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Resource Use Efficiency in Agriculture

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ABSTRACT

Trajectories over time of nitrogen use and yield show that the fertilizer is used as efficiently at the high end of the yield range, as at the low end. Apparently, any decrease in marginal returns as predicted by the law of diminishing returns is more or less compensated by the benefits of other technological changes. Main processes that govern such opposing trends are analyzed in this paper to contribute towards more efficient use of resources in agriculture. The analyses elaborate on the optimum law of Liebscher, formulated at the end of the 19th century. This law states that a production factor which is in minimum supply contributes more to production, the closer other production factors are to their optimum. With some reservations regarding the control of pests, diseases and weeds, this law is fully confirmed. Accordingly, no production resource is used less efficiently and most production resources are used more efficiently with increasing yield level due to further optimizing of growing conditions. Whether external means of production are used at all depends of course on their price, but as soon as the farmer can afford them, they should be used in such a way that the production possibilities of all other available resources are fully exploited. It thus appears that with further optimizing of the growing conditions 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 piece of land. Therefore 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 resources, as towards the search for the minimum of each production resource that is needed to allow maximum utilization of all other resources.

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INTRODUCTION

The Second World War marked a turning point in the yield per hectare of arable crops in the western, industrialized world. Before the Second World War, yields of wheat in the United Kingdom and the USA increased only by a few kg/ha/year, if at all. Since then, however, yields have increased consistently at much higher rates from 35–70 kg/ha/year (de Wit *et al.*, 1987). This first 'green revolution' was economically due to a rapid increase in demand and was technically brought about by soil amelioration and mechanization that enabled 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, such as the sturdy, short-straw wheat varieties of Heine that became available in the early forties in continental Europe.

In the second half of the 1950s, it became clear that yield-increasing agricultural techniques developed in temperate regions were also indispensable in tropical regions. This led to the establishment of a number of internationally financed research centers. These appeared to be remarkably successful in initiating a second green revolution 25 years after the first in some of the main rice and wheat regions in Asia and Latin America. For example, the yield of rice in Indonesia stayed at about the same level before 1968, but has increased since then at a rate of over 100 kg/ha/year (de Wit *et al.*, 1987).

These revolutions brought about the necessary increase in production, but have led also to a number of unintended consequences. Farming in less endowed regions was marginalized, and in well endowed regions, small farmers were lost in the 'rat race'. Also, the diversity of farming systems decreased and the increased use of biocides and industrial fertilizers appears to be detrimental for the environment.

The environmental pollution of the post revolution, high-yielding agriculture, is often associated with the law of diminishing returns which states that the relationship between the amount of a production factor and the yield level is not linear, but levels off so that more and more external inputs are needed to push up the yields to their potential level. However, this law is formulated for situations where all the other production factors stay the same and this is obviously not the case when changes over time are considered. It should therefore come as no surprise that such a phenomenon is not confirmed by statistical data on yield increase and fertilizer use. This is illustrated in Fig. 1 for the relation between maize yield and the use of nitrogen fertilizer in the United States for the period 1945–1982, where at the high end of the yield range the

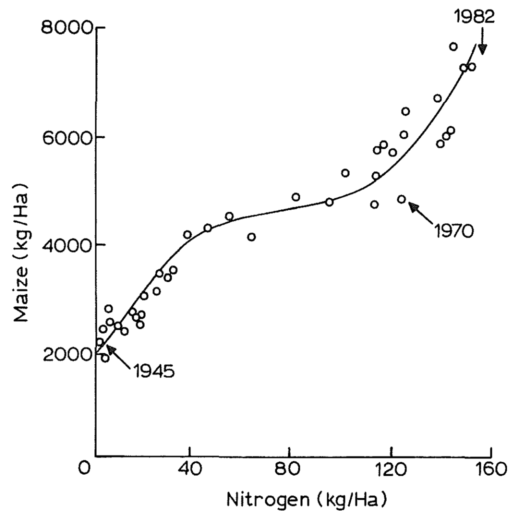


Fig. 1. Maize yield versus nitrogen fertilizer rate in the USA during the period 1945–1982 (After Sinclair, 1990).

efficiency of nitrogen fertilizer is at least the same as at the low end. The relation flattened out for some years at the end of the sixties. However, farmer practices improved again in the seventies, probably under influence of concern about fertilizer prices during the first oil crises. A similar relation is found in Fig. 2 for the use of fertilizer and rice yields in Indonesia. Figure 3 with nitrogen input and nitrogen output in milk and meat for the highly intensive pastoral farming system in The Netherlands shows that such constancy is not restricted to arable farming.

Hence, instead of showing a steady decrease, the ratio between yield and nitrogen use did not change systematically in the post green revolution era. When expressed in terms of yield versus energy use, there are even strong indications of a systematic increase (de Wit, 1975, 1979). This does not mean that the law of diminishing returns is not valid, but that any decrease in marginal returns to increased fertilizer use has been roughly compensated by the benefits of technological change. This is not an isolated phenomenon; for instance, it is analogous to the general observation that the output–capital ratio for the industrialized economies as a whole has been approximately constant during this century (Samuelson & Temin, 1976). Unlike the law of diminishing returns, such constancies are not a law of nature, but reflect a cancelling of opposing trends, depending on the kind of technological change.

