by 1840. However, one must remember that the rise in yield over the last hundred years was limited not so much by technical possibilities, as by the demand for food and the ability of the population to pay for it. Since the mid-nineteenth century, farmers have been able to produce all the food required, but only over the last thirty years, at least in Western Europe, has income become distributed in such a way that everyone can afford to buy the food they need.

3. POTENTIAL, ATTAINABLE AND ACTUAL PRODUCTION LEVELS

3.1 Potential production

As indicated in Figure 1.1, yield from agricultural crops is still rising rapidly in the Netherlands, as elsewhere, despite already being at a high level. This increase cannot continue indefinitely, however, and the question arises of what maximum yields can be achieved, using good varieties, which are provided with sufficient minerals, nitrogen and water. Total production of organic matter under such conditions depends on the rate of photosynthesis in the green leaves of the crop, expressed as kg CO_2 per hectare per hour (Figure 1.3).

Photosynthesis is the process by which, plants, using energy from the sun, convert CO_2 and water to energy-rich sugars. In a single leaf, photosynthesis is directly proportional to light intensity at lower intensities, but at high light intensities the rate of photosynthesis reaches an upper limit. The relationship between photosynthesis and light intensity in one leaf is shown in Figure 1.3. Before light saturation is

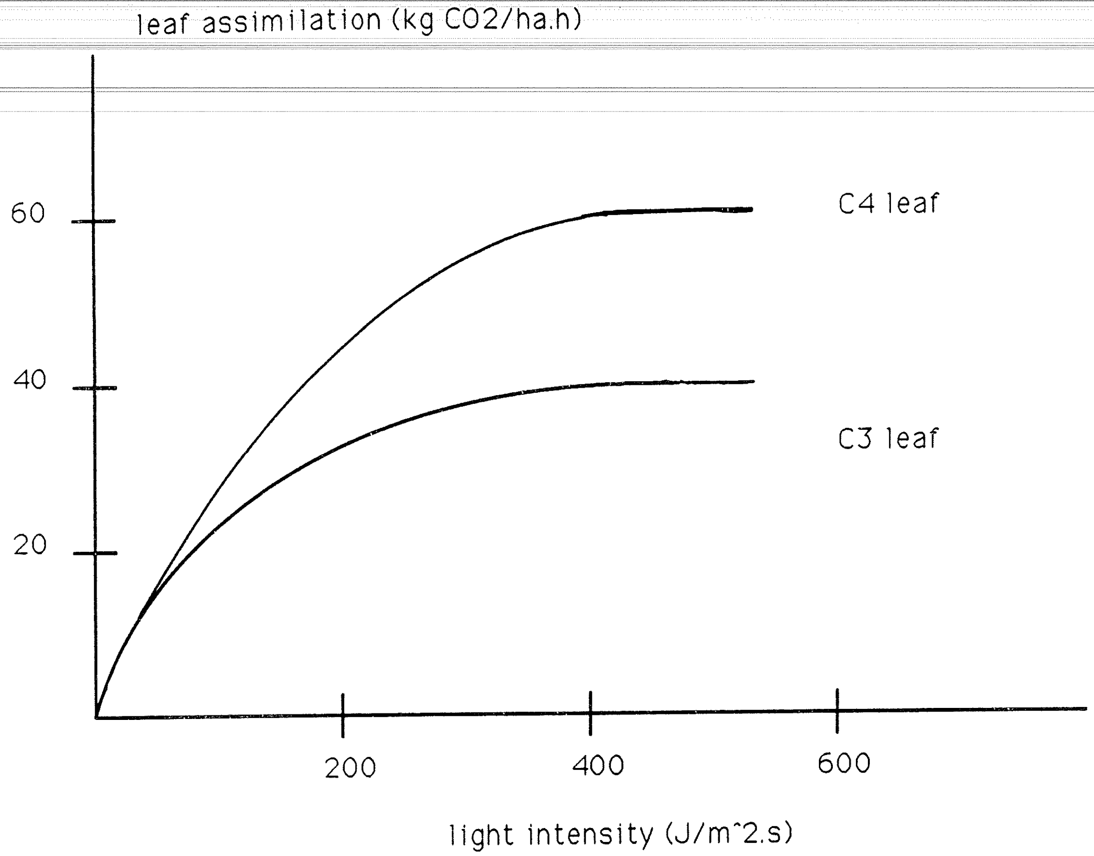

Figure 1.3. Leaf assimilation light response.

reached, the slope of the curve does not vary significantly among plant species. The production of sugars at low light intensities (initial light use efficiency) is around 0.3 kg per hectare per hour for every Joule absorbed by the leaf per m^2 per second (0.3 kg CH_2O ha^{-1} h^{-1} / (J m^{-2} s^{-1})). However, the maximum rate of photosynthesis (at high light intensities) can vary significantly among species. It can be assumed that the average maximum rate of photosynthesis in the individual leaves of many of the important agricultural crops is approximately 20 kg of sugars per hectare per hour.

