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On the Efficiency of Resource Use in Agriculture

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1. Introduction

The second world war marked a turning point in the yields per hectare of arable crops in the Western world. This is illustrated in Fig. 1 for wheat in the United Kingdom and the USA. Before the war, yields increased only by a few kg/ha/year, if at all. However, since then yields have increased consistently at much higher rates. Curves for these two countries have been chosen for illustration because the trends in yields have not been disturbed by ravages of war, so that the sharp inflection in the rate of yield increase stands out. Other arable crops show comparable increases in yield.

This "first green revolution" was economically due to a rapid increase in demand and was characterized by intensification and specialization, and innovative combinations of old and new techniques. For example, soil amelioration and mechanization to enable better water management and timeliness of farm operations, inorganic fertilizers to improve soil fertility, biocides for better control of weeds, pests and diseases and the use of varieties adapted to improved growing conditions, like the more sturdy, short-straw wheat varieties of Heine in Germany.

Such intensification and specialization has led to profound changes in rural areas. In little endowed regions, agricultural activities were marginalized, leading to a break down of their social and environmental infrastructure. In well endowed regions, reallocation and reconstruction has resulted in widespread changes in the landscape at the expense of its diversity. Together with the increased use of biocides and fertilizers, this is causing considerable concern to environmentalists and consumers. In particular, the increased use of nitrogen fertilizer became a focal point of concern because of its large external effects, due to leaching of nitrate to the ground water and evaporation of ammonia to the atmosphere.

According to the report of the German Council of Experts for Environmental Problems (RAT FÜR UMWELTFRAGEN 1985, page 112) and others, the environmental effects of fertilizers are governed by the law of diminishing returns, which states that the relation between amount of fertilizer applied and yield is not linear, but levels off and even reverses at high rates. This would explain why present day high yielding agriculture is so environmentally polluting. In the same report (page 116), a table is given with yields of wheat per hectare and fertilizer use per hectare in Germany from 1950-1982. These data show that, as in other countries, yields continued to increase at a rate of about 80 kg/ha/year. The use of nitrogen continued to increase also, but for phosphorus and potassium, the fertilizer use levelled off in the middle of the sixties.

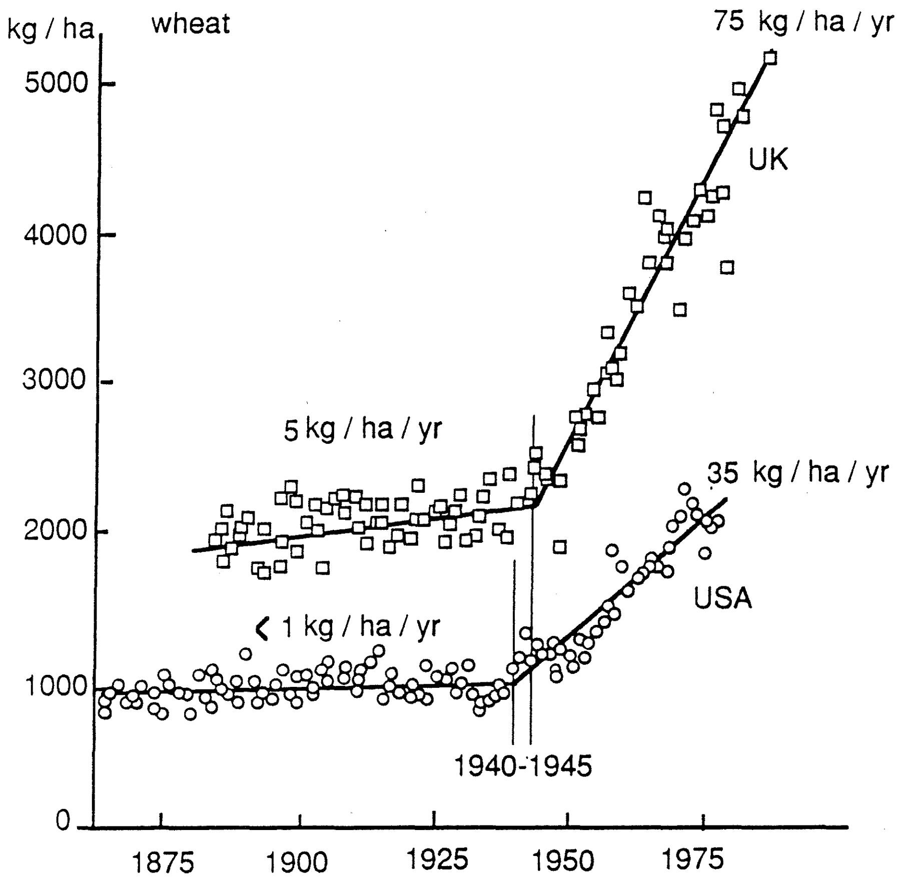

Fig. 1: Wheat yields over more than 100 years in the United Kingdom (UK) and the United States (USA) (DE WIT, HUISMAN and RABBINGE 1988).

The observation that a yield increase of 210 % to 4900 kg/ha over thirty years is accompanied by an increase in nitrogen use of 470 % to 120 kg/ha suggests diminishing returns. However, such percentage differences are due to the simple fact that in 1950 other sources of nitrogen made possible a 1950 base yield of some 2000 kg/ha without application of any inorganic nitrogen fertilizer. Starting from this base year the percentage increase of yield would be finite and of nitrogen fertilizer use infinite. It is therefore much more revealing to consider absolute increases as in Fig. 2, where the absolute yield is plotted against the absolute value of nitrogen fertilizer use over the whole period. The relation that manifests itself shows that at the high end of the yield range the efficiency of nitrogen use is at least the same as that at the low end, so that any sign of diminishing returns is absent. The same relation is shown in Fig. 3 for nitrogen fertilization rate and yield of maize in the USA (SINCLAIR 1990). This relation flattened off for some years at the end of the sixties. However, since then the farmer practices improved, so that for the period as a whole the productivity of nitrogen fertilization remained the same.

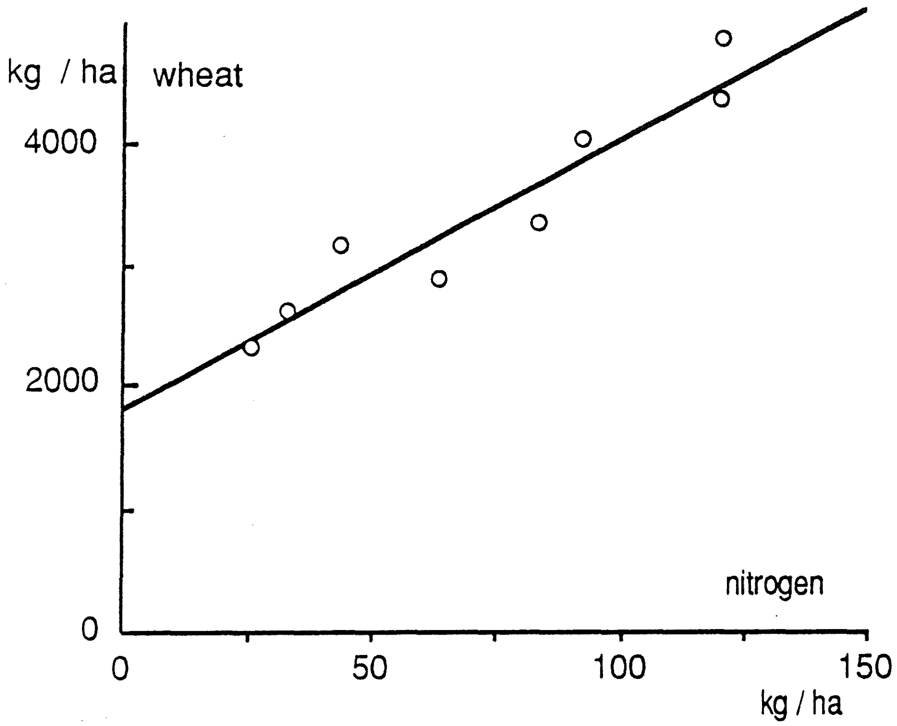

Fig. 2: Wheat yield versus nitrogen fertilization rate in the German Federal Republic at 5-year intervals during the period 1950-1982 (RAT FÜR UMWELTFRAGEN 1985).

Such apparent discrepancies between common opinion and statistical evidence justifies further analysis, and more so because lack of understanding of the interrelations between intensification and resource use may lead to the adoption of measures and practices that do not optimally contribute towards control of adverse environmental effects of agriculture. For this, some classical literature on growth response functions is reconsidered to obtain a better grasp of the so-called law of diminishing returns and the demand for nutrients in situations where yield increases are due to further optimizing of growing conditions. This is further elaborated for other production resources by considering nitrogen uptake by the crop as an intermediate between amount of fertilizer applied and crop yield.

Subsequently, the resource use efficiency of arable farming and dairy farming is considered by making a distinction between intensification and specialization.