The processes that govern such technological changes are little understood, and this may lead to the adoption of measures and practices that

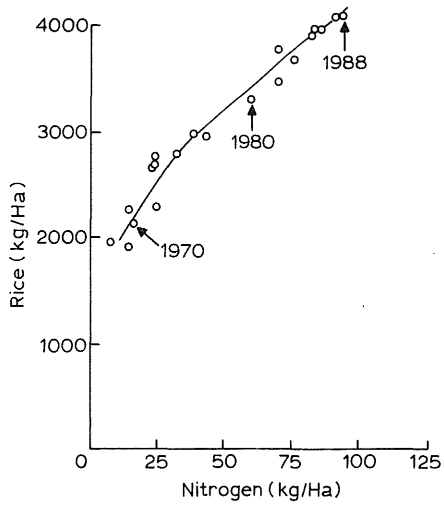


Fig. 2. Rice yield versus nitrogen fertilizer rate in Indonesia from 1968 to 1988 (FAO production yearbooks and FAO fertilizer yearbooks).

do not optimally contribute towards efficient use of resources and control of the environmental effects of agriculture. This justifies a further analysis of production principles. For this purpose, some classical literature on growth response functions is reconsidered to obtain a better grasp of the law of diminishing returns under conditions of technical change. This is elaborated by particularly considering nitrogen uptake by the crop as an intermediate between fertilizer rate and yield response. In conclusion, a strategic approach to agronomic research that serves both agriculture and the environment is presented.

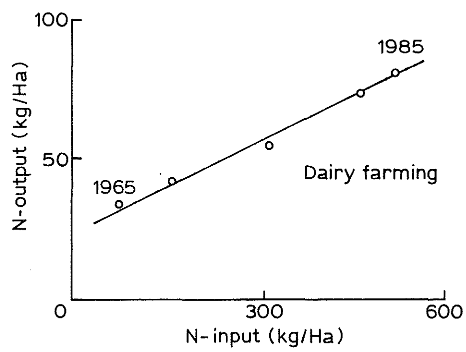


Fig. 3. Input of nitrogen in the form of fertilizer and concentrates and output of nitrogen in the form of meat and milk on Dutch dairy farms. Five-year averages from 1965 onwards (Van der Meer, CABO-DLO, Wageningen, pers. com.).

GROWTH RESPONSE FUNCTIONS

The law of the minimum

In agronomy, the law of diminishing returns is associated with von Liebig (1855) under the name of the law of the minimum. This law states that 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. Hence, only one nutrient is in minimum supply and the yield response to this nutrient is the same, whatever the supply of other 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 here more gradually than in the barrel model. The amount of nutrient available from sources other than the fertilizer can be expressed as an equivalent supply and is marked here by a vertical line at the horizontal axis, the nutrient on the right of the vertical line being provided by the fertilizer. A characteristic of the law of the minimum is that curves for different yield levels coincide in the region where the nutrient under consideration is limiting.

This law of Liebig reflects the principle of diminishing returns in situations where more and more of one element is applied while the availability of other nutrients remains the same. The law also reflects the

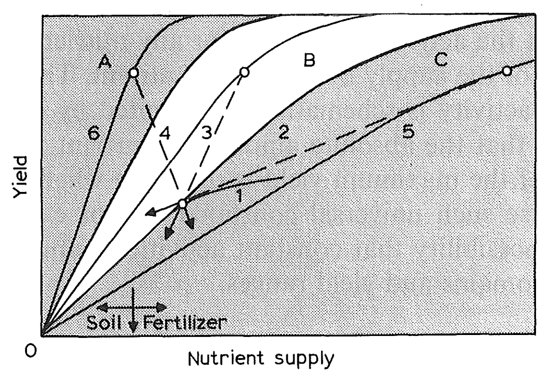


Fig. 4. Schematic presentation of yield response laws. Curves 1 and 2: Liebig's law of the minimum; Curves 1 and 3: Liebscher's law of the optimum; Curves 1 and 4: Mitscherlich's law of constant activity. (See text for further explanations.)

assumption that fertilization has to be balanced in such a way that the availability of each element is proportional to the yield. The first principle applies to situations where the nutrient is the independent variable and it characterizes the yield response to increasing amounts of fertilizer. The second assumption concerns situations where the yield is the independent variable and characterizes the fertilizer demand for a given yield.

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 played a leading role. Based on many experiments with the main nutrients, N, P and K, he formulated the law of the optimum at the end of the 19th century (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. In other words, all production factors are most efficiently used when they are all at their optimum. This law is schematically presented by curves 1 and 3 in Fig. 4. Liebscher formulated this law in terms of production factors because he found that it also holds true with growth-controlling factors other than nutrients, such as pH of the soil, weather or water.

The law of constant 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 of constant activity is schematically presented by curves 1 and 4 in Fig. 4. It implies that the absolute amount of nutrient needed to reach a certain fraction of the maximum yield is the same whether yields are low or high. Of course such universal constants do not exist, but this does not exclude the possibility that constant activities manifest themselves in more restricted domains and yield ranges.

A classification of response curves

All growth response functions reflect decreasing minimum returns when the supply of one production factor is increased, while maintaining all other growing conditions the same. Their precise form, more abrupt according to a negative exponential or to some hyperbolic function, has been much debated but is not considered an important issue in this paper. Here the question arises as to how the relative position of the response function to a certain growth factor changes with changing maximum yield level due to a changing availability of other growth factors.

This was first recognized by Van der Paauw (1939), who used the various laws for classification of nutrient responses (Fig. 4). Three regions are distinguished in Fig. 4, separated by the response function characteristic for Mitscherlich's law of constant relative activity and Liebig's law of the minimum.

In region C, responses are worse than according to the law of the minimum. Lines that join the same relative yields of curve 1 and curve 5, for instance, cross the vertical axis above the origin. Accordingly, the need for the minimum nutrient increases both in absolute and relative terms with increasing maximum yield level in this region. Such dismal responses to nutrients are soil-chemically and plant-physiologically unlikely; examples have not been found.

In region A, the responses are better than predicted by the law of constant relative activity. Lines that join the same relative yields are now reversed and compared with the previous situation; the need for the minimum nutrient decreases both in absolute and relative terms with increasing maximum yield level. Van der Paauw (1939) found that crops are more tolerant of a lower pH when their yields are higher (Fig. 5) and considered this a striking example for such a benign response. However, this may be questioned because lime used to enhance the pH acts mainly as a soil conditioner and not as a calcium or magnesium fertilizer.