Some tropical crops produce yields at least double these at favourable temperatures. This is due to the fact that the basic processes of photosynthesis in these crops differ from those of other cultivated crops, legumes and trees. There are two types of photosynthesis: C_4 and C_3 photosynthesis, named after the number of carbon atoms in the first molecule formed after fixation of atmospheric CO_2. The majority of plants have C_3 photosynthesis, while only a few - a number of tropical grasses and crops such as maize and sugar cane - have the C_4 type. At high light intensities, photosynthesis is lower in C_3 plants (Figure 1.3). This is mainly the result of photorespiration[4] which in C_3 crops increases in proportion to light intensity, while it does not occur at all in C_4 crops. Initial light use efficiency is virtually identical in C_3 and C_4 photosynthesis.

Photosynthesis in the leaves reaches saturation as light intensities increase. This means that, at light intensities of approximately 100 Joules per m^2 per second the leaves of C_3 crops have virtually reached their maximum rate of photsynthesis. Such levels of light intensity are reached on cloudy days when the sun stands at its zenith; on clear days, intensities of up to 1,000 J per m^2 per second may occur (cf. Figure 1.4). A large proportion of the light reaching crops with one or more layers of large, horizontally positioned leaves is lost. However, many crops have narrow leaves arranged in various positions so that light can penetrate deeper into the crop and is therefore distributed more evenly over the leaves. Photosynthesis with this type of foliage is correspondingly higher than maximum photosynthesis in a horizontal leaf (cf. Figures 1.3 and 1.4). The amount of energy available for the conversion of CO_2 varies depending on the distribution of the leaves, their position and the amount of light they reflect, transmit and absorb. Knowledge about the geometrical and optical properties of crops is sufficient to calculate the amount of energy fixed.

De Wit (1968) calculated that on a completely clear day closed crops[5] - whose individual leaves have a maximum photosynthesis rate of 20 kg of sugars per hectare per hour (see Figure 1.3) and a leaf arrangement like that of a cereal crop - photosynthesize at a rate of 35, 50 and 55 kg of sugars per hectare per hour (see Figure 1.4) when the sun stands at an angle of 30, 60 and 90 degrees respectively. These figures are significantly higher than the maximum of 20 kg for a single leaf. When the sky is cloudy light intensities are approximately one fifth of those found under clear conditions, but the rate of photosynthesis is reduced by no more than half because light is distributed more evenly under cloudy conditions.

The daily level of photosynthesis in a crop in a particular place depends on the amount of clouds, the latitude and the time of year. In the Netherlands, potential photosynthesis is approximately 400 kg of sugars per hectare per day in summer, and some 60 kg in winter. These daily totals were calculated on the basis of the available light and will only

[4] Plants need to respire in order to create new matter and maintain existing matter.

[5] A crop is closed when virtually non of the light reaching the crop reaches the soil.

be reached if the average temperature is at a reasonable level, i.e. a 24-hour average of 10°C or higher, which is normal in the Netherlands from mid-April to mid-October, roughly speaking. If the daily totals over this period are added, potential photosynthesis of a healthy crop surface, if it is maintained throughout the period mid-April to mid-October, is approximately 60 * 400 + 120 * 200 = 50,000 kg of sugars per hectare. This