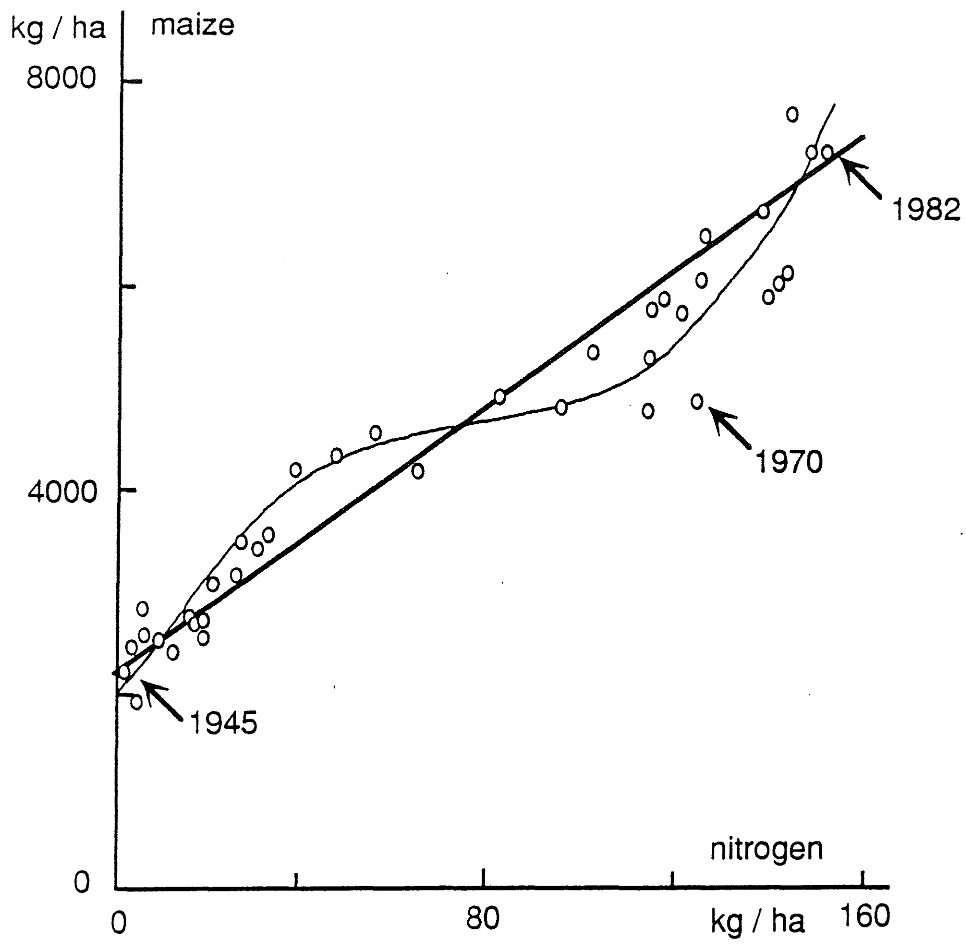

Fig. 3: Maize yield versus nitrogen fertilization rate in the USA during the period 1945-1982 (SINCLAIR 1990).

2. Growth response functions

2.1 The law of the minimum

Justus von Liebig, the godfather of agricultural chemistry in the middle of last century, has had a much smaller impact on practical agriculture than Lawes and Gilbert, the founders of Rothamsted. This is because LIEBIG (1855), working from behind his desk, advised to return to the soil only that quantity of minerals that was mined by the crop. However, replenishing the small amounts of minerals that were taken up by poorly growing crops did nothing to build up the fertility of the soil, so that yields remained as low as they were before.

On the contrary, LAWES (1847) in association with Gilbert took an experimental approach and thus recognized from the beginning that to increase yields and to sustain these yield increases, more minerals had to be applied to the soil than were taken up by the crop in order to build up their availability for the crop and to compensate for unavoidable losses. Hence, it was recognized that the fertility of the soil could not be maintained only by applying the amounts withdrawn by the crop. But Lawes and Gilbert could not foresee the time when some soils would be so overloaded with some minerals that it would be unnecessary to apply these minerals for a long time to come.

Liebig became engaged in a caustic debate with Lawes and Gilbert on the principles of fertilization in which Liebig referred to Lawes and Gilbert as those "fertilizer manufacturers" and Lawes and Gilbert remarked that "the contempt the practical farmer feels for the science of agricultural chemistry arises from the errors made by its professors" (DE WIT 1968).

Although only experiments like those of Lawes and Gilbert could prove its existence, the law of diminishing returns is very much associated with Liebig under the name of the law of the minimum. This law states that the the yield of a crop is proportional to the supply of that element that is essential for the full development of the crop and that is available in relatively the smallest amount.

The classical model of this law is a barrel with staves of different heights. The height of the individual staves represents the relative availability of the individual nutrients and the maximum height of the water in the barrel represents the yield. This maximum height is determined by the lowest stave. This model reflects the notion that crops that yield two times more contain about two times more of the necessary nutrients.

Such interaction between growth factors is schematically presented by curves 1 and 2 in Fig. 4, be it that the transition from the limiting to the saturated situation is presented somewhat more gradual in the curves than in the barrel model. For instance, curve 1 could present the relation between nitrogen supply and yield at a suboptimal supply of phosphorus and curve 2 the same relation, but with an optimal supply of phosphorus. Characteristic for the law of the minimum is that both curves coincide in the region where the same nutrient is limiting. The amount of an element that is available from sources other than the fertilizer can be expressed in principle as an equivalent supply and is marked along the horizontal axis, as done here at the bottom of the diagram. Thus, the nutrient on the right of the vertical line is provided by the fertilizer.

On the one hand, Liebig's law reflects the principle of diminishing returns in the situation where more and more of one element is applied under the condition that the availability of other nutrients remains the same. On the other, the law reflects the principle that fertilization has to be balanced in such a way that the availability of each element is proportional with the yield. The first principle applies to situations where the nutrient is the independent variable and thus characterizes the yield response to increasing amounts of fertilizer. The second principle concerns situations where the yield is the independent variable and characterizes the fertilizer demand for a given yield. The problem with many of today's discussions is that these basically different situations are confounded.

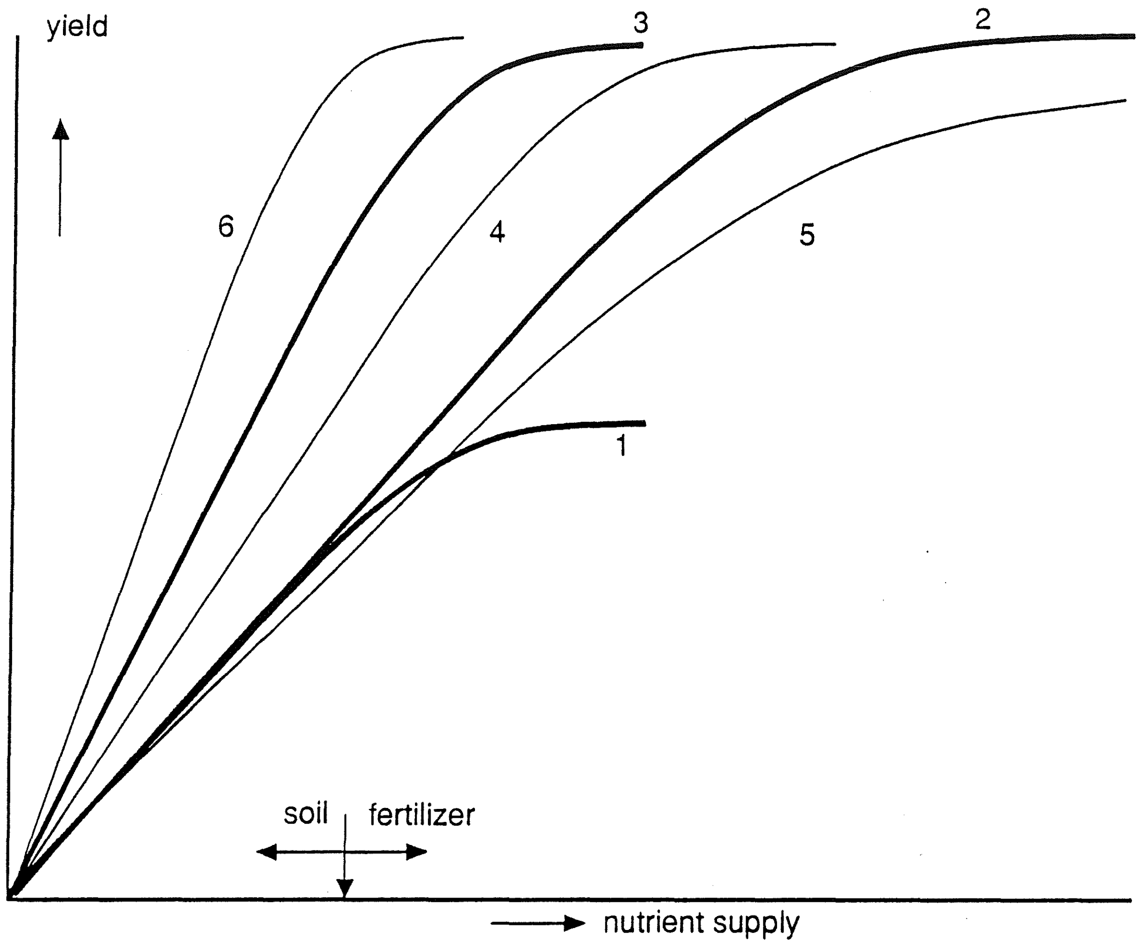

Fig. 4: Schematic presentation of yield response laws. Curves 1 and 2: Liebig's law of the minimum. Curves 1 and 3: Mitscherlich's law of constant activity. Curves 1 and 4: Liebscher's law of the optimum. Curves 1 and 5: see text. Curves 1 and 6: see text. The arrow indicates the availability of nutrients in the soil, expressed in equivalent amount of fertilizer.