Region B, finally, is the domain of the optimum law of Liebscher. The line that joins the same relative yields of curve 1 and curve 3, for

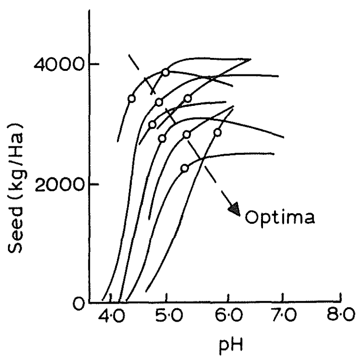


Fig. 5. pH response curves for barley at different yield levels (Van der Paauw, 1939).

instance, indicates that the absolute need for the minimum nutrient increases with increasing yield level in this region. However, the relative need decreases at the same time. In other words, the amount of nutrients needed increases with increasing yield level when expressed per hectare, but decreases with increasing yield level when expressed per unit yield. Like Liebscher half a century before, Van der Paauw found that most nutrient response curves were in region B or sometimes slightly over the border into region A, but never in region C.

FURTHER ANALYSES

A graphical presentation

A further elaboration of these phenomena requires information on nutrient contents in relation to their supply and maximum yield level as determined by other production factors. Most data in the literature are available for nitrogen because it is the most dynamic nutrient and has to be applied every year to ensure enhanced and sustainable yields. Therefore, the analyses presented in this paper are mainly on crop responses to nitrogen in relation to variety, physical resources, other nutrients and pests, diseases and weeds. Where relevant, the reciprocal effects of nitrogen status on the factors that determine the maximum yields are also considered.

Most of the experiments are treated by using the uptake of the nutrient as an intermediate between its rate of supply and the yield by means of three-quadrant diagrams (de Wit, 1953; Van Keulen, 1982) (Fig. 6). In these diagrams, the relationship between the rate of fertilization and the uptake of the nutrient by the crop is given in the fourth quadrant (IV), and that between this nutrient's uptake and yield in the first quadrant (I). By eliminating the uptake from both graphs, the familiar relationship 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 the uptake out of the soil. The recovery of a nutrient at a certain amount of fertilizer is the uptake at this amount minus the uptake without fertilization, divided by this amount.

Varieties

In the example of Fig. 6 (Baan Hofman, 1988), the two different responses are due to the use of two perennial ryegrass varieties that differed mainly in persistence. Dry matter yields and nitrogen uptake concern the harvested above-ground materials of the six cuts in the second year of growth. The uptake–yield curves in quadrant I pass through the origin because no dry matter yield is possible with zero uptake, and no uptake is possible with zero dry matter yield. The initial slopes of these curves is the same for both varieties. Better persistence reflected itself in a better utilization of the nitrogen that was taken up in the higher range. It appears in quadrant IV that the recovery of nitrogen is also higher in the higher range. Thus, although the absolute demand for nitrogen increases with increasing yield level, the relative demand decreases, in accordance with Liebscher's law of the optimum. It is not clear why this improved persistence did not reflect itself in a better uptake in the unfertilized situation.

The main difference between traditional leafy varieties and modern, more short and sturdy varieties of wheat 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 traditional varieties was prevented by mechanical means. He found that new wheat varieties not only yielded more under high fertility conditions with high nitrogen, but also yielded more under low fertility conditions with low nitrogen. Sandfaer *et al.* (1965) showed that the larger response of modern varieties of barley was due to both an improved rate–uptake

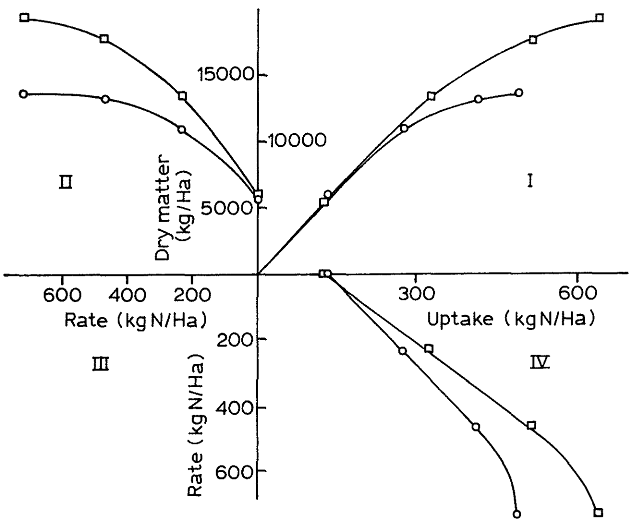


Fig. 6. Three-quadrant diagram with graphs for the relationship between fertilizer rate and uptake in quadrant IV, uptake and yield in quadrant I and fertilizer rate and yield in quadrant II. (After Baan Hofman, 1988). —□—, selectie; —O—, splendor.

and uptake–yield relation. Both experimental series again confirmed Liebscher's law.

Nevertheless, differences in nitrogen uptake at low fertilizer rates are less conclusive than at high rates. Sandfaer *et al.* (1965) and Watson *et al.* (1963) found that new varieties had a somewhat better uptake, but in an experiment by Sanchez *et al.* (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 sowing density, 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.

Differences in uptake–yield curves between traditional and modern rice varieties are mainly due to the larger grain/straw ratio of modern varieties (Van Keulen, 1977). The total uptake of N needed to produce 1000 kg of dry matter was found to be the same at 7·6 kg for modern short-straw varieties of rice and for more leafy, older varieties of rice (Sanchez *et al.*, 1973). However, modern varieties needed only 14 kg total uptake of N per ton of grain whereas older varieties needed 18 kg.