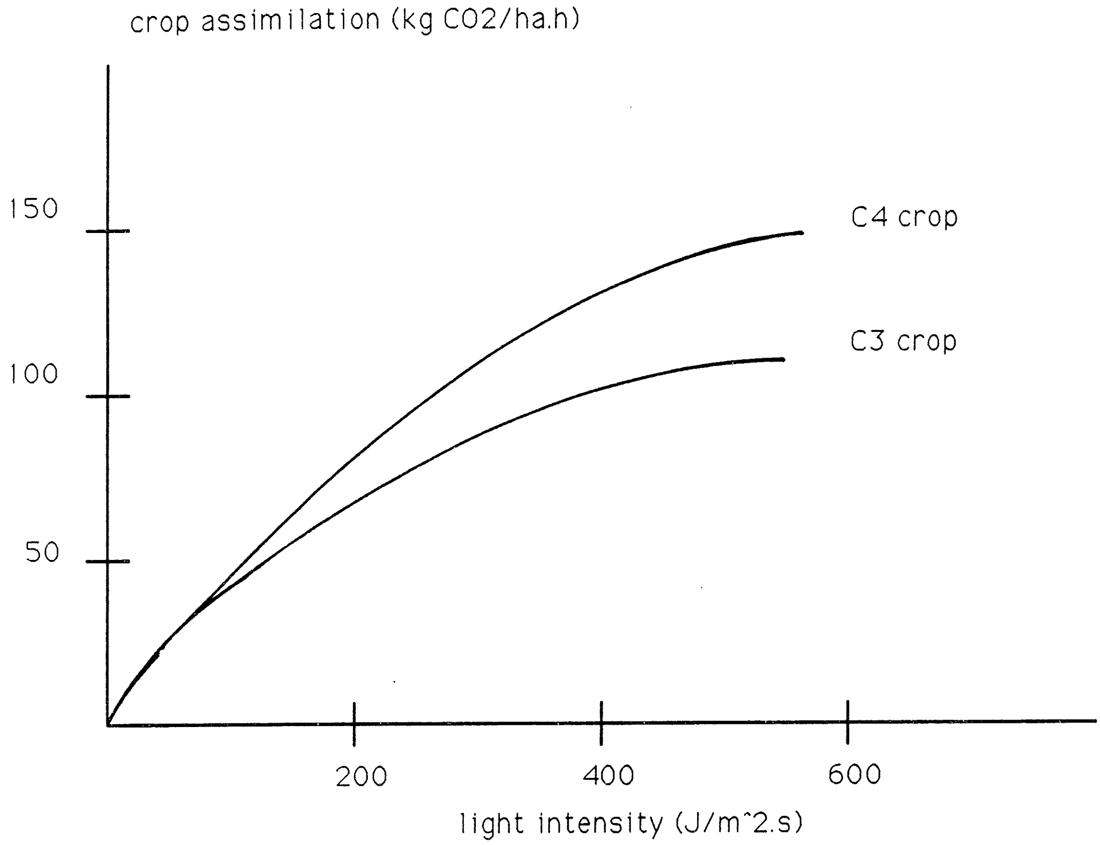

Figure 1.4. Crop assimilation light response.

assumes potential photosynthesis rates of 200 kg of sugars per hectare per day in spring and autumn (120 days) and 400 kg per hectare per day in summer (60 days). The sugars produced are not stored as such, but are used by the plant to produce its roots, stems, leaves, flowers, fruits and seeds. Calculations have shown that the production of one gramme of proteins, fats or cellulose and absorption of one gramme of minerals requires 1.92, 3.23, 1.28 and 0.12 grammes of sugar respectively. For one gramme of plant material containing 25% protein, 5% fat, 60% cellulose and

10% minerals by weight, some 1.42 grammes of sugar are needed. This means that the rate of 400 kg of sugars per hectare per day which is possible in June produces plant growth totalling some 275 kg of organic matter per hectare per day. As roughly a quarter of this organic matter is respired to keep the constituent parts of the plant alive, tests to determine potential yield must assume production of 200 kg of dry matter per hectare per day. This growth rate actually occurs in the Netherlands under favourable conditions, as is shown in Figure 1.5.

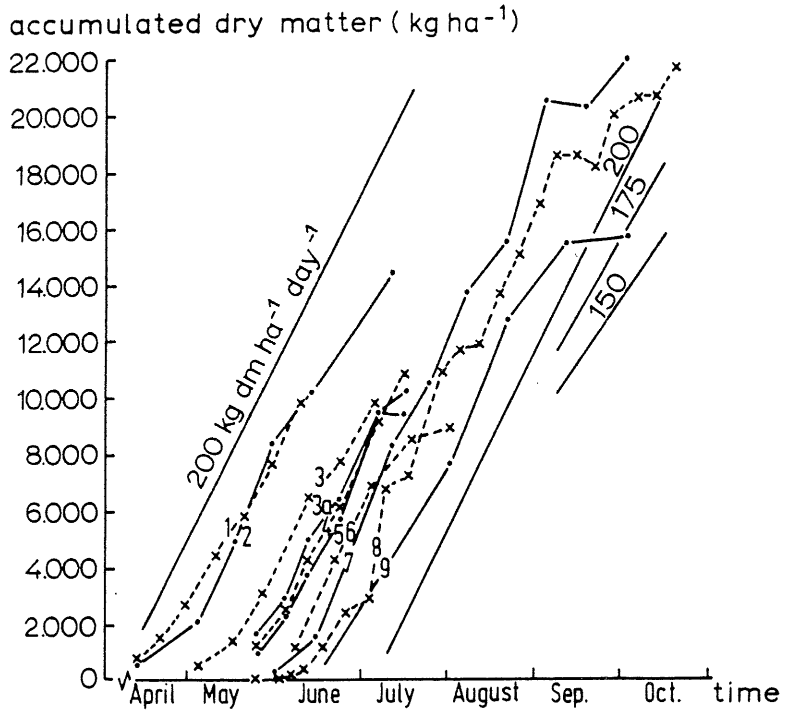

Figure 1.5. Growth pattern of a number of crops. Source: Sibma (1968).

Figure 1.5 shows the pattern of the quantities of dry matter produced by different crops during the growing season. The slopes of the experimentally derived growth curves correspond fairly closely to the theoretical production rate of 200 kg of dry matter per hectare per day.