2.2 The law of the optimum

The question that remained to be answered was in which proportion the nutrients have to be applied to the soil to achieve a balanced nutrition. This required considerable experimentation, in which Liebscher of the Göttingen University played a leading role at the end of the 19th century. He did not restrict himself to simple fertilizer experiments in containers and in the field, but determined also the uptake of the main nutrients in the course of growth. His experiments were of excellent quality, and because at that time results were still published in toto, they have been used by many others for many years. Based on that wealth of experimental data, he formulated his law of the optimum (LIEBSCHER 1895). This law states that a production factor that is in minimum supply contributes more to production, the closer other production factors are to their optimum. Otherwise formulated, it states that all production factors are most efficiently used, when they are all at their optimum.

A well known example of Liebscher's law is the positive interaction between the yield response to nitrogen and phosphorus, also under conditions when both are in short supply. Such conditions hardly exist any more in Western Europe, but under the poor fertility conditions prevailing in most of Africa, this positive interaction is easily confirmed (PENNING DE VRIES and VAN KEULEN 1982).

Liebscher formulated his law in terms of production factors because it appeared to hold also when growth controlling factors other than nutrients, like pH of the soil, weather or water were involved. This is illustrated in Fig. 5, with the results of an experiment from Denmark on the response of oats to the application of sodium nitrate during 1924-1940. These results are grouped in years with relatively good, medium and bad weather (NIELSEN 1963). Contrary to Liebig, but in accordance with Liebscher's law, the increased response to nitrogen under better weather conditions, did not only manifest itself at high rates of application, but also when nitrogen was in short supply.

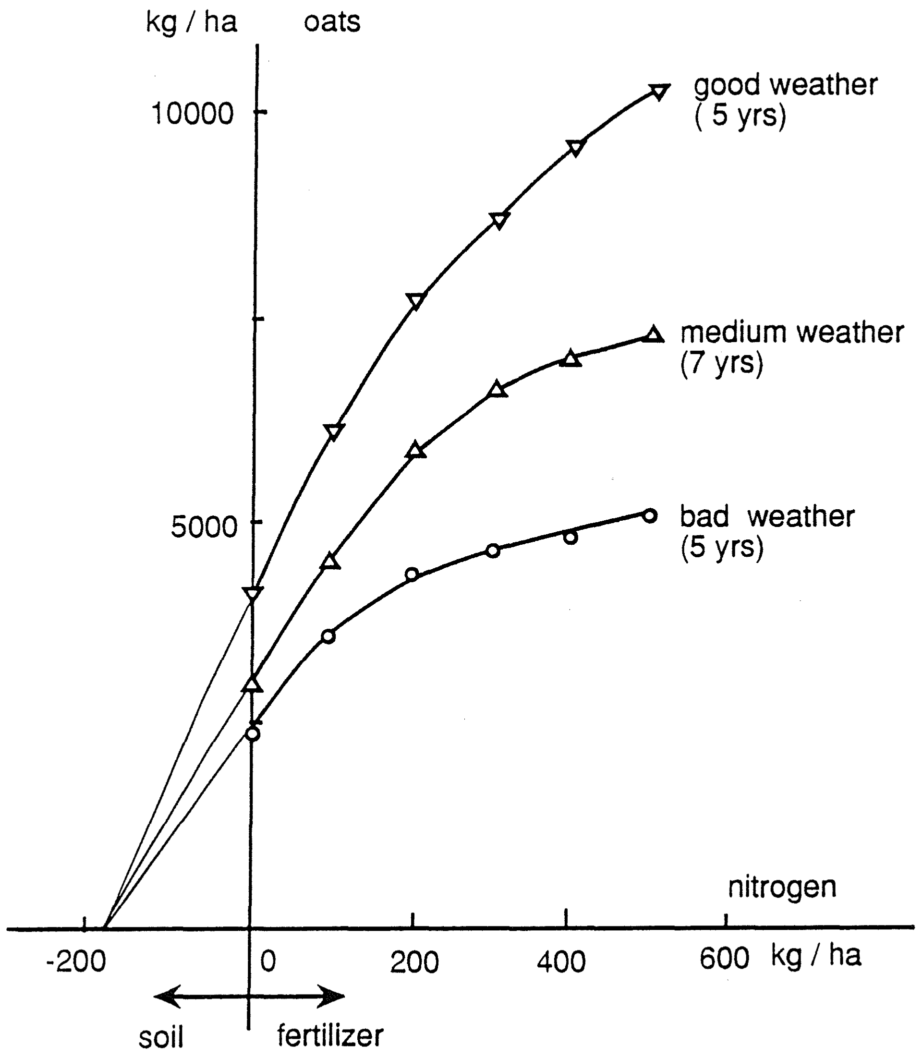

Fig. 5: Nitrogen response curves of wheat averaged for years with relatively good, medium and bad weather during the period 1925-1940 (NIELSEN 1963).

2.3 The law of constant relative activity

As a special case of Liebscher's law, Mitscherlich and his co-workers (MITSCHERLICH 1924) proposed a negative exponential equation to describe both the diminishing returns and the interaction between nutrients, and assumed that the activity coefficient for any nutrient in the exponent was independent of the supply of any other nutrient. This heroic assumption implies that the amount of nutrient that is needed to reach a certain fraction of the maximum yield is the same for any yield level. This is illustrated by curves 1 and 3 in Fig. 4.

The law of constant relative activity is often referred to as Mitscherlich's law (LEMMERMANN 1954), because he dedicated his long life to its propagation. An erroneous statistical analyses, lead him to believe that the activity coefficients and hence the amounts of nutrients that were needed for optimum yields, were also independent of weather, soil, plant species or any other factor that effected the level of that optimum (MITSCHERLICH 1947). Of course such a kind of universal constant does not exist, but this does not exclude the possibility that Mitscherlich's law is valid in more restricted domains and yield ranges.

2.4 A pragmatic approach

By now three principles have been discussed to characterize the demand for fertilizer as a function of increasing yields. According to Liebig it should increase proportionally, Liebscher believed it should increase less than proportionally with the yield level, while Mitscherlich concluded that the demand should be independent of this yield level.

Overviewing the battle field, VAN DER PAAUW (1939) of the Institute for Soil Fertility in the Netherlands, came to the conclusion that the search for one unifying principle to characterize the demand for fertilizers under different growing conditions would remain futile. Instead, he used the different laws to characterize the whole spectrum of possibilities in a way that is best illustrated by means of the curves in Fig. 4.

As has already been said, curves 1 and 2 reflect the situation where the increase in nutrient demand is proportional with the increase of the maximum yield, in accordance with Liebig's law, whereas curves 1 and 3 reflect the situation where the amount of nutrients that is needed to reach a certain fraction of the maximum yield is independent of the level of this maximum, in accordance with Mitscherlich's law.

Van der Paauw further distinguished the situations where the response curves are positioned to the left and to the right of curve 3 and to the left and to the right of curve 2. When the maximum is at the right of curve 3, as in curve 4, the demand for nutrients increases with increasing maximum yield level.

However, as long as the curve remains to the left of curve 2, this increase in nutrient demand is lower than the increase of the maximum yield, so that the efficiency of nutrient use increases. The range between curves 2 and 3, covered by far most of the Groningen experimental results over many years with several crops and the nutrients nitrogen, phosphorus and potassium applied in different amounts, alone as well as in combination. Hence, Van der Paauw's analysis confirmed the general validity of Liebscher's law of the optimum for nutrient interactions, but it also appeared that any further quantification would not be a simple matter.

For curves to the right of curve 2, such as curve 5, the demand for nutrients increases more than proportionally with the increase of the maximum so that the efficiency of nutrient use decreases. That would imply that a production factor that is in minimum supply contributes less to production, the closer the other production factors are to their optimum. Examples of this reversal of Liebscher's law have not been found, and nobody has been tempted to formulate such a law of negative interference.

If the maximum is shifted to the left of curve 3, as for instance curve 6, the demand for nutrients decreases with increasing optimum yield level. It was already recognized by Mitscherlich, that this occurs when two nutrients are both limiting and are able to replace fully or partly each others function in the plant, like sodium and potassium in sugar beets. Van der Paauw showed that crops are more tolerant for a lower pH when their yields are higher, as illustrated in Fig. 6. This is another example of the shift of the optimum to the left. In these experiments, the lime that was used to enhance the pH acted mainly a soil conditioner and not as a fertilizer to improve the availability of Ca and Mg for the crop.

