International Potash Institute

Nutrient Balances and Fertilizer Needs in Temperate Agriculture

Proceedings of the 18th Colloquium
of the International Potash
Institute held in Gardone-Riviera/Italy

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Contents

Opening Session Page

1st Session — **Nutrient Balances in Farming Systems**

2nd Session — **Evaluation of Nutrient Balances**

3rd Session — **Building Yields by Fertilizer Input in Temperate Agricultural Systems**

4th Session — **Fertilizer Needs in Temperate Ecosystems**

5th Session **Agricultural Productivity in Ecosystems**

Introduction

A. Malquori, Chairman of the 18th IPI-Colloquium, Member of the Scientific Board of the International Potash Institute*

As Chairman of this Colloquium, my first, and very pleasant, duty is to welcome you all to Gardone. We are honoured that after an interval of some years the *International Potash Institute* decided on Italy as the venue for the 18th Colloquium. In the early years of the Institute we were hosts in Rome for the 1955 Congress '*Potassium in the Soil*'. Later, in 1968 the Colloquium dealing with the '*Fertilization of Protected Crops*' was held in Florence.

The title for the current cycle of IPI's scientific colloquia is: '*Nutrient Balances and Fertilizer Needs in Different Climates*'. This title expresses our concern as to how much fertilizer per unit area is needed if we wish to sustain optimum plant growth now and to maintain soil fertility for the future.

Essential in the nutrition of plants under natural conditions is the cycling of nutrients between the pedosphere, the biosphere (microorganisms, plants, animals), the hydrosphere and, to some extent, the atmosphere. Rates of nutrient transition between these must be known if the balance of nutrients is to be adequately defined from the ecological point of view. In agriculture, we, as scientists, are especially concerned with the soil's ability to supply nutrients to the growing crop over a growing season. Plants take up nutrients from the soil solution in which concentrations are buffered by nutrients adsorbed to clay minerals and organic matter and we might consider nutrient balance as that situation in which plant nutrients are in the equilibrium situation required for optimum growth. However, conditions can never be static owing to nutrient uptake by plants and to losses by leaching or volatilization.

A useful practical approach is to consider nutrient balances over a growing season or over a rotation and so to establish balance sheets based on nutrient inputs and outputs. This 'book-keeping' approach is appropriate for planning fertilizer use on a regional or national basis.

In taking the nutrient balance concept into the field we really need more detail and we have to take into account effects which the soil, the weather and the crop might have on the mobility and availability of plant nutrients. These can best be investigated in field experiments. The aim is to arrive at the situation where the field produces economically optimum yields which can be maintained over many years and where the efficiency of fertilizer use is high. These are the aspects which will be principally discussed here, as they were in last year's Colloquium in Morocco dealing with arid and semi-arid climates and will be next year in a tropical environment.

We have five working sessions: 1) Nutrient balances in farming systems, 2) Evaluation of nutrient balances, 3) Building yields by fertilizer input in temperate agricultural systems, 4) Fertilizer needs in temperate eco-systems, 5) Agricultural productivity in eco-systems. When the lectures and discussions are finished, the excursions will allow you to see something of specialized agriculture in the region.

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The choice of northern Italy to represent the temperate zone places our Colloquium in the centre of a type of agriculture which can be considered advanced in its control of soil fertility, in the use of selected crop varieties and which is highly productive both in general farming and in highly specialized enterprises. Touching the soils of this region which have been cultivated over so many generations, it is interesting to remark that in his first report on Italy, *Bonaparte* described the plains of northern Italy as being among the most fertile in the world.

The propitious natural conditions have favoured the development of industry and in some regions such as Piedmont, Lombardy, Venetia and Emilia excellent relations have been established between agriculture and industry.

I am sure that the results which will be presented here and the discussions we shall have will contribute conspicuously to the perfection of fertilizer use in the temperate area and that this will in turn be evidenced by a further improvement in agricultural production in both quantitative and qualitative terms. We should never forget that the main problem which agriculture has to face is the constant growth in world population; there is no doubt that fertilizers have a key role to play in solving this problem.

I am glad that you are all able to take part in this Colloquium. Knowing the standing of our speakers, I am sure you will find your participation to be fruitful. I wish you all a pleasant stay on the shores of this beautiful lake which has something to offer to everyone and which was found so congenial by *Catullus, Virgil, Dante* and *Goethe.*

Chairman of the 1st Session

Dr. *T. Walsh,* former Director of the Institute of Agriculture of Ireland, Dublin/Ireland; member of the Scientific Board of the International Potash Institute

1st Session

Nutrient Balances in Farming Systems

Characteristics of Nutrient Cycling and Nutrient Balance Sheets in Low-Input and High-Input Agriculture

A. van Diest, Department of Soil Science and Plant Nutrition, Wageningen Agricultural University/Netherlands*; Member of the Scientific Board of the International Potash Institute

Summary

Nutrient cycles for the elements N, P, and K were considered. It was shown that for all three nutrients the cycles can be divided into subcycles. For each cycle, in one of the subcycles the nutrient involved is channeled toward the crop that is grown. The other subcycles act as competitors with the crop for the nutrient. In the case of N, microorganisms and the atmosphere are the main competitors. For P, the soil is the primary competitor with microbes taking a second position. For K, surface water and the oceans are competing with higher plants, while under certain conditions the soil can be a strong competitor.

To maximize the efficiency of utilization of nutrients applied as fertilizers, care should be taken that the general growing conditions allow a crop to compete as effectively as possible with other agents in the various nutrient cycles for the nutrient involved. The examples shown in this paper make it clear that the degree of recovery of a fertilizer nutrient is usually a function of the quality of the growing conditions and also of the type of farming, but not of the quantity of the nutrient applied as long as the quantity is adjusted to the need of the crop grown. The efficiency of utilization of fertilizer nutrients is generally much lower in livestock farming than in arable farming. This is associated with the circumstance that in livestock farming two types of efficiency calculations are in order, one in which the degree of recovery of the fertilizer nutrient in the herbage and one in which the degree of recovery of the herbage nutrient in the animal and its products is involved. The first recovery is usually high, but the second one is much lower thus accounting for the low overall recovery of fertilizer nutrients in livestock farming.

1. Introduction

The cycling of nutrients through ecosystems is a phenomenon deserving our attention for several reasons. It the first place it is of interest to know to what extent in natural habitats a vegetation succeeds in drawing nutrients to its root system and in retaining these nutrients in its tissues. In this respect the natural vegetation, as a part of the biomass in that ecosystem, has to compete with other components of the ecosystem for these nutrients. These other components are:

1) the atmosphere
2) the hydrosphere
3) the pedosphere
4) the lithosphere
5) the biosphere, excluding the higher plants.

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All components, or pools, in an ecosystem as pictured in Figure 1 may serve as suppliers of nutrients or as competitors for nutrients. In agronomic societies it is customary to place the higher plant in a central position and to study how the other components can best be conditioned to serve as effective suppliers to the higher plant and how their roles as potential competitors can be most effectively suppressed.

Not all these components are of equal importance as suppliers of nutrients or as competitors for nutrients. For instance, with respect to potassium the higher plant has nothing to expect from the atmosphere when it comes to potassium supply, and has nothing to fear from the atmosphere when it comes to competition for available potassium sources. It can, however, be reasoned that the lithosphere is of utmost importance as K supplier, considering the fact that a large part of the K in the earth's crust is present in the form of potash minerals belonging to the lithosphere. For nitrogen, on the other hand, this lithosphere lacks all importance, both as a supplier and as a competitor, but it is quite evident that for this nutrient the atmosphere is of utmost importance both as a supplier and as a competitor.

The way of presenting the compartments so far has been rather simplistic. It did not do justice to the fact that the compartments can be interconnected and thus give rise to cycles in which higher plants form one compartment without necessarily occupying a pivotal position.

In a more realistic version, the picture of a nutrient cycle can make clear that a nutrient, when moving from one compartment into another, in many instances can go several ways only one of which is usually desirable from the viewpoint of crop production. The degree of versatility of a nutrient is often a function of a number of intrinsic characteristics of the element involved. The fact that N and S can occur in many different valencies adds to their versatility. For these nutrients the number of compartments in the various subcycles is therefore larger than for nutrients like P and K which occur in only one valency. It will be shown, however, in the following that, in spite of their limited versatility, P and K move through cycles which have about as many subcycles as is the case for the more versatile N.

In the following, attention will be given to the behavior of these elements in low-input and high-input types of agriculture.

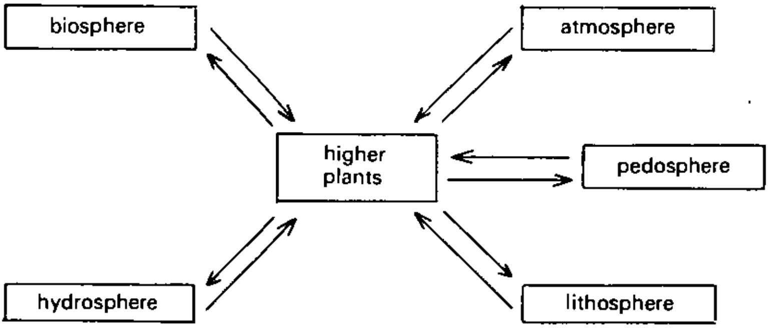

Fig. 1. Plant-centered arrangement of spheres that may supply nutrients to plants or may compete for nutrients with plants.

2. The nitrogen cycle

When the nitrogen cycle is observed it is evident that this cycle actually consists of three subcycles. *Jansson [5]* assigned the following names to these subcycles: the elemental cycle (E), the autotrophic cycle (A) and the heterotrophic cycle (H). They are schematically presented in Figure 2. The name 'elemental cycle' refers to the fact that by far the largest pool from which N can be drawn into an agro-ecosystem is the atmosphere in which N is present in the elemental form. The transition of elemental N into an ecosystem can take place by means of either biological or industrial N_2 fixation. The transition of N into an ecosystem can have a very permanent character, *e.g.* when N is incorporated into soil humus, but can also be very short-lived, *e.g.* when within one growing season N is introduced in fertilizer form and is lost by denitrification. No matter how long the N will be withdrawn from the atmosphere, sooner or later it will return to the atmosphere by denitrification. Return to the atmosphere in any other gaseous form (*e.g.* NH_3, N_2O or NO_2) is only temporary as

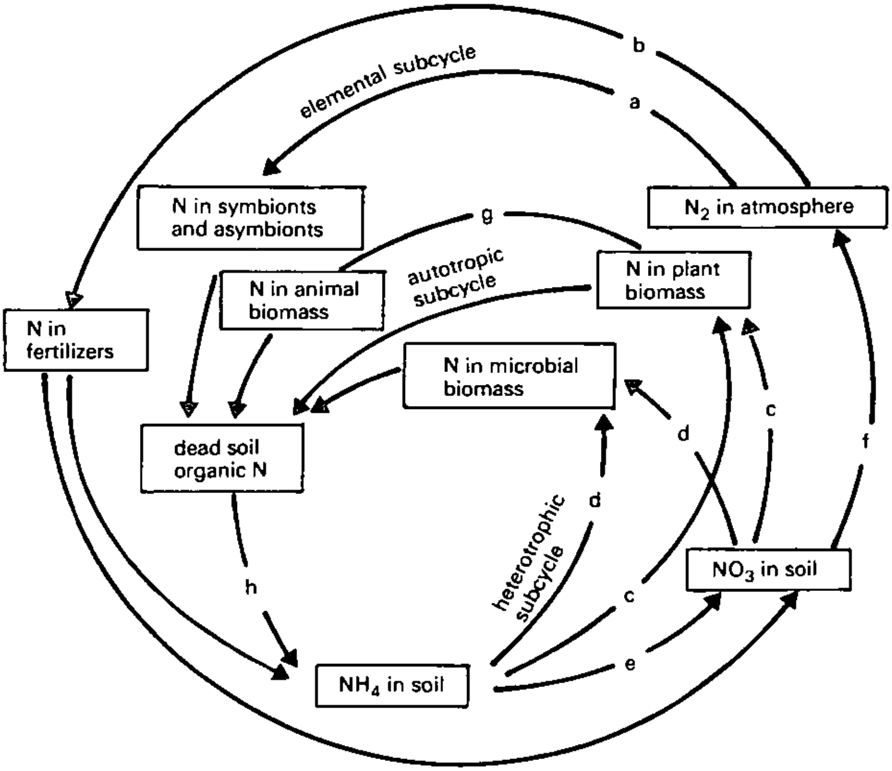

Fig. 2. The nitrogen cycle subdivided into its three subcycles: The 'elemental', the 'autotrophic' and the 'heterotrophic' subcycle. The letters in the figure designate the following processes: a) biological N_2 fixation, b) industrial N_2 fixation, c) plant assimilation, d) immobilization, e) nitrification, f) denitrification, g) animal consumption, h) ammonification.

these forms will re-enter the hydrosphere or the pedosphere soon after having escaped from these spheres. Once an N atom has returned to the atmosphere it will take another 16 × 10^6 years before it becomes eligible for another temporary escape from the atmosphere.

The second subcycle is named the 'autotrophic cycle' on account of the fact that the carbon-autotrophic higher plants are primarily responsible for the functioning of this subcycle. The primary organic N compounds formed by higher plants in this subcycle are partially utilized by animals before the N returns to the soil and continues its course through the same subcycle or switches to either one of the other subcycles. Considered from the viewpoint of an agronomist, it is desirable that N is contained in this subcycle and that it does not escape to the above discussed elemental subcycle.

The third subcycle is called the 'heterotrophic cycle' since it is dominated by the activities of C-heterotrophic microorganisms. In soils, these microorganisms are usually in a favorable position to compete with higher plants on account of the fact that in comparison with plant roots (a) the microorganisms are in much closer contact with the abiotic soil constituents, and (b) the microorganisms are permanently present. Their dominance over higher plants is clearly felt when organic material high in C and low in N is added to the soil, but their competitive abilities are certainly not restricted to situations of excessive C-input. When organic materials having moderate C/N ratios enter the soil, microbial immobilization of N will also take place, but will not last long and will be accompanied by mineralization. The same can be said for nitrogenous fertilizers. It is well-known, although rather disconcerting, that shortly after the incorporation of N fertilizers into soil a sizeable portion of this N cannot be recovered in inorganic form, but appears to be present in organic form in the microbial biomass. Shortly after this immobilization, however, the inorganic N starts to reappear. This turnover of N in the heterotrophic subcycle has received the name 'mineralization-immobilization turnover (MIT)' *(Jansson [6])*. As is the case with so many of the steps in the N cycle, from an agronomic standpoint this MIT has its advantages and disadvantages. On the one hand, it protects inorganic N inputs against loss from the soil due to leaching, denitrification and/or NH_3 volatilization, but on the other hand it interferes with the utilization of N by crops for whose benefit the N was applied to the soil.

One noteworthy characteristic of the compartment designated as 'dead soil organic N' in Figure 2 is that it has 4 pathways leading to it and only one pathway leaving from it. Although its size is small in comparison with that of the pool of elemental N in the atmosphere, it constitutes a reservoir of N that serves as a generator for both the autotrophic and the heterotrophic subcycles. When an arable soil has a plow layer of 20 cm thickness and an N content of 0.1%, the total amount of combined N present per ha is 2000 kg of which approximately 1600 kg may be present in the form of dead organic material and 400 kg in the form of microbial biomass. Under normal circumstances there is a constant exchange of N between these two pools and this exchange is known as the MIT.

Until recently, it was commonly believed that the tropical rainforest formed an exceptional ecosystem in that more N was supposed to be present in the plant biomass than in the pool of dead organic matter. Recently published data of *Sanchez [11]* shed a different light on this ratio of biomass N and soil N in forests of the humid tropics (Table 1).

Table 1. Nitrogen in virgin-forest biomass and soils in some localities in the humid tropics

Locality	Soil	pH	Forest biomass (kg N ha^{-1})	Soil (0–15 cm) kg N ha^{-1})	Total eco-system (kg N ha^{-1})	% of system-N in soil	Annual additions to the soil* (kg N ha^{-1})
Manaus, Brazil	Orthox	3.8	3294	8906	12 200	73	106
Mérida, Venezuela	Tropept	na**	1088	4638	5 726	81	57
Carare, Colombia	Aquox	3.3	740	1812	2 551	71	141
Kade, Ghana	Ustalf	5.2	1017	4336	5 353	81	199

* through decomposition of litter

** not available

P.A. Sanchez, Plant and Soil, *67,* 91–103 (1982)

It can be seen from these data that (a) 70–80% of the N present in these forest ecosystems is to be found in the topsoils, (b) 3–20% of the N in the forest biomass annually returns to the soil, and (c) these annual additions to the soil represent 1–6% of the total amounts of N present in these ecosystems.

Incidentally, the quantities of N mentioned in this table as being present in the top 15 cm soil layer in some cases far exceed the quantity of 2000 kg N mentioned above as normal value for an agricultural soil having an N-content of 0.1%. It is all too well known how this wealth of natural fertility in tropical rainforest ecosystems can be squandered through injudicious deforestation practices.

Returning to the picture of the overall N cycle, it must be emphasized that three arrows depart from the NH_4 compartment and that each one of these represents a pathway toward a different subcycle. The same can be said of the NO_3 compartment, but whether or not sizeable quantities of NO_3 enter into the heterotrophic subcycle depends on the degree of availability of NH_4. When microbes have a choice between NH_4 and NO_3, they prefer the former. This phenomenon can have important implications for practical agriculture. Notwithstanding the higher efficiency of utilization of NH_4 fertilizers due to the ability of soils to retain NH_4 on exchange complexes, it must be realized that NH_4 is more readily immobilized by soil microbes than is NO_3. This can mean that NO_3 applied to soils during growing seasons in which evapotranspiration exceeds precipitation may be more effectively utilized by crops than is the case with NH_4, at least as long as next to the NO_3 some NH_4 is available to satisfy the microbes' hunger for inorganic N.

Also with respect to NH_4, the plant does have an opportunity to compete with microbes for the N source. This is particulary evident from the data presented in Figure 3. It contains data on quantities of N withdrawn from 20 soils by lowland rice grown in a pot experiment. No fertilizer N was applied to the soils which means that the rice plants could only make use of N supplied by the soil. All other nutrients had been added in sufficient quantities. The amounts of NH_4-N present in flooded, fallow samples of the same soils were determined weekly during the growth period of the rice. The highest values measured per soil are also listed in Figure 3. The shaded areas represent the differences between the quantities of maximum NH_4-N measured in the soils and of N withdrawn by the rice. The light shading indicates situations in which N withdrawal exceeded maximum N quantities present; with dense shading the reverse was true.

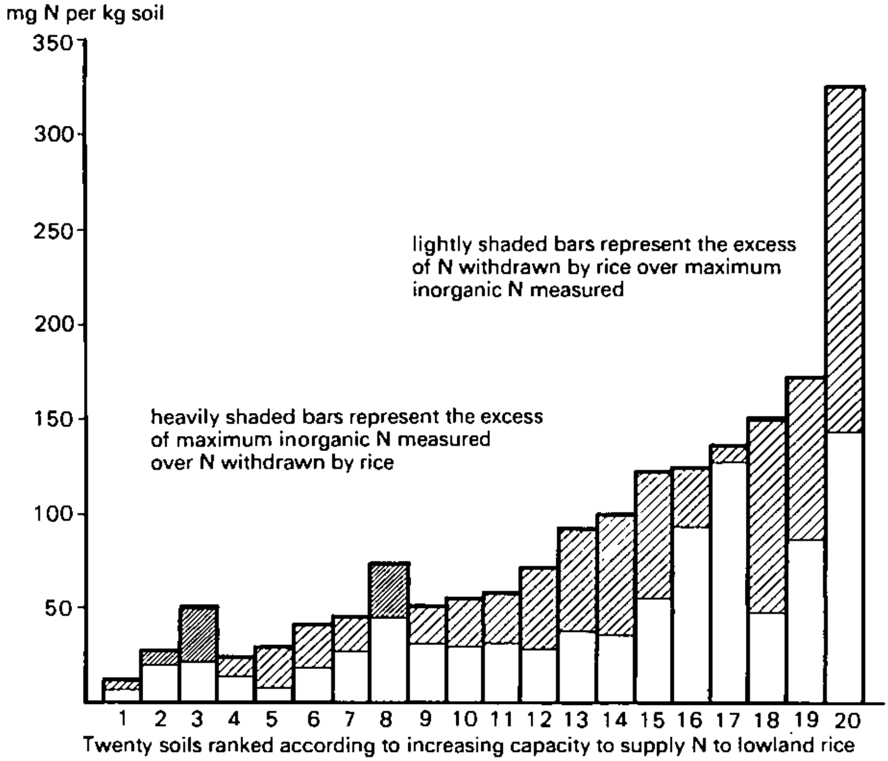

Fig. 3. Differences in values on organic N withdrawn by lowland rice and values on maximum inorganic N measured during the growing season on fallow soil for 20 soils tested in a pot experiment *[1]*.

Two observations can be made:

1) In many soils the quantities of NH_4-N withdrawn were about twice as high as the maximum quantities of NH_4-N detected in the soils.

This finding proves that growing plants can be competitive with microbes for available N. This is probably true especially when no cultural measures are taken that stimulate microbial activities, such as the addition to the soil of energy-rich materials.

2) The soils in which the reverse situation occurred (more NH_4-N present than withdrawn) were all low-yielding soils.

This observation evokes the following hypothesis, the validity of which will be tested in the remainder of this paper:

The efficiency with which inputs can be utilized by crops is determined more by the general quality of the growing conditions than by the size of the input, as long as this size is adapted to the utilization potential of the crop.

2.1 Nitrogen balance sheets for farming systems

Turning now to balance sheets regarding the element N in agricultural ecosystems, two important questions will receive primary attention here. These questions are:

1. Is the efficiency of utilization of an N input dependent on the size of the input?
2. Is the efficiency of utilization of an N input dependent on the type of farming and on climatic conditions?

One other important question will be left out of consideration. This is the question whether the efficiency of utilization of an N input is affected by the chemical and physical characteristics of a soil. It cannot be denied that such characteristics do exert an influence, but less so than in the case of phosphorus. For reasons of time and space this question will not be dealt with here as far as the element N is concerned.

In 1976, a symposium was held in Amsterdam in which researchers from all over the world presented data they had collected on inputs and outputs of nutrients in a variety of ecosystems. The results of this symposium were published in a special issue of 'Agro-Ecosystems' called 'Cycling of Mineral Nutrients in Agricultural Ecosystems' *[3]*. Some results reported in that symposium are used here for the formulation of answers to the questions raised above.

2.2 N utilization in arable systems

In Figure 4 data on arable systems are collected. In all these systems, the contributions made through biological N_2 fixation to the total inputs were lower than 35 kg N ha^{-1} or were unknown, which in most cases meant negligible. In the figure, mention is made of consumable farm output which stands for products such as grain, roots, tubers and leaves, the latter in cases of vegetable and tea growing, but not straw and crop residues remaining in the field. The farm inputs were mainly fertilizers and manure. Due to the wide variety in both inputs and outputs per ha, all data are presented on logarithmic scales.

It can be seen that, with one exception, all points lie between the 40% and 100% efficiency lines. The efficiency is higher with low than with high applications, but this effect is probably influenced by the type of crop grown. In the one case of efficiency lower than 40%, the crops grown were fruit trees of various kinds. The points representing efficiencies between 40% and 50% were obtained with potato, known for its poor root system, with tea often known to be treated with excessive quantities of N and with sugar beet in the Netherlands to which in the past also excessive quantities of N were applied. Especially as a result of actions taken by sugar beet processing companies and by the advisory service, the quantities of N applied to sugar beet in the Netherlands nowadays are lower than shown in the graph.

Unfortunately, among the crops that received relatively high quantities of fertilizer N, no cereals were present. It is known that with insight into (a) the yield potential of the crop, and (b) the quantity of soil inorganic N present at the start of the growing season, the quantity of fertilizer N needed for optimal growth can be calculated. It is to be expected that under such circumstances the efficiency of N applied can be high.

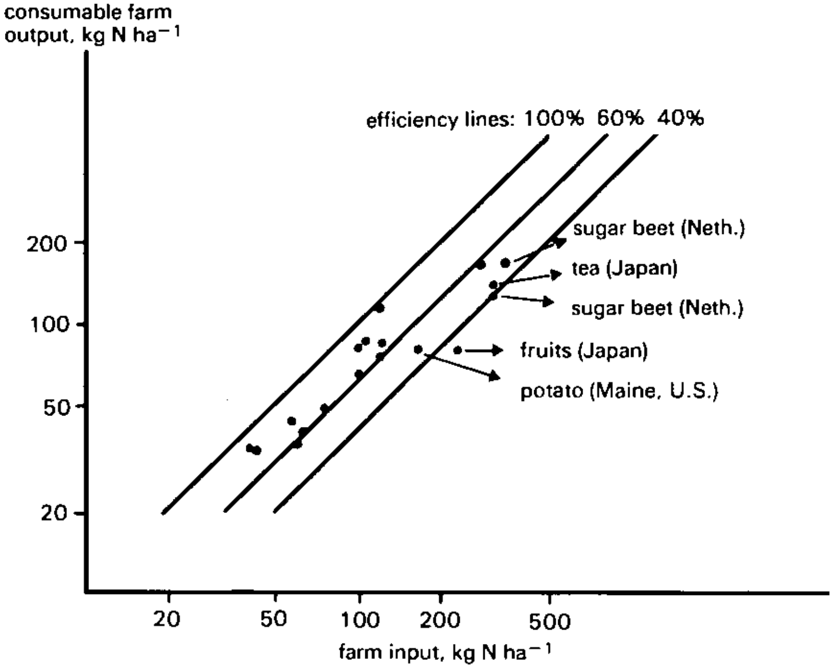

Fig. 4. The outputs of N in consumable primary products plotted against the man-made inputs of N in arable farming systems without appreciable inputs through biological N_2 fixation *[3]*.

To illustrate such a situation, information is presented in Figure 5 on an experiment carried out in the Netherlands on three adjacent farms with uniform soil conditions. The soil is a young, marine, calcareous clay loam. The farming systems on the three farms are different. On one farm, the aim is to obtain top yields with the use of as many crop-protective chemicals and as much fertilizer as is deemed necessary to reach these high yields (blue-print farming, BPF). On the second farm, the main objective is to control pests, diseases and weeds as much as possible through the use of natural agents, and to use chemicals only then when natural means of control are missing or failing. Also the use of chemical fertilizers is restricted to quantities lower than employed in blue-print farming. Because of an integrated use of biological and chemical agents, this type of farming is called 'integrated farming' (IF). On the third farm with organic farming (OF) according to biodynamic methods, one of the principles is to abstain from the use of chemical fertilizers and to apply nutrients strictly in organic materials. In 1982, the general growing conditions for winter wheat, produced simultaneously on the three farms, were carefully monitored by a group of students *[2]*. Among other things, 7 times during the growing season they determined the quantities of inorganic N present in the soils to a depth of 90 cm. These data are of particular importance for the purpose at hand and are therefore recorded in

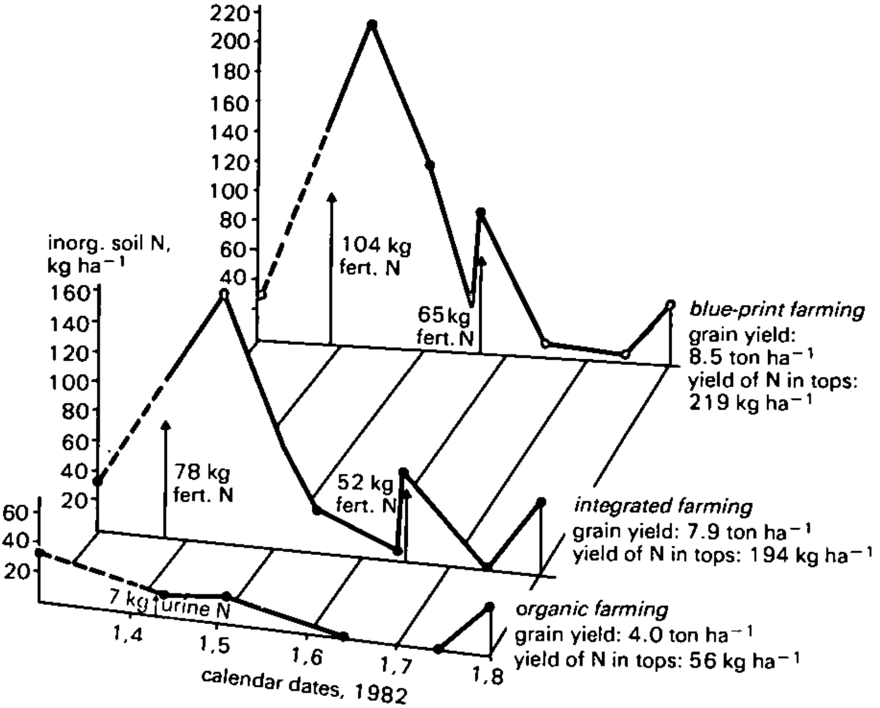

Fig. 5. The course of inorganic soil N during a growing season, as affected by size of the N-fertilizer input and withdrawal of N by winter wheat in three arable farming systems differing in input intensity *[2]*.

Figure 5. The total quantities of fertilizer N applied were 0, 130 and 169 kg N per ha on the OF, IF, and BPF, respectively. The splitting and timing of applications are recorded in the figure. Once during the growing season the OF parcel received 6 kg N in the form of cow urine.

Two circumstances met in this experiment justified the use of the yield of N obtained on the OF parcel as a control (zero fertilizer N) yield. These circumstances were: (a) similar organic matter contents of the soils on the three farms, and (b) identical values, by coincidence, of the quantities of inorganic N present in the soil (0–90 cm) of the three parcels at the start of the growing season. One circumstance, namely the application of the 7 kg N in the form of cow urine during the growing season weakens the assumption that the yield of N obtained was solely derived from soil-N sources. When it is assumed that the value of 56 kg N harvested in the crop of the OF farm is derived completely from soil sources, the values obtained for the efficiency of utilization of fertilizer N applied to the wheat on the two other farms might by slight underestimations of the real values. The values calculated with the use of the 'difference method' are:

96% for the blue-print farming system,
106% for the integrated farming system.

Values over 100% suggest the occurrence of a priming effect, but the overall conclusion can be that in both systems the efficiency with which the fertilizer N was utilized by the wheat far exceeded the 50% mark.

It must be emphasized that on all three farms the general soil conditions were ideally suited to the growth of wheat, that the weather conditions were favorable, and that in the BPF and IF systems all nutrients were present in optimal quantities. Furthermore, excellent care was taken to protect the crops of the BPF and IF farms against possible diseases and pests. The finding that under such conditions the efficiency of utilization of fertilizer N can be high justifies the following statement:

Low values for the efficiency of utilization of fertilizer N are often caused by environmental conditions preventing the crop from fully utilizing the N applied. This also means that for a high efficiency of fertilizer N, care should be taken that the crop is adequately supplied with other nutrients.