The great differences in total production by crops are not so much the result of differences in growth rate, but of the length of the period for which a closed, healthy green crop surface can be maintained. For winter wheat in the Netherlands, this period is no longer than just over three months, which means that total production is limited to approximately 100 x 200 = 20,000 kg of organic matter. Summer wheat has an even shorter growing period and therefore has a lower total production level.

Furthermore, some 50% of the organic matter ends up in leaves, roots and stems, so potential production of grain could be estimated at 10,000 kg of dry matter per hectare per year. Average wheat production in the Netherlands is now over 7,500 kg of dry matter per hectare per year, and on experimental fields levels of 8,500 kg are now normal. In some parts of the world, such as Scotland, the amount of solar radiation reaching the ground every day is higher than in the Netherlands due to the longer days, and the growing season is slightly longer. In those areas, yields as high as 10,000 kg of dry matter per hectare per year and higher have been achieved. With potato, a closed, healthy green crop surface can be maintained for four months, making possible a total production of 24,000 kg of organic material, 80% of which eventually ends up in the tubers. Tuber yield is thus 20,000 kg of dry matter per hectare per year, or 100 tonnes of potatoes with a dry matter content of 20%. Experiments have shown that it is possible to obtain this potential yield. In practice, the yield is around 40 tonnes, with some farmers achieving 60-80 tonnes per hectare.

3.2 Attainable and actual production

Potential yield has been examined above, but this is only achieved under exceptional conditions. In the majority of the cases, the *attainable yield* is considerably lower, because for part or even all of the growing season, growth is restricted due to a shortage of water and/or nutrients. In addition, crops are plagued by diseases, pests and weeds, making the attainable yield lower than the potential yield. In the majority of the world's agricultural regions, the attainable yield is less than 20% of the potential yield. The *actual yield* is generally even lower, because, given the opportunities, agricultural practices are not carried out optimally.

In areas with a high level of land reclamation, actual yield is often further below attainable yield than in areas with a low level of land reclamation, which is the case with most of the world's agricultural land (see Figure 1.6). The difference between high and low levels of reclamation can be seen in the degree to which attainable production approximates potential production. Actual yield can be raised to the level of attainable yield by the use of good cultivation practices, particularly in areas with a high land reclamation level. One can thus differentiate between potential, attainable and actual yield.

The potential yield is determined by *growth defining factors* incoming solar radiation and temperature, and the characteristics of the crop: its physiological characteristics (photosynthetic characteristics), its phenological characteristics (crop development), the optical properties of the leaf (reflection, transmission and absorption of radiation) and its geometric characteristics (leaf arrangement and ability to intercept radiation). The incoming solar radiation and temperature vary according to geographical position, time in the year, etc. It is possible to calculate potential yield and good methods for doing so were developed by De Wit in the 1960s.

The attainable yield is the yield which can be achieved under the restrictions imposed by the absence of a number of the *growth limiting factors*, such as water and nutrients. A shortage of water during part of the growing season leads to a reduction in growth rate and growing period, making attainable yield considerably lower than potential yield. The same applies to a shortage of nutrients such as nitrogen and phosphate. In