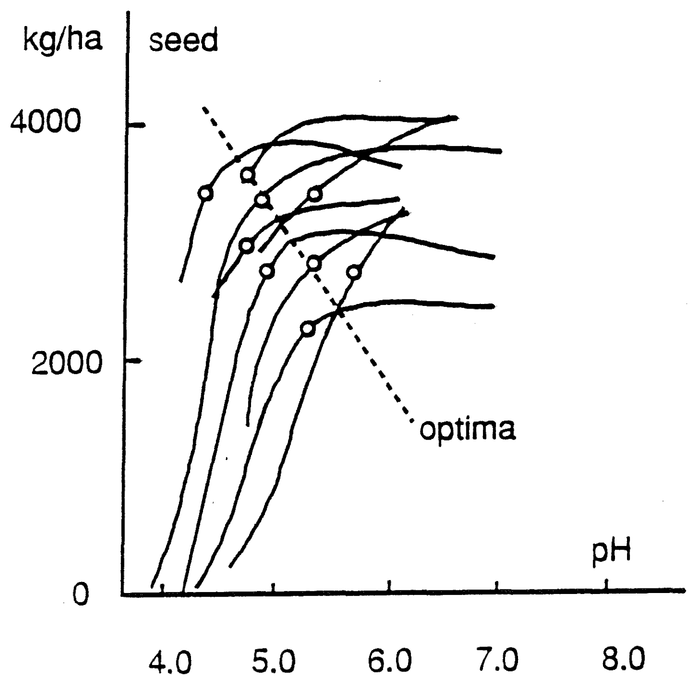

Fig. 6: pH response curves for barley at different yield levels (VAN DER PAAUW 1939).

2.5 Further analyses

2.5.1 A graphical presentation

It was already emphasized by Liebscher that a good understanding of fertilizer responses requires determination of nutrient uptake by the crop. For a further analysis, such data are most conveniently used as an intermediate in three-quadrant diagrams (DE WIT 1953, VAN KEULEN 1982), as in Fig. 7. The relation between the rate of fertilization and the uptake of the nutrient by the crop is given in the fourth quadrant (IV) of the diagram and that between this nutrient uptake and the yield in the first quadrant (I). By eliminating the uptake from both graphs, the familiar relation between fertilizer rate and yield in the second quadrant (II) is obtained, although in mirrored form. The uptake of the nutrient at zero fertilization in quadrant IV is referred to as the uptake out of the soil. The recovery of the fertilizer at a certain amount of application is defined as the uptake at this amount minus the uptake out of the soil, divided by this amount. Although the uptake out of the soil is not necessary fully independent of the rate of fertilization, values for the recovery that are lower than 0 and higher than 1 or 100% are in general not observed.

The graphical analyses is restricted here to the crop response to nitrogen under different environmental conditions because it is the most mobile nutrient and has to be applied every year to ensure optimum yields. Phosphorus and potassium are in general far less mobile, and are therefore often applied at levels where an optimal supply of nutrients is ensured by an occasional application at some relatively low maintainance level. Also, the widespread existence of positive interactions between nutrients were the main reason for Liebscher to formulate his law of the optimum. Further analyses of phosphorus and potassium effects would therefore add little to a better understanding of the problem of resource use efficiency.

2.5.2 Varieties

In the example of Fig. 7 (BAAN HOFMAN 1988) the two different responses are due to the use of two perennial rye grass varieties that differed mainly in persistence. Dry matter yields and nitrogen uptake concern the harvested above ground material of the six cuts in the second year of growth. The uptake- yield curves in quadrant 1 pass through the origin because no yield is possible with zero uptake and no uptake is possible with zero yield. The initial slopes of these curves is the same for both varieties, but better persistence reflected itself in a better utilization of the nitrogen that was taken up in the higher range. Thus, these uptake-yield curves reflect the law of the minimum of Liebig. However, this is only part of the story, because it appears in quadrant IV that the recovery of nitrogen is also higher for the more persistent variety. Accordingly, the combina-

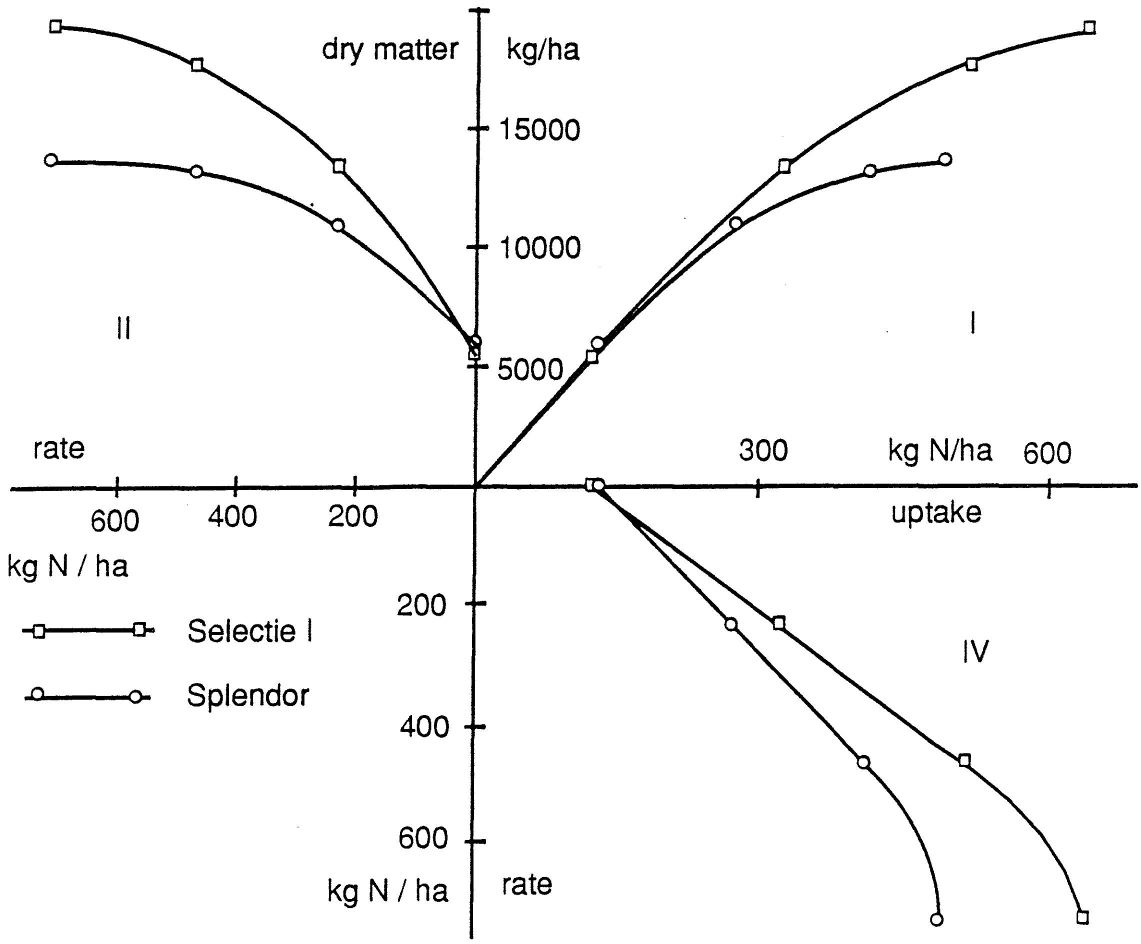

Fig. 7: Three-quadrant diagram with graphs for the relation between fertilizer rate and uptake in quadrant IV, uptake and yield in quadrant I and fertilizer rate and yield in quadrant II. The data refer to a nitrogen fertilization experiment with varieties of perennial rye grass under field conditions. They concern a total of six cuts in the second year for the two varieties that differ most (BAAN HOFMAN 1988).

tion of both relations in quadrant II shows that also in the region where nitrogen is limiting, nitrogen is better used by the more persistent variety, also when it is limiting. This confirms the law of Liebscher.

Baan Hofman showed that the higher uptake of more persistent varieties was due to a greater number of tillers and the greater number of roots associated with it. Uptake in the non-fertilized situation was the same for both varieties. This suggest that improved persistence does not reflect itself in open swards at low N. Moreover, if the less persistent varieties had been invaded by grassy weeds and both the rye grass and weeds had been harvested, the yield differences between swards with persistent and not persistent varieties would have been smaller.

The main difference between old leafy varieties and new, more short and sturdy wheat varieties is that the latter do not lodge very easily and thus can stand much higher rates of nitrogen fertilization. To compare their efficiency of nitrogen use, AUSTIN (1980) determined their responses under conditions where lodging of old varieties was prevented by mechanical means. He found that new wheat varieties yielded not only more under high fertility conditions with high nitrogen, but also under low fertility conditions with low nitrogen. SANDFAER a.o. (1965) showed that the larger response of modern varieties of barley was due to both an improved rate- uptake and uptake-yield relation. Both experimental series confirmed Liebscher's Law.