One other aspect of the experiment discussed is that, as can be seen in Figure 5, immediately following the date on which the wheat had reached maturity and ceased to absorb further N from the soil, inorganic soil N started to appear again in quantities not related to the quantities of fertilizer N applied to the crop. In the present experiment, the quantities of inorganic N found in the 0–90 cm soil layers on the date of harvest (August 3) were 41, 51 and 34 kg N ha^{-1} for the BPF, IF and OF systems, respectively. This finding shows that a reduction or an abandonment of the use of fertilizer N is not necessarily a safeguard against environmental pollution. The following statement seems to be in order:

More so than a restricted use of N fertilizer a permanent coverage of the soil with actively growing crops during the period in which organic N mineralization can take place serves as an effective protection against environmental pollution.

2.3 N utilization in livestock systems

The special issue of 'Agro-Ecosystems' also contains information on N utilization in livestock systems. The findings in those cases in which biological N_2 fixation did not contribute much to the N input are presented in Figure 6. As in the previous case the inputs consisted of N in fertilizer and/or manure. Two observations demand particular attention: (a) the efficiencies of utilization, lying between 10% and 30% of the inputs are much lower than for the arable systems, and (b) the levels of efficiency bear no relationship with the magnitude of the input.

In most cases reported on here, the outputs consisted entirely of meat and milk products and it is known that the N contained in these products is only a fraction of the N absorbed by the animal in the form of feed. Most N is excreted with the faeces and urine and the fate of this N is more uncertain than that of other fractions of N in farming systems.

It is noteworthy that the level of efficiency is not influenced by the height of the input. A ready explanation for this is not at hand, but it must be borne in mind that the situation is complicated by the fact that two types of utilization efficiency are involved. In the first place, attention must be paid to the efficiency with which N applied to grassland is utilized by the grass, and in the second place the matter of retention of N in the grass or the hay by the animal is involved. The special 'Agro-Ecosystems' issue provided little information on the former subject so that the data presented in Figure 7 were collected largely from other sources *[10, 12]*. All data in this figure lie between the 55% and 90% efficiency lines whereby the lowest efficiency value reported was obtained with a N-fertilizer input far exceeding that which is recommended in the Netherlands for optimal grass production. In British lysimeter experiments with the use of ^{15}N *[9]* it was observed that after annual

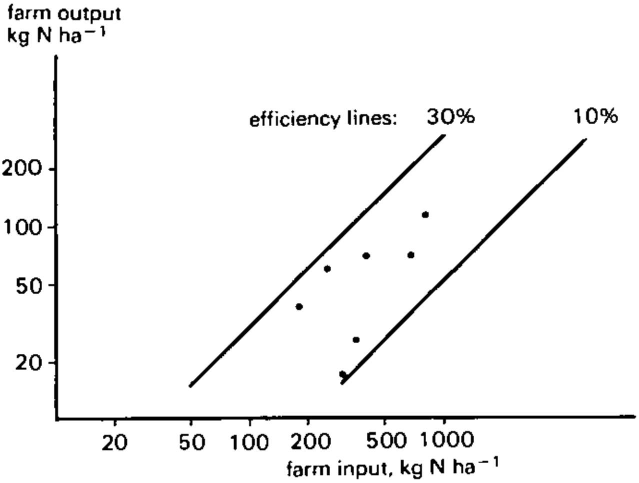

Fig. 6. The outputs of N in animal products plotted against the man-made inputs of N in livestock farming systems without appreciable inputs through biological N_2 fixation *[3]*.

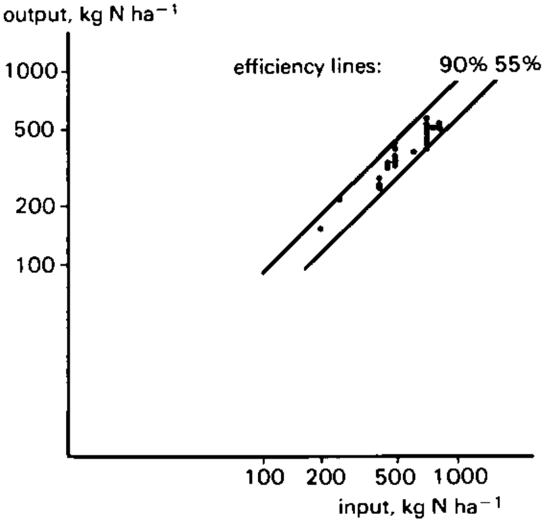

Fig. 7. The outputs of N in herbage plotted against fertilizer-N inputs in zero-grazing pasture systems *[10, 12]*.

applications of 250 kg fertilizer N per ha the amount of fertilizer N lost in drainage never exceeded 0.4%, irrespective of the rainfall, and that with 500 kg N applied in 2 out of 3 years the loss-in-drainage percentages stayed below 1% with the value rising to 9.5% in an exceptionally wet year.

These results support the assumption that low efficiency values for fertilizer N in livestock farming are caused primarily by losses associated with the consumption of the grass by the livestock. It is generally assumed that 15% of the N taken up by the animal is utilized for the production of milk and meat, that of the remaining 85% about two-thirds is excreted in the form of urine, and that of this urine-N two-thirds is lost in gaseous form (denitrification plus NH_3 volatilization). This would amount to ±38% of the applied N lost in gaseous forms.

In Figure 8, data from the special issue of 'Agro-Ecosystems' are collected on cases in which measurements or estimates were made of annual losses of N in gaseous forms from arable and livestock systems. For arable systems, the percentages lost vary between 5% and 30%, whereas in the livestock systems examined the losses lie between 30% and 60%. The latter can serve as partial explanation for the generally low values for efficiency of fertilizer-N utilization in livestock systems as shown in Figure 6.

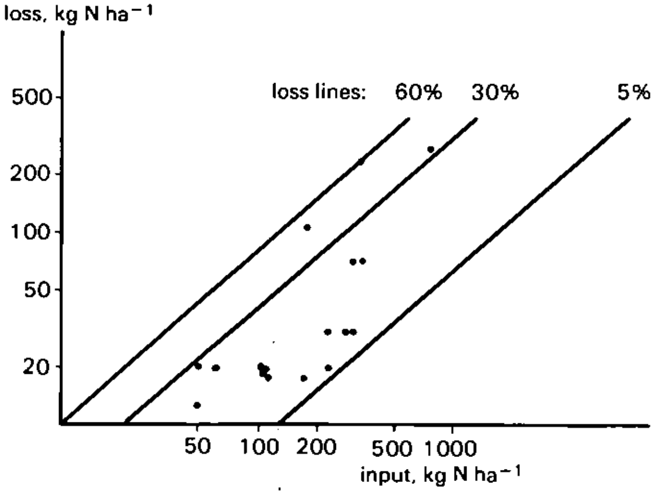

Fig. 8. The losses of N in gaseous forms (denitrification plus NH_3 volatilization) from soils plotted against the man-made inputs of N in arable systems (between 5% and 30% loss lines) and livestock systems (between 30% and 60% loss lines) *[3]*.

3. The phosphorus cycle

Although the behavior of P in nature is usually not looked upon in a cyclic manner, it is not difficult to construct a phosphorus cycle showing some similarities with the nitrogen cycle dealt with earlier. Such a cycle is presented in Figure 9. The P cycle

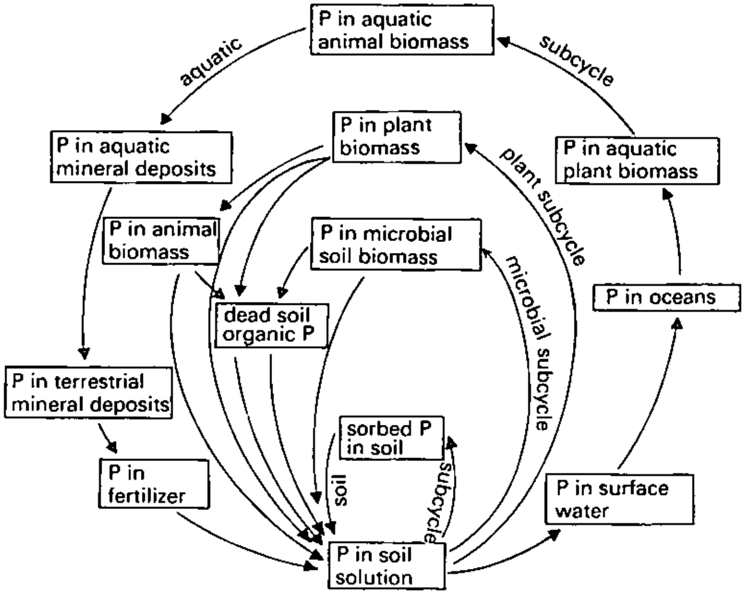

Fig. 9. The phosphorus cycle subdivided into its four subcycles: the 'aquatic' the 'plant', the 'microbial' and the 'soil' subcycle.

can also be subdivided into subcycles, although the names assigned to these cycles in the case of N are not applicable here. The subcycles could be called: the 'plant', the 'microbial' the 'aquatic' and the 'soil' subcycles.

Like N, phosphate is incorporated into the organic structures of both higher plants and microorganisms. Consequently, soil organic matter contains both nitrogenous and phosphatic organic compounds. In soil, a competition can take place between microbes and higher plants for available inorganic P, but this competition is usually less keen than that existing for available inorganic N. The pool of soil organic P, derived from both macrobial and microbial materials, is often an important generator for the functioning of the two terrestrial subcycles.

Much more so than in the case of N, man is responsible for the closing of the P cycle. In spite of the large quantity of N annually fixed in industrial processes and applied as fertilizer, the quantity of N fixed in natural, biological processes is estimated to be 3–5 times larger. In the case of P, however, natural processes through which P in terrestrial mineral deposits is channeled into the terrestrial subcycles are very scant, and without the human influence P cycles sooner or later lose momentum on account of the fact that the ocean floors act as formidable sinks. Nature itself offers a partial escape out of this dilemma, when due to tectonic activities ocean floors are lifted above the ocean surfaces. Even then, however, very little P in the resulting terrestrial mineral deposits finds its way into the terrestrial subcycles. This inertness of P in mineral deposits is of course caused by the extremely low solubility of the apatites of which these deposits exist. For the same reason, another form of enrichment of the terrestrial mineral P deposits, namely the apatites present in magmatic materials appearing in volcanic eruptions likewise fail to stock the terrestrial subcycles.

The 'soil' subcycle consists of only two compartments, but considered from an agricultural viewpoint it is a very important one. Much P entering the soil solutions from the other subcycles is sidetracked toward a pool of phosphate in soil which is partially labile and partially non-labile. Inasmuch as the pool is labile it forms the reservoir from which crops draw their P needed for growth. Inasmuch as the pool consists of non-labile P, it constitutes a sink in which much P is to be found that was earlier added to soil in fertilizer form. As long as the sorption capacity of the soil is not yet saturated, this sink can be responsible for low efficiency values of fertilizer P. When, however, the sorption capacity is saturated the sorbed P can form a reservoir from which other terrestrial subcycles are stocked.

Due to the low solubilities of most phosphatic compounds very little P in natural ecosystems will escape from the terrestrial subcycles, so that such subcycles can be operative for centuries without becoming depleted of P. The very little P lost will be replenished by P emanating from weathering soil minerals which in the P cycle of Figure 9 are considered included in the quantity of sorbed P. Soon after man starts to interfere with these natural cycles, P will be lost from them in the form of harvestable products and due to erosion and leaching. For the regeneration of the terrestrial subcycles it is then important that P fertilizer, produced from the terrestrial deposits, is introduced into these cycles. When this occurs P in the aquatic subcycle will not remain trapped forever in the mineral deposits, but will re-enter the terrestrial subcycles from which it once escaped.

The size of the deposits of phosphate rock potentially available for agricultural use is of course infinitely smaller than the reservoir of N in the atmosphere potentially available for fixation, but the known reserve base of phosphate rock that could be mined under existing economic conditions has increased substantially over the last few decades. Still, it is foreseeable that in the distant future man cannot wait for the next tectonic activity to lift more marine phosphate rock deposits above the ocean surface, and that as a consequence phosphate rock will be mined from the ocean floor. It is to be expected that by that time not only P, but many other minerals as well will be obtained from oceanic deposits. This at least does not sound as futuristic and fantastic as mining other planets for minerals essential to mankind.

Returning now to the present agricultural scene, regarding P we must face a number of facts. These are that:

a) most rock phosphates as such are too insoluble to be used successfully on all soils for all crops,

b) only a limited number of known deposits lends itself for beneficiation,

c) beneficiation requires a certain input of energy, and consequently raises the price per unit P,

d) even with the use of the beneficiated forms of P, the efficiency with which P is utilized by crops is often disappointingly low.

Especially the last point is of concern when nutrient balances of low-input and high-input types of agriculture are concerned.

3.1 P utilization in arable systems

The special issue of 'Agro-Ecosystems' also contains data from which estimates on efficiency of utilization of fertilizer P can be calculated. In Figure 10, information is presented on arable systems. It can be noticed that a wide spread in efficiency values occurs and that the degree of efficiency is not very strongly related to the quantity applied. Each value presented merits its own case study. A few cases will be selected for discussion here.

The values on potatoes in Maine (USA) and irrigated beans in France represent examples of excessive use of fertilizers in horticulture. In the US, potatoes are looked upon as a horticultural crop and are often fertilized as such. In horticulture, the price to be paid for fertilizers represents such a small percentage of total costs that growers often apply more than is needed, even when the soils are already well stocked with nutrients. It is hardly surprising that under such circumstances efficiency values will be low.

Among the cases of near 100% efficiency there are two representing small farms in S.E. Brazil in an area with large estates on which fertilizer use is a standard practice and where small farmers embraced the follow-the-leader principle and have used moderate quantities of fertilizers over an already long period. With moderate, but steady annual inputs of fertilizer P, high recovery values are obtained. Other cases of moderate inputs of fertilizer P are the two Dutch farms producing sugar beet. After many decades of annual fertilizer P inputs far exceeding the outputs, the P-sorption capacities of the soils have become saturated far enough to justify farming systems in which P is applied in quantities equal to the quantities removed with the harvestable products.

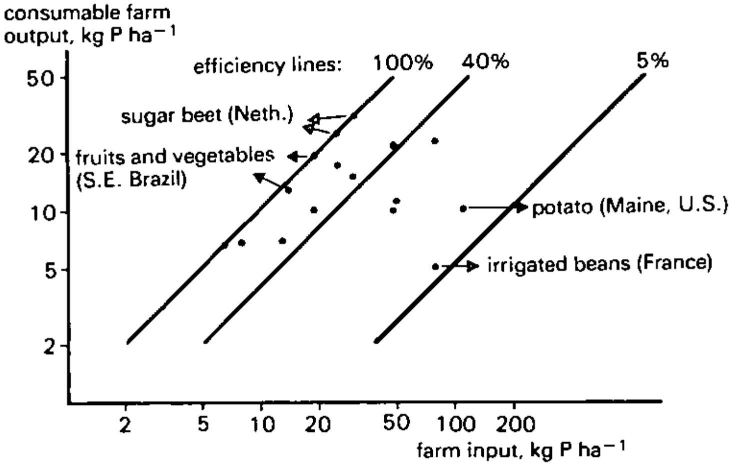

Fig. 10. The outputs of P in consumable primary products plotted against the inputs of P in arable farming systems *[3]*.

It must be remarked here that especially in such cases of maintenance fertilization, wide differences will appear between estimates of actual and apparent utilization of fertilizer P. The former estimate, when obtained *e.g.* with the use of radioisotopes, will indicate that the actual contribution made by the fertilizer to the P nutrition of the crop is small. This is a reflection of the fact that most of the fertilizer P has exchanged places with P in the large pool of labile soil P. When, however, the estimate of fertilizer P utilization is obtained in the conventional way with the use of control plots not receiving any fertilizer P, it may seem that the utilization of fertilizer P is high whereas in reality the main function of the fertilizer P has been to exchange places with P in the labile pool, whereupon the soil P thus released has served to supply the crop with P. This situation is illustrated in Figure 11.

These wide differences between estimates of apparent and real utilization of fertilizer P have become the basis of an argument between two schools, one claiming that the efficiency with which P is utilized by crops is usually high, whereas the other school expresses the opposite view *[7]*. The argument concerns the above mentioned discrepancy between actual and apparent utilization efficiency of fertilizer P, and furthermore the question whether or not residual effects of fertilizer P should be taken into account when efficiency values are calculated. The lower drawing of Figure 11 shows that for soils low in sorbed P but high in sorption capacity actual and apparent efficiency values are equally low. The argument concerns the question whether or not the sorbed fertilizer P will become available to future crops.

When considered from a practical standpoint, the argument is a rather academic one. It is of course true that, since P in soil is neither volatile nor soluble, practically all fertilizer P that is not absorbed by the crop to which it was applied, will remain potentially available to succeeding crops. In other words, a patient farmer will always get a high recovery value for the P that he applied. The trouble, however, is that even farmers who by nature are patient, cannot always afford to be patient. When a small farmer in a developing country invests money in P fertilizer, he wants a quick return on his money. It is cold comfort for him to hear that in the long run he can expect an almost 100% return, when he needs a quick return. The farmer who does not have to worry about a slow or quick return is the one who built up in his soil such a large reserve of potentially available P that he only needs to see to it that this large reserve is maintained by means of small annual additions.

The urgent question then remains how a small farmer in a developing country with low-input agriculture can be helped in obtaining a reasonably quick return on his investment in P fertilizer. The advice then can be:

a) to place the fertilizers in rows or in the plant holes,

b) to make a large basal application of rock phosphate supplemented with small annual applications of beneficiated fertilizer P placed in rows or in plant holes,

c) to make use of leguminous green-manure crops that have shown to be efficient feeders on rock phosphates,

d) to practice mixed cropping in which gramineous crops could possibly benefit from the P-mobilizing capacity of legumes,

e) to make sure that mycorrhizal fungi are present which through a symbiosis with the host plant can contribute to the P nutrition of this host.

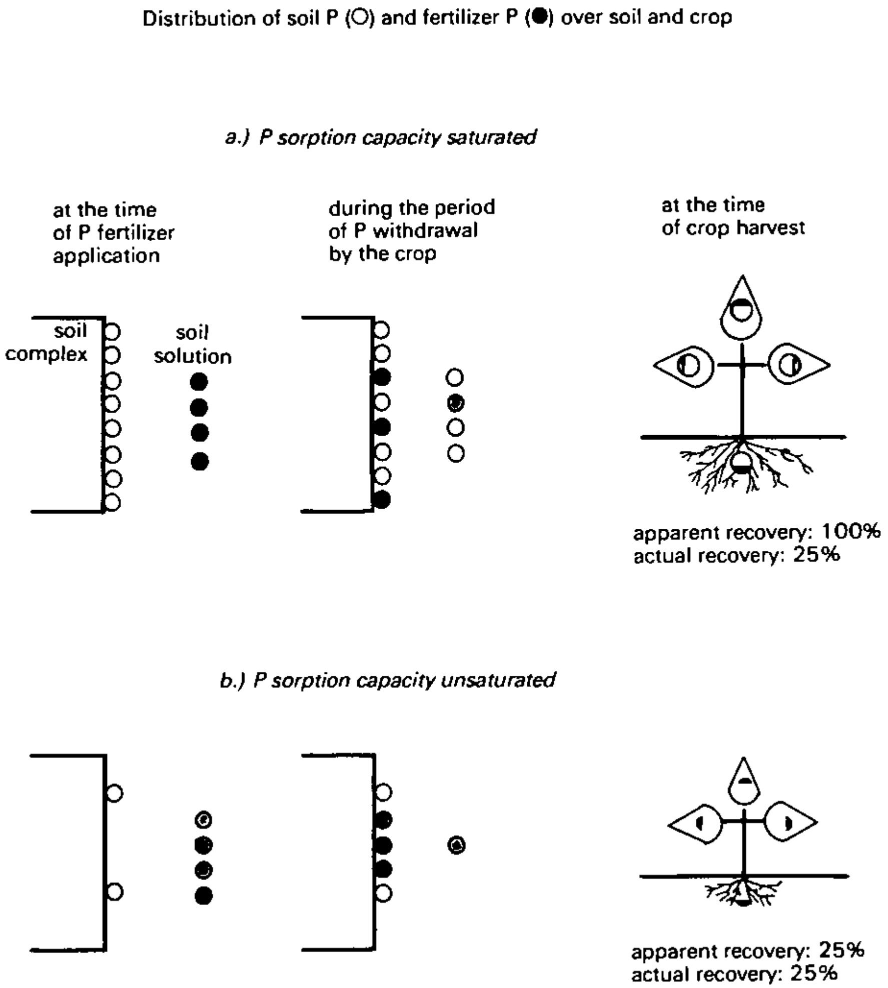

Fig. 11. A schematic drawing of the fate of fertilizer P added to soil with a) a saturated P-sorption capacity and b) an unsaturated P-sorption capacity, and the consequential estimates of apparent and actual fertilizer-P recovery to be expected.

3.2 P utilization in livestock systems

The data of Figure 12 on livestock farming show that in general the efficiency of utilization of fertilizer P in livestock farming is lower than in arable farming. In contrast to N, the P efficiency does not improve greatly in zero-grazing systems. The one case with higher than 100% efficiency might on first sight be looked upon favorably, but it represents a system of what might be called 'soil-exhaustive farming'. The soil is forced to yield more nutrients than it receives. This type of farming was practiced in the Mid-West and Great Plains of the US for almost a century and eventually turned some areas into what became known as a 'dust bowl'. The case shown in Figure 12 was constructed from old records carefully collected for a Dutch livestock farm around 1800. It was the time before Liebig had shown the need for nutrients in farming, and in those days in the countries that are now called developed, farming took place in a soil-exhaustive manner.

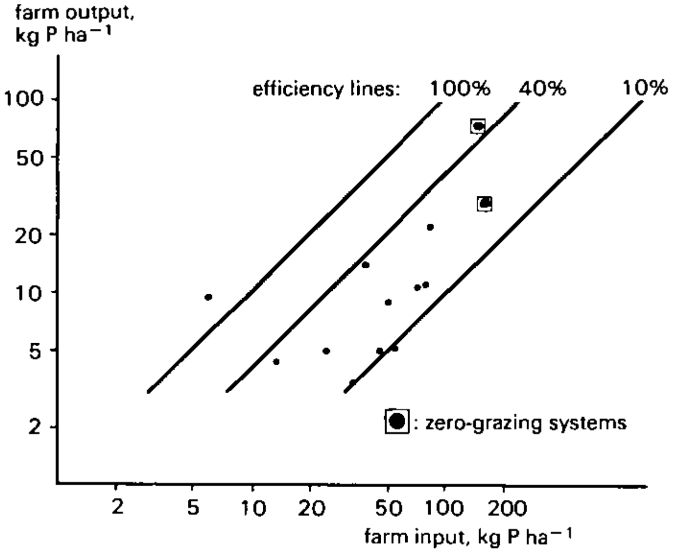

Fig. 12. The outputs of P in animal products plotted against the inputs of P in livestock farming systems *[3]*.

4. The potassium cycle

In several respects, the potassium cycle (Figure 13) shows similarities with the phosphorus cycle. One evident difference is the absence of K in organic structures, resulting in the absence of a subcycle in which microbes have a function. This does not mean, however, that soil organic matter fails to play a role in the behavior of K in terrestrial subcycles, as it is important in retaining exchangeable K.

An aquatic subcycle for K includes large depositions of K in marine sediments. In contrast to P, K is not deposited in biotic material but as a result of precipitation of K salts on the floor of slowly evaporating seas. Like for P, these sea floors constitute a sink for K, and it is again human action being responsible for the re-introduction of this K as fertilizer into the terrestrial subcycles.

K often has to be mined from much greater depth than P but one advantage that K has over P is its higher solubility. The beneficiation of K salts into K fertilizers is cheaper than is the case with P, which accounts for the relatively low price to be paid for a unit of K in fertilizer form. The uneven distribution of K deposits over the various continents is, however, responsible for the relatively high prices of K fertilizers in many developing countries.

Losses of N and P from soil due to leaching have two negative aspects: (a) valuable nutrients are lost from agro-ecosystems and (b) the losses add to the eutrophication of aquatic ecosystems. When K enters surface waters, this latter aspect is never involved. In fact, K is hardly ever the growth-limiting factor in aquatic ecosystems, and transfer of K from soils to surface waters is therefore never the cause of undesirable biomass productions in these waters.

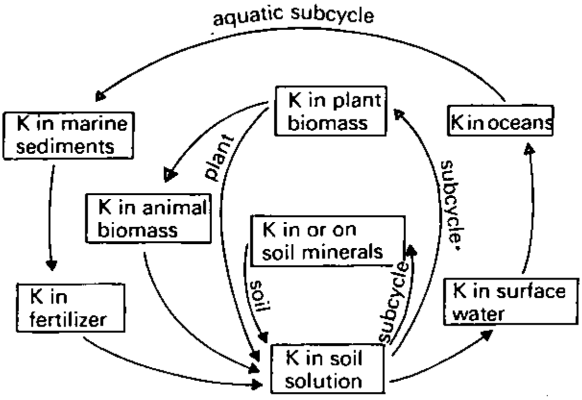

Fig. 13. The potassium cycle subdivided in its three subcycles: the 'aquatic-', the 'plant-' and the 'soil' subcycle.

4.1 K utilization in arable systems

When there is no need for concern about any role of K in environmental pollution, there is need for concern about low efficiency values of fertilizer K. The data of Figure 14 for arable farming systems, again obtained from the special issue of Agro-Ecosystems, show a wide variety of efficiency values. There does not seem to be any clear-cut relationship between size of the input and degree of efficiency. The lowest efficiency value was again obtained on the horticultural farm with irrigated beans in France.

Efficiency values exceeding 100% are found with both low and high inputs. The value with the lowest input represents a case of wheat farming in the Great Plains region of the US. After about a century of farming without any fertilizer input, N and P fertilizers are applied now, but due to the relatively high level of K availability in the soils fertilizer K is still not applied. Further east, in the Corn Belt, K fertilizer application does take place. When only the maize grain is leaving the farm and the stover is returned to the soil, the quantity of K removed is small and even moderate inputs far exceed the outputs. In the case listed in Figure 14, 56 kg K was applied per ha, 20 kg was removed with the grain, and 15 kg was lost due to leaching. The remaining 21 kg is held in exchangeable and non-exchangeable forms and serves to improve the fertility status of the soil.

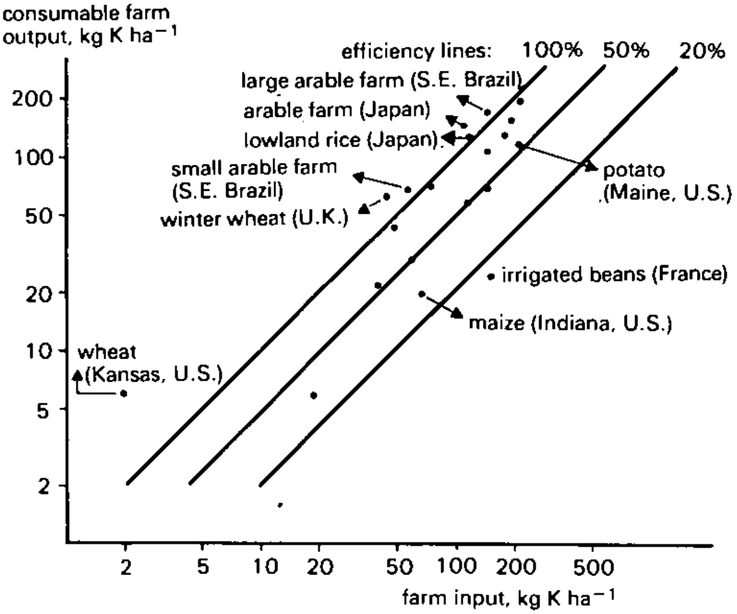

Fig. 14. The outputs of K in consumable primary products plotted against the K inputs in arable farming systems *[3]*.

One of the highest applications listed was the one concerning potatoes grown in the N.E. section of the US. Since in contrast to grain, tubers remove a large quantity of K from a soil, a large application of K in this case makes more sense than the large application of P to this crop discussed earlier. Consequently, the K efficiency value is rather high (56%) and the loss due to leaching (20 kg per ha) is not much higher than that encountered with maize in the Mid West receiving only one-third of the K applied to the potatoes.

In the K cycle of Figure 13 the 'plant' subcycle receives K through 3 entries and loses K through 3 exits. This implies that fertilizer K introduced into this subcycle can go three ways: (a) it can be absorbed by plants, (b) it can be lost due to leaching, and (c) it can be retained by the soil in exchangeable and non-exchangeable forms. From an agronomic standpoint it is desirable that as much as possible of the added K is directly utilized by a crop. In the following examples, it will again be shown that the quality of the general growing conditions determines how much K is utilized by the crop and how much is diverted to the 'soil' subcycle and the 'aquatic' subcycle.

Figure 15 contains the results of lysimeter experiments conducted in Denmark *[8]*. When barley was grown, the efficiency of fertilizer K was little affected by the quantity of N applied. Little fertilizer K appeared in the drainage water, and consequently most of the K added was retained by the soil. Apparently the soil was already stocked well enough with K to guarantee optimal K nutrition of the crop irrespective of the quantity of fertilizer K applied. In other words, fertilizer K was not needed, and most of the K added disappeared into the soil reserve.

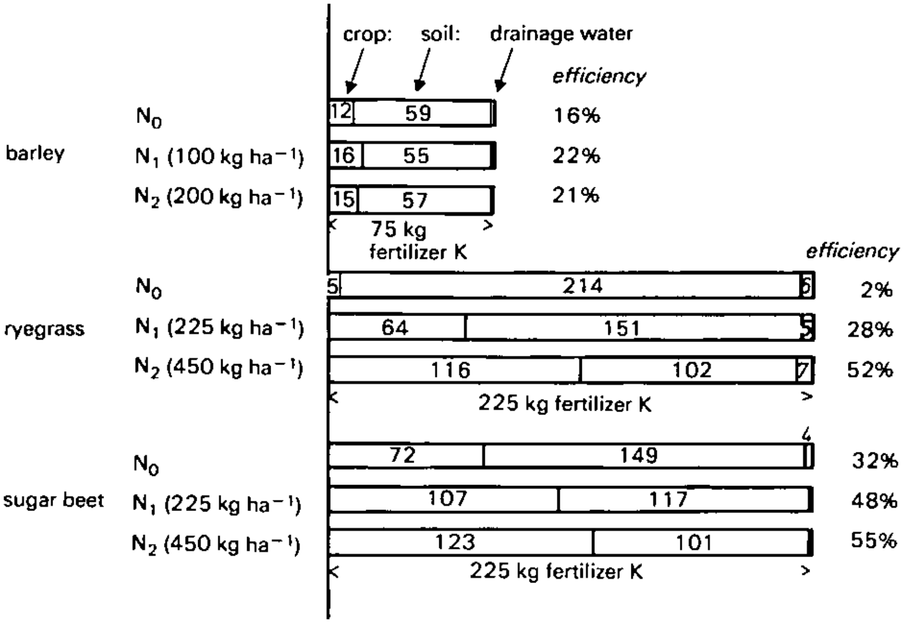

Fig. 15. The distribution of fertilizer K over crop, soil and drainage water, as affected by the type of crop grown and the quantity of fertilizer N applied. Data obtained from a lysimeter experiment in Askov, Denmark *[8]*.