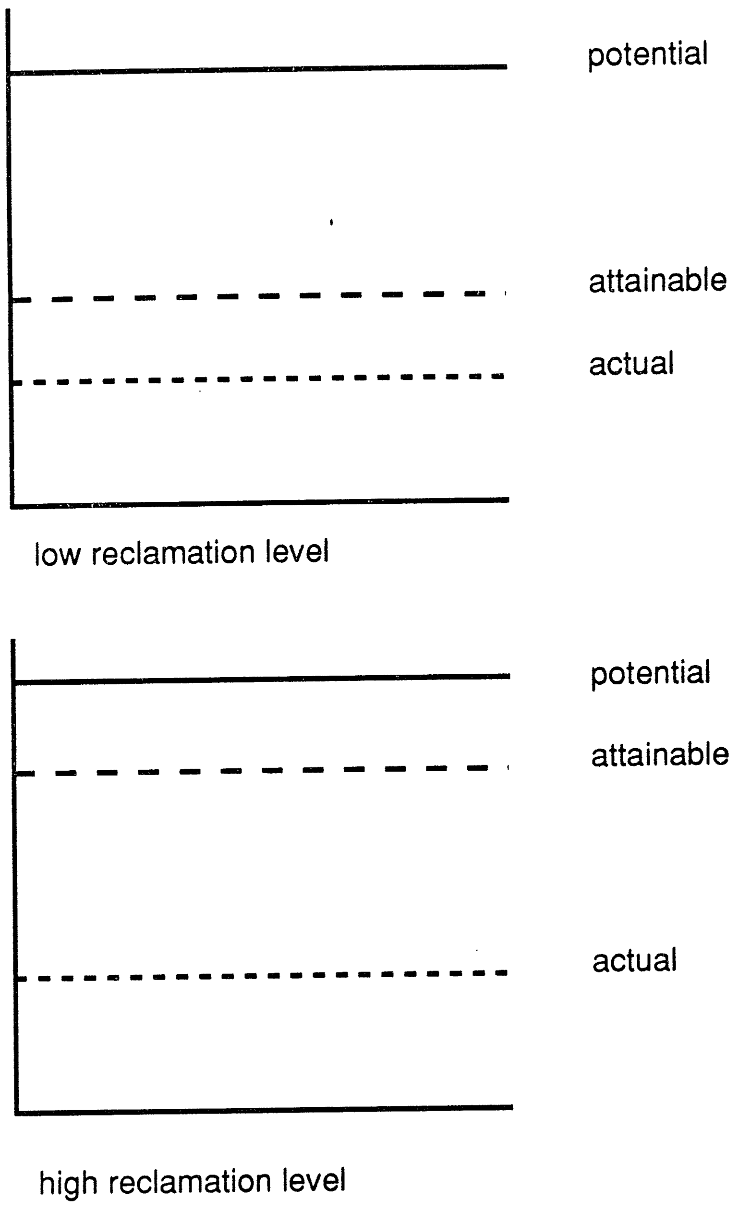

Figure 1.6. Yield level.

virtually all the agricultural areas of the world, growth rate and therefore production are limited during at least a part of the growing season by a shortage of water and nutrients. Growth rate is usually limited throughout the growing season by one factor after another. An analysis of growth and production of Sahelian rangelands showed that for part of the period phosphate is in short supply, then nitrogen, and, at other times, water shortages are the limiting factor. If the problem of poor soil fertility were eliminated, the attainable yield would be 2 to 5 times the present yield. Despite appearances, water is not the sole, preeminent growth factor in this case.

Factors which *reduce growth* include diseases, pests and weeds, and these also reduce the attainable yield. Various processes may be affected by diseases and pests; there may be competition for light, and photosynthesis and respiration may be affected.

To examine this in detail would be beyond the scope of this paper. It suffices to say that actual growth and yield lag far behind what is attainable, while this in turn is way below the potential yield.

3.3 Potential production in the world

As indicated above, potential photosynthesis in the Netherlands is around 50,000 kg of sugars per hectare per year, or 35,000 kg of organic matter per hectare per year. Given the fact that part of this is needed for respiration and that only part of the biomass is suitable for human consumption, it is not unreasonable to assume that, with our current level of knowledge and the crop varieties available, it should, in a commercial setting, be possible to obtain 35% of the biomass in a form which is suitable for human consumption. This comes to 175 GJ per hectare per year: 12,500 kg per ha per year * 14 MJ per kg of dry matter. Since one person requires some 3.5 GJ of energy each year, in the Netherlands one hectare could feed around fifty people a year, assuming that they were satisfied to eat only vegetable products and did not waste much food.

In other parts of the world potential production may be lower or higher, depending on the length of the growing season, the temperature and the level of solar radiation. If enough nutrients and water are supplied, it is possible to grow crops all year round in the tropics. This gives a potential photosynthesis of some 120,000 kg of sugars per hectare per year, or a production of approximately 30,000 kg of organic matter suitable for consumption. In this case it should be possible to feed 120 people for a year from one hectare. These yields have been shown to be attainable with crops such as rice and sugar cane.

These calculations demonstrate that the world population, which currently stands at 5 billion (5×10^9) could, under European conditions, feed itself from an area of no more than 100 million hectares. The entire world population could thus be fed from an area smaller than the current amount of agricultural land in Europe, which for the European Community is 127 million hectares of agricultural land. However, it should be noted that by no means all of this land is capable of producing such high yields. Less than 60% of the cultivated land in Europe would be capable of reaching such levels of production. Nevertheless, the potential for food production is unimaginably big. Naturally, a situation for which Europe grew food to feed the rest of the world is highly unlikely, but it demonstrates how enormous the potential of agricultural production is. In fact, this theoretical situation illustrates the upper limits of cultivation practices, although it does not take account the socio-economic and ecological constraints.

If potential production is calculated by area, the figures given in Table 1.2 are obtained.

Table 1.2. The area of suitable land, the number of months with average temperatures above 10°C, the potential yield, the land area required to feed each person after possible cultivation of all the land and the potential number of people to be feeded, between 70° N and 50° S.

Degrees North	land area (10^8 ha) (all potenial land)	no. of months with temp. >10°C	total organic matter/ ha/yr (1,000kg) (pot. production)	area/ person (m^2) after conversion to useful prod.	no. of people 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

It shows that, given potential production, 150 m^2 are required for food production for one person and that more than 1,000 billion (1,000 x 10^9) could live from the total land area (excluding the oceans). This figure is more than 200 times the current world population. However, this number of people could live *from* the earth, but would not have enough space to live *on* the earth.

Estimates of the amount of land one person needs for food, work and relaxation strongly depend on the cultural background of the person making the estimate. If we assume that at least five times the area needed for food is needed for other purposes, we obtain 5 x 150 m^2 = 750 m^2 per person. This is still a small area which has, moreover, been calculated in a rather arbitrary fashion.