Both the rate–uptake and uptake–yield relations are better for hybrid rice compared with its non-hybrid counterpart (Fig. 7), such that the first does not need any more nitrogen fertilizer to sustain its high performance (Chen Caihong & Liu Chenliu, 1989). Hence, lines in quadrant II

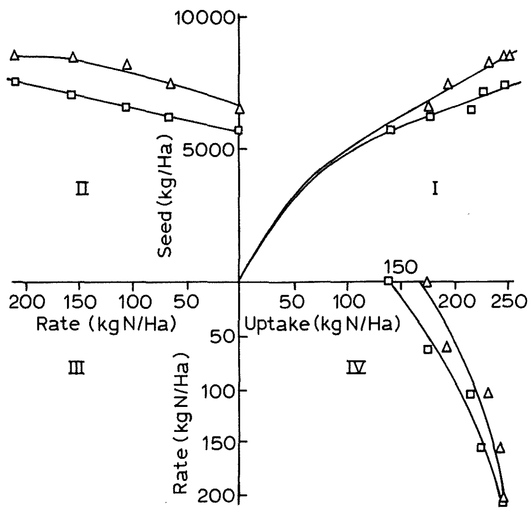


Fig. 7. Three-quadrant diagram for a nitrogen experiment with a hybrid and non-hybrid variety of rice (Chen Caihong & Liu Chenliu, 1989). Δ, Sanyou hybrid (36); □, Sanyou control (6).

that join the same relative yields are almost vertical, in accordance with Mitscherlich's law of constant activity. It is also interesting that the uptake from the non-fertilized fields was enhanced by using hybrids. This was confirmed by experiments in the next year. It is suggested that such differences between traditional and hybrid varieties are due to more rapid early development of the latter.

Physical resources

Nielsen (1963) grouped the results of an experiment in Denmark on the response of oats to sodium nitrate application during 1924–1940 into years with relatively good, medium and bad weather (Fig. 8). 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. This again confirms Liebscher's law of the optimum. Nielsen (1963) also conducted an elaborate pot experiment on the interactions between nitrogen and water using a soil that contained no nitrogen to begin with. Quadrant I (Fig. 9) shows that the yield–uptake curves are in accordance with Liebig's law; the uptake of nitrogen, however, reflects Liebscher's law of the optimum. Accordingly, the same holds for the rate–yield curves in quadrant II.

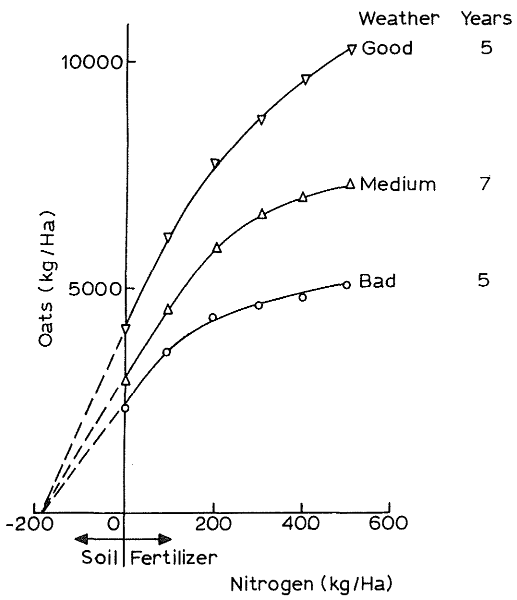


Fig. 8. Average nitrogen response curves of wheat for years with relatively good, medium and bad weather for 1925–1940 (Nielsen, 1963).

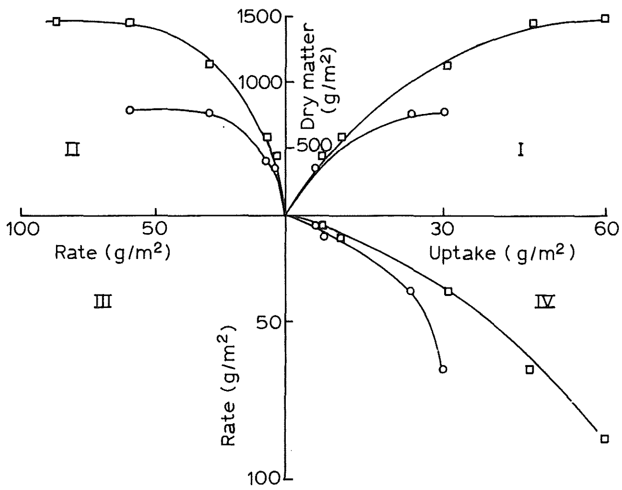


Fig. 9. Three-quadrant diagram for a pot experiment with perennial ryegrass with various nitrogen levels and 2 levels of available water (Nielsen, 1963). Data refer to the sum of five cuts. —O—, water level 2; —□—, water level 4.

Hoogerkamp & Woldring (1965) analyzed a semi-permanent experiment on the response of grass and arable crops to the control of groundwater on river basin soil in The Netherlands. It was found that the initial slopes of the uptake–yield curves were in general the same, but at higher uptakes the utilization of nitrogen increased. Also, the uptake of nitrogen from unfertilized fields improved both in the situation where the optimum was approached from the wet side and from the dry side. This is again in agreement with Liebscher's law of the optimum. Similar results were reported for an experiment on the interaction between nitrogen fertilization and sprinkler-irrigation (Middelkoop *et al.*, 1990). In general, when the optimum water supply is approached from the wet side, the uptake of N increases because nitrogen losses due to denitrification and leaching decrease. On the other hand, when approached from the dry side, it increases due to increased water in the top soil where the nitrogen is located. The latter was confirmed by experiments with non-irrigated rice (Rehatta *et al.*, 1979).

Figure 10 shows that the reciprocal effect of increased nitrogen supply on the relation between evapo-transpiration and production was very beneficial. At low yields (de Wit, 1958) this may be due to both a decrease in the transpiration coefficient and a relative shift of water loss from evaporation to transpiration, but at higher yields only the latter occurs. The evaporative water loss from flooded rice land without any crop is already close to its potential, so that the loss of water shifts dramatically from evaporation to transpiration, with increasing yields. This was also

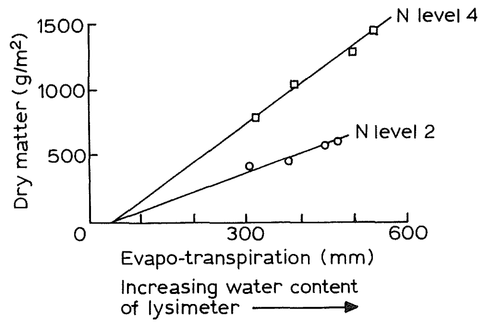


Fig. 10. Relationship between evapo-transpiration and yield at two nitrogen levels for the same experiment as in Fig. 11.