The other examples represent different situations: with ryegrass, the fertilizer-K efficiency is extremely low when no N is applied. Considering the small contribution made by fertilizer K to the leaching loss, the conclusion can be drawn that without N fertilizer most added K enters the 'soil' subcycle. When fertilizer N is applied the ability of the ryegrass to utilize the fertilizer K is greatly improved which is reflected in the higher fertilizer K efficiency values. Grass responds favorably to also the second addition of 225 kg N ha^{-1}, whereas sugar beet does not. Consequently, for grass the K efficiency value increases sharply when the N application is raised from 225 kg to 450 kg ha^{-1}, whereas for sugar beet the increase is less spectacular. These results again show that crops growing under favorable conditions are in a much better position to respond to nutrients added than are crops growing under suboptimal conditions.

4.2 K utilization in livestock systems

The data on fertilizer K applied in livestock farming (Figure 16), taken again from the special issue of Agro-Ecosystems, show a scattering even wider than experienced with the arable-farming data. The only value showing an efficiency higher than 100% represents vast areas in the tropics and subtropics, where extensive livestock farming slowly leads to soil exhaustion. The two cases with extremely low efficiency values are both on intensive sheep farming in the UK where only 2% of the net K input leaves the farm in meat and wool.

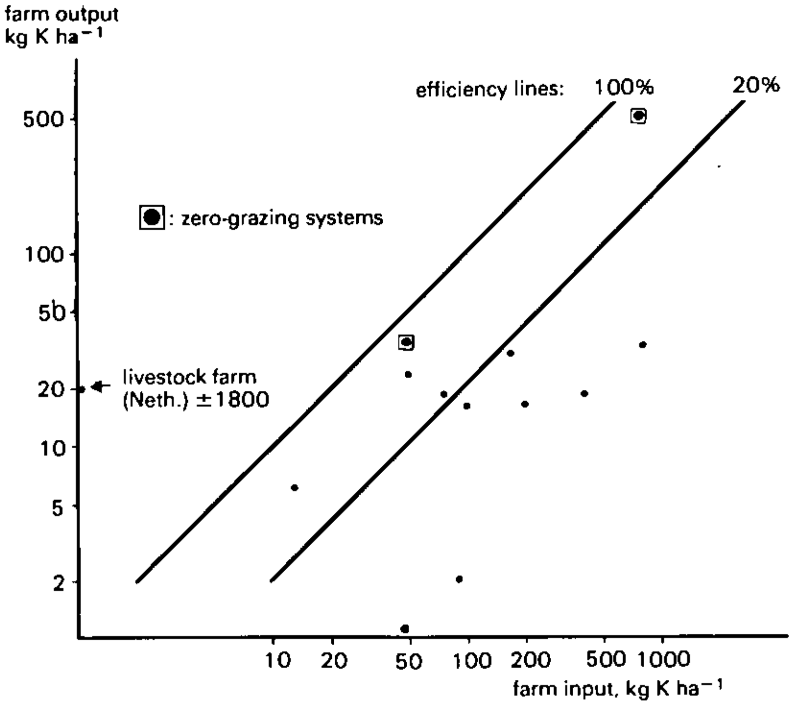

Fig. 16. The outputs of K in animal products plotted against the K inputs in livestock farming systems *[3]*.

Relatively high efficiency values (60–70%) were obtained where zero-grazing was practiced. Under favorable growing conditions efficiency values are often higher yet, as can be seen in Table 2. The data refer to a zero-grazing experiment in Scotland *[4]* where over a 3-year period annually 3 cuts from a legume-grass meadow

Table 2. The contribution of soil- and fertilizer K to the K nutrition of a legume-grass sward during a three-year period in Scotland. Values are 3-year totals

Treatment*	K applied kg ha⁻¹	Herbage yields, ton ha⁻¹	K removed in herbage, kg ha⁻¹	K withdrawn from exchangeable soil fraction, kg ha⁻¹	K withdrawn from non-exchangeable soil fraction, kg ha⁻¹
0	0	13.4	214	179	36
N	0	22.1	265	202	64
K	370	15.6	350	11	-31**
NK	370	27.4	561	191	1

* All other nutrients, besides N and K, applied in adequate quantities

** A negative withdrawal is a gain

R.G. Hemingway, J. Sci. Food Agric. *14,* 188–195 (1963) were obtained. It can be noticed that without any K fertilizer applied not only the exchangeable, but also the non-exchangeable fraction of soil K contributes to the K nutrition of the crop. When K, but no N is applied the unbalanced nutrition prevents the crop from fully utilizing the applied K, some of which is stored in the non-exchangeable fraction. The efficiency value is in that case 95%. With a balanced nutrition (both N and K applied) the fertilizer K is fully utilized by the crop and in addition the exchangeable fraction of soil K makes a sizeable contribution to the K nutrition of the crop.

5. Conclusions

The fate of that part of a nutrient input which is not utilized by the first crop grown following the input, varies among nutrients. For nitrogen the hazard exists that a large portion of what is not absorbed by the first crop escapes either to the atmosphere or to the groundwater and surface water. A portion of the applied N is incorporated into the living and dead components of soil organic matter, but rapid turnover of N in the heterotrophic subcycle may expose also this portion of the added N to the hazards of volatilization and leaching. Consequently, for nitrogen more so than for other nutrients it is imperative that not only the size but also the timing, the form and the manner of an application, are adjusted to environmental circumstances and yield expectations. When the size of an N application is tailored to the N-absorption capacity of a crop, the best guarantees for a high efficiency are:
a) adequate availability of other nutrients,
b) adequate availability of water,
c) adequate protection of the crop against pests and diseases.
When such conditions are met, not only the efficiency of utilization can be high, but also the environment is protected against the polluting effect of nitrogen in effluents.
The conditions which must be met for an optimal functioning of fertilizer N also apply for nutrients like P and K. For P the chemical characteristics of a soil may on the one hand constitute a safeguard against environmental pollution, but on the other hand they may be responsible for low P-fertilizer efficiency values. When the capacity of a soil to retain P is by far not met, the tendency of such a soil to fix phosphates can be a formidable obstacle to attaining acceptable efficiency values and can be a heavy burden on a farmer's budget. When, however, after a number of years of annual P applications the retention capacity of a soil becomes gradually saturated, the former burden will turn into an asset. The term 'fixation capacity' can then be changed into 'sorption capacity' and the annual applications can gradually be reduced to match the crops' needs. It is the task of agricultural scientists – and it should be a challenge to them – to devise methods with which farmers in developing countries can obtain acceptable efficiency values for P fertilizers also in the first years of application. Mycorrhizal fungi might be helpful here, and probably more so than when these fungi are introduced without simultaneous P-fertilizer use. In the latter case, the Mycorrhizae may serve only in further stripping already impoverished soils of their last vestiges of soil phosphate.
When annual P applications gradually start to form a labile pool of soil phosphate this P can become very helpful in improving the efficiency of utilization of fertilizer

N. There are numerous examples to show that the agricultural productivity of a country or a region substantially improved after nitrogen or phosphate fertilization came into use. Sometimes N came first as in the case of lowland rice; sometimes P was first as when the rotation system included legumes. We know many examples of cases in which the introduction of one of these nutrients created a need for the other. The interaction between the two was often instrumental in enabling yields to climb further.

Nowadays, in many regions of the world, the continued use of N and P fertilizers is rapidly creating a need for other nutrients. Next to S, Mg and the minor elements, K is often in low supply. The application of K opens up further possibilities for interactions between the various nutrients and for further increases in yield. Apart from promoting the efficiency of fertilizer N, a judicious use of P and K fertilizers will also enable farmers to make better use of that gift of nature which comes to us in the form of biological nitrogen fixation. Only plants that are well supplied with mineral nutrients can serve as efficient hosts for microorganisms capable of steering N from the elemental subcycle into the autotrophic and heterotrophic subcycles.

Finally, returning to the hypothesis stated under 2, it can be concluded that:

a) for all three nutrients covered, the efficiency values are determined much more by the general quality of the growing conditions than by the magnitudes of the inputs,
b) low and high efficiency values can be found under all kinds of climatic conditions, so that it appears justified to state that climatic conditions do not exert an overriding influence on the degree of efficiency with which applied nutrients are used,
c) for each of the three nutrients, efficiency values are considerably higher in arable farming than in livestock farming systems,
d) in most instances, low efficiencies of utilization of nutrients in livestock systems do not stem from poor recovery of nutrients by the herbage but from low resorption of nutrients in the herbage by the livestock.

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Long-term Development of Soil Nutrient Status in an Intensive Cropping System

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Summary

Results from a long-term experiment in which the combinations of N, P and K fertilizers are applied to various crop rotations are discussed. The experiment started in 1967 and the second complete cycle will be completed in 1984. Principal findings to-date are that the effects of N, NP and NPK treatments on individual crops and between rotations differ and that the effects of fertilizers, particularly of P and K increase with time. Application of P fertilizer appears to have been sufficient to maintain or improve soil P status. Soil K status depends much on cropping pattern, being reduced by higher yields, resulting in greater crop removals of K, which are increased by application of N and P fertilizers and differ between cropping systems. K removal is greatest when sugar beet is included in the rotation.

1. Introduction

A priority requirement of intensive cropping systems is that they should maintain soil fertility but the choices sometimes suggested by economic and socio-economic pressures do not always lead to this end. These pressures may lead to: oversimplification of the rotations, insufficient attention to returning organic matter to the soil, cultivation practices such as irrigation and the use of heavy machinery which causes soil compaction.

The aspect which we are concerned with in this paper is the effect of cropping system on soil nutrient supplies which is determined by cultural practice, yield level and the supply of nutrients in the form of fertilizers. In order to investigate the problem a long-term experiment was established in 1967 at our Institute in which the effects of different fertilizer treatments and of organic manures on various crop rotations were compared. Some preliminary results of this work, which is still in progress, have already been published *(Giordani* and *Toderi [3], Toderi, Catizone* and *Giordani [5, 6, 7]).* In this paper we report the effects of nitrogen, phosphate and potash fertilizers on crop yield, nutrient removal by crops and P and K content of the soil.

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2. Material and methods

A full description of the experimental techniques is to be found in the publications referred to above.

The soil on which the experiment is sited at the *Experimental Teaching Centre* of the *Agricultural Faculty at Bologna* is described, according to Soil Taxonomy (1975), as Aquic Haplustolf *(Busoni et al. [1])*. Analytical data are as follow: sand 58%, silt (0.02 -0.002 mm) 15%, clay 27%, free $CaCO_3$ trace; pH (1 soil: 10 H_2O) 6.9; organic matter *(Lotti [4])* 1.33%; assimilable P_2O_5 *(Ferrari [2])* 108 ppm; exchangeable K_2O *(Dirks-Scheffer)* 173 ppm.

The treatments applied were as follows:

Rotations

a) 9 year (Nov) maize, wheat, maize, wheat, maize, wheat, 3 years lucerne rotation.
b) cereal only (Bm) in which maize and wheat alternated.
c) 2 year wheat, sugar beet rotation (Bb).
d) continuous grain maize (Mc).
e) continuous wheat (Fc).

In all crop sequences, wheat was followed immediately after harvest by a forage maize catch crop (E).

Fertilizer treatments

a) Control – no fertilizer
b) Nitrogen only (N)
c) Nitrogen + phosphate (NP)
d) Nitrogen + phosphate + potash (NPK).

For the first 9 years (1967–1975) the rates used were such as to supply 100 kg/ha per year of both P_2O_5 and K_2O as superphosphate and potassium sulphate applied after ploughing. Nitrogen as ammonium nitrate was surface-applied at rates appropriate to the different crops – 150 kg/ha N for wheat and maize catch crop, 200 kg/ha N for grain maize and sugar beet, nil for lucerne.

After the first 9 years, in the light of results, the rate of P was increased to 150 kg/ha P_2O_5 and that of N to 200 and 300 kg/ha.

Also after the first 9 years for the maize catch crop a thinly planted grain hybrid (Asgrow 88) harvested for silage at the end of the milky ripe stage replaced the thickly sown (110 kg/ ha) forage hybrid Mielmais 50. Grain maize was Dekalb 238 for the first 9 years and Funk's G Top thereafter. For wheat, Resistente was used throughout.

The experimental design was a split-plot, replicated twice, with cropping treatments on main plots and fertilizer treatments on sub-plots of 48 m^2.

Cultivations were in accordance with normal practice for the region.

3. Results

3.1 Yields

Yields of the various crops for the early and later periods of the experiment and for different rotation treatments are given in Tables 1–4 for wheat, grain and forage maize, sugar beet and lucerne, respectively.

Table 1. Effect of fertilizer on wheat yield (t/ha grain)

Treatment	1967–1973			1976–1982		
	rotation	continuous	mean	rotation	continuous	mean
Control	2.91	2.18	2.55	2.14	1.66	1.90
N	5.07	3.53	4.30	5.46	3.15	4.31
NP	5.46	4.42	4.94	5.90	4.75	5.33
NPK	5.48	4.30	4.89	6.03	5.07	5.55
Mean	4.73	3.61	4.17	4.88	3.66	4.27

Table 2. Effect of fertilizers on maize yield (t/ha grain and dry matter)

Treatment	Grain, t/ha			Forage, t/ha dry matter		
	1967–1973	1976–1982	Mean	1967–1973	1976–1982	Mean
Control	5.04	5.03	5.04	7.42	3.06	5.24
N	7.82	9.11	8.47	10.15	7.04	8.60
NP	8.06	9.38	8.72	10.70	7.39	9.05
NPK	7.92	9.86	8.89	10.47	7.65	9.06
Mean	7.21	8.35	7.78	9.69	6.29	7.99

Table 3. Sugar beet. Effect of fertilizers on sugar yield (t/ha) and % sugar in roots

Treatment	Sugar, t/ha			Sugar, %		
	1968–1974	1976–1982	Mean	1968–1974	1976–1982	Mean
Control	5.4	3.0	4.2	14.2	15.3	14.8
N	6.5	3.6	5.1	13.5	13.3	13.4
NP	8.0	6.3	7.2	13.8	13.0	13.4
NPK	8.3	7.2	7.8	14.0	13.4	13.7
Mean	7.1	5.0	6.1	13.9	13.5	13.9

Table 4. Effect of fertilizers on dry matter yield of lucerne (t/ha)

Treatment	1967–1972	1976–1981	Year from sowing			
			I	II	III	Mean
Control	8.1	8.2	4.9	9.7	9.9	8.2
N	8.6	8.4	5.7	9.3	10.5	8.5
NP	9.3	9.3	6.3	10.9	10.7	9.3
NPK	9.1	9.3	5.8	10.9	10.8	9.2
Mean	8.8	8.8	5.7	10.2	10.5	8.8

Nitrogen and phosphate both increased the yield of *wheat* in both periods. There was a marked difference in response to P between continuous wheat where it was 0.89 t/ ha in the first period and 1.6 t/ha in the second, and the wheat grown in rotation where it was 0.39 and 0.46 t/ha. Nitrogen had a greater effect on rotation wheat where the general yield level was higher than that from continuous wheat. The effects of both nutrients were greater in the second period especially that of phosphate on continuous wheat and that of N on rotation wheat. The effects of K were much less than those of the other nutrients and K improved yield only in the second period and only in continuous wheat.

The maize catch crop responded differently and there were no differences whether it followed continuous wheat or wheat grown in rotation. The effect of P was small compared with that on wheat and differed little between the two periods. Dry matter production was substantially lower in the second period due to the change in practice referred to above.

Grain maize showed a smaller response to P (0.25 t/ha) than did wheat and the increase was not significant for either period. K on the other hand had a greater effect, increasing grain yield by 0.48 t/ha in the second period.

The responses in maize grain to N were very large, 2.78 and 4.08 t/ha, respectively in the first and second periods, for the latter of which the N rate was increased from 200 to 300 kg/ha N.

P had large effects on sugar yield: 1.5 and 2.7 t/ha in the first and second periods (100 kg/ha P_2O_5 first period, 150 kg/ha second). The effect of potassium was much greater on beet than on other crops and was significant even in the first period (0.3 t/ ha); it increased sugar yield by nearly 1 t/ha in the second period. On the other hand, the effect of N was by no means as marked as it was on other crops (1.1 and 0.6 t/ha in the first and second periods).

The only fertilizer to increase the yield of lucerne appreciably was P (0.8 t/ha dry matter over both periods). Surprisingly, K had no effect on yield. Response to residues of N applied to preceding crops was very slight. The effect of P was greater in the first two years of the crop than in the last, while the effect of residual N showed in the first and in the third year.

3.2 Effects on removal of P and K from the soil

All the above-ground parts of the crop were removed from the field, thus their P and K contents are included in the removal data. Removals of P and K for the periods 1973–1981 and 1976–1979, respectively, are shown for the combination of rotation and fertilizer treatments in Tables 5 and 6. Cropping sequence and fertilizer treatment both had effects on P removal. Comparing the control and NPK treatments, complete fertilizer increased P removal by a factor of about 2 except when the rotation included lucerne where the increase was only approximately 50% (on account of the relatively high yield of the control treatment). N increased P removal by 25 to 50% depending on cropping system. P fertilizer increased P uptake most in continuous wheat and wheat–beet rotations and least with continuous maize. K affected P uptake only in the beet–wheat rotation.

K removal was increased by N fertilizer by 38 to 77 kg/ha depending on crop sequence and P had a major effect on K removal by continuous wheat. As would be expected the highest K removals were recorded on the complete fertilizer treatment (mean 172 kg/ha). Regarding rotation effects, the lowest K uptakes were by maize monoculture and the greatest by wheat–beet, followed by the 9-year rotation including lucerne.

Table 5. Effect of fertilizers and rotation on P removal by crops (kg/ha) (1973–1981)

Treatment	Rotation					
	Nov.	Bm	Bb	Fc+E	Mc	Mean
Control	20.4	14.6	16.4	14.7	11.4	15.5
N	25.2	24.6	23.0	21.3	20.6	22.9
NP	29.5	27.9	32.1	30.3	22.1	28.4
NPK	29.9	28.2	35.6	30.8	22.0	29.3
Mean	26.3	23.8	26.8	24.3	19.0	24.1

Table 6. Effect of fertilizers and rotation on removal of K (kg/ha) (1976–1979)

Treatment	Rotation					
	Nov.	Bm	Bb	Fc+E	Mc	Mean
Control	98	59	109	83	55	81
N	141	136	169	121	120	137
NP	154	127	182	143	116	144
NPK	177	161	219	168	137	172
Mean	143	121	170	129	107	134

3.3 Effects on soil P and K contents

Phosphate. Table 7 lists assimilable *(Olsen)* P contents of the soil for the 4 year period 1976–1979. Both fertilizer and rotation treatments had effects.

Soil P content, in samples taken after harvest, was decreased by N fertilizer, increased by P fertilizer and was unaffected by K fertilizer. Regarding the effect of rotation, the lowest contents were recorded in the continuous wheat system; the figures were also rather low in the 2 year maize-wheat rotation. The differences between rotations under control and N-only fertilizer treatments largely disappeared when P fertilizer was applied.

Potassium. Assimilable K contents, measured in samples taken at the end of summer are listed in Table 8. Applying N or NP fertilizer slightly reduced K content while NPK plots were 5–16 ppm higher than N and NP plots. Regarding rotation, the lowest K content (80 ppm) was found in the wheat–beet sequence and the highest (109 ppm) in continuous maize.

Table 7. Effects of fertilizers and rotation on assimilable *(Olsen)* P content of soil (ppm) (1976–1979)

Treatment	Rotation					
	Nov.	Bm	Bb	Fc+E	Mc	Mean
Control	8.3	10.2	15.9	7.3	16.0	11.5
N	8.3	8.7	12.8	4.9	15.0	9.9
NP	22.8	17.9	19.5	15.9	21.9	19.5
NPK	24.7	18.2	20.1	16.1	22.4	20.3
Mean	16.0	13.8	17.1	10.9	18.8	15.3

Table 8. Effects of fertilizers and rotation on soil content of assimilable K (NH_4Ac) (ppm) (1976–1979)

Treatment	Rotation					
	Nov.	Bm	Bb	Fc+E	Mc	Mean
Control	91	86	83	103	112	95
N	93	79	82	92	114	92
NP	89	78	74	95	98	87
NPK	105	93	79	100	110	97
Mean	95	84	80	98	109	93

4. Discussion and conclusions

The marked difference in P response by continuous wheat and rotation wheat is not explained by higher P removal by continuous wheat since P removals did not differ significantly between the two systems on the control and N only treatments. But soil P was lower under continuous wheat, which can be explained by the fact that soil sampling of the continuous wheat plots was done while the forage maize catch crop was on the ground, *i.e.* when P uptake by the crop was great, while in the other rotations the sampling time was delayed from the period of maximum P uptake, allowing time for the assimilable P level to recover. The poor response to P fertilizer by continuous wheat is probably due to impairment of the root system by parasites. Similar considerations may apply to K response by continuous wheat.

Similarly, the fact that rotation wheat is more responsive to N fertilizer than continuous wheat may also be due to the yield limiting effects of continuous cropping.

Response to individual nutrients differs between the various crops, pointing out the advisability of differentiating the dressings of P and K as well as of N given to the different crops in the rotation. Beet showed the greatest responses to P and K. Among the cereals, maize is more responsive to K, while the reverse applies with respect to P. Lack of K response by lucerne was unexpected.

The lucerne results show that N deficiency in the soil is reflected in the first year yield (particularly of the first cut) because of the time needed for the establishment of effective symbiosis, and in the third year due to greater invasion of the sward by non-legume species.

Comparison of results for the early and late periods shows that fertilizer effects increase with time. Some marked responses were obtained in the first period (nitrogen on all the crops and P and K on beet) but others appeared only in the second period.
Nutrient removal by crops depends on yield level and cultivation system. The low removals of P and K by continuous maize appear to be related to the fact that, under this system, the soil is only cultivated once, while, in the continuous wheat with forage maize system there is double cultivation and high P removal. K removals were highest under the beet–wheat rotation and under the nine year rotation including lucerne owing to the high K removals by these crops.
There was no close relationship between P removals and soil P levels, and particularly so for the continuous wheat system, however on the no-P treatments there was a higher soil P level than under other cropping systems and this rotation was the least exploitive of soil P. Differences in soil P level between cropping systems were reduced when P fertilizer was applied, except under continuous wheat.
Soil K content was less affected by fertilizer treatment than was soil P but was greatly affected by cropping pattern. The highest values were found under the least K extractive crop (continuous maize) and the lowest where K removal was greatest (wheat–beet).
We have not yet been able to do sufficient analysis to evaluate the effect of time on soil P and K contents; it is intended to carry this out at the end of the second complete cropping cycle this year (1984). Data available so far indicate that the phosphorus dressings applied in the experiment have been more than sufficient to compensate for crop removals of P and are improving the P status of the soil.

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Factors Affecting the Production and Composition of Mixed Grass/Clover Swards Containing Modern High-Yielding Clovers

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Summary

From 1978 to 1981 the effects of irrigation and five rates of nitrogen fertilizer were studied on mixtures of S. 23 ryegrass with S.100 or Blanca clover, grown on a silty clay loam soil at Rothamsted and a sandy loam at Woburn and cut six times per year. The effects of a combined pesticide treatment that included aldicarb, phorate, benomyl and methiocarb were also tested, in combination with irrigation and nitrogen rates, on the S.23/Blanca mixture cut three times per year.

Without irrigation or nitrogen fertilizer the six-cut Blanca mixture gave greater yields than the S.100 mixture in every year at both sites and, on average, at every cut except the last.

Yields of six-cut plots were increased by irrigation and nitrogen fertilizer, with generally larger effects on the S.100 mixture and on the sandy loam soil but the distribution of yields with time was little affected. Six-cut plots gave greater yields than comparable three-cut plots. Yields of three-cut plots were greatly increased by the pesticides treatment which interacted positively with irrigation and with N.

Percentages of N, P, K, Ca and Mg in herbage from the two swards varied little, changed only slightly during the season, and were not affected by irrigation, nitrogen or pathogen control. Differences between sites could be explained by known differences in nutrients in soil.

Offtakes of potassium were large ranging from 205 to 558 kg K/ha and it was necessary to increase K manuring during the experiment to prevent depletion of soil reserves. Large amounts of N also were harvested ranging from 194 to 451 kg N/ha. The Blanca sward without nitrogen fertilizer contained from 366 to 449 kg N/ha little of which came from the soil.

1. Introduction

The value of clover in mixed grass-clover swards has been recognized since at least the early 17th century *(Ernle [2])* but it was not until the second half of the 19th century that it was known that much of this benefit could be attributed to the ability of clover to fix atmospheric nitrogen *(Hellriegel [5]).*

Later the use of fertilizer nitrogen on pasture was shown to lessen the proportion of clover in mixed grass/clover swards *(Murphy [11]).* Although clover grown alone

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may benefit from nitrogen fertilizer *(McEwen et al. [10])* the short-petiole cultivars, the only ones available until recently, are unable to compete with the taller, denser growth of grass in N-fertilized swards.

Recently, clover cultivars have been bred which have longer petioles and consequently greater competitive ability and one such cultivar, Blanca, was compared in this experiment with the short-petiole cultivar, S. 100, each in mixture with S. 23 ryegrass. In addition, the effects of cutting frequency and pesticides were tested on the Blanca mixture. The work was part of a larger investigation of factors affecting the performance of a range of herbage crops and lasted four years from 1978–81 *(McEwen et al. [9])*.

2. The experiment

2.1 Treatments

The treatments considered here were the factorial combinations of four species, five N rates and two watering regimes:

(i) Species:
S.23 ryegrass mixed with S.100 clover cut six times per year; S.23 ryegrass mixed with Blanca clover cut six times; S. 23/Blanca mixture cut three times; S.23/Blanca mixture cut three times given pesticides (see below).

(ii) Nitrogen:
Total per year, dressing divided equally between cuts: 0, 100, 200, 300, 400 kg N/ha

(iii) Watering regimes:
None, irrigated to return a soil moisture deficit of 25 mm to zero.

The treatments were duplicated on two soil types. One was a silty clay loam developed in drift over Clay-with-flints (Batcombe series) at Rothamsted which had been in arable crops since 1964. The other was a sandy loam developed in drift over lower Greensand (Cottenham series) at Woburn *(Catt, King* and *Weir [1])* which had been in arable crops for at least 30 years. Some soil characteristics are in Table 1.

Table 1. Rothamsted and Woburn. Soil characteristics of experimental sites

	pH	%N	%C	$NaHCO_3$ soluble P	Exchangeable K	Exchangeable Mg
				mg/kg		
Rothamsted Silty clay loam	7.5	0.144	1.23	40	180	45
Woburn Sandy loam	6.7	0.079	0.80	70	127	125

The pesticide treatment was a combined application of aldicarb at 10 kg/ha in early spring plus phorate at 5.0 kg/ha and benomyl at 0.5 kg/ha immediately after, and midway between, each of the three cuts. The treatment included additional benomyl sprays applied during the winter (two in the winter 1978/79, four in the winters 1979/80 and 1980/81). From late 1979 a slug bait was also included, methiocarb at 0.5 kg/ha, applied after each cut and monthly during the winter.

Rainfall received and irrigation applied during each period of growth are shown in Table 2. The mean rainfall at Rothamsted was 391 mm (range 352 to 444) and at Woburn was 408 mm (range 342 to 481 mm). Total annual rainfall plus irrigation was 70 mm larger at Woburn than at Rothamsted. Plots cut six times per year were cut first in mid-May then at 28-day intervals; those cut three times were cut on the second, fourth and sixth dates of the six-cut plots.

Table 2. Rothamsted and Woburn. Rainfall (R) received and irrigation (I) applied during the growing seasons (mm water)

	1978		1979		1980		1981		Mean	
Period*	R	I	R	I	R	I	R	I	R	I
Rothamsted										
1	170	0	156	0	108	25	171	0	151	6
2	44	50	92	0	20	100	77	0	58	38
3	62	25	28	38	86	25	12	50	47	34
4	54	50	16	70	65	0	61	25	49	36
5	33	25	75	20	49	25	41	0	50	18
6	20	25	16	38	24	12	82	25	36	25
Totals	383	175	383	166	352	187	444	100	391	157
R plus I	558		549		539		544		548	
Woburn										
1	149	0	156	0	99	38	174	0	144	10
2	31	50	84	0	36	75	74	25	56	38
3	44	50	42	62	108	25	10	75	51	53
4	72	62	14	100	98	12	42	32	56	52
5	23	25	70	25	118	25	53	38	66	28
6	23	50	16	38	22	12	79	25	35	31
Totals	342	237	382	225	481	187	432	195	408	212
R plus I	579		607		668		627		620	

* The first period is from first nitrogen application to first cut, remaining periods are those between cuts

2.2 Standard features

The experiment was sown in May 1977, ryegrass at 10 kg/ha, clover at 4 kg/ha, and neither nitrogen treatments nor irrigation treatments were applied that year. At Rothamsted ground chalk (7.5 t/ha) was given the preceding autumn and 120 kg/ha of P_2O_5 and K_2O to the seedbed. At Woburn the seedbed fertilizer supplied 50 kg N/ha and 120 kg/ha of P_2O_5 and of K_2O to all treatments.

All treatments were applied and yields taken from 1978 to 1981. Both sites were given compound fertilizer each winter to supply 150 kg P_2O_5/ha and 300 kg K_2O/ha and at Woburn 2.5 t/ha magnesian limestone was applied annually. Nitrogen was first applied each year in March when the temperature of the soil at 30 cm depth rose above 4 °C or, if it did not, on 1 April. It was applied as a compound fertilizer containing 25% N and 16% K_2O; plots without N were given potassium chloride after the fourth cut to supply 64 kg K_2O/ha in 1978 and 1979; this was increased to 192 kg K_2O/ha in 1980 and 1981 after considering offtakes in the first two years.