According to VAN KEULEN (1977), differences in uptake-yield curves are fully due to the improved grain/straw ratio of new varieties. For example, SANCHEZ a.o. (1973) found that the total uptake of N needed to produce one ton of dry matter was the same at 7.6 kg for modern short straw varieties of rice and for more leafy, older varieties of rice. However, modern varieties needed only 14 kg total uptake of N per ton of grain whereas older varieties needed 18 kg. Differences in nitrogen uptake from the soil and at low fertilizer rates are less conclusive. SANDFAER a.o. (1965) and WATSON a.o. (1963) found that new varieties had a somewhat better uptake, but in an experiment by SANCHEZ a.o. (1975), the nitrogen uptake from unfertilized soils by new varieties was somewhat smaller, whereas recoveries at low fertilizer rates were the same. Such results are, however, confounded by density of sowing, since less profusely tillering varieties have to be sown at higher densities to ensure a sufficiently dense root system at an early stage of development.

2.5.3 Physical resources

NIELSEN (1963) did an elaborate experiment to study the interactions between nitrogen and water. Quadrant I of Fig. 8, shows again that the yield-uptake curves confirmed Liebig's law, and quadrant IV that increased water supply improved the recovery of nitrogen. Fig. 9, which illustrates the relation between evapo-transpiration and yield at two levels of nitrogen shows that the efficiency of water use is also improved with increasing nitrogen supply. Hence the beneficial effects of nitrogen and water are reciprocal, so that Liebscher's law is confirmed both ways.

The analyses of an elaborate experiment over several years by HOOGERKAMP a.o. (1965) on the response of grass and arable crops to the control of groundwater on river basin soil, also confirmed Liebscher's law. The results show that the response to nitrogen improved both in the situation where the optimum was approached from the wet side and from the dry side. When the optimum water supply is approached from the wet side, the recovery increases because nitrogen losses due to denitrification and leaching decrease. When approached from the dry side, it increases due to increased water content in the top of the soil where the nitrogen is located (REHATTA a.o. 1979).

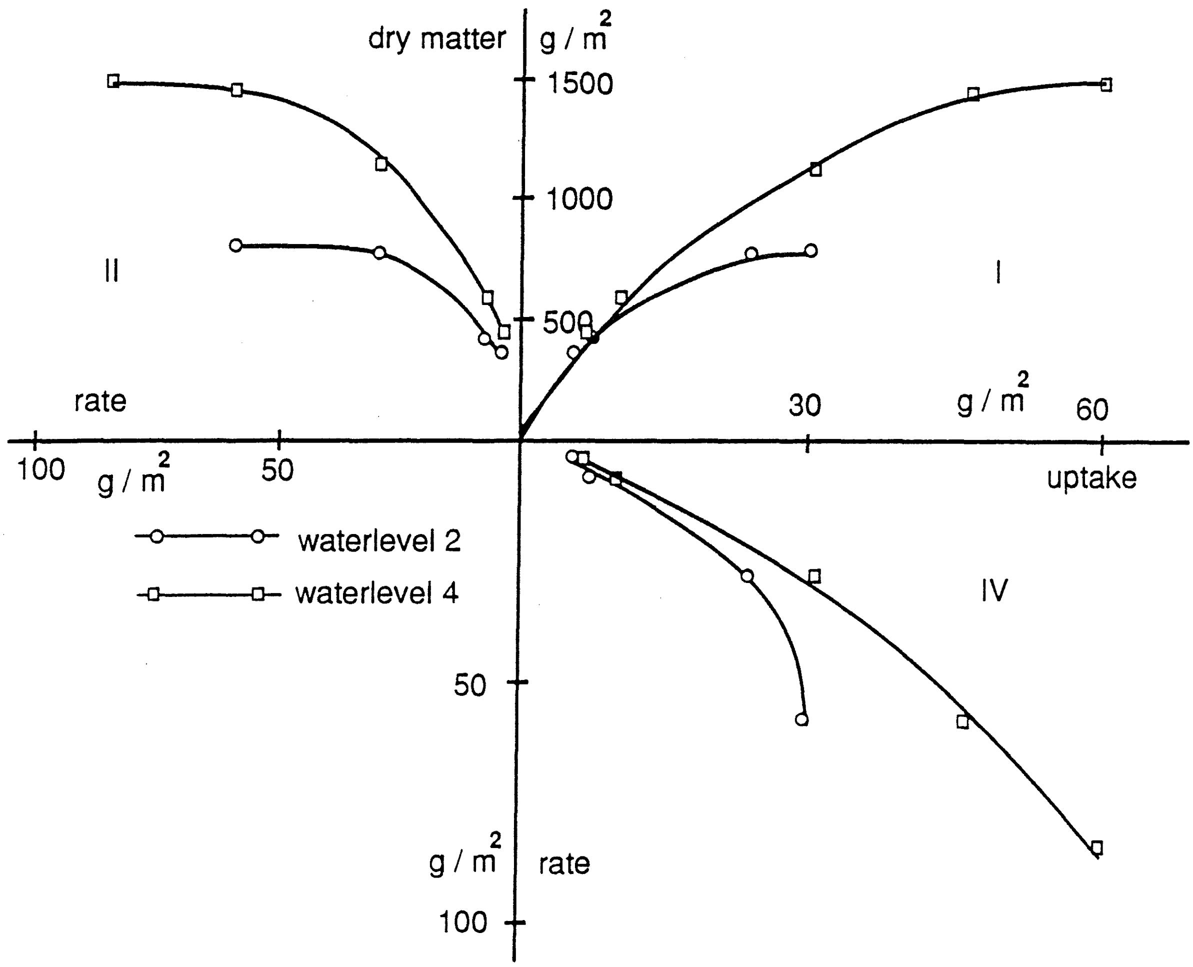

Fig. 8: Three quadrant diagram for a pot experiment with perennial rye grass with various nitrogen levels and 2 levels of available water (NIELSEN 1963). The data refer to the sum of five cuts.

Liebscher's law is similarly confirmed in elaborate experiments on the effect of carbon dioxide concentration of the air on the uptake and utilization of nitrogen and the effect of nitrogen on the response to carbon dioxide (VAN KRAALINGEN 1990, pers. com.).

2.5.4 Diseases

In the example of Fig. 10 (SPIERTZ 1980), the two different responses to nitrogen were created by controlling and not controlling so-called ripening diseases. In this case, the yield referred to is grain, whereas the uptake of nitrogen concerns both seed and straw. Quadrant I shows that the disease control

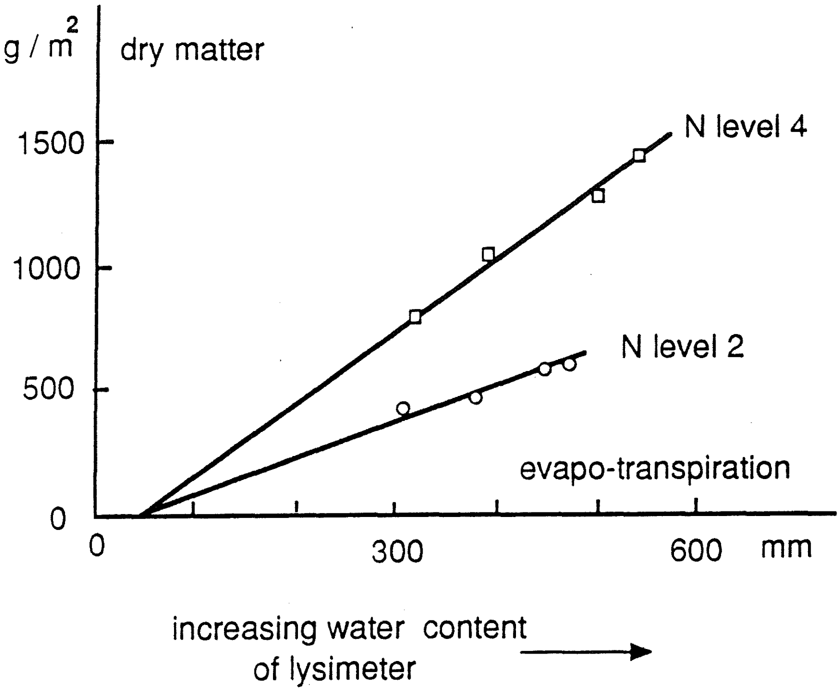

Fig. 9: The relation between evapo-transpiration and yield at two nitrogen levels for the same experiment as in Fig. 8.

expresses itself in an improved uptake-yield relation in the region where the nitrogen content of the crop is well above its minimum. At that level, sufficient nitrogen is available for the leaves to stay green and for the seeds to reach their genetically determined maximum size (SINCLAIR a.o. 1975, VAN KEULEN a.o. 1987). However, seed filling requires assimilates and these are not available when the leaves die prematurely because of diseases. Since the minimum content to which the nitrogen in the seed and straw can be diluted is specific for the species, and seed/straw ratios are characteristic for the variety, the initial slopes of the uptake-yield curves are in general the same, whatever the growing conditions are that make the curves deviate at higher uptake levels (VAN KEULEN a.o. 1982).

It appears in quadrant IV that the uptake of nitrogen increased also as a result of disease control. The reason is that the longer the plants are healthy, the longer the roots remain active. This prolonged activity reflects itself in both an increased uptake in the absence of fertilization and an increased slope of the curve. This slope of the rate-uptake curves represents the recovery of the fertilizer N. The uptake in seed and straw is 55 % in case of disease control, but increases to 70 % with disease control. The additional uptake in roots and stubble is about 25 %, so that in the disease control case the total recovery during growth is over 90 percent. In general, such high recoveries require that the nitrogen fertilizer be applied in three portions in the course of the growing season (VAN DOBBEN 1966).