On the basis of this figure and an average of 150 m^2 for food production, a total of 900 m^2 per person is required. This allows for a maximum world population of 145 billion (145 x 10^9). In the Netherlands, 15 million people live on some 30,000 km^2 of land, approximately 20,000 km^2 of which is used for agriculture and horticulture. This population should require only 20% of the land area for its own food production, rather than the current 70%. This land, suitable for modern agricultural practices, is available.

However, man does not solely live by potatoes and, if meat is to be included on the menu, approximately twice the land area is required, assuming that only a small amount of meat figures in the diet, since it takes 10 kg of vegetable matter to produce 1 kg of meat. This reduces the number of people which Earth can support to

$$\frac{150 + 750}{2 \times 150 + 750} \times 145 = 125 \text{ billion } (125 \times 10^9)$$

This is still an impressive figure.

However, there will be those who believe that each person requires 1,500 m^2 to live from and for non-food-related purposes. The maximum number of people who could live on Earth, when excluding meat consumption, would then be

$$\frac{150 + 750}{150 + 2 \times 750} \times 145 = 80 \text{ billion } (80 \times 10^9)$$

Comparison of the above figures demonstrates that the size of the world's population depends not so much on the land area required for food production, but on the land desired for other purposes. To a certain extent, therefore, scope for food production need not restrict the size of the population. Irritation is likely to be a more important factor, along with the need to dispose of waste products.

De Wit made the above estimates in 1975, on the basis of a very simplified calculation. Since then, more accurate estimates have been obtained for various regions using computer simulation models. These models use properties of the soil and climate as basic data and simulate the growth and production of different crops (quantitative analysis). On the basis of the location, the prevailing climate and the properties of the crop, the potential and attainable production, based on the availability of growth factors, can be calculated. On behalf of the European Community, the Advisory Council on Government Policy (WRR) commissioned the Winand Staring Centre (SC-DLO) in Wageningen to carry out just such a detailed analysis. All their estimates show that, on the basis of the potential soil productivity, production levels several times the current ones could be obtained. If the land area suitable for different types of agriculture is determined (qualitative analysis), it becomes clear, for instance, that the land area in Greece which is suitable for arable farming (the most demanding type of land use) is only 10% of the total area. In the other 90%, the land is too steep (making mechanized agriculture impossible), or the soil is too shallow, too saline, too acidic or too rocky. In other countries, such as Denmark and the Netherlands, more than 50% of the total land area is suitable for demanding forms of land use. Through a combination of quantitative and qualitative land evaluation, a fairly accurate assessment can be made of the potential and attainable yields for different crops under the different conditions found throughout the world. The analysis of SC-DLO was used by the WRR for a study of possible developments in the agricultural regions of the European Community. This study indicated that agricultural production could be several times higher than it is at present. Nevertheless, European agriculture, certainly in the most suitable areas, is more productive than in the rest of the industrialized world and much more productive than in developing countries (WRR, 1991).

4. PRODUCTION EFFICIENCY; GREEN REVOLUTIONS

4.1 Labour productivity and production efficiency

The rise in labour and soil productivity mentioned above is set to continue for some time, for two reasons.

The first lies in the fact that, as has been illustrated, potential production is much higher than actual production. In 99% of the world's agricultural areas, soil productivity is considerably lower than its potential. In general, less than 15% of potential production is achieved. This difference could be made up if the rise in productivity continues.

The second and, in fact, more important cause of increased soil productivity resulting from innovation lies in the efficiency of use of inputs. It will be demonstrated below that, at higher production levels, efficiency in terms of input per unit product is higher than at lower levels of production. The effect of this increase in efficiency at higher production levels promotes continued growth in production per unit area.

The rise in soil productivity over the past few decades has been accompanied not only by an increased efficiency in input use, but also by higher labour productivity. Around the turn of the century, the production of one tonne of wheat in the Netherlands required some 300 hours of labour, while the same amount of wheat can now be obtained with about 1.5 hours of labour. The growth in the demand side of the market has been another significant incentive fostering the ever-increasing growth in production.

The additional inputs needed to achieve these higher yields are sometimes grouped together on the basis of their energy content. Table 1.3 contains data obtained by Pimentel & Hall (1984).

Table 1.3 Energy production and consumption, both direct and indirect. Human labour and animal traction are related to four different methods of maize production (Pimentel & Hall, 1984).