In 1977 broad-leaved weeds at Woburn were controlled by the weedkiller 2,4-DB; none was needed at Rothamsted or at either site in subsequent years.

Plots were small, 1.8 m wide (1.7 m at Woburn) and 4.4 m long and yields were taken from a central swath 0.9 m wide and 4.1 m long. Paths, 0.6 m wide, between plots were sown to timothy grass and given weedkiller to prevent spread of clover from plot to plot. Irrigated and unirrigated blocks were separated by 4.6 m (6.1 m at Woburn) headlands of similarly treated timothy.

2.3 Design and analysis

At both sites the design was a single replicate. Irrigation, applied by overhead oscillating lines, was tested on blocks, to limit the land needed for discards between treated and untreated areas; the other 20 treatments were tested on plots within blocks. Treatments not considered here, some of them duplicated, increased the number of plots per block to 50. These duplicated treatments were used to estimate the standard errors given in the yield tables.

3. Results

3.1 Persistence of clovers

In 1980 and 1981 the proportions of clover in the swards were assessed by hand sorting samples from the harvested produce; those for the sixth cut are in Table 3. Without fertilizer nitrogen there was little difference in the persistence of S.100 and Blanca and irrigation had little effect. With 200 kg N per annum and without irrigation S.100 was almost eliminated at Rothamsted, but its persistence was a little greater at Woburn where it was slightly better with irrigation than without. With 400 kg N per annum and without irrigation no more than 1% of S.100 was found at either site in either year and only at Rothamsted in 1980 was persistence improved by irrigation. In contrast Blanca constituted about 50% of the harvested produce with 200 kg N at both sites, with and without irrigation. With 400 kg N this proportion remained unchanged at Woburn but was lessened at Rothamsted to about 35% in 1980 and 10% in 1981.

The effects on persistence of cutting S.23/Blanca three times per year and of using pesticides are not shown in Table 3 because results did not consistently differ from cutting six times without pesticides.

Table 3. The percentage of clover in the dry matter of ryegrass/clover mixtures at the sixth cut in 1980 and 1981

Cultivars	Total N per annum kg/ha	1980				1981					
		Rothamsted		Woburn		Rothamsted		Woburn		Mean	
		O	I	O	I	O	I	O	I	O	I
S.23/S.100	0	52	52	73	69	80	80	77	79	71	70
S.23/S.100	200	1	39	5	31	1	25	26	15	8	28
S.23/S.100	400	0	17	1	0	1	2	0	0	1	5
S.23/Blanca	0	74	82	65	68	67	85	82	83	72	80
S.23/Blanca	200	49	62	44	70	43	40	56	61	48	58
S.23/Blanca	400	30	39	35	79	11	8	58	41	33	42

I = irrigated

3.2 Yield of total dry matter

The total yield of dry matter each year and the mean for four years are shown in Table 4. Without fertilizer N, yields of ryegrass/Blanca cut six times and without irrigation were greater than those of ryegrass/S.100 in every year at both sites. On average, the extra yield was twice as large at Woburn as at Rothamsted although the mean rainfall was slightly larger at Woburn. The response to irrigation was greater by the S.100 sward at both sites, with irrigation the advantage of Blanca on plots without nitrogen was halved. However, the largest mean yield without N was from the Blanca sward at Woburn when irrigation was given. Responses to nitrogen were generally greater with S.100 partly because the yield with no nitrogen was less and partly because with 400 kg N/ha the S.100 had been virtually eliminated (Table 3) and the response was the greater one to be expected from ryegrass alone.
Without pesticides, cutting grass/Blanca swards three times per year always gave less herbage than cutting six times. The differences without irrigation, averaged over all N rates, were 0.6 t/ha at Rothamsted, 1.0 t/ha at Woburn and were three times greater with irrigation. Increases in yield from pesticides were substantial and, from plots with other treatments identical, ranged from 1.1 t/ha to 5.6 t/ha, effects were generally greater with nitrogen, with irrigation and at Woburn.

3.3 Distribution of yield during the season

Figure 1 shows the effects of nitrogen and irrigation on the distribution of mean yields during the season at Rothamsted of the two ryegrass/clover swards cut six times per year (only no nitrogen and 400 kg N/ha are shown for the sake of clarity). With neither nitrogen nor irrigation the Blanca sward gave the greater yield at all cuts except the last; plots with S.100 were more responsive to both inputs and with both maximum nitrogen and irrigation equalled or exceeded plots with Blanca at each cut. The mid-season (third cut) 'trough' of yield was slightly lessened by Blanca but was almost unaffected by nitrogen and irrigation.

Table 4. Total yield of dry matter (t/ha) from ryegrass/clover mixtures

Treatment	1978		1979		1980		1981		Mean	
	O	I	O	I	O	I	O	I	O	I
Rothamsted										
Six cuts/year										
G/SC N0	9.4	9.4	6.7	9.3	7.2	11.0	7.6	9.1	7.7	9.7
G/SC N1	9.8	11.4	7.5	10.4	8.8	12.4	8.2	9.5	8.6	10.9
G/SC N2	11.2	12.2	8.9	10.0	10.1	12.4	8.2	11.6	9.6	11.5
G/SC N3	12.4	13.4	10.2	10.8	11.6	13.3	9.3	11.7	10.9	12.3
G/SC N4	11.7	13.4	9.9	12.1	13.3	14.4	10.8	13.1	11.4	13.3
G/BC N0	10.2	10.7	7.8	9.2	9.7	11.5	8.0	9.6	8.9	10.2
G/BC N1	10.6	11.2	8.0	9.6	10.9	12.5	9.1	9.7	9.7	10.8
G/BC N2	11.4	11.6	8.9	10.0	11.5	13.1	10.2	11.2	10.5	11.5
G/BC N3	11.9	12.5	9.4	10.6	12.1	12.3	10.3	11.3	10.9	11.7
G/BC N4	13.0	12.5	10.1	9.7	12.9	13.8	11.1	12.6	11.8	12.2
Three cuts/year										
G/BC N0	9.8	8.9	7.1	6.3	9.0	9.6	8.3	6.6	8.5	7.8
G/BC N1	11.3	11.0	6.3	7.1	10.5	8.3	9.2	7.4	9.3	8.5
G/BC N2	11.6	12.4	7.9	7.3	9.3	8.9	9.0	7.2	9.4	8.9
G/BC N3	13.2	14.1	7.0	7.1	10.9	11.5	9.6	8.2	10.1	10.4
G/BC N4	14.7	14.3	8.1	8.1	11.9	10.9	10.5	9.4	11.3	10.7
G/BC N0 C	9.3	10.5	8.9	9.1	9.9	13.1	10.3	11.1	9.6	10.9
G/BC N1 C	10.9	12.2	9.2	8.3	13.0	13.4	11.1	9.1	11.1	10.8
G/BC N2 C	12.4	13.0	8.5	10.2	13.4	13.3	10.7	11.0	11.2	11.9
G/BC N3 C	14.7	15.0	8.7	10.3	14.7	13.8	11.2	11.1	12.3	12.5
G/BC N4 C	13.1	12.5	10.6	9.5	14.5	15.4	12.1	10.6	12.6	12.0
SE(±)	0.85		0.79		0.76		0.82		0.49	

Patterns of yield were similar at Woburn (Figure 2) but yields of comparable treatments at the first cut were about twice those at Rothamsted even though rainfall was almost identical and little irrigation was given. For the unirrigated Blanca sward this was the major peak; for the others, as at Rothamsted, the major peak was at the second cut. Unlike Rothamsted the trough came at the fourth cut without irrigation. With neither nitrogen nor irrigation the superiority of the Blanca mixture was even greater at Woburn than at Rothamsted but, as at Rothamsted, when both were given, S.100 plots were equal or superior at all cuts.

The distribution of yield from plots cut three times is not shown because the pattern was much simpler. Successive cuts were each less than their predecessors and the decrease was approximately linear. Benefits from irrigation, nitrogen fertilizer and pesticides were generally similar for the first two cuts, much less for the third.

3.4 Nutrient concentrations

The concentrations of N, P, K, Ca and Mg were determined in every crop harvested except for Mg in 1978–79. The concentrations of the five elements in the produce of the ryegrass/Blanca and ryegrass/S.100 swards, given neither N nor irrigation for

Table 4 continued

Treatment	1978		1979		1980		1981		Mean	
	O	I	O	I	O	I	O	I	O	I
Woburn										
Six cuts/year										
G/SC N0	4.8	10.1	4.5	9.7	5.8	11.6	7.7	11.3	5.7	10.7
G/SC N1	8.5	11.8	6.6	9.6	6.4	11.7	8.2	10.7	7.4	10.9
G/SC N2	8.5	13.1	6.9	10.1	8.4	12.1	7.0	10.7	7.7	11.5
G/SC N3	8.5	12.7	7.1	9.9	10.4	12.7	7.5	10.7	8.4	11.5
G/SC N4	12.0	15.6	7.8	12.2	12.2	14.8	9.5	13.5	10.4	14.0
G/BC N0	7.0	12.4	7.3	11.0	9.2	12.0	9.0	11.7	8.1	11.8
G/BC N1	9.8	13.1	8.0	10.3	10.8	10.7	9.5	10.7	9.5	11.2
G/BC N2	10.1	13.0	8.4	10.8	10.4	11.2	9.6	10.4	9.6	11.3
G/BC N3	10.3	14.6	9.4	11.6	11.3	11.8	10.6	11.4	10.4	12.4
G/BC N4	11.9	14.4	9.8	10.7	11.9	11.5	10.8	12.6	11.1	12.3
Three cuts/year										
G/BC N0	8.3	10.5	5.9	7.0	7.4	8.6	6.9	8.0	7.1	8.5
G/BC N1	9.6	12.4	6.4	7.4	8.0	8.2	7.6	7.6	7.9	8.9
G/BC N2	10.2	13.9	7.9	7.1	8.2	9.5	8.0	9.1	8.6	9.9
G/BC N3	12.6	13.3	9.1	7.8	8.2	8.7	8.6	7.0	9.6	9.2
G/BC N4	12.8	12.9	9.3	7.4	8.1	8.5	7.3	7.2	9.4	9.0
G/BC N0 C	8.6	12.6	8.2	9.0	10.1	13.2	8.2	10.8	8.8	11.4
G/BC N1 C	12.1	13.5	9.0	10.2	10.9	12.6	9.4	8.7	10.3	11.3
G/BC N2 C	13.2	12.6	10.1	9.5	11.6	13.7	9.4	9.7	11.1	11.4
G/BC N3 C	14.2	16.1	11.2	10.2	13.1	13.4	9.3	10.9	11.9	12.7
G/BC N4 C	15.7	16.5	12.0	12.1	12.7	15.1	10.5	14.5	12.7	14.6
SE(±)	–		0.80		0.77		0.82		0.42	

G/SC = S.23 ryegrass/S.100 clover; G/BC = S.23 ryegrass/Blanca clover; NO, 1, 2, 3, 4 = 0, 100, 200, 300, 400 kg N/ha/annum; C = aldicarb, phorate, benomyl and methiocarb; I = irrigated (use S.E. only within O or I).

each cut at Rothamsted and Woburn and averaged over the four years, are in Figure 3. Nutrient concentrations in both swards were little different and there were consistent differences between sites only for Ca and Mg. Therefore, whatever factor caused the differences in yield between swards at each cut (Figures 1 and 2) there was sufficient P, K, Ca and Mg to maintain essentially the same concentration in the plants. Except for P at Woburn, and K at the fourth cut at both sites, concentrations did not fall appreciably during the season. In many cases they increased slightly as yield declined so the feeding quality of the herbage, in terms of its mineral content, was maintained throughout the season. The large concentration of P in the first two cuts at Woburn reflected the high level of bicarbonate-soluble P in that soil (Table 1). The large amounts of K removed in the early cuts caused the decline in %K at the third and fourth cuts at Woburn and the fourth cut at Rothamsted, the latter soil having the greater K buffering capacity. The application of K following the fourth cut increased %K. There is no suggestion that %K fell to lower than optimum levels, but the peaks in concentration might have been smoothed if K had been applied in smaller but more frequent dressings. At Rothamsted soil pH was higher

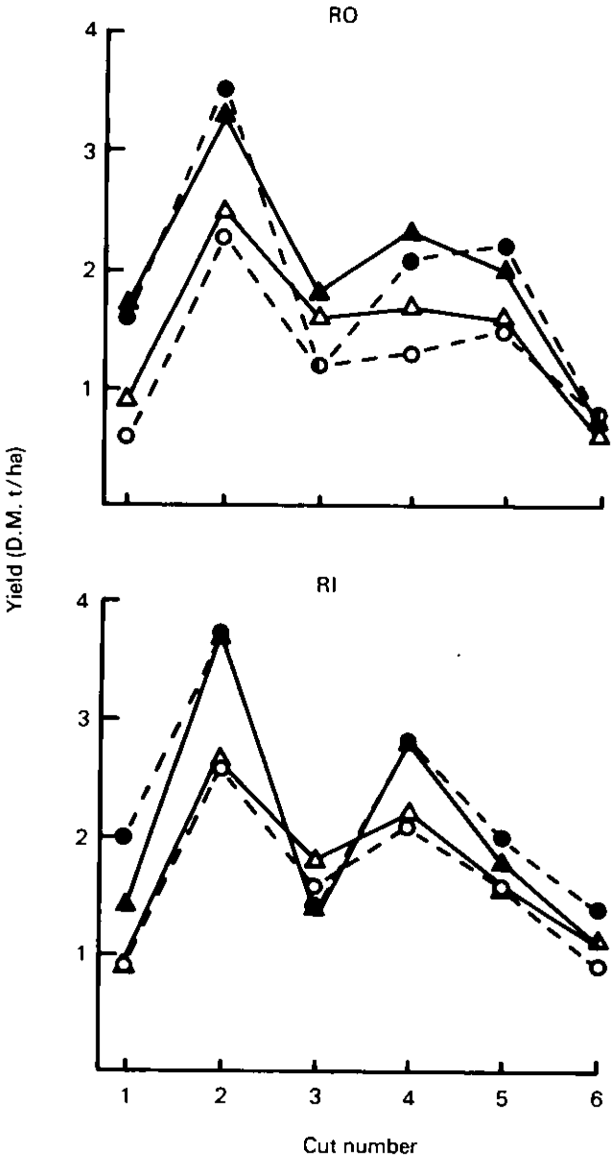

Fig. 1 Mean yields (1978–81) per cut at Rothamsted, unirrigated (RO) or irrigated (RI) from S.23 ryegrass mixed with S.100 clover with no N fertilizer O......O or with 400 kg N/ha/year ●......● and from S.23 mixed with Blanca clover with no N fertilizer Δ——Δ or with 400 kg N/ha/year ▲——▲

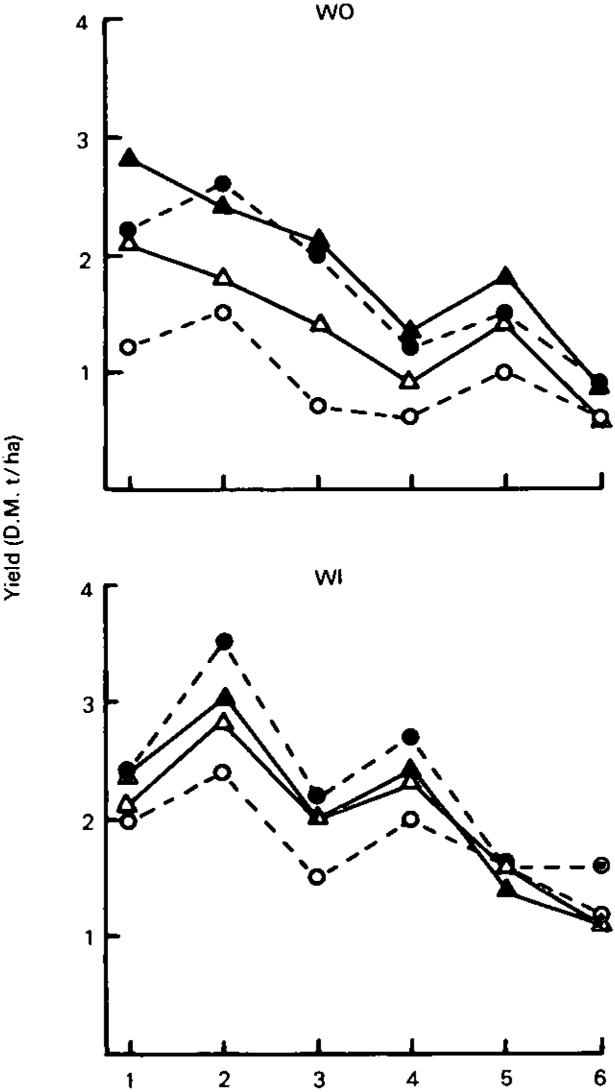

Fig. 2 Mean yields (1978–81) per cut at Woburn, unirrigated (WO) or irrigated (WI) from S.23 ryegrass mixed with S.100 clover with no N fertilizer ○......○ or with 400 kg N/ha/year ●......● and from S.23 mixed with Blanca clover with no N fertilizer △——△ or with 400 kg N/ha/year ▲——▲

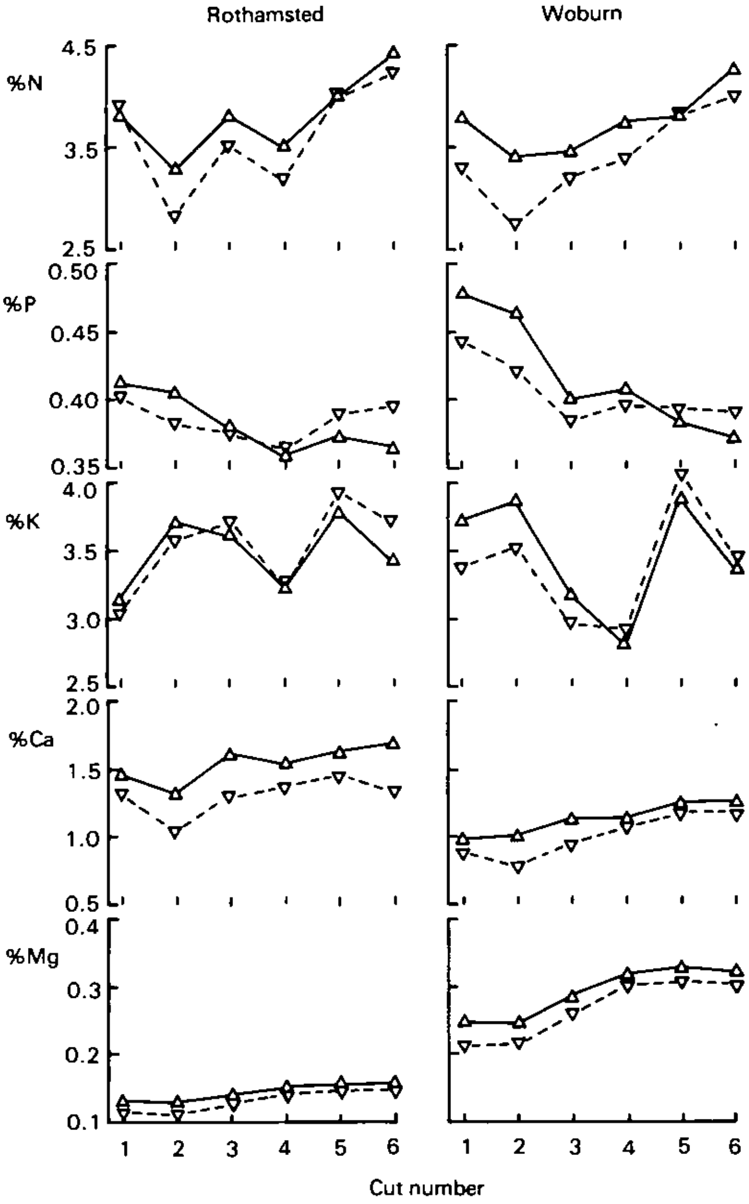

Fig. 3 Percentage, N, P, K, Ca and Mg in S.23 ryegrass mixed with S.100 clover with no N fertilizer ∇---∇ and from S.23 mixed with Blanca clover with no N fertilizer Δ—Δ at Rothamsted and Woburn

than at Woburn (Table 1) and %Ca was consistently larger. Exchangeable Mg was much larger at Woburn probably because magnesian limestone was applied annually and this maintained twice as large a concentration of Mg in the herbage. The effect of fertilizer N, irrigation and pathogen control on nutrient concentrations in each cut have been examined for each factor, and no interactions were observed for either sward. The effects of each factor, averaged over the other two, are summarized in Table 5 for the average annual composition of the ryegrass/Blanca herbage. There was remarkably little effect on composition at either site, with the one exception that %K was increased a little with increasing amounts of fertilizer N. This was because the N was added as an NK compound and equal proportions of K^+ and NO_3^- ions were probably absorbed by the plants.

Table 5. Effect of fertilizer N, irrigation and pathogen control on the average composition of herbage from the ryegrass/Blanca sward cut six* times.

Treatment	N	P	K	Ca	Mg
	% element in dry matter				
Rothamsted					
NO	3.74	0.38	3.53	1.56	0.138
N1	3.63	0.40	3.47	1.49	0.136
N2	3.56	0.39	3.60	1.30	0.135
N3	3.57	0.39	3.68	1.27	0.131
N4	3.56	0.38	3.88	1.14	0.128
Woburn					
N0	3.82	0.43	3.52	1.23	0.280
N1	3.85	0.43	3.19	1.25	0.301
N2	3.76	0.43	3.30	1.17	0.310
N3	3.68	0.43	3.60	1.10	0.274
N4	3.76	0.42	3.81	1.07	0.284
Rothamsted					
O	3.62	0.38	3.52	1.34	0.134
I	3.62	0.39	3.74	1.36	0.133
Woburn					
O	3.71	0.42	3.47	1.07	0.282
I	3.84	0.43	3.49	1.25	0.297
Rothamsted					
O	3.06	0.35	3.52	1.28	0.133
C	3.16	0.37	3.54	1.33	0.144
Woburn					
O	3.23	0.37	3.40	1.10	0.264
C	3.26	0.42	3.45	1.16	0.269

NO, 1, 2, 3, 4 = 0, 100, 200, 300, 400 kg N/ha/annum; I = irrigated; C = aldicarb, phorate, benomyl and methiocarb.

* Three cuts only for O, C comparisons

Table 6. Mean annual offtake of nutrients (kg element/ha) 1978–81

Treatments	N		P		K		Ca		Mg	
	O	I	O	I	O	I	O	I	O	I
Rothamsted										
Six cuts/year										
G/SC N0	268	358	30	39	281	357	100	140	10	14
G/SC N1	268	380	34	45	308	412	95	142	10	15
G/SC N2	276	355	37	47	355	439	79	114	11	16
G/SC N3	324	356	43	51	416	489	85	106	12	15
G/SC N4	371	426	46	56	459	558	83	120	15	18
G/BC N0	326	366	35	40	320	374	134	161	12	15
G/BC N1	332	381	38	44	342	394	136	161	14	16
G/BC N2	354	383	41	46	377	441	130	140	15	16
G/BC N3	373	392	42	47	394	461	135	140	15	16
G/BC N4	388	410	45	49	463	482	119	134	16	17
Three cuts/year										
G/BC N0	252	259	29	29	287	280	119	124	11	12
G/BC N1	259	277	31	33	297	310	115	123	13	11
G/BC N2	263	277	31	34	326	334	103	121	12	11
G/BC N3	288	277	33	37	358	366	103	114	13	13
G/BC N4	300	297	36	37	385	390	108	106	15	12
G/BC N0 C	298	350	35	44	320	419	138	154	14	17
G/BC N1 C	325	344	41	43	367	374	144	153	17	17
G/BC N2 C	306	368	39	46	355	438	131	159	17	18
G/BC N3 C	351	373	43	49	415	463	130	155	18	18
G/BC N4 C	359	344	44	45	446	443	127	140	19	18

3.5 Offtake of nutrients

Table 6 shows the mean annual offtake of N, P, K, Ca and Mg in the harvested produce; data for individual cuts are omitted for the sake of brevity.

Offtakes of nitrogen ranged from 194 to 451 kg N/ha and were much affected by site, irrigation and clover cultivar. When no fertilizer N was given the smallest values at each site came from unirrigated plots with S.100 which contained 268 kg N at Rothamsted and 194 kg N at Woburn, whereas produce from comparable plots with Blanca had an additional 58 kg N/ha at Rothamsted and 105 kg N/ha at Woburn.

Because S.100 was more responsive to irrigation than Blanca the N offtakes from irrigated no-N swards were similar at Rothamsted although at Woburn the Blanca sward contained an additional 60 kg N/ha. At Woburn, herbage from the irrigated Blanca sward given no N fertilizer contained a remarkable 449 kg N/ha averaged over the four years and this exceeded the comparable S.100 offtake by 60 kg N/ha. The comparable irrigated Blanca sward at Rothamsted contained 366 kg N/ha.

Plots cut three times per year had substantially smaller offtakes of nitrogen than six-cut plots. Increases from pesticides ranged from 43 to 109 kg N/ha but even with this treatment offtakes were less than from six-cut plots.

The effects of nitrogen fertilizer on nitrogen offtakes were relatively small and their

Table 6 continued

Treatments	N		P		K		Ca		Mg	
	O	I	O	I	O	I	O	I	O	I
Woburn										
Six cuts/year										
G/SC N0	194	389	24	47	205	387	56	122	18	34
G/SC N1	232	371	31	48	252	368	67	117	19	31
G/SC N2	222	340	32	50	264	399	51	95	16	28
G/SC N3	244	336	36	50	307	408	50	85	18	28
G/SC N4	320	382	44	61	397	535	57	77	24	30
G/BC N0	299	449	36	52	298	423	89	154	26	34
G/BC N1	351	437	42	50	322	366	108	143	31	33
G/BC N2	342	434	42	49	343	372	94	143	29	36
G/BC N3	372	443	46	55	379	469	103	135	32	31
G/BC N4	404	451	48	54	436	476	99	124	31	37
Three cuts/year										
G/BC N0	225	294	28	35	237	308	80	104	19	24
G/BC N1	227	279	30	36	252	307	83	98	19	21
G/BC N2	253	288	32	38	280	360	82	96	21	23
G/BC N3	261	284	34	36	320	325	76	92	20	23
G/BC N4	275	295	34	36	330	316	84	91	20	23
G/BC N0	280	377	37	51	297	403	102	148	24	32
G/BC N1 C	318	388	42	51	323	380	115	144	29	35
G/BC N2 C	344	354	44	50	383	401	126	133	29	30
G/BC N3 C	344	399	49	57	431	462	107	140	29	35
G/BC N4 C	377	399	52	60	458	528	120	117	31	26

G = S.23 ryegrass; G/SC = S.23 ryegrass/S.100 clover; G/BC = S.23 ryegrass/Blanca clover; N0, 1, 2, 3, 4 = 0, 100, 200, 300, 400 kg N/ha/annum; I = irrigated; C = aldicarb, phorate, benomyl and methiocarb.

interpretations are complicated by the effects of the nitrogen on the amount of clover persisting in the swards. The largest difference in N offtake between applying no nitrogen fertilizer and 400 kg N/ha was only 126 kg N/ha (unirrigated S.100 at Woburn). On the irrigated swards at Woburn applying fertilizer N had no effect on N uptake.

Offtakes of phosphorus ranged from 24 to 61 kg P/ha. None exceeded the annual application of 65 kg P/ha.

Offtakes of potassium ranged from 205 to 558 kg K/ha. The manurial policy adopted for the first two years after the establishment year supplied 249 kg K/ha in winter to all plots and in addition during the growing season 53 kg K/ha to plots given no nitrogen and 53 kg K/ha per 100 kg N applied to other plots. Initial results showed that this apparently generous policy would not replace all offtakes from plots given no nitrogen and led to the increase to 159 kg K/ha during the growing season to these plots. This increase, to a total of 408 kg K/ha was almost sufficient to maintain soil reserves of K on these plots even with irrigated Blanca which had the greatest offtakes. Irrigation and nitrogen fertilizer increased offtakes and many of the treatments which received both had offtakes exceeding the amounts applied despite using a compound fertilizer containing N and K as the source of nitrogen.

Calcium offtakes ranged from 50 to 161 kg Ca/ha. For comparable treatments they were consistently greater from the Blanca mixture and from Rothamsted than from S.100 and from Woburn. This reflects the consistent differences in %Ca in herbage from the two swards and site differences in soil pH.

Magnesium offtakes ranged from 10 to 37 kg Mg/ha. Amounts were always greater at Woburn reflecting the consistently larger %Mg in herbage at that site. Offtakes were generally a little greater at both sites with Blanca than S.100, with six-cut Blanca than with three-cut, with irrigation and with pesticides.

4. Discussion

The results showed the general superiority of Blanca clover relative to S.100 for persistence in the sward, yield and offtake of nutrients although it must be remembered that the experiment reported here did not include the effects of the grazing animal. Under some circumstances yields under grazing may be substantially less than under cutting *(Jackson* and *Williams [7])*.

The yield of unirrigated Blanca cut six times per year was increased by nitrogen fertilizer but the rate of response, about 7 kg DM/kg N, was small and was greatly decreased by irrigation. Indeed irrigation increased yield more than the application of 400 kg N/ha at Woburn, and more than about 200 kg N/ha at Rothamsted, with similar effects on nitrogen offtakes.

An outstanding feature of the results was the large amount of N harvested from the ryegrass/Blanca plots without fertilizer N. It is unlikely that this N came from the soil because %N at each site (Table 1) was similar to that of comparable soils in long runs of arable crops. Also ryegrass alone in the same experiment *(McEwen et al. [9])* recovered only 32 and 18 kg N/ha at Rothamsted and Woburn respectively when no N was applied. The seed was not inoculated, therefore the same *Rhizobium* was available to nodulate both clover cultivars.

Without irrigation the superiority of Blanca may be because of greater tolerance to drought and the greater ability of the long-petioled leaves to supply adequate photosynthate to meet the needs of the bacteria. A greater response to irrigation at Woburn, despite similar rainfall to Rothamsted (Table 2) would be expected from the less available soil water of the sandy loam *(French* and *Legg [3])* and perhaps also because adequate oxygen concentrations were more readily maintained in the light-textured soil when irrigation was given, but it is uncertain why the effect should be greater with S.100.

The comparison of three cuts per year with six cuts was complicated by interactions with irrigation and pesticides. With neither, the yields of three-cut plots were rather less than six-cut; a possible cause could be greater susceptibility to pests and diseases as a result of older, bulkier growth, with a moister microclimate on these plots between cuts. This possibility is supported by the negative response on these plots to irrigation at Rothamsted (and at Woburn with the two larger N rates), the large positive response to pesticides and the positive interaction between irrigation and pesticides.