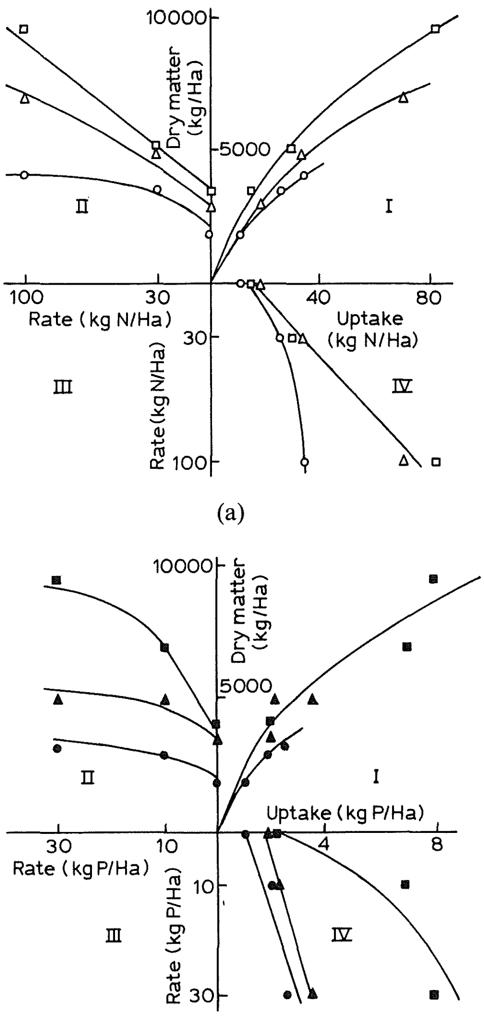
observed in the semi-arid region of the Sahel where evapotranspiration of natural pastures is supply-limited by rainfall (Penning de Vries & Van Keulen, 1982). Under such conditions, the fraction that is lost by transpiration typically increases from less than 25% to over 75% with increased yields due to fertilization.

The response to CO_2 increases in general with the increasing availability of nutrients, whereas poor soils may be better scavenged for nutrients due to better root mycorrhizal fungi development (Kimball, 1985; Larigauderie *et al.*, 1988). This is again in agreement with Liebscher's law of the optimum.

Nutrient supply

The classical example of Liebscher's law is the positive interaction between the yield response to nitrogen and phosphorus under conditions where both are in short supply. Such conditions rarely exist in Western Europe and the USA under present-day conditions, but under the poor fertility conditions that prevail in most of Africa such positive interactions are readily confirmed.

Penning de Vries & Van Keulen (1982) conducted an elaborate experiment on natural pastures in the Sahelian region of Mali (Fig. 11). Figure 11(a) shows the response to N at three levels of P, and Fig. 11(b) shows the response to P at three levels of N. The data in both figures were adjusted for plot size. There is a positive interaction between both nutrients, as shown in the uptake–yield curves in quadrant I and the rate–uptake curves in quadrant IV. Hence, for both nutrients, the law of Liebscher is furthered. The recovery of N in the presence of P appears to be over 70% and the recovery of P in the presence of N over 20%. These are high figures and it could well be that low recoveries in arid regions



(a) (b)

Fig. 11. Three-quadrant diagrams for a field experiment on natural pastures; (a), with the three levels of N and (b) three levels of P, in all nine combinations (Penning de Vries & Van Keulen, 1982). (a): ○, 0 kg/ha; Δ, 10 kg/ha; □, 30 kg/ha of P. (b): ●, 0 kg/ha; ▲, 30 kg/ha; ■, 100 kg/ha of N.

are due not so much to water shortage, but to the lack of balanced nutrition.

A similar positive interaction between N and P was found by de Wit & U Khin Win (1957) for bunded rice in Myanmar. In this case, the positive effect of P on rice yield was completely due to the positive effect of P on the uptake of nitrogen, so that fertilization with P could be considered as a disguised fertilization with N. This phenomenon has been observed more often under conditions of N shortage (Van Keulen, 1977; Penning de Vries & Van Keulen, 1982). It may be explained by the favorable effect of P on root development in the early stages of growth when N is still in a reasonable level of supply (de Wit, 1953). This enhances early N uptake so that less of this element is subsequently lost or made unavailable. Fertilization with only P thus only leads to an accelerated exhaustion of nitrogen in the soil, so that, after a few years, the yields are again as low as the yields on the fields that never received any P. This is not the case when there are nitrogen-fixing legumes in the pasture or in the rotation.

Pests, diseases and weeds

Spiertz (1980) observed two different responses to nitrogen created by controlling and not controlling ripening diseases (Fig. 12). Quadrant I shows that disease control resulted 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 & de Wit, 1975; Van Keulen & Seligman, 1987). However, seed filling requires assimilates and these are not available when leaves die prematurely because of diseases. Since the minimum content at which 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

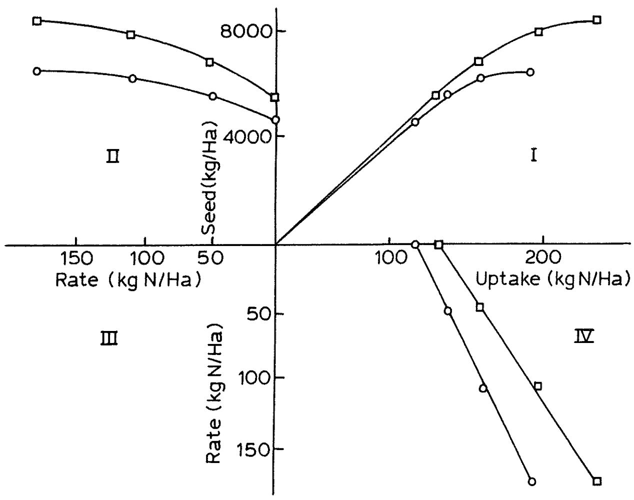


Fig. 12. Three-quadrant diagram of a nitrogen fertilization experiment with and without control of ripening diseases (Spiertz, 1980). —○—, no disease control; —□—, disease control.