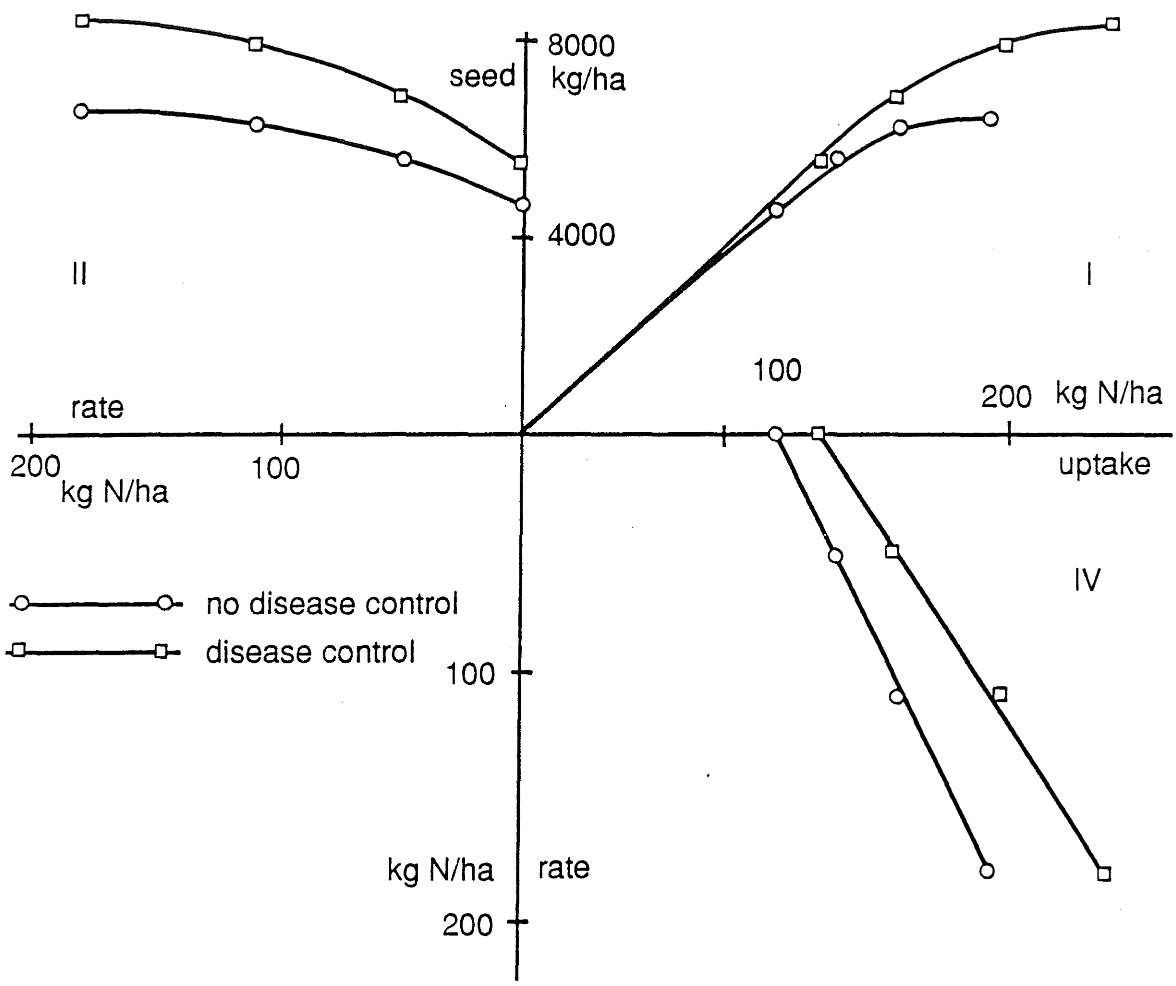

Fig. 10: Three-quadrant diagram of a nitrogen fertilization experiment with and without control of "ripening" diseases (SPIERTZ 1980).

Disease control resulted both in higher uptakes over the whole range of applications in quadrant IV, and in a reaction according to Liebig's law of the minimum in the uptake- yield graph of quadrant I. Therefore, the combination in quadrant II again confirms Liebscher's law of the optimum.

The variety of pests, diseases and weeds are large and their damaging effects depend to such an extent on environmental conditions, that it is difficult to generalize about the reciprocal effect: the biocide requirements in relation to yield level in general and nitrogen supply in particular. On the one hand, higher yielding crops may be more susceptible to obligatory parasitic pests and diseases like aphids, mildew and rusts (RABBINGE a.o. 1986, 1989, pers. com.), mainly as a result of higher nitrogen contents in the attacked tissues (WHITE 1984). This has contributed to the practice of insurance spraying, i.e. spraying without first establishing whether any damage will be done. However, integrated pest management methods were developed to constrain this high use of biocides in the seventies (ZADOKS 1981). These rely on varieties with a broad resistance, observation-driven control systems and cultural practices like broader crop rotation and better controlled use of nitrogen. With such methods, the average number of sprayings in wheat has been kept at 2.5 in the Netherlands, compared to 8.5 in the United Kingdom and 7 in the north-west of the German Federal Republic (RABBINGE 1987).

On the other hand, higher yielding crops may be less susceptible to non-obligatory parasitic diseases like septoria, fusaria, etc. (RABBINGE a.o. 1986, 1989, pers. com.). This is illustrated in Fig. 11 for potatoes on soils infected with verticillium species (HAVERKORT a.o. 1989). Fertilization of potatoes not only increases the yield directly, but also by reducing nematode damage (VAN DER WAL a.o. 1989). Well developed crops are also able to suppress weeds better than low yielding crops (KROPFF 1986), so that under high yielding conditions less herbicides are needed at later stages of growth. This is contrary to the widely held belief that high yielding crops require in general more biocides for their protection.

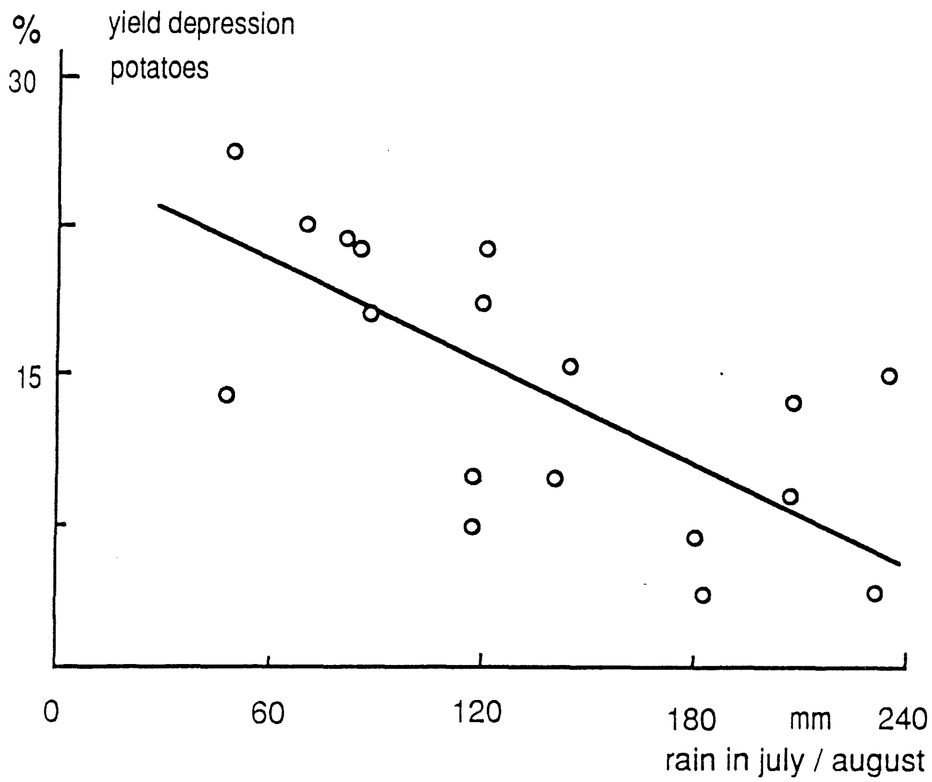

Fig. 11: Percent yield depression of potatoes in two 1:3 rotations compared with a 1:6 rotation in reaction to rainfall in July and August. The depressions are probably due to an infection of verticillium sp. (HAVERKORT a.o. 1989).

3. Resource use efficiency

3.1 Arable crops

Application of the three-quadrant diagrams facilitates the analyses of strategies aiming at a more efficient use of resources in agriculture. These are schematically presented for a low, medium and high yielding situation in the diagrams of Fig. 12A and B. Fig. 12A represents the law of Mitscherlich and Fig. 12B the law of Liebig. For easy comparison, it is supposed that the curves for the medium yielding situation in the three quadrants, as well as the three uptake-yield curves in quadrants I are the same in both diagrams. The same minimum and the same maximum nitrogen percentage for these three uptake-yield curves imply that varietal differences are not considered in this example. There are important differences between crops. N fertilization of sugar beets is checked by quality considerations. This is far less the case for potatoes, so that N is liberally used on the latter crop (NEETESON 1989). Wheat comes as a good second, since lodging may be controlled by spraying culm strengtheners, like CCC.