The multiple pesticide treatment was included in the experiment to study the possibility that cutting frequency, nitrogen rates, irrigation and soil type might have not only a direct effect on yield but also an effect via their influence on pests and diseases and this was clearly shown. It was not expected that such a multiple treatment could give unequivocal information on the pests and diseases involved although many were monitored. Some which are known to cause loss *e.g.* shootboring Chloropidae on grass *(Henderson* and *Clements [6])* and clover-rot, *Sclerotinia trifoliorum (Jenkyn [8])* were either present in numbers too small to be damaging or were absent. Known pests found in sufficient numbers to cause loss were migratory nematodes, particularly *Trichodorus primitivus* and *Tylenchorhynchus dubius,* at Woburn and slugs, mainly *Deroceras reticulatum,* at both sites. However the magnitude of the responses to pesticides was too great for them to be solely attributed to these pests and the topic is clearly one deserving further research. An unexpected effect of the treatment with pesticides was to increase the amount of root infection by vesicular/arbuscular mycorrhiza from 19% to 46%. It is known that mycorrhiza can benefit grass and clover on sites deficient in phosphate *(Powell* and *Sithamparanathan [12], Hayman* and *Mosse [4])* but whether sites such as these, which were well supplied with phosphate, would benefit is not known.

The results on mean yields suggest that a mixture of ryegrass and Blanca clover may be managed most profitably without nitrogen fertilizer and the results on distribution of yield during the season support this by showing that nitrogen fertilizer will not aid a more even distribution. The mineral requirements per tonne of dry produce were only 4 kg P but 37 kg K.

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Nutrient Balances in Farming Systems – Intensive Grassland in Northwestern Europe

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Summary

The flow of nutrients in intensive grassland in north western Europe is examined from an input and output viewpoint. It is necessary to supply phosphorus and potassium as fertilizers to the system in order to balance losses mostly caused by the system of handling slurry. Extra nitrogen is necessary as it is not held in the soil from year to year. The positions of sulphur, magnesium and trace elements are examined and also problems of imbalance that frequently arise.

In Europe the percentage of the utilized land that is devoted to grassland varies from about 20 per cent in Hungary and Denmark to over 90 per cent in Ireland and Iceland (Table 1).

Table 1. Percentage of utilized agricultural area devoted to grassland

Country	%	Country	%	Country	%
Hungary	20	Spain	35	Austria	56
Denmark	21	Sweden	36	Netherlands	59
Germany D.R.	22	German F.R.	40	Luxembourg	60
Czechoslovakia	30	Yugoslavia	44	U. Kingdom	73
Bulgaria	30	Belgium	45	Switzerland	80
Italy	30	France	49	Ireland	90
Romania	30	Portugal	50	Iceland	99
Poland	33	Norway	52		
Finland	35				

Sources: Eurostat *2* (1981) and FAO Production Year Book, vol. *33* (1979)

The northwestern part of Europe has the highest rainfall and the most even distribution of precipitation. This together with moderate temperatures makes it the most favoured area for herbage growth and grazing. Over 70% of the utilized land consists of grassland in the Netherlands, United Kingdom and Ireland. In the intensive grassland areas of northwestern Europe the main advantage is a long growing season in which the forrage can be utilized by grazing and surplus grass can be con-

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served as hay or silage for feeding in winter. Only small amounts of conserved forrage is fed in short drought periods in summer.

In most of northwestern Europe conserved grass is the most economical source of winter feed although the ratio of the cost of silage to concentrates varies considerably from country to country. As a result of the pattern of grassland farming and the differences between soils and climates there can be considerable differences in the measures necessary to maintain nutrient balances in intensive grassland farming. However, the differences are more differences of degree rather than type and therefore the problems of maintaining balances are common to all northwestern European countries even though they may be more severe in some areas than others.

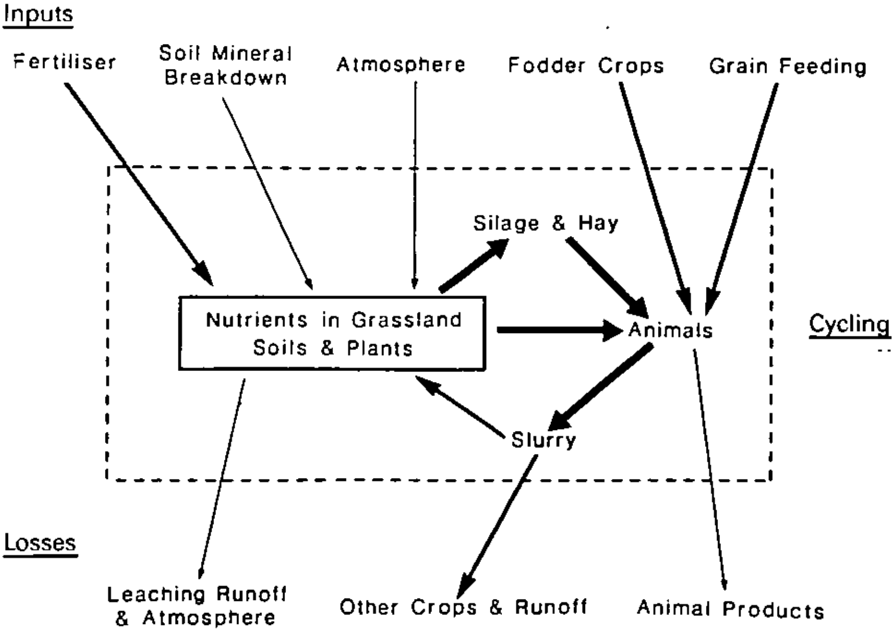

Fig. 1. Main flows of crop nutrients in intensive grassland

Nutrients are supplied to the system mainly by either fertilizers or supplementary feeding of the animals. Breakdown of soil constituents and deposition from the atmosphere are small but consistent sources for the macro nutrients but may be very important for trace elements. Nutrients are removed in animal products or lost through leaching, volatilization, denitrification or transfer to other crops in the form of slurry or farmyard manure (Figure 1).

Within the plant/soil system nutrients move between the soil, the soil organic matter and plants. The rate and extent of these movements depend on soil conditions, texture, drainage and soil pH. The condition most under control of the farmer is soil pH especially in northwestern Europe where the soils tend to be acid due to the high rainfall and leaching. The pH is controlled by liming and the application of ground limestone can have a very large effect on the animal output from pasture *[4]*. In a grazing experiment on old permanent pasture the stock carrying capacity was increased by 54 per cent using 7.5 t ground limestone per ha (Table 2). The animals gained 1 kg per head per day.

Table 2. Effect of liming on stock carrying capacity of old pasture. Animals (275 kg) per ha.

Tonnes ground limestone per ha.			
Year	0	7.5	15
1	6.4	8.9	9.1
3	4.3	7.5	7.5

In the second year of the experiment an animal health problem interfered with the results. The effect of lime was twofold (a) it allowed the clover in the sward to increase from 5% to 14% and there was a release of nitrogen from the soil organic matter.

The nitrogen releasing effect of lime was demonstrated in a cutting trial on new pasture in which the response to lime was measured at different rates of nitrogen (Table 3).

Table 3. Interaction of lime and nitrogen on grass yields (T DM per ha)

N kg/ha	Ground limestone	
	0	15 t/ha
0	4.8	7.8
100	8.6	11.3
200	12.7	13.3
300	14.7	14.8

At zero nitrogen there was a 63% response to lime and at 300 kg N per ha there was no response indicating that the effect of lime on the soil was to increase nitrogen release.

1. Phosphorus

The chief sources of supply of phosphorus to intensive grassland are fertilizers and transfers of phosphorus in animal feeds from tillage land in the same area as arable forrage crops or from tillage land in remote areas as cereals. In the long term very small amounts of P are derived from breakdown of soil minerals. The losses of phosphorus to the system are in animal products during the grazing season and in animal manures applied to non grassland areas. Whilst phosphorus may be fixed in the soil the fixed P acts as a reserve and is not lost to the system. The effect of removal of phosphorus in animal products is illustrated by a long term experiment at *Johnstown*

Castle Research Centre in which young cattle were grazed at two stocking rates and P was applied at 0, 15 and 30 kg per ha in an attempt to determine the amount of P required to maintain the productivity of a ryegrass sward (Table 4).

Table 4. Effect of P application on liveweight (gain kg/ha)

Year	−P	+P	% increase
2	803	913	14
3	880	1031	17
4	883	1034	17
5	795	944	19
6	854	1136	33
13	690	1046	52
14	665	860	29
15	999	1455	45
16	985	1394	42

The effect of the loss of P from the system was to reduce grass yields in the first 5 or 6 years and at that stage the decreased soil supply caused a botanical change in the control plots. From about year 10 onwards the liveweight gains on the control decreased to less than 60 per cent of that for the treated plots. The loss of phosphorus to the system when silage is made depends on the amounts of animal manure returned to the cutting area. One silage cut of 5 tonnes dry matter per ha abstracts at least 17.5 kg P per ha as the herbage usually contains 0.35% P in the dry matter when it is suitable for animal feed.

2. Potassium

The level of potassium in herbage dry matter is very high ranging from less than 2% to over 5% depending on the soil supply. Because of this, harvesting of herbage has a big effect on K balance within the grassland system. Where different systems of utilization of land were examined *[9]* the soil K levels varied from 52 ppm at the end of 3 years cropping as hay to 236 ppm after 3 years grazing on plots that received an average of 88 kg K per ha per year. In another experiment at Johnstown Castle, *Blagden [3]* found that yields increased by over 20% when potassium was used in a one cut silage system and by over 40% in a two cut system (Table 5).

Table 5. Effect of potassium on silage yields

	K applied (kg/ha)	Yield Cut		Soil K (ppm)
		kg DM/ha	Relative	
	0	3613	100	39
one cut	75	4521	125	50
	150	4379	121	103
	0	5411	100	32
two cuts	75	7298	135	36
	150	7779	144	68

The supply of potassium from concentrate feeding to animals is not large because cereal grain tends to be relatively low in K. The main sources of supply are therefore fertilisers and breakdown of soil minerals. The supply from soil varies greatly depending on soil type. In Ireland in an investigation of the productivity of different soils, *Ryan [11]* found that the yield of zero K treatment as a percentage of maximum yield varied from 51% to 80% after complete removal of herbage four years. *Moss [7]* showed an almost four fold difference in K uptake by grass in a separate study on two of these soils.

Removals of potassium from the system are mainly in the form of animal manures applied to other crops. Animal products only account for about 10 kg K per ha per year. The effect of leaching is also very small except in pure peats and extremely sandy soils.

3. Nitrogen

The sources of nitrogen for intensive grassland are fertilizers, nitrogen fixation of atmospheric nitrogen and supplementary feeds. The losses from the system are leaching, slurry application to other crops, volatilization, denitrification and animal products. The amount of nitrogen removed in animal products is about 70 kg per ha under high stocking rate milk production and 70 kg per ha under beef production. The inputs of nitrogen for highly stocked dairy farms are frequently 400 kg N per ha from fertilizer plus 60 kg per ha from meal feeding and imported fodder crops. The amount supplied by clover is virtually nil when high rates of N are used on the swards but can be over 150 kg N per ha in the absence of applied N. Some small amounts are obtained from the atmospheric precipitation leaving almost 400 kg N per ha to be accounted for in accumulation in soil organic matter, leaching losses, denitrification and volatilization losses and transfer to other crop systems as slurry.

There is only a limited possibility of maintaining a balance of nitrogen from year to year to meet the requirement for intensive production in the system as transformations of N in the soil tend to produce nitrate, which is leached below the rooting zone in the winter. However, there is some build-up of available nitrogen over the first 4 years of high nitrogen treatment. In a study of response to N in a number of grazing trials in Ireland, *Ryan et al. [12]* showed that the response to 200 kg N ha^{-1} at low clover contents decreased from a range of 30 to 45% in the first year to 23 to 33% in the second year. Volatilization of ammonia can be very high when N is applied as slurry or urea and runoff from the surface after spreading can also account for a large proportion of slurries and mineral fertilizers. *Sherwood* and *Fanning [13]* showed that rate of runoff depends on rainfall immediately after application, the moisture content of the soil, the permeability of the soil and weather conditions at the time of spreading. The losses can be over 30% of the nutrients applied.

4. Sulphur

Sulphur is an important element in grassland systems. The sources of sulphur are atmospheric deposition and fertilizers plus small quantities in imported feeds. Losses of sulphur from the system are caused mainly by leaching and transfer to other crops via slurry. The quantities in animal products are very small.

In recent years there has been a tendency to change the systems of manufacturing fertilizers so as to exclude sulphur from compounds and also to permit blending rather than compounding of fertilizers. This reduces the amounts of S available to crops and grassland. This tendency has advanced further in Ireland than in any other European countries (Table 6).

Table 6. (N + P + K)/S ratio of fertilizers in some European countries 1980.

Country	NPK/S ratio
Ireland	33
France	12
U.K.	8
Italy	3
Spain	2

As the level of emission of sulphur dioxide from fuel combustion is low in Ireland, responses to sulphur have been found over wide areas *[8]*. The responses were found on light textured soils where the possibility of leaching was greatest. The results of one experiment in Co. Kilkenny is shown in Table 7.

Table 7. Effect of sulphur application (50 kg/ha) on DM yield (kg/ha).

	S applied (kg/ha)		
Date of harvest response	0	50	Per cent
April	3640	3 917	8
June	2296	2 546	11
August	1589	2 735	72
October	2050	4 370	113
Total	9575	13 568	42

Responses have also been reported from areas receiving low amounts of sulphur from the atmosphere in Scotland. It may be expected that the requirement for added S will increase on fertilizer technology changes and sulphur dioxide emission control.

5. Magnesium

The only large external source of Mg used in intensive grassland is dolomite which is used as a liming material. Soil sources seem to provide enough Mg for plant growth but levels vary widely in herbage from less than 0.2% in spring to over 0.4% in summer and autumn *[5]*. The low levels in spring expose dairy cows to the risk of hypomagnesaemia and grass tetany and so some supplementary Mg is fed to the animals. This is a small source of Mg for the intensive grassland system. The main loss from the system is by leaching but breakdown of soil constituents seem to be able to maintain a balance of available magnesium suitable for high productivity.

6. Trace Elements

Most soils have sufficient trace elements for grass growth and maintaining this situation is not a problem. However, the levels of trace elements in plants and the availability of the elements to ruminants are often such as to cause animal health problems. Soil conditions, botanical composition of herbage and stage of growth are important factors affecting the supply of trace elements to animals.

7. Copper

Some areas of soils derived from old red sandstone have low levels of soil copper and levels of Cu in the herbage of 5 ppm and lower are common. Whilst these levels are not sufficient for animals in intensive production systems the application of copper to the soil is effective in raising Cu concentration in the plants for a number of years *[2, 10]*.

8. Copper, Molybdenum, Sulphur Complex

The presence of levels of molybdenum in grazed plants higher than 3 ppm may cause an interference in the ability of animals to utilize copper even when it is present in the plant at maximum uptake levels. It has been found *[15]* that the application of sulphur reduces the uptake of Mo by the plant. However, it has also been found *[14]* that the presence of high levels of dietary sulphur enhances the ability of the molybdenum to interfere with the utilization of Cu by the animal. It is also well known that high soil pH increases the availability of soil molybdenum. All these circumstances are present in several intensive grassland areas in northwestern Europe. They are a cause for concern and indicate a need for extreme care and vigilence in farm and advisory practice in problem areas. It is fortunate that most of the high soil molybdenum is to be found on fairly heavy textured soils and that sulphur deficiency is almost invariably found on soils with medium or light texture and low organic carbon content. On the other hand the pH of low sulphur areas and high molybdenum areas can be either too low or satisfactory for intensive production. Where molybdenum is high and pH low, a compromise must be reached between the best practice for herbage yield and the best practice for maintaining a satisfactory trace element balance.

9. Cobalt and Manganese

Cobalt deficiency in sheep is well known and has traditionally been associated with granitic hill soils. More recently the importance of high soil manganese in interfering with the uptake of cobalt has been established *[1, 6]*. The situation occurs in many intensive grassland areas and may well affect bovine as well as ovine animals. In these situations application of cobalt to the soil is of little value and cobalt supply must be maintained by treating the animals.

10. Conclusion

It is essential for intensive production to maintain a balance of nutrients in the grassland swards that not only allow maximum growth of herbage but also provide correct levels for optimum animal health and production. In intensive grassland in northwestern Europe there are problems of deficiency and areas of nutrients. The deficiencies can usually be corrected by using fertilizers and by improved management of the nutrient cycles. Some of the problems of excess such as excess molybdenum are associated with particular soil types and may require particular skill in managing the situation to even achieve suboptimal levels of productivity. In other cases a long term build up of major nutrients such as phosphorus and potassium may be due to feeding large amounts of imported feeds and the spreading of pig slurry on land that is either in grassland or part of a grass/tillage rotation. In the long term, soil fertility conservation and protection of the environment considerations may force farmers to rely more completely on grassland for animal production and put a limit to the apparent productivity of intensive grassland.

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Nutrient Balance in Mixed Farming Systems with Low and High Stocking Rates

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Summary

The nutrient balance on mixed farms depends mainly on the number and type of livestock, on stock management and feeding systems and on the crop rotation. The number of cattle a farm can support is directly related to crop rotation (forage production) but pig and poultry numbers are not so limited. However, it is preferable that most of the feed should be home produced and thus stocking should be in reasonable proportion to farm area.

Potassium, magnesium and phosphorus in farm manures are to all intents and purposes as available to crops as in fertilizers. These should be included in the nutrient balance on which P, K and Mg fertilizer requirements are based.

In the case of nitrogen, the calculated balance is less valuable as the efficiency of N in farm manures is so variable. Availability of N in solid manures varies between 30 and 85% depending on crop. The availability of ammonium N in slurry ranges between 50 and 100% when applied in the spring but only between 10 and 20% when applied in autumn. Lack of storage capacity for manure often makes it impossible to apply it at the optimum time.

1. Introduction

In the absence of mineral fertilizers, the stocking rate has a decisive influence on the nutrient balance of individual fields, and of the whole farm and on the fertility of the soil. On a dairy farm without mineral fertilization, the calculated nutrient input and output is almost balanced since nutrient exports in meat and milk are comparatively small. On the other hand, farms based solely on crop production almost always have negative balances, thus exploiting the soil's natural nutrient reserves until they are more or less depleted. This is the reason why shifting cultivation was and still is practiced in some regions. The introduction of mineral fertilizers has made it possible to close the nutrient cycle, thereby making pure crop production feasible. This, of course, being the primary function of mineral fertilizers.

I would now like to show how various factors influence the nutrient balances of a farm under Swiss conditions. From this it should be possible to estimate the mineral fertilizer requirement of a farm or even of individual fields.

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2. Influence of stocking rates, animal species and stabling system on nutrients in manure

The amount and concentration of nutrients obtained in manure is primarily determined by the stocking rate and types of livestock. Also influential are housing systems and feeding regimes. In Table 1 averages are given for high and low stocking rates of cattle (in large animal units per hectare) and pigs (hog units per hectare). Clearly, the animal species primarily affects the content of potassium and, to some extent, that of phosphorus.

The values given for the readily available nitrogen in slurry are estimated on the results of forage trials, also taking into account the ammonium content of the different kinds of slurry *(Künzli [5], Hasler* and *Hofer [2])*. Those for solid manure are primarily based on field crop experiments (among others *Künzli [4]*). Table 2 demonstrates the influence of different stabling systems at a medium stocking rate on the amount of nutrients produced. The differences between deep-straw loose box and slurry systems are due principally to the decreasing use of straw. The relationship of total nitrogen (N_t) to the readily available nitrogen (N_a) changes from liquid manure to slurry primarily because of the percentage of faeces contained.

Table 1. Average amount of nutrients in manure as determined by the stocking rate and the animal species

Nutrients	Amount of nutrients (kg/ha)				
	Low stocking rate		High stocking rate		
	1 LAU* per ha	6 HU** per ha	2.5LAU* per ha	1 LAU*/ha +9HU**/ha	15 HU** per ha
Total Nitrogen (N_t)	85	72	212	193	180
Available Nitrogen (N_a)***	55	54	137	136	135
Phosphorus (P_2O_5)	34	45	85	101	112
Potassium (K_2O)	120	30	300	165	75

* LAU = Large animal unit (head of cattle with an average liveweight of 600 kg)

** HU = Hog unit (stall space required for fattening 2.3 hogs from 20 to 100 kg per year)

*** Application losses are not included

3. Effect of crop rotation on the average nutrient requirements

The derivation of a nutrient balance calls for knowledge of the nutrient demands of a farm's crops as well as its indigenous nutrient supply. The requirements, however, also depend on the percentage of the individual crops in the rotation (Table 3). It is to be noted that the cattle stocking-rates stand in a fixed relationship to the crops planted. In rotations 1, 2 and 3 (Table 3), enough roughage is produced to feed 1 LAU/ha, while in rotations 4 and 5 2.5–3.0 LAU/ha can be maintained. This means that dairy and beef production cannot be increased independently of the type of rotation. In contrast, hog and poultry production are basically independant of the rotation since concentrates can be transported at low cost over a greater distance. Despite this fact, the goal should be to grow as much of the pig and poultry feed as possible on the farm itself, therefore keeping livestock production in meaningful relation to the available agricultural acreage.

Table 2. Manure and nutrients produced by different housing systems with a medium stocking rate (1.5 LAU*/ha)

System	Solid manure (rotted)					Slurry (undiluted)					Total			
	t/ha	Nutrients (kg/ha)				m³/ha	Nutrients (kg/ha)				Nutrients (kg/ha)			
		N_t	N_a	P_2O_5	K_2O		N_t	N_a	P_2O_5	K_2O	N_t	N_a	P_2O_5	K_2O
Stall with deep straw bedding	22	143	53	62	209	—	—	—	—	—	143	53	62	209
Tie stall with generous bedding	12	60	24	51	68	9	62	56	4	131	122	80	55	199
Tie stall with limited bedding	9	45	18	31	54	16	82	70	22	136	127	88	53	190
Tie stall with slotted floor or loose box stand without bedding	—	—	—	—	—	26	130	86	52	182	130	86	52	186

* LAU = Large animal unit (head of cattle with an average live-weight of 600 kg)
N_t = total nitrogen
N_a = readily available nitrogen

Table 3. Average nutrient demands of various crop rotations

Crops	Percentage of each crop in the rotation				
	Rotation 1	Rotation 2	Rotation 3	Rotation 4	Rotation 5
Pastures	30	0	20	20	60
Small Grains	40	20	60	20	20
Maize	0	30	0	60	20
Potatoes/Beets	20	50	10	0	0
Seed rape	10	0	10	0	0
	Average nutrient requirements (kg/ha)*				
Nitrogen (N)	137	124	138	130	142
Phosphorus (P_2O_5)	89	99	82	94	94
Potassium (K_2O)	221	250	189	232	256

* Nutrients in crop residues (straw, beet foliage, etc.) which may be left on the field after harvesting are not taken into account

4. Factors affecting the nutrient efficiency of manures in crop production

The theoretical balance calculated from the difference between the average supply of nutrients in manure and the average demand by crops might be used to estimate fertilizer requirement.

Such a balance is meaningful in the case of the major elements phosphorus, potassium and magnesium, assuming sorption capacity of the soil is sufficient, since these nutrients in manures have an efficiency similar to that of the same nutrients in fertilizers *(e.g. Koriath et al. [3]; Finck [1])*. This holds so long as soil fertility is optimal and that care is taken in distribution between and within fields, taking the nutrient composition of the manure into consideration.

As is well-known, the situation with nitrogen is more complicated. This is because nitrogen appears in our open-ecosystem environment in various, mostly reversible, chemical forms. With the exception of legumes, only its most highly oxidized state (NO_3) is of immediate importance for plant nutrition and the environment. But in stable manure, nitrogen is not present as nitrate but in its ammonium and organic forms. To what extent plants are able to use these nitrogen compounds, either directly or after transformation into nitrates, depends on many, in part incalculable and uncontrollable, natural processes.

In a long-term experiment, the effects of nitrogen from stable manure on the various crops of a rotation were compared to those of mineral nitrogen fertilizer. The utilization of nitrogen from stable manure, measured as yield increase per kg nitrogen applied, ranges from 30–60% in field crops and from 80–85% in leys (Table 4). The effectiveness seems to be primarily determined by the length of the different crops' growing periods. Also to be considered is a possible shift in the botanical composition of leys in favour of legumes or grasses.

Further, the combined use of stable manure with nitrogen fertilizer, a common agricultural practice, could influence the N-efficiency of stable manure. As already stated, the figures in Tables 1 and 2 concerning the available nitrogen in slurry are based primarily on results from forage crop experiments. But at higher stocking rates, especially of pigs or poultry, the application of at least a part of the slurry on field crops is usually unavoidable. As can be seen in Figure 1, the time of slurry application here differs greatly from that in forage production. According to the crop, slurry use in summer by present-day standards and techniques is impossible for three and half to seven months. This necessitates the construction of large tanks capable of storing the slurry all summer.

During the remainder of the year (late autumn, winter, spring) it is possible to take out the slurry. It is questionable, however, if this is agriculturally meaningful or useful when the time, amount, topography and soil status (dry, saturated, frozen, snow-covered, etc.) are taken into consideration. Due to leaching during the winter months, it is inadvisable to apply slurry after harvesting maize, sugar beets or potatoes. Most of the mineral nitrogen will be lost to the root zone and could pollute the groundwater.

Some figures for the mineral fraction of nitrogen remaining in the soil after late-autumn slurry application are given in Table 5. These show that 80–90% of the mineral nitrogen (NH_4-N) contained in the slurry and applied at this time has leached out of the root zone by spring. If, on the other hand, the slurry is taken out in the

Table 4. Yield response of various crops to nitrogen applied as solid manure compared to nitrogen fertilizers in a long-term experiment (1949–1980)

Crop	No. of harvests	Average N application (kg N/ha)			Average yield increase per kg nitrogen applied			Relative yield increase per kg N in solid manure	
		Solid manure	N fertilizer		Solid manure	N fertilizer			
			N_1	N_2		N_1	N_2	$N_1 = 100$	$N_2 = 100$
Winter wheat	8	86	52	101	7.4	18.4	14.2	40.2	52.1
Potatoes	2	95	62	122	50.0	145.2	138.5	34.4	36.1
Sugar Beets	2	90	60	120	80.8	205.8	167.0	39.3	48.4
Seed rape	1	124	75	150	2.6	8.7	5.3	29.9	49.1
Silage Maize	6	80	63	125	17.1	33.9	25.9	50.4	66.0
Artificial Ley	9	93	57	109	14.2	16.5	17.7	86.1	80.2

Wheat and rape: kg grains; potatoes: kg tubers; sugar beets: kg roots; silage maize and artificial leys: kg dry matter

Table 5. Effect au autumn applications of slurry on the soil's mineral nitrogen content (N_{min}) the following spring

Slurry application		N applied with slurry		N_{min} content of soil (0–100 cm)			Relative increase of N_{min} content in % (NH_4-N application through slurry = 100)
Amount (m^3/ha)	Month/Year	Total N (kg N/ha)	Ammonium N (kg N/ha)	Month/Year	N_{min} (kg N/ha)	Increase through slurry application (kg N/ha)	
0	—	—	—	March 81	49	—	—
100	Nov. 80	274	160	March 81	83	34	21
0	—	—	—	March 82	29	—	—
100	Nov. 81	145	124	March 82	41	12	10
0	—	—	—	March 83	23	—	—
60	Nov. 82	150	100	March 83	35	12	12

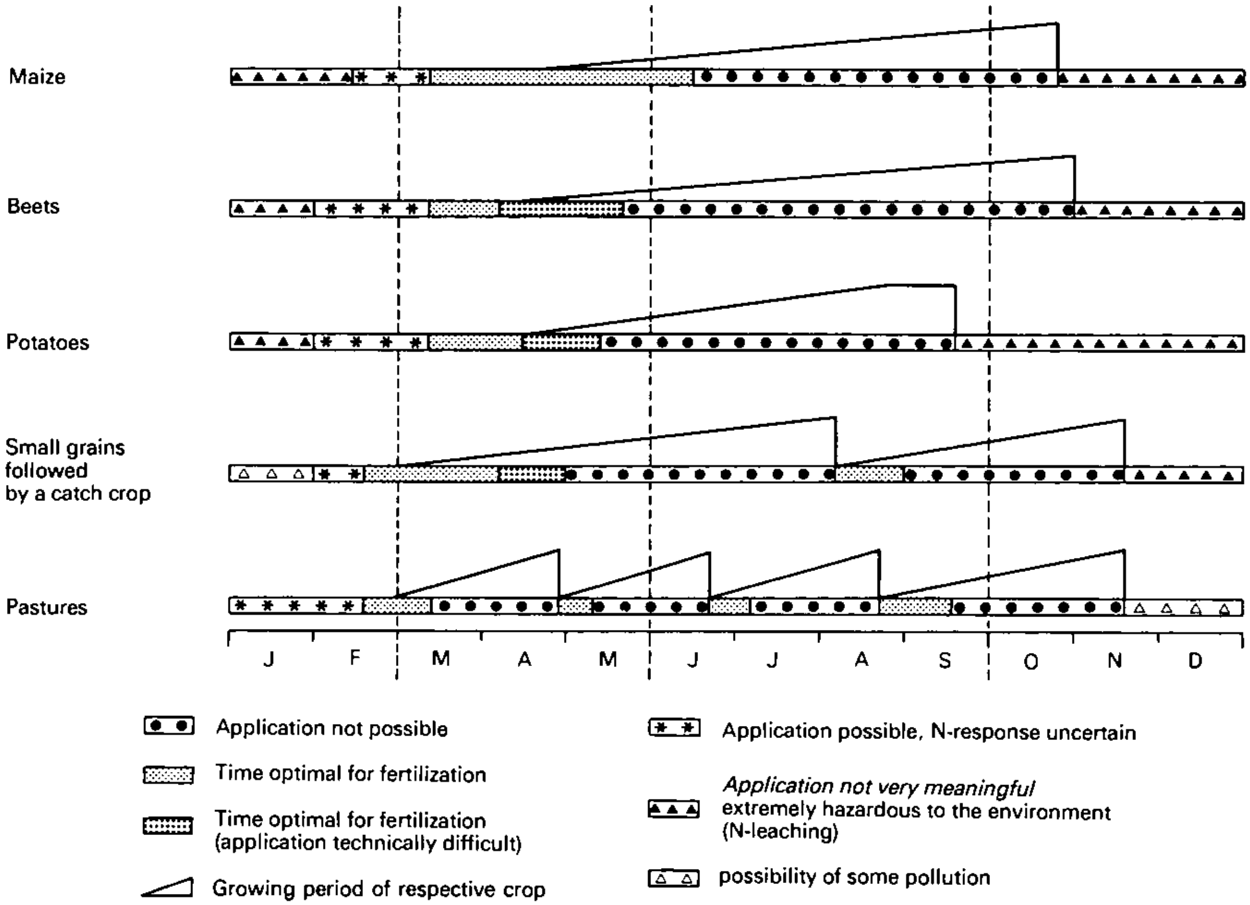


Fig. 1. Plant production aspects about application time of slurry on soil in asorbtive state.

spring, most of the ammonium-nitrogen will be available to the crops at the beginning of the vegetation period (Table 6).