	N -consumption kg ha^{-1}	Yield kg ha^{-1}	Output GJ ha^{-1}	Input GJ ha^{-1}	Out/In
Mexico Only human labour, no industrial fertilizers	0	1,944	28.89	39.40	0.73
Mexico Human labour and oxen, no industrial fertilizers	0	941	13.98	19.26	0.72
USA Human labour, horses, industrial fertilizers	152	7,000	102.58	111.79	0.92
USA Human labour, machines, industrial fertilizers	152	7,000	102.58	48.2	2.14

In contrast with the prevailing instinct and many energy surveys conducted in the 1970s, Table 1.3 showed that the fully mechanized, high yielding American maize-growing industry is three times more efficient in its use of energy than traditional methods of cultivation where all work is carried out by hand or by animal traction and no industrial fertilizers are used. For that matter merely grouping together all energy carriers, including food, fuel and the petrol needed to run a tractor, with a view to a high energy use efficiency, is not always useful. On the basis of direct and indirect energy consumption, this comparison nevertheless shows that the Law of Diminishing Returns for single inputs does not hold true for agricultural production as a whole. This is due to the fact that energy is not an input with a single effect, but a resource which can be used in varying amounts depending on the production level and degree of technological development. This increasing energy use efficiency demonstrates that technological advances in agriculture make possible increasing yields with a relatively lower unit input per unit product.

The reason for this is that the relative costs of fixed activities in agriculture, such as ploughing and sowing, decrease as yield increases. In principle, a farmer does not need to sow or plough more in order to obtain higher yields, although, at higher yields, the number of fixed activities increases while the number of variable activities decreases. For instance, in order to obtain modest yields, the acidity of the soil has to be adjusted by applying lime, but higher yields require no more lime than lower yields. The same applies with plant nutrients. This means that many inputs are not variable costs, but are part and parcel of the decision to grow a particular crop. The number of variable costs decreases as yields rise. No farmer who has improved water management on his land will fail to improve soil fertility by using fertiliser. He will also ensure that his crops are adequately protected. In areas with a low level of land reclamation crop protection and fertilizers can be regarded as variable costs, whereas, in areas with a high level of land reclamation, they are fixed costs. This statement fully challenges the widespread prejudice that variation in inputs depends on relative prices.

One consequence of this increase in fixed activities over variable activities is that, with higher yields, the applied inputs can be better controlled than with lower yields. In other words, in situations where high yields are obtained, growth processes are better understood and managed than in low-yielding situations, where the effects of various external factors on those processes are subject to a stronger mutual influence. Application of the energy-demanding nitrogen fertilizers is better controlled in high-yielding situations, where the unforeseeable losses resulting from evaporation, denitrification, leaching and immobilization are greatly reduced.

Wheat yields in the Netherlands rose from 3,500 kg per hectare in 1950 to 7,500 kg in 1990 (see Figure 1.1), whereas the efficiency of the use of direct and indirect energy rose from 145 kg of wheat per GJ to more than 200 kg of wheat per GJ. This happened despite the increase in labour productivity and the concomitant increase in energy input, which rose by a factor of 4 or 5 over the same period.

Crop protection is also an important precondition for higher yields. It does not take much energy to apply the correct biological, mechanical and chemical crop protection methods, but it does require knowledge and experience. The farmer must therefore be highly skilled. Lack of skill can be compensated for by using excessive and therefore untargeted chemical crop protection agents, but that constitutes very unsound agricultural practice. Integrated protection against disease and pests, for which as much use as possible is made of the natural enemies of and a crop's resistance to certain diseases and pests, alongside preventive phytosanitary measures, requires frequent field observations. By applying suitable measures at the right time and in the correct way, much loss of production can be prevented. The same applies to other agricultural practices.

High production levels do not, therefore, principally require more chemical energy in the form of artificial fertilizers, machines and pesticides; rather they call for well-trained farmers who are capable of taking numerous well-considered decisions throughout the growing period of a crop. Brain power is much more effective than energy in the form of tangible inputs, and the amount of energy it takes to think is negligible.

Yields continue to increase until the attainable level is reached, which in case of a high level of land reclamation lies only just below the potential yield. The foregoing indicates that the increase in yield per unit area is determined not so much by economic factors as by the rate at which knowledge and experience are assimilated and operationalized by the farmer and inform his actions. If it is economically feasible to run a farm, it seems obvious that technology should be properly used. In this way of thinking, it is not a matter of whether to use more or less technology or inputs, but of whether one is going to farm or not. If one chooses to farm, one should do it rationally, with suitable resources and technology.

4.2 Green revolutions

The rise in labour and soil productivity discussed above has been accompanied by a number of breaks with tradition. In the late 1940s and early 1950s there was a sudden rise in the growth of the grain production per unit area in the industrialized world (see Figure 1.1). This first green revolution, as it was known, was the result of a combination of developments in a number of scientific disciplines. In the field of plant breeding, the short-stem varieties, which had been developed by Heine during the Second World War, were introduced; the use of nitrogen fertilizers increased rapidly; herbicides were introduced. The resulting rise in yield and the rapid mechanization of farm work raised labour productivity to unprecedented levels.