The situation for the latter two crops is illustrated by the points marked 1 on the three graphs for the medium yielding situation in both graphs of Fig. 12A and B. These points are relatively close to the maxima of the rate-uptake curve in quadrant IV and of the uptake-yield curve in quadrant I. This holds for both diagrams. Therefore, the rate of fertilization could be considerably reduced to the situation presented by the points marked with 2, without much sacrifice in yield and without being obliged to use culm strengtheners.

All this is well known, but prices of nitrogen fertilizers present little incentives to farmers to economize on their use because they are at an all time low. For instance, nitrogen prices in the Netherlands, corrected for inflation dropped 50 percent from 1950 to 1970 and since then they have declined with another 30 percent, in spite of the increasing energy prices in the seventies (VAN DER WEIJDEN 1990). Therefore, the German Council of Experts for Environmental Problems (RAT FÜR UMWELTFRAGEN 1985, page 363) suggested an environmental tax to double the present price of inorganic, industrial nitrogen fertilizers. To visualize the long term effects of such a tax, a comparison could be made with tax on gasoline: in countries with high taxes on gasoline, small and energy efficient cars have been developed that do the job of transporting the driver and his occasional passenger equally well as big, gas-guzzling cars in countries with low gasoline taxes.

Yield can be augmented by good husbandry, characterized by timeliness of operations, variety choice, control of pests, diseases and weeds and more optimal control of water and of nutrients other than nitrogen, whereas a compromise on any one of these factors will reduce yields. The ensuing production situations are presented by the points 3 and 4 in both diagrams. For ease of comparison, these points are positioned in such a way at the uptake-yield curves in quadrant I, that the nitrogen uptake of the crop per ton production is the same as in situation 2. For wheat, this limiting value may be seen as the percentage nitrogen in the crop beyond which the chance of lodging is too high and for sugar beet as the percentage nitrogen beyond which nitrogen interferes too much with the sugar extraction process.

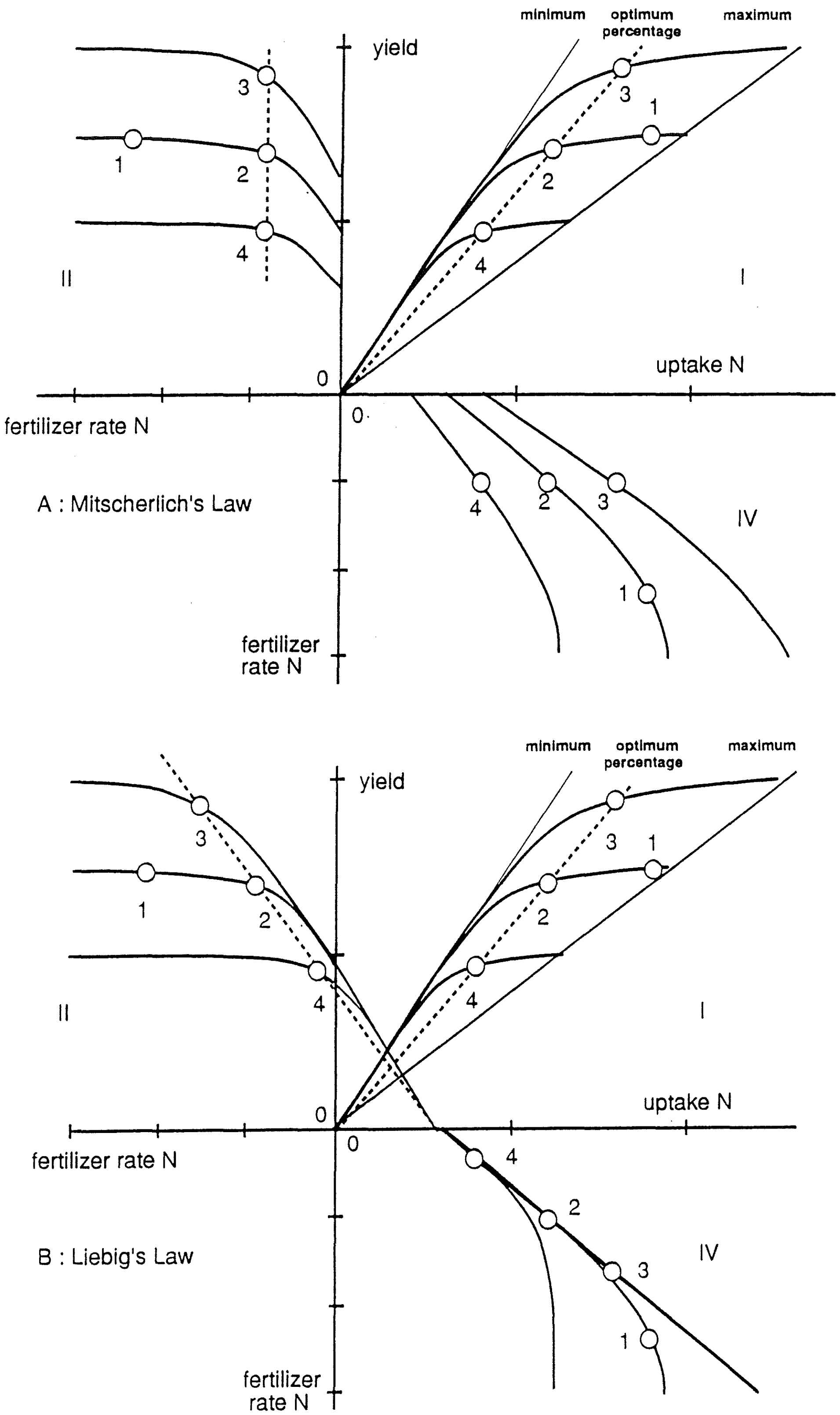

Fig. 12A and B: Schematic three-quadrant diagrams for wheat at three different yield levels, reflecting Mitscherlich's law of constant activity (diagram A) and Liebig's law of the minimum (diagram B). See text for a discussion of the production situations marked by the points.

In Fig. 12A, the recovery of the fertilizer (quadrant IV) increases with increasing yield so that in quadrant II, the optima 2, 3 and 4 are at the same rate of fertilization, in accordance with Mitscherlich's law. In Fig. 12B, reflecting the law of the minimum of Liebig, the points 2, 3 and 4 on the fertilizer response curves in quadrant II are situated on a straight line that intersects with the horizontal axis at the same point as the extrapolated response curves. Hence, the nitrogen requirements per kg seed remains the same.

According to the optimum law of Liebscher, the actual response is somewhere between these two limiting situations.This means that with increasing yields resulting from further optimizing of the growing conditions, the amount of nitrogen needed per hectare increases less than proportional with the yield so that less nitrogen is needed per unit of produce. The same holds for other nutrients and water. The environmental pollution per unit produce is likely to decrease even more not only because the recovery of fertilizer increases, but also due to the increase of the amount of nutrients that are incorporated in the organic matter of the soil with increasing yields, as shown by WOLF a.o.(1989).

Other resource expenditures are on machinery, labour and fuel. These requirements are partly determined by activities that are surface-related and partly by activities that are quantity-related. Examples of surface-related activities are ploughing, preparation of the seedbed, sowing and most harvesting operations. Their resource use per ton of grain is inversely proportional to the yield level. Examples of quantity-related activities are transport of harvested products and the drying of seed. The use of resources for these purposes is proportional to the amount of seed harvested. Hence, taken together, the use of machinery, labour and fuel per ton of seed decreases with increasing yields.

Albeit with some reservations regarding pest and disease control (see section 2.4.5), it is concluded that for arable farming, no production resource is used less efficiently and most of them are used more efficiently with increasing yields due to further optimizing of growing conditions. Whether a production resource is used at all depends on its price. Some may be so expensive, that the farmers cannot afford them, but where this is otherwise they should be used to such a level that the production possibilities of all other available resources are fully exploited.

Many production resources are freely available in the market, so that their cost per unit is the same whether they are applied at low or high rates. However, the closer one approaches the situation where water is in optimal supply, the more water supply regulation becomes an encompassing public venture. Hence, when society is no longer willing to furnish the capital costs that are required for further improvements of the physical conditions for production, ultimate yield limits come in sight. But even at the present level of amelioration, there are still a considerable yield gaps between what farmers do and could do, as has been shown by system analysis for many regions of the world (VAN KEULEN a.o. 1986, FAO 1984, BURINGH a.o. 1979).

In regions where farming is considered to be economically viable, further yields increases are thus determined through an autonomous process which is fuelled by public and private research, extension and marketing. This makes any optimum a moving target for the farmer. Continuing increase in production and production efficiency in these regions exerts a downward pressure on prizes. This, however, does not slacken the rate of yield increase in regions at the agriculturally well endowed end of the scale where farming remains anyhow a profitable enterprise, but leads to continuing marginalization of regions a the poorly endowed end of the scale. This is even more so in situations where demand is slackening.