A large number of studies, as well as practical experience, have demonstrated that grain yields are closely correlated to the soil's N_{min} content at the start of the vegetation period. An example of the effect of slurry applied in autumn and spring, respectively, on the soil's N_{min} content at the beginning of growth and on grain yields is given in Table 7. The results show conclusively that slurry spread in autumn is agriculturally ineffective, as should be expected from the soil's N_{min} content.

All of these results lead to the evident conclusion that late autumn slurry application is virtually senseless both agriculturally and environmentally and is therefore not to be recommended. It follows from this, that the slurry must also be kept throughout 3–5 autumn and winter months. A farm practicing pure crop production therefore needs storage capacity for slurry for a total of 4–8 months (Figure 1).

In 1980, a long-term experiment was initiated to try to determine – besides the immediate effects of nitrogen in the year of slurry application – the extent of its after-effects. Tables 8, 9, and 10 give the yields, yield responses and N removal of the crops during the first 3 trial years with increasing amounts of slurry. The responses to manure nitrogen are compared to the results obtained by equivalent applications of nitrogen in the form of ammonium nitrate. During the first trial year (1980), the efficiency of the NH_4-N in the slurry, as measured by the response in tuber yield, was relatively low; just 45–53% that of ammonium nitrate (Table 8). The increase in nitrogen removed by potatoes was relatively higher than the increase in tuber yields at a medium level (50 m^3/ha) of slurry application. A higher level produced a relatively lower N response compared to tuber yield.

Winter wheat (Zenith) followed the potatoes and was fertilized in spring, 1981, with slurry and ammonium nitrate, respectively. The resulting grain yields, yield responses and nitrogen removal are shown in Table 9. The yield responses to the NH_4-N of the slurry are much better (70-80%) than in 1980, under rather unfavourable weather conditions. If one takes the nitrogen yield as the measurement, the slurry's efficiency is even higher.

Immediately after the wheat harvest, a catch crop (a rye-grass/clover mixture) was sown with no nitrogen fertilizer. The germination and growth of the mixture was very slow, so no yield measurements could be made that autumn. Next spring, however, the first growth developed well and was harvested on May 13, 1982. The yields, as presented in Figure 2, give an idea of the after-effects of the nitrogen fertilizer treatments taken in 1981 and, possibly, in 1980. A significant yield increase of 500–600 kg dry matter/ha was found only where the high level (150m^3/ha) of slurry was used the previous two years.

Next, the catch crop was ploughed under, slurry brought out, and maize planted (May 19; Pau 207). Table 10 gives the grain yields, yield responses and nitrogen removed for this crop. Here, one notices that the relative yield response increases from about 60–70% to about 100–110% with rising levels of ammonium supplied with the slurry. This response was even more pronounced for the nitrogen removed with the crop. This, at first surprising, result could be due to a very low N_{min} content of the soil at seeding (9 kg N/ha), that is a narrow C:N ratio of soil and manure. In the future, further studies about the utilization of slurry in crop production must examine the question of the N efficiency of slurry if applied together with mineral N fertilizers.

Table 6. Effect of spring applications of slurry on the soil's mineral nitrogen content (N_{min}) at the start of spring growth

Slurry application		N applied with slurry		N_{min} content of soil (0–100 cm)			Relative increase of N_{min} content in % (NH_4-N application through slurry = 100)
Amount (m^3/ha)	Day/Month/ Year	Total N (kg N/ha)	Ammonium N (kg N/ha)	Day/Month/ Year	N_{min} (kg N/ha)	Increase through slurry application (kg N/ha)	
—	—	—	—	22.4.80	27	—	—
100	26.3.80	176	85	22.4.80	85	58	68
—	—	—	—	23.3.82	29	—	—
100	9.3.82	235	117	23.3.82	113	84	72
—	—	—	—	7.6.82	45	—	—
50	17.5.82*	112	59	7.6.82	75	30	51
100	17.5.82	224	118	7.6.82	104	59	50
150	17.5.82	336	177	7.6.82	164	119	67
—	—	—	—	22.4.83	20	—	—
100	29.3.83	199	102	22.4.83	109	89	87

* 19.5.: Sowing date of maize

Table 7. Effect of slurry applied in autumn or spring on the N_{min} content of the soil at the start of growth and the yield of spring wheat

Slurry application		N applied with slurry		N_{min} content of soil (0–100 cm) on March 23 (kg N/ha)	Yield (t/ha)		
Amount (m^3/ha)	Day/Month	Total N (kg N/ha)	Ammonium N (kg N/ha)		Without mineral N fertilizer	With mineral N fertilizer*	
						N_1	N_2
—	—	—	—	29	4.28	5.92	6.15
100	22.Nov.	145	124	41	4.71	5.74	6.02
100	3.Feb.	210	91	94	5.51	5.51	5.98
100	9.March	235	117	113	5.63	5.63	6.11

* N_1: 100 kg N/ha less the N_{min} content of the soil at sowing time

* N_2: 100 kg N/ha less the N_{min} content of the soil at sowing time plus 40 kg N/ha at the end of tillering plus 60 kg N/ha at the beginning of heading

Table 8. Comparison of the effect of ammonium nitrogen (NH_4-N) in slurry with ammonium nitrate (AN) on potatoes. First trial year (1980)

Treatment	N application in slurry (NH_4-N) resp. AN (kg N/ha)	Tuber yield (t/ha)	Yield response to the applied mineral nitrogen		N removal by tubers (kg N/ha)	Increased N removal as result of N fertilization	
			kg tubers per kg N	Relative (AN = 100)		kg N/ha	Relative (AN = 100)
Without N fertilizer	0	12.5	—	—	29.2	—	—
With slurry*							
A	43	16.6	94	53	38.0	8.9	64
B	85	18.9	74	45	42.4	13.2	35
C	128	23.7	87	53	51.6	22.4	41
With AN							
A	43	20.1	177	100	43.1	13.9	100
B	85	26.5	163	100	67.1	38.0	100
C	128	33.6	164	100	84.1	55.0	100

* A = 50 m^3/ha; B = 100 m^3/ha; C = 150 m^3/ha

Table 9. Comparison of the effect of ammonium nitrogen (NH_4-N) in slurry with ammonium nitrate (AN) on winter wheat. Second trial year (1981)

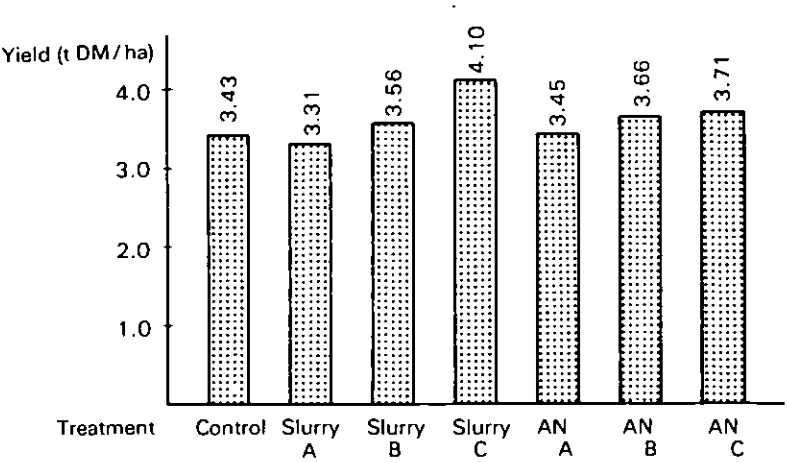
Treatment	N application in slurry (NH_4-N) resp. AN (kg N/ha)	Grain yield (t/ha)	Yield response to the applied mineral nitrogen		N removal by grain and straw (kg N/ha)	Increased N removal as result of N fertilization	
			kg grain per kg N	Relative (AN = 100)		kg N/ha	Relative (AN = 100)
Without N fertilizer	0	4.70	—	—	97	—	—
With slurry*							
A	44	5.44	16.8	69	118	21	75
B	88	6.07	15.6	81	147	50	79
C	132	5.94	9.4	79	160	63	86
With AN							
A	44	5.78	24.5	100	125	28	100
B	88	6.38	19.1	100	160	63	100
C	132	6.27	11.9	100	170	73	100

* A = 50 m^3/ha; B = 100 m^3/ha; C = 150 m^3/ha

Table 10. Comparison of the effect of ammonium nitrogen (NH_4-N) in slurry with ammonium nitrate (AN) on maize. Third trial year (1982)

Treatment	N applied in slurry (NH_4-N) resp. AN (kg N/ha)	Grain yield (t/ha)	Yield response to the applied mineral nitrogen		N removal by grain and straw (kg N/ha)	Increased N removal as result of N fertilization	
			kg grain per kg N	Relative (AN = 100)		kg N/ha	Relative (AN = 100)
Without N fertilizer	0	6.76	—	—	96	—	—
With slurry*							
A	59	8.82	34.9	69	130	34	60
B	118	10.29	29.9	94	166	70	91
C	177	11.21	25.1	105	207	111	111
With AN							
A	59	9.73	50.3	100	153	57	100
B	118	10.53	31.9	100	173	77	100
C	177	10.99	23.9	100	196	100	100

* A = 50 m^3/ha; B = 100 m^3/ha; C = 150 m^3/ha



Treatment		Control	Slurry A	Slurry B	Slurry C	AN A	AN B	AN C
N-fertilizer								
– to main crop	1980	–	50	100	150	43	85	128
	1981	–	50	100	150	43	88	132
– to catch crop	1981/82	–	0	0	0	0	0	0
			m³/ha	m³/ha	m³/ha	kg N/ha	kg N/ha	kg N/ha

Fig. 2. Residual effect on yield of an Italian-ryegrass/red clover mixture, stemming from two years application of slurry or ammonium nitrate (AN) to the main crop.

5. Nutrient balances and fertilizer requirements

A calculated balance can provide some indications about the nutrient requirements of a farm or an individual field. It gives, however, only a rough estimate of the fertilizers needed, because figures about inputs and outputs are usually approximate. Often, only regional or national means are available for the composition of manure and the nutrients removed by the crops. Such information is insufficient for a correct fertilization with respect to plants and environment. For that, specific figures about the nutrients obtained in manure, the reserves in the soil, the yield potential, etc., are needed for each individual farm. For phosphorus and potassium – both usually given in amounts to maintain a certain reserve in the soil – balances could give important information on the fertilizer requirements.

Calculating a balance for nitrogen has little meaning with regard to the amount of mineral fertilizer needed. Too many incalculable factors influence the requirements for mineral nitrogen. Of great importance are the weather conditions before and during the vegetation period, as well as the varying efficiency of nitrogen from manure, depending on the crop and time of application. Further difficulties arise from the insufficient storage capacities for slurry and technical problems for timely application, which should be synchronized with the N-demand of the crops.

Future research activities should again put more emphasis on how to make the nitrogen in manure available to the plant rather than polluting the environment with it. Main points for better utilization and efficiency of manure nitrogen and a reduction of losses are: 1) improvement of the quality of manure by correct handling; 2) taking plant aspects and soil characteristics into consideration while choosing the proper time for spreading the manure; and 3) improving the application techniques, especially for slurry.

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Co-ordinator's Report on the 1st Session

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Nutrient Balances in Farming Systems

The subject of this introductory session, *i.e.* 'Nutrient Balances in Farming Systems' was, by definition, of a generalized nature and the outcome must be seen in the context of previous Colloquia and Congresses and in relation to the other somewhat more specific sessions at this meeting. This has presented some difficulties in co-ordination.

1. A complex problem

Professor *Van Diest* set out the basics in dealing with the problem of nutrient cycling in low-input and high-input systems of agriculture. His task was a very difficult one and in approaching it through the use of models or schema relating to nutrient cycles and their components, he presented clearly the nature and complexity of the problems involved – the various interactions, and the sources of gains and losses, as related to crop and animal production. If we were to proceed further with these schema and walk along some of the pathways traced out, perhaps progress could be made to better identifying knowledge deficient areas. One such, and indeed the only one referred to in the discussion, was that relating to microbial biomass nitrogen. This subject has been with us for a long time – it was a main subject in *Waksmans* book on humus of well over a half century ago. In general in this respect it seems reasonable to conclude, that while the general scene has been set, it is the quantification of the sub-cycles and components and the more thorough pursuit of the various interactions listed, which are of importance now.
In his conclusions, *Van Diest* raised a number of important points – these again in turn must give rise to questions. Let us look again at the following.

a) "Efficiency values are determined much more by the general quality of the growing conditions rather than by the magnitude of the inputs." This conclusion merits, I submit much further analysis.
b) "That climatic conditions have no overriding influence on the degree of efficiency of applied nutrients." While perhaps generally true, climate in many temperate conditions, exerts a major influence.

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c) and d) Refer to the comparative efficiency values of crop and animal farming systems. There are some matters relating especially to efficiency values in livestock farming which require further comment here. How we approach the matter depends very much on the definition of "efficiency values". I would in this respect specifically want to take up pastoral farming systems. On the face of it, his statement is accurate enough – but let us trace what happens in some such systems:

Animals of different types graze pasture, using some of the ingested feed for producing meat or milk, wool or hides and so on. The amount of those produced is, of course, the final determinant of economic efficiency. Proceeding further, dung and urine are deposited on pasture. This is an inefficient nutrient distribution process. Under very intensive management conditions, only some 15% of the area grazed receives nutrient returns in any one year, with deposition in patches. The swards so affected change ecologically, depending on whether they received faeces or urine. It has been clearly shown by studies in our country that if they are "cattle" residues they will not be grazed by cattle, but will be by sheep. So here greater efficiency is easily achieved in combining sheep and cattle in grazing management.

Another point of significance and argument which evolved from the paper is the efficiency of potassium. Again this has been interpreted in terms of applied K. It is some twenty-five years since we had to deal with this matter in 'efficiency' terms especially for silage growing advice. We identified two main sources of K *i.e.* applied and soil – the latter in various categories. In a systematic fashion and based on soil survey (soil type) classification we characterized the K supplying power of our soils. Some had low supplying power 20–50 kg/ha per year after four years – while another group was still releasing 100–150 kg/ha after the same time. A silage or hay crop will remove some 150–200 kg/ha. This was applied on the basis of applying full needs of the crop on low K supplying soils, while for those of the higher K capacity category, a much lower rate of application – some 50 kg/ha was applied. Control of this process can be achieved through periodic soil testing.

A similar approach has been developed in relation to P. For our soils, relatively high in organic matter, especially in the surface layer of permanent pastures, cycling of P takes place mainly through this layer. Losses are relatively low, with little fixation. In tillage soils, the picture is of course entirely different, following admixture with mineral soil and the mineralization of organic matter. Even where the latter is concerned the experience, as stated by *Murphy* of liming on N release, points up still further the complexity of the interactions. We continue still with too little information on the dynamics of organic matter in the soil, its buildup and breakdown, as a source of N, P, S, various trace elements and carbohydrates for energy and activity, *e.g.* the effect on sulphur release, as quoted by *Murphy* in his paper. These are some of the thought processes which Professor *van Diest*'s very thorough analysis of this subject has released to relate one's own experiences.

2. Quantifying N fixation

The paper by *McEwen and Johnston* I found intriguing. In two soils they have established some balance parameters for N, P and K. They have clearly illustrated an important difference in the capacity of two strains of white clover to fix N in major quantity, as measured in foilage dry matter. The figure as given ranging between 200

–450 kg per hectare can be a highly important addition to the nitrogen economy if it can be practically exploited. One would like to know more, however, about the effect on soil nitrogen and soil dynamics. Similarly there are major quantities of K involved. These are important balance sheet effects. It its pertinent to enquire as to how this contribution of clover can be used most effeciently. It is our experience that under grazing Blanca will behave differently, as indeed also will applied N creating a new ecological regime. Here vital husbandry and a variety of other factors intervene, with once again the efficiency being determined by the management system used.
The authors attributed the difference between the two soils studied to initial nutrient effects. In the light of Dr. *Tinker*'s subsequent paper on the effect of site characteristics, one might question this conclusion. A very important effect of pesticide has been recorded. This is a matter well worth taking further, especially its relevance in relation to several organisms which play a role in soil fertility and organic matter dynamics generally.

3. Defining cropping sequence effects

The paper by *Toderi and Giordani* confirms, and further quantifies some of the matters raised in *van Diest*'s paper, emphasizing especially the place of husbandry practices. For instance our experience has shown that the sequence in which four crops were used in a rotation had a vital effect on nutrient removal and yields. In this respect the whole question of luxury consumption of K can intervene to restrict efficiency. This paper basically substantiates for one site, data and concepts developed elsewhere. There is, however much, as implied by the authors, that is tentative about the findings.

4. Using farmyard residues efficiently

This session's primary remit was to study nutrient balances in farming systems. Of the papers presented that of *Walther* is especially relevant in this context. He points out that cattle stocking rates are basically related to crops in the rotation. This in essence is the basis of many traditional farming systems. Again in this paper the terminology used, points to the need for some standardization of animal systems reporting in this respect. We are used to dealing with a definition of stocking rate which refers to the capacity of a unit area of land to achieve a specific desired level of production or performance from pasture alone, including conserved grass, on an annual basis. In his appraisal *Walther* is rightly concerned with nutrient conservation through effective use in slurries and other farmyard by-products. He stresses the serious losses which arise from inefficient storage, handling and methods of application and his figure for loss of N at 80–90% from slurries applied in the autumn is striking in terms of efficient cycling. In this respect the results of *Sherwood* which showed that at least some fraction of the organic matter in slurry can act as an energy source for denitrifying organisms, depending on soil temperature and oxidation-reduction balance. Again much of the information presented in this paper is location specific, while his stress on the effect of weather conditions before and during the vegetative growth period questions what has been reported elsewhere at this meeting.

5. The potential of EEC pastures

I have left specific comment on the paper of *Murphy* until last because of its rather separate content. He was asked to discuss intensive grassland development in North Western Europe. This is a very major subject, one of itself deserving a special meeting and one moreover of major significance in relation to the EEC. In this respect his presentation of the grassland potential map of EEC countries, by any standards a significant product of research staff from his centre. It is a map based on the concept that each soil has an inherent production capacity and can hence be accorded a productivity rating. For this purpose production data were experimentally established for major soil types. Using soil, climatic, vegetational, insolation and elevation parameters, a projection was made for European conditions. For pasture economics, it sets a basis for looking at the question of the comparative advantage of different regions in the EEC and ultimately, if we accept the soil approach, of establishing balance data for inputs. His model of the main flow of nutrients in intensive pasture management, again as for *van Diest,* establishes a basis for exploring rationally new research needs. Most good work is simple and this is clearly exemplified in the relationship presented between animal performance and P application, which work, pursued on a farmlet scale over a long period, has established (a) basic criteria for P use (b) the most economic rate of application as measured by animal production and (c) the most effective use of soil P.

While the main emphasis at this meeting has been on N, P and K, *Murphy*'s paper points to practical problems met for a number of other elements involved in intensive grassland production. There are problems of excess, of luxury consumption, of imbalance and of achieving quality in herbage to meet animal needs.

6. Some important paths to pursue

From these presentations and the discussion at this session, there are a couple of major threads which might be followed. There is the need to firmly establish what is meant by efficiency, *i.e.* scientific, technical, economic or even perhaps social. Problems of the relationship of nutrient cycles to environmental effects have only been referred to marginally here, with little or no quantification. Yet they are of increasing importance.

In dealing with farming systems, actual management problems occupy a central place in relation to nutrient cycling but again have only been referred to marginally. There has in respect, been little reference as to how components should be slotted into effective management blue prints and the methodology of research for this purpose.

While in this session there was some reference to the prime role of soil as an individual entity in recycling – each soil having its own dynamic in this respect – it is pleasing to see a better understanding emerging of the role of site characteristics. The clock seems to have turned a full circle. Some 25 years ago as soil scientists we focussed on the meaning of the soil as such an individual entity, with its diverse composition – physical, chemical and biological – and taking into account edaphic considerations. A rough model of the factors involved in deciding nutrient application was constructed. There were, in all some one hundred. It is obvious that this, experimentally, is a very complex subject, requiring much further quantification, not, of individual components but of their interactions also, with the need for realistic syntheses taking into account the management (educational) and social (psychological) attributes of individual operators.

We have now reached a certain, perhaps 'next stage', in our work. It is time to look at new developing areas and interfaces for research and the presentations at this Session have an important relevance in that respect.

Chairman of the 2nd Session

Dr. *A. Vez,* Director, Swiss Federal Research Station for Agronomy, Changins-Nyon/Switzerland; member of the Scientific Board of the International Potash Institute

2nd Session

Evaluation of Nutrient Balances

Prospects and Limitations of Soil and Plant Analysis for Establishing Nutrient Balances for Major Crops

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Summary

Soil testing and plant analysis are common methods for describing the nutrient status of soil and plant respectively. However, texture, structure and moisture content of soil as well as climatic factors and the rate of nutrient requirement by the crop being important modifying factors, the value of soil testing and plant analysis for the definition of an optimal, long-term nutrient balance is difficult to elaborate. Long-term experiments at many sites and preferably with crops which are most responsive to the respective nutrient are the best approach as some examples given in the paper demonstrate.

1. Introduction

At any level of agriculture the farmer wants to obtain the maximum return for the inputs. In controlling the fertility level of the soil and the actual nutrient status of the crop soil testing and plant analysis are indispensable complementary not competetive tools *(Bergmann [1972], Cottenie [1980]).*
For many years now agricultural chemists have been searching for convenient methods which, while giving information on the plant-available nutrient content of the soil, could also be used to predict the quantity of fertilizer required to produce optimum economic yield *(Hasenbäumer [1931], Meyer [1930], Rippel [1930], Bergmann [1958]).* Such a presumptuous claim is unlikely to be realized, because it confounds the physicochemistry of nutrient dynamics in the soil with the short-term pricing policy for agricultural commodities *(van der Paauw [1980]).* Two quotations from the *FAO Soils Bulletin on* 'Soil and Plant Testing and Analysis' point out how little progress has been made in routine soil testing and that prospects for improvement are limited: 'The large number and diversity of methods indicates by itself their speculative character' *(Cottenie [1980])* and 'Because of the great complexity of the soil-water-plant system soil and plant testing will probably always remain empirical and never reach the perfection of engineering that permits the design of new craft' *(Viets [1980]).*
The situation is not as desperate as it sounds from these quotations if modern analytical methods and computer facilities are used to record the diverse influencing parameters.

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The principles, benefits and limitations of soil and plant analysis are described in all text-books of plant nutrition *(Finck [1979], Mengel* and *Kirkby [1982])* as well as in a number of reviews and monographs *(Lundegårdh [1945], Chapman [1971], Walsh* and *Beaton [1973], Beaufils [1976], Cottenie [1980], Bergmann [1983])*. It is appropriate, therefore, to repeat only the salient points which must be considered in a reliable interpretation of soil testing and plant analysis: Content of soil in clay and organic matter *i.e.* cation exchange capacity, nutrient buffering and nutrient fixation, soil structure and redox potential, soil-pH, plant available soil moisture in the root zone, size and affinity of the root system for nutrients, crop and soil management *(Marschner [1983], Beringer [1984])*. As far as plant analysis is concerned the standardization of sampling is of utmost importance and the analysis of only one single nutrient insufficient to evaluate the balance of nutrients required for optimal growth *(Bergmann [1983])*.

Rather than treating all these biotic, chemical and physical factors in detail again the guideline in discussing the given topic will be the question: What evidence do soil and plant analysis provide in deciding the most economical and ecological strategy for farming? Is it sufficient just to replace the nutrients which have been removed from the field in the harvested parts of the crop (input/output balance sheet concept) or, secondly, should more emphasis be put on optimal and harmonious ratios of plant available nutrients (basic cation saturation concept) or, thirdly, should the maintenance concept be followed which aims to achieve that nutrient level in soil at which yield responses to additional fertilizer will be unlikely, but which must be maintained by regular fertilizer application *(McLean [1977], Mehlich [1980], Liebhardt [1981], Olson et al. [1982])*.

2. The definition of nutrient balances by soil and plant analysis

The term nutrient balance will be used in the following considerations in the sense of that nutrient status, which is needed to achieve and maintain a high soil fertility of long duration. Nutrient balances in the sense of nutrient equilibria are more of a short-term character and can be less achieved because of the many soil and plant factors affecting nutrient uptake and nutrient ratios during the vegetation period. Under conditions of highly productive farming, where generally factors other than macronutrients are the yield limiting factors the concept of a man-made balanced nutrition anyway changes into the mere task of avoiding extreme imbalances of nutrients in the plant.

2.1 Correlation between soil-/plant analysis and yield

In the range of low and medium nutrient availability the correlation between yield and increasing amounts of nutrient *i.e.* the reliability of fertilizer recommendations based on soil testing is generally high (Figure 1a). Similarly plant analysis correlates well with yield in the range of mild deficiency (Figure 1b). Under severe deficiency a given unit of nutrient is immediately utilized for growth and the concentration of the nutrient can even be diluted, whereas nutrient uptake over and above the physio-

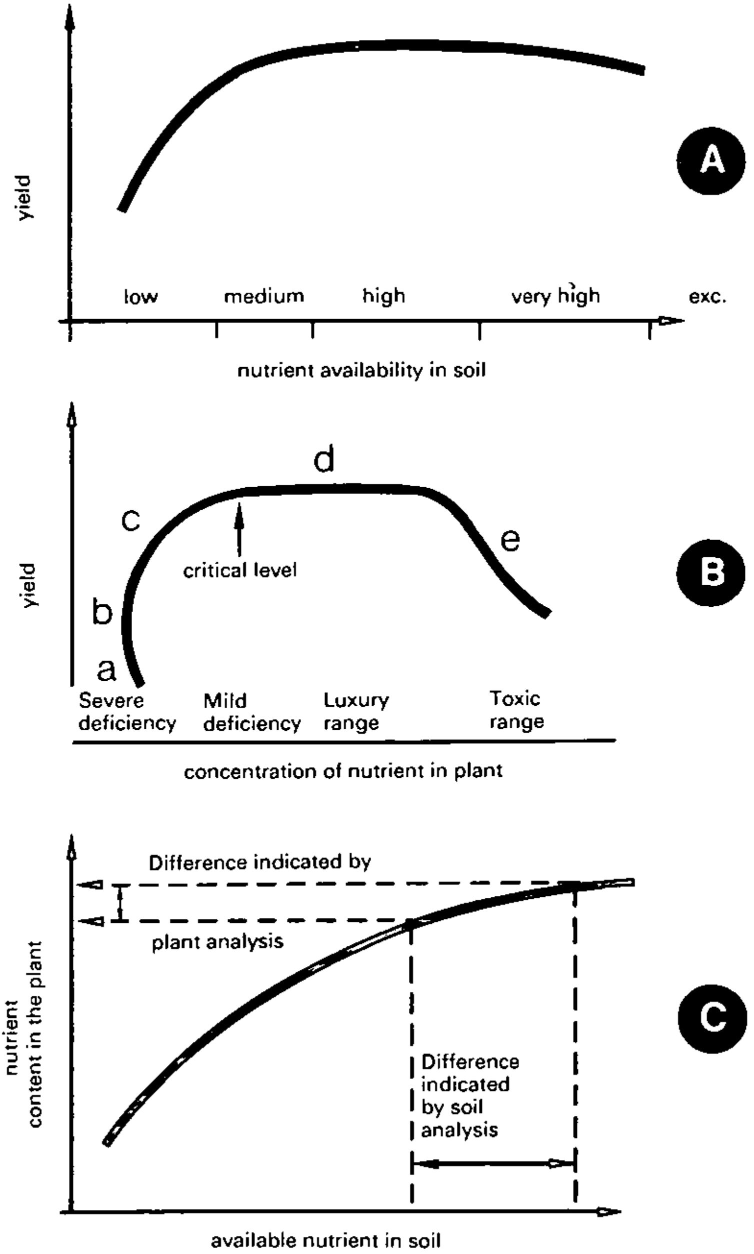


Fig. 1. Schematic relationships between yield and soil analysis (A) or plant analysis (B) and relationship between both analytical approaches.

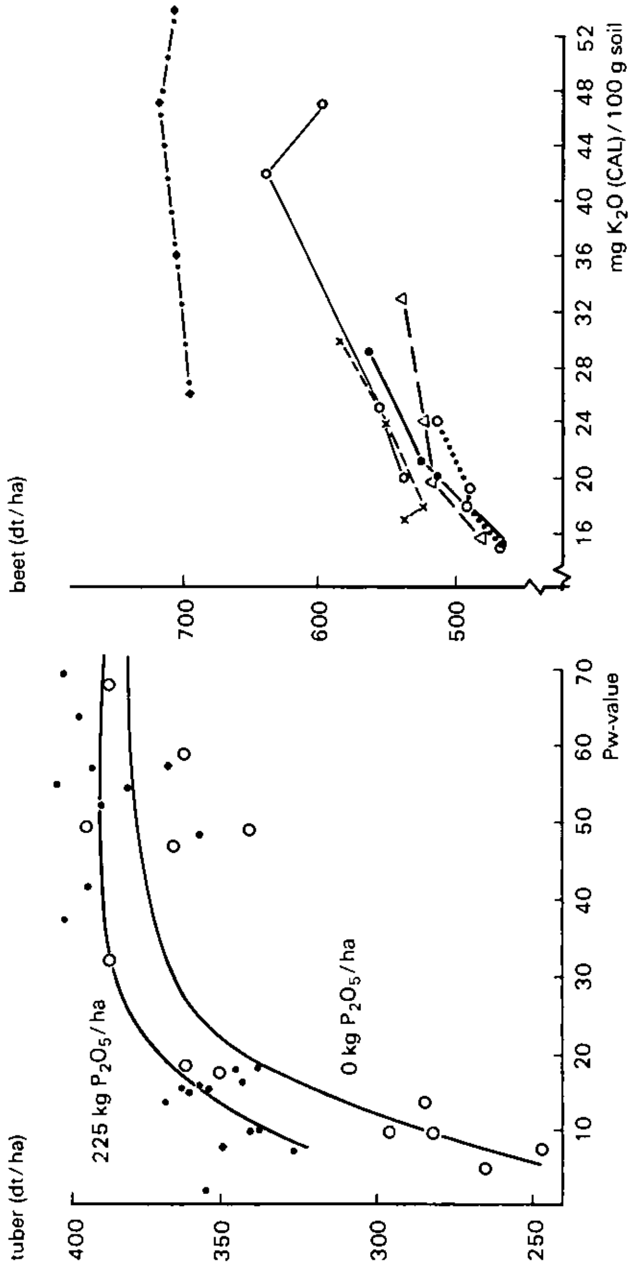


Fig. 2. Effect of an increasing P- (left) and K-availability (right) in individual soils on yield of potato tubers and sugar beet root at a uniform dressing of 0 kg or 225 kg P_2O_5 (left) and of 300 kg K_2O/ha (right) *(Prummel [1981], von Braunschweig,* pers. commun.).

logical requirement results in a luxurious nutrient accumulation. In both cases the correlation between yield and plant analysis is poor. In this range of luxury consumption, plant analysis is also a less differentiating method than soil testing for the evaluation of the nutrient balance in a soil (Figure 1c).