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 & Van Heemst, 1982).

Nitrogen uptake also appears to increase as a result of disease control (quadrant IV, Fig. 12); the longer the plants are healthy, the longer the roots remain active. This prolonged activity is reflected 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% without disease control, but increases to 70% with disease control. The uptake in roots and stubble is about 25%, so that with disease control the total recovery during growth was over 90%. In general, such high recoveries require that the nitrogen fertilizer be applied in several portions during a growing season (Van Dobben, 1966). Disease control resulted both in higher uptakes over the whole range of applications in quadrant IV, and in an improvement of the uptake–yield curve in quadrant I in the higher ranges of N uptake. The combination in quadrant II again confirms Liebscher's law of the optimum.

The experiment of Baan Hofman & Van der Meer (1986) concerns a pasture where two different production situations were created by treating the soil with the biocide thionazin (Fig. 13). The recovery of N was about the same, but the treatment resulted in a considerable increase of mineralization (quadrant IV). This process probably made other elements more available so that the utilization of nitrogen increased as well (quadrant I). Combined with quadrant II, the treatment proved to be most useful in the lower range of fertilization. The experiment may be considered an example of the benign situation where both the absolute and relative amounts of N needed to reach the same relative yield decrease with increasing yield level.

The number and variety of pests, diseases and weeds are so large, and their damaging effects depend to such an extent on environmental conditions, that it is difficult to generalize about the reciprocal effect of biocide requirements in relation to yield level.

There is little or no evidence that the damage of diseases increases with increasing yields for sugar beets and potatoes. Small grains, when high yielding, however, are especially susceptible to obligatory parasitic pests and diseases like aphids, mildew and rusts (Rabbinge, 1986; Rabbinge & Bastiaans, 1989), mainly as a result of higher nitrogen content in the affected tissues (White, 1984). More effort to control these diseases and insects is therefore needed. It may very well be that the development of some of the epidemic diseases is so slow at low yields and nitrogen content that no control is needed, but so fast under

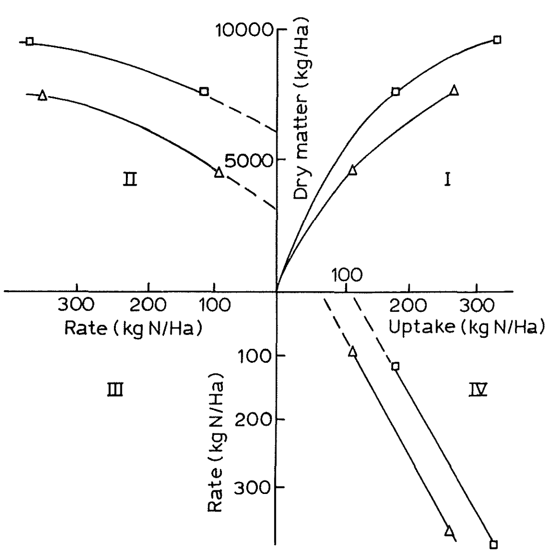


Fig. 13. Three-quadrant diagram for a nitrogen fertilization experiment with and without treatment of the pasture soil with thionazin (Baan Hofman & van der Meer, 1986). Δ, control; □, thionazin.

optimum growing conditions that biocides have to be used for their control. In that case, even the control effort per unit yield would increase with increasing yields, as in region C of Fig. 4.

In any case, the dependence on environmentally-damaging and health-threatening biocides is considered so high and so risky, that integrated pest management methods are being developed to constrain their use (Zadoks, 1981). These rely on varieties with a broad resistance, observation-driven control systems, cultural practices and a constrained use of biocides. 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 northwest Germany (Rabbinge, 1987).

In many irrigated regions of the tropics, rice is grown year-round, and year after year so that, upon intensification, whole regions are covered permanently with the same crop in different stages of development. The use of biocides to control obligatory pests and diseases has been excessive under these conditions, and thus integrated pest management is advocated and is received as a timely blessing. A number of cultural measures that are advocated are old practices (Van der Veer *et al.*, 1948). That does not make them any less useful, but should encourage scientists to make good use of the knowledge of the farmer in developing integrated pest management packages. An example was the (admittedly forced) colonial practice in Java of broadening the rotation by introducing other crops, such as growing one third of the irrigated rice land for one year with sugar cane without allowing any ratooning (Koningsberger, 1948).

Crops that are growing under optimal conditions may be less susceptible to non-obligatory parasitic diseases like septoria, fusaria, etc., than crops that are growing under environmental stress (Rabbinge, 1986; Rabbinge & Bastiaans, 1989). This is illustrated in Fig. 14 for potatoes on soils infected with *Verticillium* species (Haverkort *et al.*, 1989). In another case, fertilization of potatoes did not only increase the yield directly, but also reduced nematode damage (Van der Wal & Haverkort, 1989). The experiment in Fig. 13, in which the relative effect of the soil treatment with thionazin decreased with increased application of N may be considered another example of this phenomenon. Accordingly, the control of non-obligatory diseases requires less inputs in both absolute and relative terms with increasing yield level, as in region A of Fig. 4. Also, for rice, it is recommended that supplemental fertilizer be applied when an economic threshold of pest infestation is reached, as a corrective measure that gives the crop the energy to outgrow insect damage (IRRI, 1991).