This first green revolution - which went largely unnoticed by the public - occurred in the Western industrialized countries and was followed some 20 years later (in the late 1960s and early 1970s) by a second green revolution, which this time took place in Asia, particularly India, China and Indonesia. The turnaround in productivity which occurred there brought a halt to the structural food shortages which had plagued that region since the early 1950s, despite the growing population.

Many parts of the world, particularly Africa and parts of the Middle East, now need a third green revolution, since they have never experienced the kind of explosion in productivity described above and have burgeoning populations.

5. ENVIRONMENTAL EFFECTS OF AGRICULTURE

5.1 Environmental effects of poverty

For centuries mankind has had to face the problems which arise when land is not used properly. The depletion of soils and overuse of irrigation systems have caused erosion and the irreversible loss of good agricultural land. The bare hills around the Mediterranean, particularly in Greece, bear witness to this tragedy. Sand drift in the Netherlands was caused by human activity. The overexploitation of the natural environment by the Aboriginals in Australia made large areas of land unsuitable for agriculture.

Until the green revolutions, the harmful effects of agriculture on the environment and natural habitats were the result of the overexploitation of the potential of agro-ecosystems. This still constitutes the main threat to the majority of the world's agricultural regions. Overexploitation of this kind is not confined to developing countries. Large-scale agriculture - which virtually amounts to overcropping - in Australia, the United States of America, South America and the Commonwealth of Independent States could seriously threaten the continuity of agriculture there. The dust storms which occurred in the USA in the 1930s could now happen again thanks to cavalier environmental management. Agricultural systems geared merely to short-term economic gains can have a drastic effect on the environment and threaten agriculture in the long term. Erosion is a particularly serious threat. Agricultural methods which ensure that soil does not become depleted, that layers of soil do not wash or blow away and that the structure and texture of the soil are kept intact are available, but according to current economic thinking are often regarded as unattractive.

A good farmer ensures the continuity of his farm, but can only do so if the right preconditions are created and there is no net economic gain to be had from exhaustive cultivation. The threat to the world's food supply as a result of underutilizing inputs and overly extensive agriculture is enormous.

5.2 Environmental effects of wealth

This underutilization of inputs in large areas of the world is in sharp contrast to the overutilization prevalent in the Netherlands and other parts of Western Europe. Partly as a result of a surplus of animal manure and the virtually constant price of artificial fertilizers over the last 15 years, which has been a consequence of improved production processes, the relative price of artificial fertilizers is now so low that farmers are encouraged to overuse it. The excessive use of nitrogen from animal manure and artificial fertilizers has reached drastic proportions in the Netherlands. An average of 550 kg of nitrogen is applied to each of the Netherlands' 1.1×10^6 hectares of grassland each year in the form of artificial fertilizers and animal manure; only 75 kg of nitrogen from each hectare finds its way into the milk and meat produced. Large amounts of nitrogen therefore accumulate in the environment.

The discrepancy between nitrogen input and output is partly caused by the unclear relationship between the technically and commercially optimum levels of input of nitrogen, which in itself is the result of the low price of nitrogen fertilizers. The truth of the maxim that 'what doesn't do any good can't do any harm' has been proved in the case of nitrogen. Technically, no benefit is gained from the overuse of nitrogen: it does not result in higher yields. It produces no commercial benefits either. But nor has it any commercial disadvantages, since the price of nitrogen fertilizers is too low. The implicit gap between the technical optimum (Best Technical Means) and the commercial optimum (Best Practical Means) would thus seem to be one cause of this overutilization. These optimum levels are not clearly linked.

However, because overuse of nitrogen fertilizers is of no commercial benefit, the gap between them cannot be the only reason for this practice. In simplified terms, overuse can only really result in 'peace of mind' for the farmer: the thought that, at any rate, the crop has sufficient nitrogen. The constraints on farmers' finances these days prompt many of them to adopt this attitude, to combine maximum yields with minimum risk.

The best way of stopping the overutilization of nitrogen fertilizers is to give farmers better information about fertilizing their land, the link between fertilizers and crop growth and the environmental impact of over-large number of animals kept on them, has meant that the link between animal and vegetable production has to a large extent been broken. The crops required to feed livestock are produced elsewhere in the world, while animal production - mostly in the form of dairy products and meat - takes place here. A significant proportion of animal products are exported, while the nitrogen in the manure produced remains behind, creating huge environmental problems. Restoring the link between animal and vegetable production would go some way towards solving these problems. This would require both technical measures, such as improvements in the composition of animal feed, the transport and processing of manure, and a reduction in the number of livestock. This "luxury" problem is by no means intractable - the means exist - it is merely a question of finding the political will.

If animal production is linked to vegetable production not on a global scale but at local or regional level, the leaching of minerals - which is so characteristic of unsustainable production systems - can be reduced. If this link were to be restored and the relationship between the industrial and agricultural sectors of the economy maintained, albeit in a modified form, it would be possible to achieve sustainable agriculture, which not only guarantees adequate food production, but also provides food security.

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