It is obvious from the graphs that in the range of maximum yield the correlation between yield and soil test data or between yield and nutrient content in the plant becomes poor. In highly productive agriculture, therefore, fertilizer recommendations cannot be as precise as in situations where soil fertility is low. This has long been known *(Neubauer* and *Neubauer [1940], Ferrari* and *Vermeulen [1956], Frederiksson* and *Egnèr [1960], Rodewyk* and *Schäfer [1969]).* If the soil is well supplied with all essential nutrients it can in most cases be left to the plant to decide what quantities and ratios of nutrients it will take up from the soil.

Arnold [1978] and *Grimme et al. [1974],* for instance, showed that grass and cereals can satisfy their Mg requirement even at high K availability in soil provided sufficient available Mg is present. Similarly it is not the K/Na ratio but the absolute Na content in the grass which is important for grazing ruminants *(Martens [1982])* and this can be raised by Na-containing fertilizers *(Pflüger* and *Neméth [1972], Finger*

The value of soil testing in characterizing the nutrient level and in being a reliable basis for fertilizer recommendation has occasionally been questioned, because coefficients of correlation between available nutrients and yield can range from r = 0.9 to r = 0.2 *(Herrmann [1938], Bergmann [1958], Vogl [1981], Kuhlmann [1983]).* It should be borne in mind, however, that a poor correlation is more likely caused by insufficient or wrong grouping of data, which may not be comparable for several reasons, than by any defect in a particular method of analysis. Many experiments provide convincing evidence for the long-term benefits of a high nutrient status in the soil. Figure 2 shows that on soils whose P or K status had been raised in the past by increasing rates of P or K fertilizer, correlation between yield and soil test data are quite good up to the critical level of nutrient availability. This good correlation is explainable because in these examples all growth factors except the P- or K-content of the plots were the same. From these graphs two conclusions can be drawn:

a) Maximum yields require large quantities of available nutrients in the soil. This is the level of nutrient balance which must be maintained; it helps to overcome temporary nutrient stress and is a safeguard against excessive yield fluctuation *(Grimme et al. [1971], Munk [1980], Johnson* and *Wallingford [1983]).*

b) An insufficient nutrient level in the soil cannot be fully compensated by a quantity of fertilizer equivalent to what the crop would take up. Input/output balance sheets should take this into consideration.

2.2 Gaps and errors in establishing nutrient balances using soil analysis

Much excellent research has been done in the past on the mechanisms of nutrient transport in soil, on nutrient dynamics in the rhizosphere as well as in the bulk soil *(Barber [1982], Jungk et al. [1982], Mengel* and *Kirkby [1982], Marschner [1983]).* Nevertheless there are still many gaps in our knowledge which make the establishment of nutrient balance difficult. Only three major ones will be considered.

2.2.1 Soil texture

Routine soil testing is done on soil samples sieved to <2 mm. In the field, however, this fraction is associated with gravel and stones. If these constituents >2 mm amount to more than 20%, the pool of analytically determined available soil nutrients is significantly diluted in the natural soil. *Bergmann [pers. comm.]* suggests that the analytically determined available nutrient content should be adjusted for actual field condition in accordance with Table 1.

If, for instance, a soil consists to 100% of fine earth and 200 ppm available nutrient are thought necessary then the concentration in the fine earth has to be raised to 250 or even to 400 ppm, if in the field this fine earth is diluted by 20% and 50% coarse material respectively. Although empirical, such a correction would improve the interpretation of soil analysis as well as the comparability of nutrient balances.

Table 1. Proposal for a correction of chemically determined available nutrients (ppm) according to soil texture *(Bergmann,* pers. comm.)

% of particles <2 mm			
100%	80%	60%	50%
100	130	170	200
200	250	330	400
300	380	500	600

2.2.2 Nutrient supply from subsoil

Routine soil testing is in general restricted to the topsoil (0–20 cm), though roots can also take up nutrients from the subsoil *(Boresch [1946], von Boguslawski* and *Erichson [1972], Mengel [1978], Bergmann [1980], Kuhlmann [1983]).* In detailed field measurements of water and nutrient uptake by crops from a loess soil it was found that as moisture content of the topsoil decreased and with decreasing uptake rates over a season up to 30% and 50% of the daily P- and K-requirement could be supplied by the subsoil *(Fleige et al. [1981], Grimme et al. [1981]).*

Again *Bergmann [pers. comm.]* suggests conversion of nutrient contents into nutrient availabilities by multiplying ppm × dm soil layer. Accordingly 90 ppm, for example, would correspond to an availability of 180 ppm with 20 cm topsoil, to one of 270 ppm with 30 cm and 360 ppm with 40 cm topsoil respectively. In other words, 90 ppm would be rated low, medium or even high with increasing depth of the arable layer and this would make quite a substantial difference in establishing a nutrient balance. Similar suggestions have been made by *Vetter* and *Früchtenicht [1977].*

2.2.3 The calculation of the nutrient balance by using soil test data

Mistakes are sometimes made in consideration of nutrient balance in the conversion of 'ppm' into 'kg/ha' available nutrient. This in any case rests on a number of arbitrary assumptions. Apart from differences in texture and rooting depth between soils the nutrient fixation or buffering capacity is an important parameter in this context. From a pure balance sheet concept one could be inclined that 'x' ppm available nutrient are equivalent to 'y' kg/ha independent of the absolute nutrient status of the soil. As Table 2, however, demonstrates the amounts of K(P) fertilizer needed to raise available soil K(P) by 1 mg/100 g soil depend very much on both clay content (K selective adsorption sites) and K(P) saturation (higher K and P fixation at low saturation). Accordingly different conversion factors should be used if soil test data are to be translated into kg/ha in nutrient balance sheets. *Vetter* and *Früchtenicht [1977]* therefore differentiate between content of soil in available nutrient and status of nutrient availability ('Gehaltsklasse' as compared to 'Versorgungsstufe').

Table 2. Quantities of K and P in kg/ha needed to raise the nutrient level by one unit in soils differing in their content of K-selectively binding minerals (from *Wiklicky* and *Németh [1981]*)

To raise		kg K/ha		kg P/ha	
EUF-K	EUF-P	K-selective minerals in %			
from	from	1–20	30–40	10–20	30–40
1→2	0.1→0.2*	300	900	>70	>100
5→6	0.5→0.6	100	250	40	60
10→11	1.0→1.1	70	100	20	30
15→16	1.5→1.6	40	50	15	15

* mg/100 g soil/30 min. EUF extraction at 20 °C

2.3 Improvements in soil testing

The differences in the actual plant availability of a unit nutrient in the low and high range of the soil testing scale respectively have led to the formulation of the basic cation saturation ratio concept (BCSR) as an alternative approach to balanced crop nutrition. In a general way *McLean [1977]* states that saturation of the CEC by 65–85% with Ca, 6–12% with Mg and 2–5% with K would be quite satisfactory. Through the determination of the cation exchange capacity this concept takes into consideration the role which clay and organic matter content of the soil play in adsorption and fixation, in the release and buffering of nutrients. It also allows us to calculate the corrective fertilizer treatment in order to bring the cation nutrient situation nearer to the optimal one.

This approach has not been accepted, however, in routine soil analysis. Instead many solvents and solvent combinations have been compared *(Fassbender [1980])*. As mentioned above none of these methods is fully satisfactory, because generally only few parameters (P, K, Mg, pH) are analyzed and the idea of a nutrient balance in the line of BSCR concept hardly considered.

One recently developed soil testing method, electroultrafiltration (EUF) promises to be an important step forward in this connection. Here, aqueous soil suspensions are exposed to an electric field of increasing strength. All nutrient ions, including inorganic nitrogen, are therefore desorbed according to their binding intensity to the soil. This gives information on the intensity and capacity of nutrient availability as well as information on the balance of nutrients and the eventual need for its correction *(Németh [1979, 1982, 1984])*. An example is given by a comparison of soil analysis of sites differing in yield (Table 3). Assuming the nutrients in the maximum yield field to be nearly optimal it can be seen that the 1 t/ha smaller yield at site two might have been due to inadequate K supply, while at sites three and four growth might have been negatively affected by the high Mn- and Fe-concentration and low P-availability, in other words by reducing or acid conditions in the soil. Much large-scale experience has been gained with this method which is the only method also including soil-nitrogen *(Németh [1984])*.

Table 3. Grain yield of spring wheat at different sites in relation to soil analysis by EUF *(Büntehof [1972])*

Yield t/ha	EUF-K me/100 g soil	EUF-P mg/100 g soil	EUF-Mg mg/100 g soil	EUF-Mn ppm	EUF-Fe ppm
5.97	0.7/0.3*	1.0	4	0.5	1.8
4.94	0.4/0.14	0.7	2	2.0	14.0
4.48	0.8/0.10	0.3	2	14.0	9.0
3.85	0.5/0.10	0.3	2	9.0	55.0

* EUF-K fractions obtained at 200 (available K) and 400 V (potentially available) respectively

2.4 Nutrient balance as determined by plant analysis

Nutrient balances in the soil can be maintained by the buffer capacity, nutrient balances in the plant are more sensitive. The plant also has a nutrient buffer capacity, but this is more easily disturbed. Because of this sensitivity, plant analysis has received much attention since the time of *Th. de Saussure* and *J. von Liebig, Bergmann [1958], Chapman [1941], Gollmick et al. [1970], Finck [1968], Bergmann* and *Neubert [1976])*, but so far it can be said that plant analysis – unless it is used in combination with soil testing – is of relatively little use in making fertilizer recommendations for annual crops. The reasons are several:

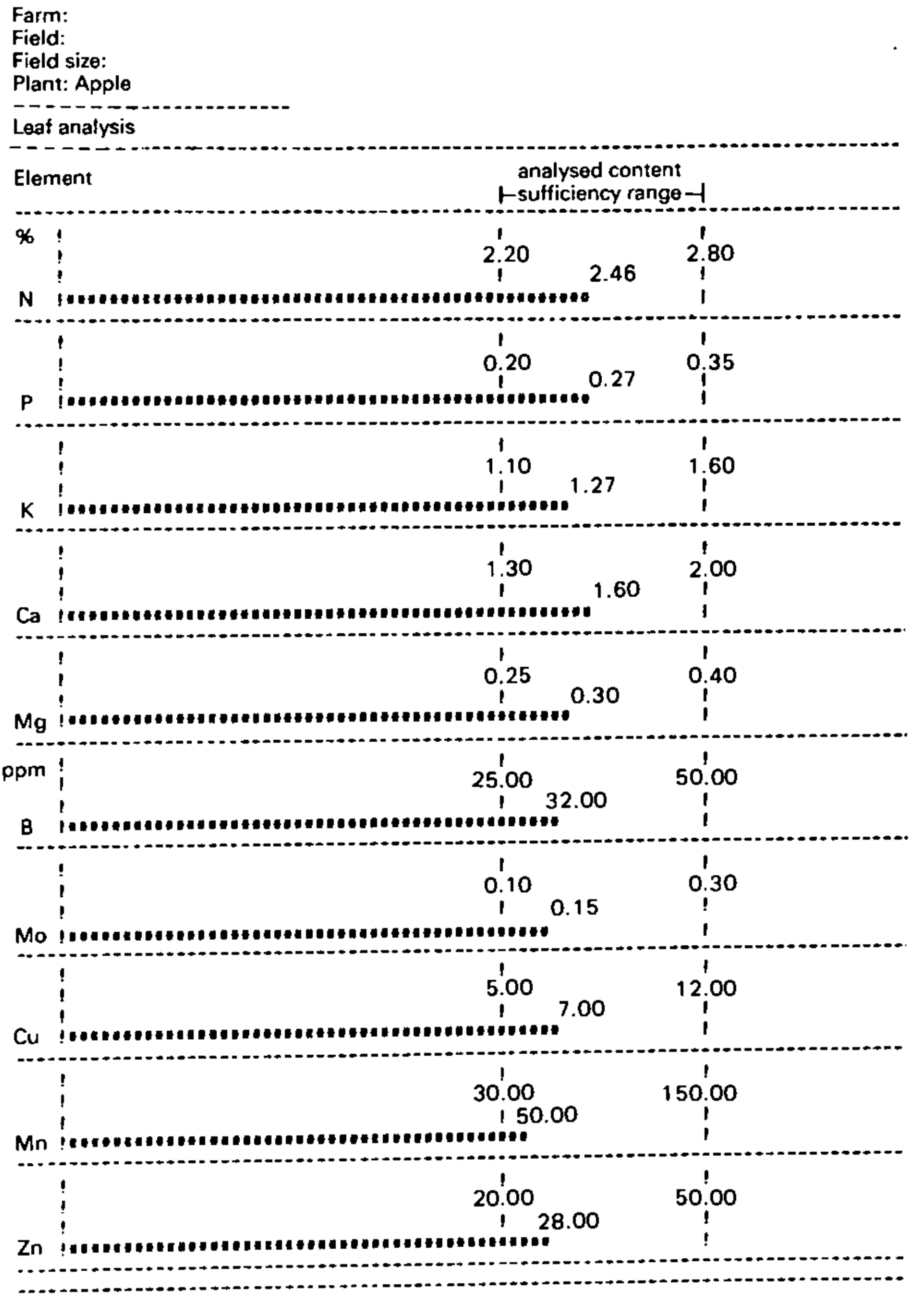
a) Rapid changes of nutrient concentrations in the tissue and time lags between sampling, analysis and corrective fertilizer treatment. For this reason semiquantitative quick tests have been recommended as an alternative, especially for nitrogen *(Williams [1969], Beringer* and *Hess [1979], Vielemeyer* and *Neubert [1980], Wollring* and *Wehrmann [1981], Wollring [1983], Scaife [1983])*.

b) Plant analysis data very much depend upon the weather and general conditions of growth.

c) The critical concentrations differ between crop species, therefore no fertilizer recommendation can be given for the following crop.

d) Plant analysis does not provide information about the reserves of the soil in plant-available nutrients.

The situation is quite different for perennial crops, where plant analysis is the essential tool in fertilizer recommendations *(Manciot et al. [1980], Bergmann [1983])*.



```
Farm:
Field:
Field size:
Plant: Apple
----------------------
Leaf analysis
---------------------------------------------------------------------------
Element                                        analysed content
                                          |-sufficiency range-|
---------------------------------------------------------------------------
%  !                                          !                   !
   !                                         2.20                2.80
   !                                          !         2.46      !
N  !####################################################          !
---------------------------------------------------------------------------
   !                                          !                   !
   !                                         0.20                0.35
   !                                          !         0.27      !
P  !####################################################          !
---------------------------------------------------------------------------
   !                                          !                   !
   !                                         1.10                1.60
   !                                          !       1.27        !
K  !##################################################            !
---------------------------------------------------------------------------
   !                                          !                   !
   !                                         1.30                2.00
   !                                          !         1.60      !
Ca !####################################################          !
---------------------------------------------------------------------------
   !                                          !                   !
   !                                         0.25                0.40
   !                                          !       0.30        !
Mg !##################################################            !
---------------------------------------------------------------------------
ppm!                                          !                   !
   !                                        25.00               50.00
   !                                          !     32.00         !
B  !#################################################             !
---------------------------------------------------------------------------
   !                                          !                   !
   !                                         0.10                0.30
   !                                          !     0.15          !
Mo !################################################              !
---------------------------------------------------------------------------
   !                                          !                   !
   !                                         5.00               12.00
   !                                          !      7.00         !
Cu !#################################################             !
---------------------------------------------------------------------------
   !                                          !                   !
   !                                        30.00              150.00
   !                                          ! 50.00             !
Mn !##############################################                !
---------------------------------------------------------------------------
   !                                          !                   !
   !                                        20.00               50.00
   !                                          !    28.00          !
Zn !################################################              !
---------------------------------------------------------------------------
---------------------------------------------------------------------------
---------------------------------------------------------------------------
```

Fig. 3. Computer print-out of leaf analysis in apple *(Bergmann [1983])*.

The nutrient balance in apple leaves is shown as a computer print-out of routine leaf analysis in Figure 3. For ten macro- and micronutrients the range of sufficiency is given and the concentration of each element found in the sample is printed in a horizontal line. The farmer can thus immediately discover which nutrient might be lacking or excessive. Looking at the nutrient balance it can be seen that the N/K ratio in apple leaves should be roughly 2:1, the K/Mg ratio 4:1 and the K/Ca ratio 0.8:1. For cereals, for oil crops or for root and tuber crops the N/K ratios, however, should be 1:1 or even 1:2 *(Beringer [1981], Mengel* and *Kirkby [1982].*

Thus in evaluating soil nutrient balance we have to consider the nutrient balance of the crop concerned and also know its specific nutrient requirement. This is, in addition, affected by the intensity and duration of nutrient uptake or in other words by growth rate and size and efficiency of the root system.

3. Experimental approaches to nutrient balances

3.1 The most demanding crop determines the required nutrient balance

In temperate zones, prevailing rotations consist of a succession of cereal crops with sugar beet, potatoes or oil seed rape as a break. The dry matter yield of root and tuber crops is generally higher, not because of different growth rates during May–July, but because of an extended growing season *(Spiertz [1982]).* Due to the size and arrangement of their leaves they need wider spacing, which could be associated with a less dense root system. Especially during the early phases of growth nutrient uptake per unit time and per unit root surface is high *(Beiss* and *Winner [1975], Werner [1976], Mengel [1978]).* Rate of nutrient transport to the root by diffusion and mass-flow must therefore be high too. This applies especially to P and K. They occur in the soil solution in concentrations mostly <0.05 and 0.5 meq/l respectively, but are needed by a crop of sugar beet in quantities of 100 (P_2O_5) and 400 kg/ha (K_2O), while for wheat the corresponding figures are about 70 and 150 kg/ha. Table 4 indicates the smaller response of cereals to K-dressings >82 kg K/ha. Sugar-beet and *Vicia faba* both being planted later and at wider spacing, on the other hand, need a higher rate of supply as expressed by larger yield responses to K dressings. Cereals can also deplete the rhizosphere for K to a greater extent than dicotyledonous species and can therefore frequently perform satisfactorily at a lower level of K availability *(Forster [1981], Hendriks et al. [1981], Steffens* and *Mengel [1981], Jungk et al. [1982], Pettersson* and *Jensen [1983]).*

Table 4. Relative yields in response to K fertilizer during ten years on six soils with clay contents between 14 and 35% (miniplots Büntehof Res. Stat.)

Crop	Years	kg K/ha/year			
		0	82	205	320
Cereals	6	91.1	100	102.6	103.5
Sugar beet	2	91.5	100	111.5	116.5
Vicia faba	2	75.1	100	116.2	130.2

Apart from the nutrient requirement of the crop the definition of a nutrient balance needed at a given site is also very much affected by the interactions between soil moisture and nutrient availability *(Barber [1982], Marschner [1983], Renger* and *Strebel [1983])*. Decreasing soil moisture causes a reduced transport of nutrients to the root. In order to satisfy the nutrient requirement of the crop under such conditions of low moisture availability the diffusive flux of nutrients must be maintained by establishing higher concentration gradients *(Grimme et al. [1971], Mengel* and *von Braunschweig [1972])*. Accordingly the nutrient balance needed for optimal growth is determined in its level also by the soil moisture as affected by soil texture and rainfall pattern.

3.2 Only long-term experiments indicate the nutrient balance

The effect of the various factors on nutrient balance can only be studied realistically in field experiments in which the effects of treatment on yield are recorded. Such experiments are site specific, so appreciable numbers are required to elucidate the problem on different soil types and under various environmental conditions.

While, for the calibration of soil test methods, large numbers of annual experiments on soils of varying nutrient status using the crop most sensitive to the nutrient in question, have been advocated by *van der Paauw [1980], Schachtschabel [1980]* and others, the study of nutrient balance demands a different approach as we are here concerned with the long-term effects of treatments. In the case of the annual experiment the aim is to avoid confounding the effects of freshly applied fertilizer with the residual effects of fertilizer applied earlier. A vital concern of the farmer, however, is the effect of treatment on nutrient reserves and their duration. Hence the advocation of long term fertilizer experiments by *Bergmann [1958], Finger [1965], Finck [1979], Richter* and *Kerschberger [1972], Vetter* and *Früchtenicht [1977], Jung [1976], Munk [1976, 1980]*.

To illustrate these points results of two experiments are given. In medium-term experiments on two soils respectively low and medium in available P at the outset Table 5 demonstrates significant responses to P on the low P site already in the second year. After the seventh year yields in the P_0 plot were only 50% of the control, whereas in the P_{32} and P_{64} plots relative yield increase became dramatic. Both these results indicate that the annual dressing of 16 kg P/ha was insufficient to maintain the P-balance. On the other field significant yield responses were rare and it seems that on this site more than 10 years would be needed until the P-maintenance dressing could be defined.

Table 6 summarizes results from a 17-year experiment on a luvisol derived from loess in which different rates of K fertilizer were applied to a rotation of cereals and sugar beet. In the first four years only sugar beet responded with significant profits while it was only in the last 4 years that also real profitable responses to K by cereals were recorded. The K_{160} treatment was designed to maintain the K balance but the highest net returns were obtained from the K_{240} treatment, probably because the K status of soil had been raised from availability class B to class C during the course of the experiment.

In summarizing what has been said so far soil testing and plant analysis are both very empirical approaches to the question: which nutrient balance is optimal for a given site and rotation on a long-term basis and which quantity of fertilizer is needed to bring the soil to this level and maintain it *(Pfulb* and *Wiechens [1971], Németh [1984])*. Both soil testing and plant analysis are essential tools in the control of long-term nutrient balances, but they are usually of less value in predicting the most economical annual fertilizer application *(Köster* and *Schachtschabel [1983], Wehrmann* and *Kuhlmann [1983])*. Nutrient balances are agronomically meaningful only for individual fields or farms. If established on a regional basis they are more related to fertilizer policies. Examples for both will be given in the next chapter.

Table 5. Relative harvestable yield in relation to P fertilizer on two sites (yields at 16 kg P/ha = 100% *(Bergmann [1965])*

Year	low P status			medium P status		
	P_0	P_{32}	P_{64}	P_0	P_{32}	P_{64}
1	97	102	103	98	112	98
2	91*	101	104*	97	98	103
3	90*	106*	106*	104	107	100
4	86*	98	105*	92	100	101
5	91*	106*	111*	101	105	114*
6	—	—	—	97	100	103
7	61*	107*	109*	97	100	103
8	55*	117*	124*	87*	98	111*
9	54*	132*	164*	93	103	101

* Significant against P_{16}

Table 6. The development of annual net returns by cereals and sugar beet in a long-term K fertilizer experiment on a luvisol derived from loess *(Lampe [1983])*

Rotation	crop	K_0* DM/ha	K_{80}	K_{160}	K_{240}
			relative to control		
1st	4 × cereals	2090	100	99	98
	1 × sugar beet	3544	117	120	127
2nd	4 × cereals	2380	102	103	104
3rd	3 × cereals	1235	102	103	103
	1 × sugar beet	3650	110	114	136
4th	3 × cereals	2492	105	113	111
	1 × sugar beet	4297	129	138	145
Ø of all crops		2544	107	110	113

* Subscript indicates kg K_2O/ha/year for cereals. For sugar beet fertilizer doses were doubled

4. Trends in the development of nutrient balances according to surveys and trials

During the last 30 years there have been dramatic changes in agricultural productivity world wide. Table 7 reflects these for the Federal Republic of Germany. Cereal yield has doubled since 1950 while sugar beet yield has increased more than that of potato. P and K application rates have doubled, while N has increased five-fold. This is due to the high response of cereals to N and resulted in a change in the ratio of fertilizer nutrients from 1:1.1:1.8 to 1:0.5:0.7. While in 1950 N_0 plots yielded only 3 t grain/ha they now give 5.5 t/ha due to improved soil fertility, varieties and management *(Sturm [1983])*. However, this higher soil productivity also requires better control of inorganic nutrients, especially of nitrogen. The use of soil and plant analysis is discussed by *Garz* and *Stumpe [1977], Wehrmann* and *Scharpf [1979], Németh* and *Wiklicky [1982], Neeteson* and *Smilde [1983], Recke [1984]* and of N-balance sheets and simulation models by *Sturm [1983]* and *Richter et al. [1982]*.

Table 7. Changes in the application of mineral fertilizer and crop yields in the Fed. Rep. of Germany *(Roemer [1983])*

Year	kg/ha/year			N:P:K	yield t/ha		
	N	P_2O_5	K_2O		grain	potato	sug. beet*
1950	26	30	47	1:1.1:1.8	2.3	24.5	32.8
1980	127	68	93	1:0.5:0.7	4.4	25.9	47.0

* Extrapolated from *van Burg et al. [1983]*

4.1 Problems of evaluating organic manure in nutrient balances

The specialization of farms on arable crops or on livestock production, which has taken place in temperate agriculture during the last 30 years has also caused changes in the nutrient balance of regions and soils. In the area of Hannover, for example, arable farming dominates on the fertile loess soils in the south whereas on the sandy soils in the north livestock farming prevails.

Soil test results of this area since 1976, when the water extraction method for P and $CaCl_2$ extraction for available K were introduced, are compared in Figure 4. The comparison is made with the assumption that those farmers asking for soil analysis do this at 3 year intervals. With all reservations with regard to the comparability of the data and to the definition of the individual ranges of availability (A = very low, C = high, E = excessive) the graph shows that for P and more so for K the proportions of soils falling in the low and medium class A + B has tended to increase. This is quite surprising for areas where the straw and sugar beet tops are recycled and where liquid manure is applied respectively. It raises a number of questions:

a) Do present soil test methods not reveal the nutrients recycled in the plant residues?

b) What are the nutrient losses from organic manure?

c) Are the fertilizer recommendations insufficient to support high yields and also to maintain the nutrient balance?

As to the first point, in a detailed study with regard to frequency of soil sampling and K uptake by ryegrass in a pot trial, *Burgdorf [1984]* found the % recoveries given in Table 8. In this experiment twice than normal quantities of straw and sugar beet tops, respectively, had been incorporated during the two previous winters at two sites each of the indicated soil types. Then soil samples were taken and the K uptake by ryegrass studied in a pot experiment. The data clearly demonstrate that recovery

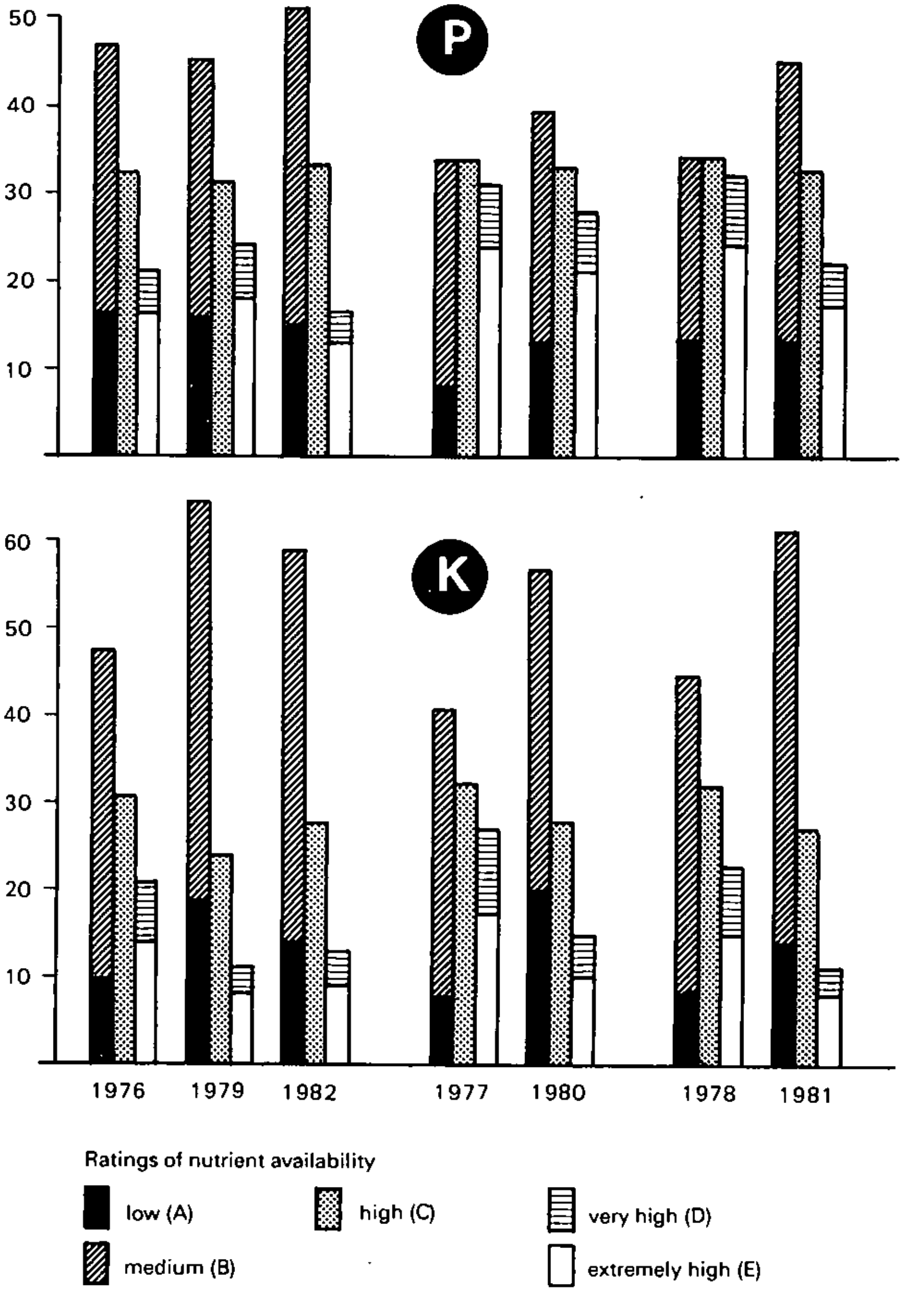


Fig. 4. Distribution of soil samples (approx. 110000/year) into different classes of P- and K-availability in 3-year intervals (Chamber of Agriculture, Hannover, Fed. Rep. Germany).