It has been repeatedly shown that rice plus weeds from non-weeded areas absorb roughly the same amount of nutrients as rice from weed-free areas across a range of fertilizer levels (Moody, 1981). Thus, weeding both increases the yield and the nitrogen recovery by the crop, so that Liebscher's law is again confirmed.

The reciprocal situation is analogous for pests and diseases. There are grain look-alikes that grow in exactly the same niche as the crop, such as 'red rice' (*Oryza sativa*) and 'djadjagoan' (*Echinochloa crusgalli*) in rice

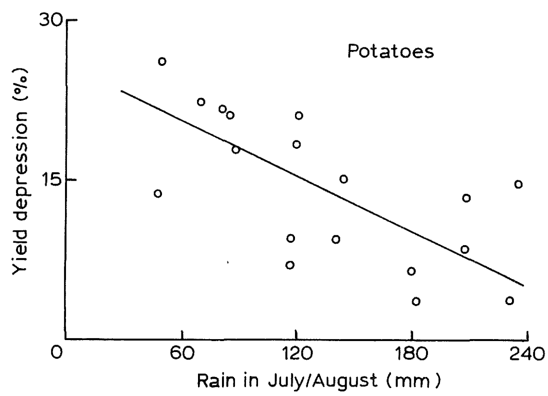


Fig. 14. Percent yield depression of potatoes in two 1 : 3 rotations compared with a 1 : 6 rotation in relation to rainfall in July and August. The yield depressions are probably due to an infection of *Verticillium* sp. (Haverkort *et al.*, 1989).

that may not even be recognized at transplanting (Van der Veer *et al.*, 1948). These may be more competitive under fertilized than non-fertilized conditions (Pande & Bahn, 1966), especially in conjunction with the modern, short and less leafy varieties (Moody, 1981). Per unit surface area, the efforts for control would then increase with increasing yields. On the other hand, whatever the cause of sub-optimal growth, there are always some weed species that do better than the crop under such conditions. Thus they have a good chance to invade and then claim their share of the resources. It may well be that most of the puddling during seedbed preparation of bunded rice is done to control the many plant species that are less adapted than rice (and its look-alikes) to waterlogged and anaerobic environments. The control of such 'weeds-of-opportunity', requires less effort both per unit yield and per unit surface area under more optimal conditions for crop growth.

RESOURCE USE EFFICIENCY

Apart from water, the most important yield-increasing inputs are nutrients. For Liebig's law of the minimum to be valid, it would require that neither the uptake from the unfertilized soil, nor the recovery of any fertilizer and the minimum nutrient content should be affected by improving growing conditions. Only the relationship between uptake and yield at higher yield levels should be improved. From the foregoing it is concluded that the likelihood of these conditions being met is so small that production functions are in general found in zone B of Fig. 4, where the optimum law of Liebscher is valid. An analogous reasoning holds for water. The demand for nutrients and water, expressed per unit surface area, therefore increases with increasing yield level, but decreases when expressed per unit yield.

The most frequently used inputs to protect yield are biocides to control pests, diseases and weeds. The demand for them encompasses a much wider range of production responses. On one side of the spectrum, there are parasitic pests and diseases and opportunistic weeds that may require less effort for their control with increasing maximum yield level. On the other side of the spectrum are obligatory pests and diseases and look-alike weeds, that may require more effort for their control with increasing yields, even when expressed per unit yield. The wider spectrum of response in the case of yield-protecting inputs, as compared with yield-increasing inputs, is related to the circumstance that in the former situation two or more interacting organisms are involved, compared to only one in the latter situation. In many situation with an increased need for biocides when expressed on a unit surface area basis, there may still be a decreased need for biocides when expressed on a unit yield basis. However, there are also situations where the need for biocides increases even per unit yield. These are of special interest for integrated pest management.

Apart from optional yield-increasing and yield-protecting inputs, there are activities that are conditional for crop growth at any yield level and require among others labor, machinery and fuel as inputs. These activities are partly surface-related and partly yield-related. Examples of surface-related activities are ploughing, seedbed preparation, sowing and most harvesting operations. Their use of inputs per unit yield is inversely proportional to the yield level. Examples of yield-related activities are transport of harvested products and seed drying. Inputs for these purposes are proportional to the yield level. Taken together, the use of machinery, labor and fuel increases per unit surface area, but decreases per unit yield with increasing yield level.

It may be concluded, with some reservations regarding the control of pests, diseases and weeds, that no production resource is used any less efficiently and that most production resources are used more efficiently, with increasing yield level due to the further optimizing of growing conditions. Although this is true by definition of fixed means of production, the analyses in this paper have shown that this is true for variable means of production. Hence, as soon as a farmer can afford any external means of production, these should be used in such a way that the production possibilities of all other available resources are fully exploited.

The use of fertilizers by African farmers is an example. Simple experiments on farmers' fields with increasing amounts of phosphate, nitrogen and potassium generally show that it pays to use phosphate fertilizer, but that the response to potassium is absent and the use of nitrogen fertilizer is far too expensive. It is then of no use to continue experimentation to determine the form of the response function to phosphate fertilizer under otherwise similar conditions, or to calculate marginal return levels. Rather, the use of phosphate to improve the efficiency of use of other available resources should be investigated. This may require adaptation of the farming system by incorporating more leguminous species in the rotation for seed and/or mulching, since their rate of nitrogen fixation depends directly on the rate at which phosphates are taken up (Penning de Vries & Van Keulen, 1982). Since leguminous species acidify the surroundings of their roots, it may be worthwhile to experiment further with the use of rock phosphate rather than phosphates in soluble form. Improved growing conditions may then make it worthwhile to reconsider the use of other fertilizers.