There may be good social, ecological and political reasons to put a brake on such marginalization by supporting agriculture in less endowed regions (DE WIT 1988). However, it has to be taken into account that this leads to higher production costs and goes at the expense of an efficient use of resources. Pollution prevention would be best served by concentrating arable farming in the most favorable regions and this especially so if combined with a stiff environmental tax to control overuse of nitrogen. This would relieve the overall burden on the environment, but because of the increased use of production resources per unit area, environmental standards would be increasingly threatened in regions where agriculture is concentrated. Moreover such concentration would not make it possible to exploit the buffering capacity for pollutants in regions where agriculture is abandoned.

A main problem of arable farming at present is its specialization. The latter reflects itself in a narrowing of the crop rotation to, for instance, wheat every year or potatoes every other year. Especially in combination with heavy mechanization, this poses serious problems. Fields are then left fallow for too long in the year and subject to breakdown of soil structure, to nitrogen leaching (DUYNISVELD a.o. 1988) and to wind- and water erosion. Another problem of such specialization is the development of pests, diseases and weeds that are difficult to control. Research and development should be directed towards further optimizing of resource use by widening of crop rotations, developing soil cultivation practices and machinery that conserve the structure of the soil and introducing crops and crop combinations that keep the soil covered for a longer time of the year (DE WIT 1990).

3.2 Dairy farming

Fig. 7 and 8 show that Liebscher's law holds also for grass production. In conformity, the nitrogen recovery of mown pastures in the Netherlands increased from about 50 percent in the sixties to about 75 percent now, as illustrated in Fig. 13 (VAN DER MEER a.o. 1986). However, pastures are for the greater part of time not mowed but grazed, and then the urine and dung drop in concentrated patches on grass that is already fertilized to an optimum level. Nitrogen from these droppings does therefore not contribute to production and is partly lost in the form of ammonia to the air and nitrate to the subsoil. A sizable fraction of the nitrogen from droppings on stable floors is also lost by volatilization as ammonia. The part that is not lost, is used as liquid manure, but often it is badly stored and used in such a way that again a considerable part of the ammonia volatilizes. Especially dairy farms on light textured soils are a focal point of environmental concern because of the large nitrate losses to the groundwater and the vulnerability for ammonia of the surrounding natural vegetation and forests.

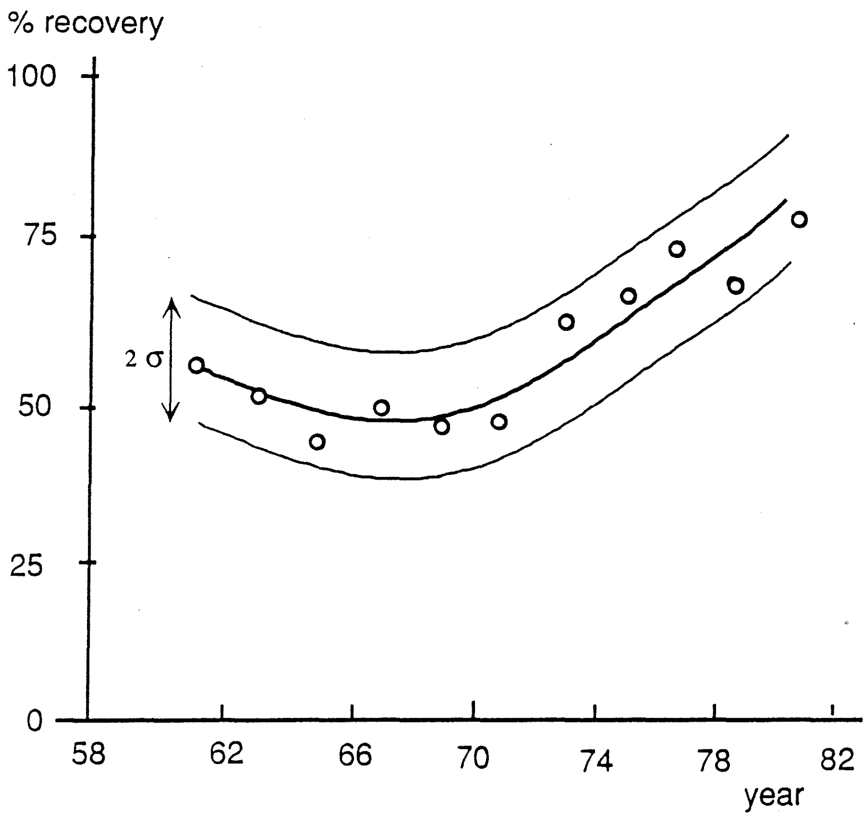

Fig. 13: The recovery of nitrogen fertilizer of mown pastures in the course of time, as calculated from the results of about 175 fertilizer experiments. (VAN DER MEER and VAN UUM VAN LOHUYZEN 1986).

From balance studies (VAN DER MEER a.o. 1986), it appears that the overall recovery in milk and meat of the nitrogen that enters the farm gate is only about 15 percent. To the extent that the remaining 85 percent of nitrogen is not incorporated in organic matter or lost as elementary N by denitrification, it contributes to the pollution of the environment. The amounts of nitrogen involved are large. For instance in the Netherlands annually, about 400 kg/ha of N are applied as inorganic fertilizer, 150 kg/ha of N enters the farm in the form of purchased concentrates and another 50 kg/ha of N is added via polluted air.

Increasing the efficiency of nitrogen use in the system as a whole requires better management, less grazing, less volatilization from the stables, better storage of liquid manure, more even and efficient application of liquid manure and the production of quality feeds, like pelleted, artificially dried grass and possibly fodder beets to replace in some part purchased concentrates. The efficiency and recirculation of nitrogen should be increased to such an extent that the overall recovery at the farm gate would be increased to about 50 percent. The same production would then be achieved by the yearly use of 150 kg/ha of N in the form of inorganic fertilizer and concentrates. The greatest technical problem may be reducing the volatilization of ammonia in the stable. Some of the air could be sucked off through the floor without creating turbulence and then stripped of ammonia. Alternately the stable floors could be regularly rinsed with liquid out of the manure that is acidified with nitric acid (OOSTHOEK 1989). However, in that way so much nitric acid has to be added to the system that the pastures may very well be over-fertilized. A biotechnical solution would be addition of urease blockers that prevent the transformation of urea into ammonia, but so far they are too unstable for use in slurries.

Extensification would certainly reduce the local environmental burden by the distribution of pollution over a larger area. The pastures could then be kept so poor that both the N from the droppings of the grazing animal are more efficiently used. This advantage, however, will have to be balanced with the unavoidable loss of efficiency in the use of other production resources. For one thing, reduction in digestibility of the herbage would decrease the milk production per cow and thus considerably increase the costs of maintainance of the herd per kg of milk and decrease the productivity of labour. Developing intensive mixed farming systems in which animal husbandry and crop husbandry are intertwined would be environmentally a more promising solution.

A cost driven solution could be to levy a stiff environmental tax on inorganic, industrial nitrogen fertilizer and on nitrogen in imported concentrates. Farmers then have an incentive to use their own nitrogen resources more efficiently by investing in techniques that reduce the present high nitrogen losses. A stiff environmental tax on nitrogen could make this nutrient also so valuable, that it becomes attractive to mine the soil in marginal regions by extensive ranching systems for the production of meat. Labour productivity is here less of a concern, because the cows do most of the work themselves.

4. Epilogue

At the beginning of this paper graphs describing the relationship between yield and nitrogen use in course of time were shown (Fig. 2 and 3). It is now clear that such trajectories reflect the balance of contrasting effects of increasing efficiency due to more optimal use of production resources on the one hand and decreasing efficiency due to further specialization and relative price changes on the other. As has been shown, much can be done to improve overall efficiency by de-specialization and through price incentives. But regulations that would force the farmer to sacrifice optimal use of production resources would put the cart before the horse, because they fail to appreciate Liebscher's law of the optimum that associates low yields with low efficiency of resource use.

This agricultural law has such a general validity because agriculture requires management of growth and production processes in a partly controlled environment and this is more difficult the more limiting and often unknown production factors interact. It has been shown that Liebscher's law is an intermediate between two limiting situations: Liebig's law of the minimum and Mitscherlich's law of constant activity. Liebig's law is likely to prevail under heavy nutrient and growth constraints. The demand for nutrients increases then linearly with yield, but the efficiency of their use remains low. On the other hand, Mitscherlich's law requires the existence of a reasonable supply of all nutrients, so that the availability of one ensures the efficient use of the other.

Such a transition from the law of the minimum to the law of constant activity along the historical technological trajectory of increasing control of the growth and production processes and increasing yields, makes that an increasing number of inputs gradually lose their variable character and the number of fixed operations on the farm increase. This makes more and more inputs not a variable cost element, but a complementary cost element of the decision to farm a certain piece of land. (DE WIT a.o. 1988, VAN DIJK a.o. 1989) Accordingly, strategic research that is to serve both agriculture and its environment, should not be so much directed towards the search for marginal returns of variable production resources, as towards the search for the minimum of each production resource, that is needed to allow maximum utilization of all other production resources of the farming system under consideration.

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