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. Water is, however, an important exception: the closer water is to its optimal supply, the more water supply regulation becomes an encompassing and expensive public venture. Hence, when society is not willing to facilitate the investments required to further improve water management, ultimate yield limits come earlier in sight. On the other hand, agro-ecological research in combination with crop growth simulation has shown that, in many regions of both the developed and developing world, there is still a considerable yield gap between what farmers do and could do at the present level of amelioration, if their economic environment would allow for the use of external means of production (Van Keulen & Wolf, 1986; FAO, 1984; Buringh *et al.*, 1979).

In regions where farming is economically viable, further yield increases are thus determined in an autonomous process for the farmer, but fuelled by public and private research, extension and marketing. This makes any optimum a moving target for the farmer. Continuing increases in production and production efficiency then exert a downward pressure on prices. This does not slacken the rate of yield increase in agriculturally well-endowed regions. The law of supply and demand ensures that farming remains economically viable in these regions, but leads to continuing marginalization of less-endowed regions. Here, agriculture is either extensified to ranching or is fully abandoned. This process of differentiation between well- and less-endowed regions first became apparent in the USA, and is now in full swing in the European Community. More influence on agricultural development in countries of the developing world is expected, especially with increasing internationalization of world markets. There may be good geopolitical reasons to grow the food where the mouths are, good equity reasons to support farmers who are being marginalized and good ecological reasons to maintain agriculture as a form of land use in less well-endowed regions. However, meeting such demands may lead to a less efficient use of external resources.

Pollution prevention is best served by the efficient use of external resources. This is achieved by concentrating arable farming in the most favorable regions. However, there are a few caveats to consider. Although the use of resources per unit product is decreased, such concentration of agriculture leads also to concentration of pollution on a small surface and this may increasingly threaten environmental standards in remaining agricultural regions. Moreover, the concentration of agriculture would make it impossible to mine large soil surfaces for plant nutrients as is done in extensive forms of agriculture and make it difficult to exploit the possibilities of reducing the effects of pollution by dilution.

Optimal conditions are different for different crops. Therefore, and because of economies of scale, crop rotations are likely to narrow down to a few crops in this process of optimizing growing conditions: for instance, only wheat and potatoes, only rice and wheat or even only wheat or rice in monoculture, year after year. In combination with heavy mechanization, such specialization may lead to serious problems. Soils may be left bare for too long a period and thus be subjected to structural breakdown, to nitrogen leaching (Duynisveld *et al.*, 1988) and to wind and water erosion. Also, the few remaining crops may be increasingly affected by pests, diseases and weeds that are difficult to control. Accordingly, increases of resource use efficiency with further optimization of growing conditions for individual crops is sooner or later counterbalanced by a decrease in resource use efficiency because of increased specialization. This may explain why agricultural research in the developed world is so preoccupied with improving resource use by widening 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 longer periods of the year (de Wit, 1990).

CONCLUSIONS

The optimum law of Liebscher has such a general validity because agriculture requires the management of growth and production processes in a partly controlled environment. This is more difficult the more that limiting and often unknown production factors interact, or where yields are low. It has been shown that Liebscher's law is 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 then increases 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 growth and production processes, and increasing yields, leads to the situation where an increasing number of inputs gradually lose their variable character and the number of fixed operations on the farm increases. More inputs then become non-variable cost elements, and assume the role of complementary cost elements of the decision to farm a piece of land (de Wit *et al.*, 1987; Van Dijk & Verkaik, 1989). Therefore, strategic agronomic 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.

The development of viable agricultural production systems should then aim at selecting production systems with the lowest costs of external input per unit output. Inspired by Holt (1988, cited in Okigbo, 1991), this selection could be based on the relation between yield and minimum costs of production, which is, according to the above analyses, necessarily sigmoid (Fig. 15). Here, the productivity goal is the independent variable and the minimum cost of production is the dependent variable. The costs of internal resources stand for those of the farmland and the labour of the farm family and P_0 is the production that can be achieved without external inputs (Fig. 15). In practice, many systems are less efficient than the minimum cost function and there are three characteristic points. The point of marginalization is at the intersection of the minimum cost curve and gross return line. Below this point, no profitable production systems exist at the available level of knowledge and prices. The point of minimum external cost per unit product added above P_0 is where the line through the intersection of this curve with the vertical axis touches the minimum cost curve. The point of unit marginal return has a tangent of 45 degrees. In case there is a range where agriculture is profitable, the point of minimum external cost per unit of added product is always at a lower productivity level than the point of unit marginal return.

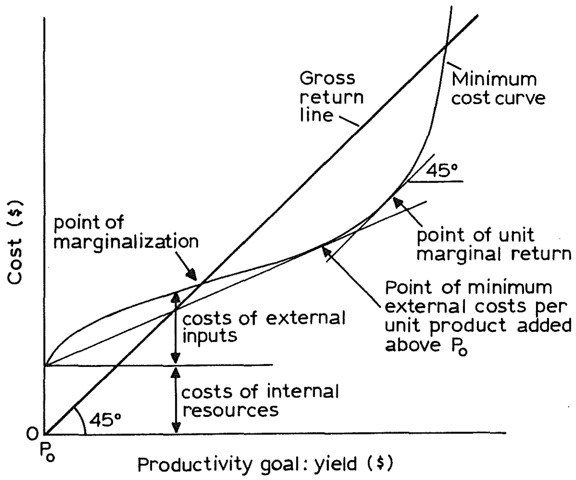


Fig. 15. Minimum production cost in dependence of productivity goals of farming systems (Holt, 1988, revised).

At the point of unit marginal return, the profit/ha is the largest, so that any move from there in the direction of a more efficient use of external inputs is inevitably at the expense of net profits. It is sometimes claimed that so-called integrated farming systems, which aim at a restrained use of inputs, also lead to a higher profit compared with conventional, intensive farming practices. However, this can only be true if there is an overuse of inputs in these conventional systems and not in the integrated system. Regulations that would force the farmer to extensify to such an extent that even the point of lowest external costs per unit product could not be reached, would put the cart before the horse. They would fail to appreciate Liebscher's law of the optimum that links low yields with low efficiency of resource use.

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