Table 8. Recoveries of incorporated plant residue-K by soil testing and plant analysis (*Burgdorf [1984]*)

	chernosem		luvisol		podzol	
	A	B	A	B	A	B
mg K($CaCl_2$)/100 g	4	6	7	15	14	24
% recovery by soil testing	25	30	47	45	51	64
% recovery by plant analysis	48	84	60	59	30*	64

* Poor growth of ryegrass

of residue-K by soil testing increases from chernozems to luvisols and podzols *i.e.* with decreasing K fixation capacity. K-recovery by plant uptake is similar on the sandy soil but higher on the luvisols and much higher than soil test recovery in the chernosems thus confirming the higher K buffer capacity of this soil type. This example reveals the enormous difficulties in establishing nutrient balances of general validity.

Nutrient losses from excessive and untimely slurry application are well known (*Scheffer et al. [1981], Fürstenfeld et al. [1984]*). Liquid manure should therefore be applied preferably in spring and be controlled by soil analysis (*Vetter* and *Klassink [1972]*).

Soil test data and yield, however, can sometimes deviate from what would be expected from nutrient balance sheets. Table 9 shows an excerpt of yield data and Figure 5 shows the trend calculations for yields and soil test data obtained in a slurry experiment on a sandy loam over six years. This experiment consisted of 4 slurry treatments: 0, 30, 60 and 2 × 60 m^3/ha applied in spring. The slurry treatments were combined with fertilizer treatments in which no fertilizer, 100 kg N/ha or 100 kg N + 240 kg K_2O/ha were applied in addition.

Looking at the yield trend regression it can be seen that N + the heavy slurry application slightly depressed yield in the first 3 years of the experiment, but yields were higher than in the no slurry treatment from 1981 onwards. It is surprising to note an increase in yield by the supplementary mineral K fertilizer in all slurry treatments, although 60 m^3 slurry/ha contained approximately 300 kg K_2O/ha *i.e.* a K balance was theoretically achieved. The trend regressions for the exchangeable K(CAL) in top- and subsoil demonstrate that in the topsoil the K-level was only maintained by 120 m^3 slurry or in the treatments where 240 kg/ha K_2O as KCl was applied. In the

Table 9. Total dry weight of maize (t/ha) in relation to slurry application and a supplementary 100 kg N/ha and 240 kg K_2O/ha as mineral fertilizer (*von Rheinbaben* and *Orlovius*, unpubl.)

slurry m^3/ha	min. fert.	1978	1979	1980	1981	1982	1983
0	–	8.3	9.5	12.5	13.6	13.2	10.9
	+N	10.4	14.5	14.8	14.8	16.5	12.5
	+NK	10.5	16.5	15.0	17.3	17.6	16.2
120	–	9.6	14.5	13.9	16.8	16.3	15.2
	+N	8.9	12.8	12.6	17.4	17.9	13.4
	+NK	9.0	16.7	14.8	17.1	17.5	16.9

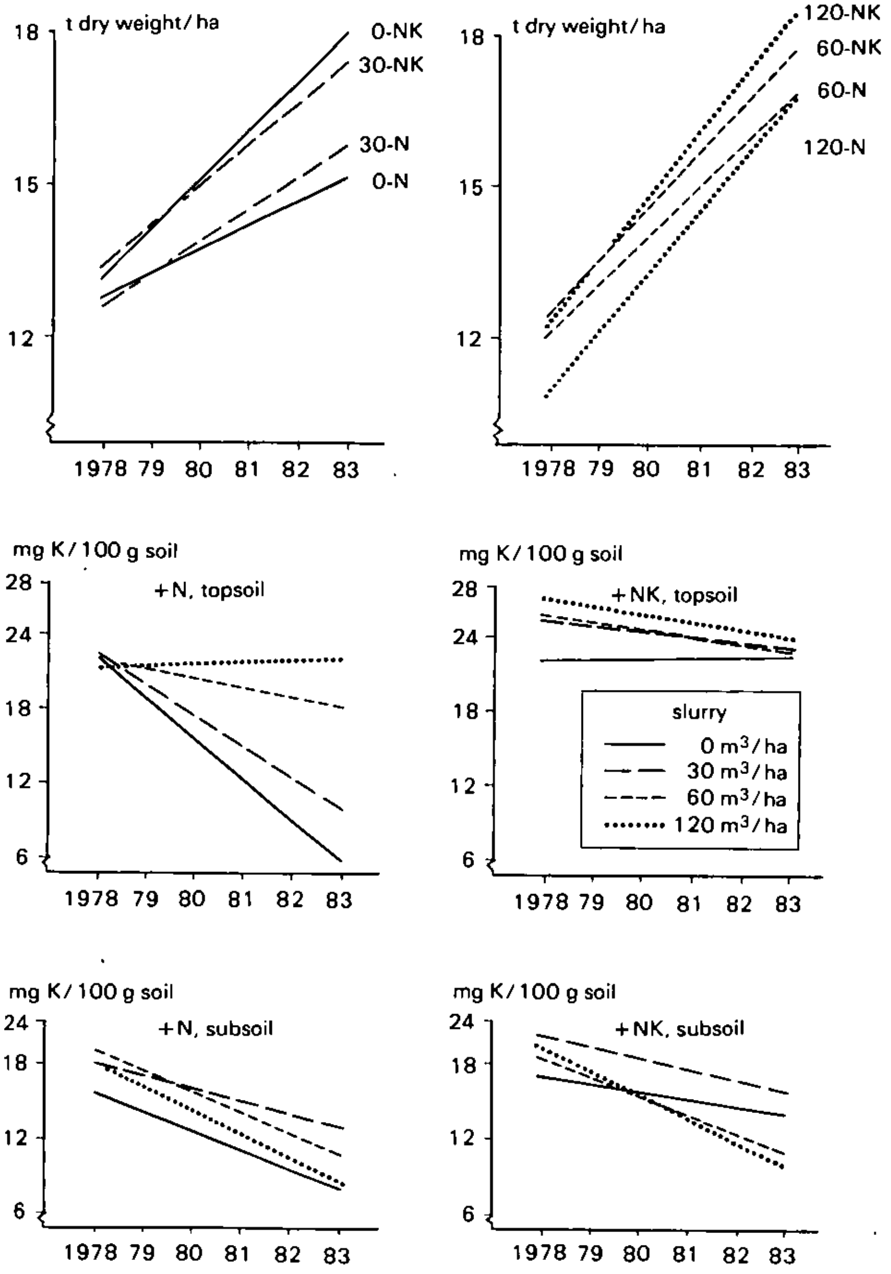


Fig. 5. Effect of annual slurry applications (m^3/ha) and supplemental mineral fertilizer (N = 100 kg/ha; K = 240 kg K_2O/ha) on the trends of maize yield and available K in a sandy loam *(von Rheinhaben* and *Orlovius,* pers. commun.).

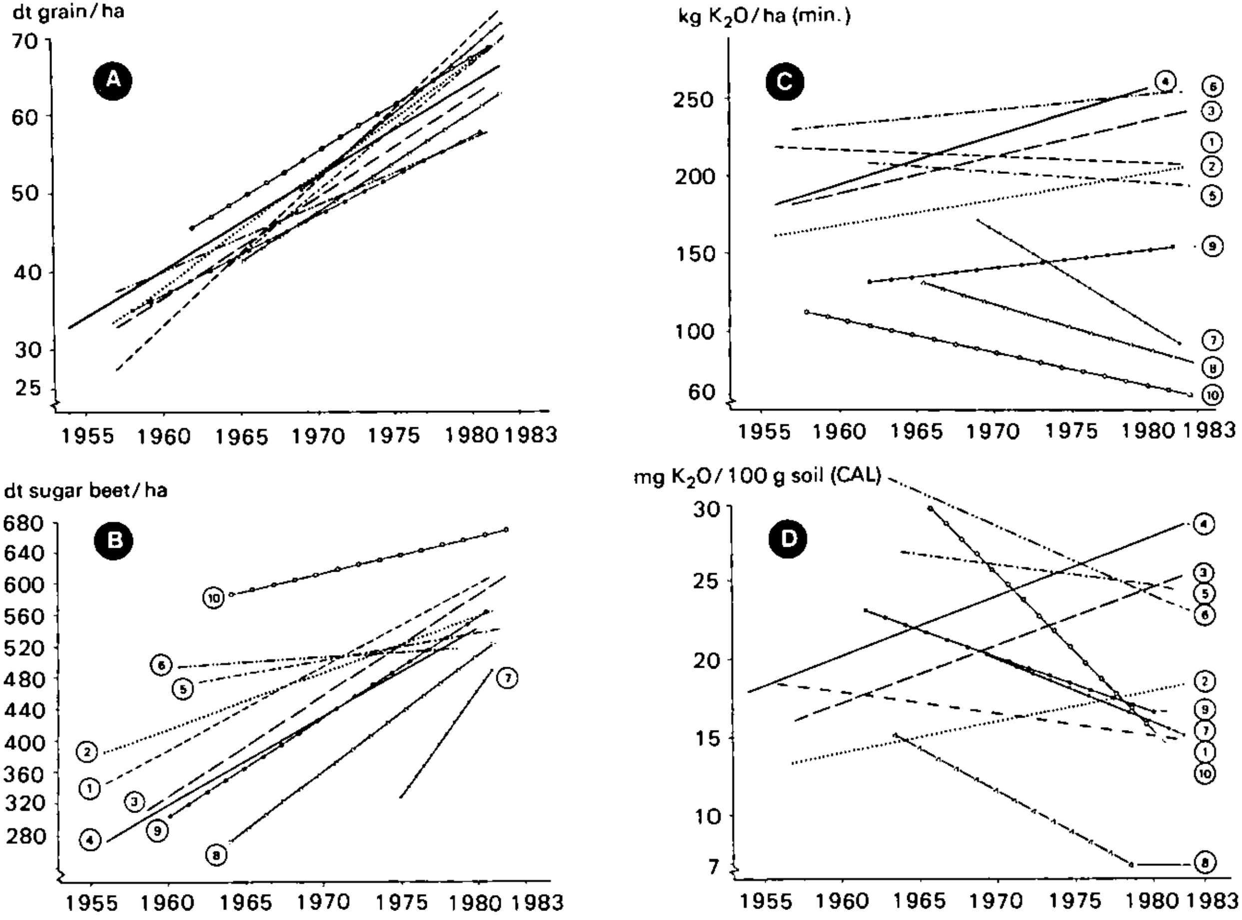


Fig. 6. Trends of yield for wheat (A) and sugar beet (B) as well as trends of K input and of available K in soil at ten different sites around Cologne, Fed. Rep. Germany (*von Rheinhaben* and *Orlovius*, pers commun.).

subsoil, however, there was a negative trend in all treatments. Because the maize could have satisfied its K requirement from the topsoil in the 60 m^3 NK and 120 m^3 NK treatments and because in these plots the decline in subsoil-K was greatest it seems that slurry-K may have percolated relatively fast and been leached. Similar data were obtained on a podzol, where soil-K trends in all treatments were negative.
From a nutrient balance point of view these experiments demonstrate the collision of interest in the definition of a nutrient balance. As long as the farmer has a benefit from the application of a supplementary mineral fertilizer he may consider this quantity to be necessary for maintaining the long-term nutrient balance. The ecologist, on the other hand, is inclined to establish an input/output balance sheet, which may not fully agree with the nutrient requirement of the crop for producing maximum yield.

4.2 Productivity and nutrient balance at specific sites

As far as the question is concerned: 'Are present fertilizer recommendations sufficient to sustain high yields and nutrient balance?' again trend calculations are shown in Figure 6. The basic annual data are from 10 sites around Cologne, Fed. Rep. of Germany. In accordance with Table 7 yields of cereals (A) and of sugar beet (B) have increased over the last twenty years at all 10 locations.
The linear trend regressions for soil-P (not shown here) were increasing for 7 of 10 sites, while for soil-K (Figure 6D) increasing trends were found only for sites number 2, 3 and 4. They correspond with the increasing rates of K fertilizer the farmers applied. Farmers of fields 1, 5, 7, 8 and 10 reduced their K-dressings and this is also mirrored by declining soil-K. Especially on site 10, the annual K dressing of < 110 kg K_2O/ha was insufficient for the excellent sugar beet and grain yields. Accordingly the soil reserves of 30 mg K_2O/100 g drop dramatically.
The data from this brief survey express visually the value of soil testing in characterizing the nutrient balance. If soil testing results are recorded continuously and evaluated in combination with the yield obtained and the quantity of fertilizer applied it will be possible to define the nutrient balance at a specific site with more precision than in the past.

Acknowledgment

The author gratefully acknowledges the contributions and criticism by Dr. *W. Bergmann.*

5. Conclusions

Reviewing the literature for the relationships between soil testing, plant analysis and long-term nutrient balance one can find both positive and negative results (see Figure 2 and 6; *Loué [1979], Rodewyk* and *Orlovius [1982], Colliver [1983], Burkart* and *Gutser [1980], Köhnlein [1981], Kuhlmann [1983]).* The reasons for this are differences between sites, soil testing methods, crops and crop management. Many parameters have been studied in detail, their integrated contributions to crop yield and nutrient balance, however, remain obscure.

For adequate definition of a nutrient balance it should be remembered that

a) long-term experiments and surveys are essential

b) the rate and extent of nutrient uptake during crop growth are better parameters of judgement than final economic yield *(Bergmann [1968], Nair* and *Grimme [1979], Fassbender [1980])*

c) the relationship between soil testing and plant analysis is best studied at an early stage of plant development *(van der Paauw [1980], Costigan* and *McBurney [1983])*.

d) soil testing and plant analysis will remain imperfect tools as long as they do not provide information on such important interactions as N/K, Al/Mg, topsoil/subsoil, etc. *(Woodruff* and *Parks [1980], Grimme [1982])*.

Both soil testing and plant analysis are of empirical character, but they are indispensible tools in the control of soil fertility. They can be improved by more comprehensive methods of analysis and especially by much better recording and processing of data by computers. But in all analyses and calculations it should finally be recalled that nutrient balances must be set at a sufficiently high level in order to avoid limitations of growth by nutrients.

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Potassium and Structural Cations Release from Micas in Dilute Solutions

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Summary

Biotite, phlogopite and muscovite particles (5–20 μ) were leached either with 0.001 M HCl or 0.0005 M $CaCl_2$ solutions. The concentrations of K and the structural cations (Mg, Fe, Mn, Al, Si) in the effluent were determined. The release of the octahedral and tetrahedral cations was approximately as high as the release of K, suggesting that dissolution of the lattice itself also contributed to the release of K to the solution in addition to the diffusion of interlayer K. Potassium and structural cations release increased markedly as the pH of the solutions decreased. Structural cations release was more sensitive to changes in pH than K release suggesting that the dissolution mechanism was more affected by pH than the exchange mechanism. Under acidic conditions biotite was the least stable mineral and muscovite was the most stable one. Under neutral conditions, more K and structural cations were released in the leaching experiments than in batch experiments. The octahedral ions were released preferentially from the micas compared with the tetrahedral cations.

Introduction

It is known that measuring potassium in the equilibrium solution, in order to predict its supplying power, can give only a first approximation. There is considerable evidence that not only the water-soluble and exchangeable potassium but also the fixed and lattice potassium may be released and utilized by growing plants *(Barber* and *Humbert [1963])*. The rate and mechanism by which this 'fixed' potassium is released into the soil solution are therefore of critical importance in plant nutrition.

It was found experimentally that potassium was readily removed from biotite and vermiculite, but much less readily from muscovite and illite *(Scott [1968], Rausell-Colom et al. [1965])*. Kinetic studies of potassium release showed that release was proportional to the square root of the duration of treatment, a relationship characteristic of diffusion controlled processes *(Rausell-Colom et al. [1965], Quirk* and *Chute [1968])*. Thus, most workers proposed that the rate-limiting stage is the diffusion of interlayer cations to the expanding edges of clay plates. However, in most of these studies, the experimental conditions favored selective release of K by interdiffusion. These experimental procedures were of two types: *(i)* selective precipi-

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tation of K in the solution by sodium tetraphenyl boron (NaTPB) *(Leonard* and *Weed [1970]);* and *(ii)* by concentrated salt solutions *(Mortland* and *Ellis [1959], Scott [1968]).*

Gilkes et al. [1973], studying biotite dissolution in HCl solutions, reported that all structural cations dissolve: the dissolution rate of K was the fastest, that of tetrahedral cations was the lowest, and that of octahedral cations was intermediate. The high rate of K release was explained by the additional mechanism of cation exchange.

The rate of K-, Al-, Fe-, and Mg-release from Fithian illite in dilute salt solutions and at $pH > 3.0$ (conditions which are dominant in nature) was studied by *Feigenbaum* and *Shainberg [1975].* They found that the cumulative cation release was proportional to the square root of duration of the treatment. The relative rate of Al release was similar to that of K release, whereas the relative rate of Fe- and Mg-release was about three times that of K- and Al-release. Since the only known mechanism for the release of the structural cations was the decomposition and dissolution of the clay, they proposed that dissolution of the clay was also an important mechanism by which K is released from the clay in dilute salt solutions.

The rate of release of K and structural cations from three micas (biotite, phlogopite, and muscovite) was measured by *Feigenbaum et al. [1981]* in dilute electrolyte solutions (0.001 N), and at pH 3.0 and 7.0. The rate of K release from phlogopite and biotite was similar to the rate of release of structural cations under acidic conditions and significantly higher under neutral conditions. These findings indicated that structural decomposition of phlogopite and biotite is dominant in acidic conditions, and that the role of interdiffusion increases in neutral conditions. Muscovite was found *(Feigenbaum et al. [1981])* to be the most stable of the three micas and the decomposition mechanism for K-release in muscovite was less important.

In the experiments of *Feigenbaum* and *Shainberg [1975]* and *Feigenbaum et al. [1981],* the release of the cations from the micas was determined in batch experiments in the presence of cationic resin which served as a sink to the released cations.

The objectives of this study were to measure the rate of release of K and other structural cations from micas (biotite, muscovite and phlogopite) exposed to leaching with dilute solutions of $CaCl_2$ and HCl. These conditions resemble natural conditions where the soils are leached with rain or irrigation water.

Materials and methods

The micas used in this study were: biotite from Bancroft, Ontario, Canada; phlogopite from Quebec, Canada and muscovite from Stoneham, Maine, USA. The minerals were obtained from Ward's Natural Science Establishment, Inc., Rochester, New York. The properties and chemical composition of the minerals are presented in Table 1. It is evident that both biotite and phlogopite are trioctahedral minerals, whereas in phlogopite 97% of the octahedral sites are occupied by Mg, in biotite only 50% of the octahedral sites are occupied by Mg, 43% of the sites by Fe and 7% by Mn. Muscovite is a dioctahedral mica, with Al as the dominant cation. Details of the analytical procedures were presented in *Feigenbaum et al. [1981].* Only the size fraction of 5–20 μm equivalent diameter, as determined by gravitational decantation,

Table 1. Chemical composition (lattice and exchange phases) of biotite, phlogopite, and muscovite

Mineral	Particle size	Chemical analysis						Exchangeable cations			
		Fe	Mg	Mn	Al	Si*	K	Mg	Na	K	CEC
		mmol/100 g						me/100 g			me/100 g
Biotite	5–20	267.7	342.4	13.3	352.4	620	175.0	3.78	0.74	1.43	10.94
Phlogopite	5–20	29.8	729.1	0.32	327.0	670	198.9	3.02	0.11	0.29	4.46
Muscovite	5–20	44.6	7.7	0.96	660.1	760	251.9	0.54	0.33	4.82	11.13

* Data from *Raussel-Colom et al. [1965]*

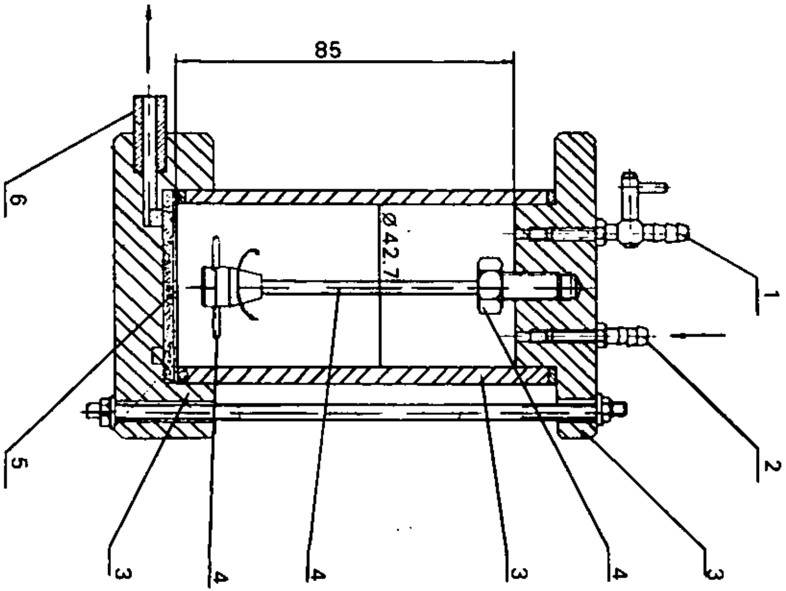

Fig. 1. Schematic presentation of the flow cell.
(1) Air relief valve.
(2) Solution entrance.
(3) Flow cell.
(4) Stirring assembly.
(5) Membrane assembly.
(6) Effluent exit.

was used in this study. The micas were freeze-dried *in vacuo* before use in the leaching experiments.

Samples of 1.5 g dry weight were placed in the flow cells, three replicates for each treatment (Figure 1). The cell is made of lucite and is provided with internal stirring and has a capacity of 120 ml. A Milipore membrane (0.45 μ) was placed in the bottom of the cell and a solution flow rate of 10 ml/hour was maintained using a peristaltic pump. The leaching solutions were either 0.001 M HCl (pH 3.0) or 0.0005 M $CaCl_2$ (pH 7.0). The effluent was collected using a fraction collector. K and Na in the effluent were determined by flame photometry. Aluminum, Fe, Mg, Ca and Mn were analyzed using an atomic absorption spectrophotometer. When very low concentrations of Al were present (<5 ppm), Al was determined following *Jayman* and *Sivasubramanian [1974]*. The Si was determined colorimetrically after *King* and *Stacy [1955]*. Cation release from the minerals was calculated in mmol/100 g of mineral and as percent of the content in the unweathered mineral.

Results and discussion

The concentration of K, structural cations, and pH in the effluent of the muscovite suspension leached with 0.001 M HCl solution is presented in Figures 2a and 2b. The concentration of most cations is initially high and decreases with leaching until a low steady state concentration is maintained. More readily soluble impurities may account for the initial high concentration of the cations in the effluent, and dissolution of the mica lattice accounts for the steady state concentration of the cations in the effluent. Also the pH of the effluent drops from an initial neutral value (due to the buffer capacity of the mineral) to a steady low value determined by the pH of the leaching solution. These changes in the pH of the suspensions in the flowing cell explain the concentration curves of Al and Fe. Initially, when the pH is neutral, the dissolution of Al and Fe is controlled by the pH. As the pH drops, the concentration of Al and Fe in the effluent increases to a maximum value, due to the increased solubility of these cations. With further leaching the concentration of these cations drops as observed with the other cations.

The concentration of K, Si, Mg and Mn in the effluent of the muscovite suspension leached with 0.0005 M $CaCl_2$ solution is presented in Figure 3. The concentration of Fe and Al in the effluent was too low to be determined by our analytical methods. The pH of the effluent was steady at pH 8.2, due to some hydrolysis of the mica. These curves are similar in shape to those presented in Figure 2, except that the concentrations are lower.

It is evident from Figures 2 and 3 that octahedral Mg, tetrahedral Al, and interlayer K were released into the solution. The diffusion and exchange mechanism alone do not account for K-release because the mechanism has to explain the release of the structural cations as well. Decomposition of the mineral evidently takes place under both acidic and neutral conditions, but the decomposition rate is several orders of magnitude higher in the acidic suspensions (Figure 2).

Similar curves were obtained for biotite and phlogopite (not presented). Based on such curves, Figures 4 and 5 for phlogopite were drawn. In these figures, the cumulative amount of K, Al, Mg and Si released by phlogopite to the effluent of HCl and

$CaCl_2$ solutions, as a function of the effluent volume, is presented. As is evident, the release of the octahedral and tetrahedral cations was approximately as high as the release of K. Thus, dissolution of the lattice itself contributed also to the release of K to the solution in addition to the diffusion of the interlayer K to the expanding edges of the minerals. Also, the effect of pH is clearly demonstrated; the cumulative amounts of K and Mg released to 3.5 l of effluent were 4.3 and 4.3 mM/100 g, respectively, at the neutral pH and 18.9 and 32.3 mM/100 g, respectively, at pH 3.5 (Figures 4 and 5). Thus, the amount of K released was multiplied by 4.4 as the pH dropped from 7.0 to 3.5, and the amount of Mg released at pH 3.5 was 7.5 times the amount released at pH 7.0. These results contradict the conclusion of *Wells* and *Norrish [1968]* and *Quirk* and *Chute* who ascribed 'no very great significance to the role of hydrogen ion concentration in the replacement of interlayer K.' Our results support *Newman's [1969]* findings that the rate of release of K was increased in the presence of H^+ ions. The fact that Mg release was even more affected by H^+ concentration in dilute solutions suggests that the protons are taken up by mica and the lattice dissolves and releases the structural cations.

It seems that under our experimental conditions, the diffusion and exchange mechanism for K release is not applicable. *Feigenbaum et al. [1981]* also found that in acidic conditions structural decomposition of the mica contributed to K release. In spite of the fact that diffusion was not the mechanism for K and structural cation release, *Feigenbaum* and *Shainberg [1975]* and *Feigenbaum et al. [1981]* found that a plot of K and structural cation released as a function of the square root of time gave a straight line. They proposed a mechanism which consisted of two elementary consecutive reactions to explain this rate law. Nevertheless, plotting our experimental results (the cumulative release of the cations) as a function of the square root of time did not give a straight line. The fact that the initial pH was high (Figure 2) and that it took about 1500 ml of 0.001 M HCl solution ($\cong$6 days) to obtain a pH of 3.5 and that the pH never dropped to the pH of the leaching solution (pH 3.0) may explain why a straight line was not obtained. The continuous change in the chemical composition of the suspension and especially the changes in the suspension pH renders it impossible to apply the analytical solutions to our data.

The total amounts of the cations released from the three micas in the leaching treatments (in mmoles/100 g) and the fraction of these amounts (calculated as the percent of the cation present in the original mineral) is presented in Table 2. Also in Table 2, the ratio, R, between the fraction of the released structural cation and the fraction of the released K is presented.

These results are compared with *Feigenbaum et al. [1981]* data which were summarized in Table 3. The following should be noted:

1) The data in Table 3 suggests that under acidic conditions biotite was the least stable mineral and muscovite was the most stable one. Whereas biotite released 96.9% of the lattice K in 7 days, muscovite released only 15.9% of the K in 21 days. In our study (Table 2), which lasted 12.5 days, much less K was released into the acid solution, and the differences between the micas were not as great.

2) Under neutral conditions (leaching with 0.0005 M $CaCl_2$ solution of pH 7.0) much more K was released in the leaching experiments (Table 2) compared with the batch-resin experiments (Table 3). Whereas in the leaching experiments, biotite released 4.1% of its lattice K in 12.5 days, in *Feigenbaum et al.* data (Table 3), only 3.03% of the lattice K was released in 55 days.

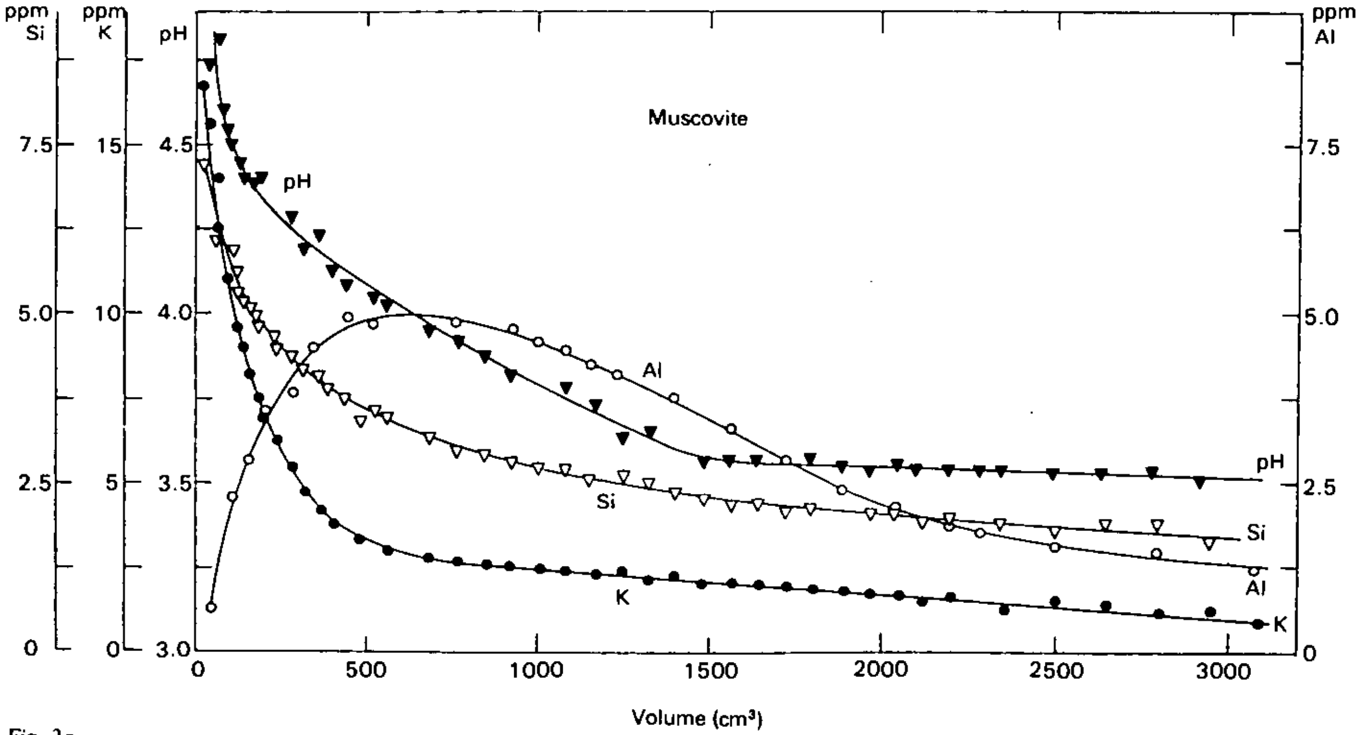
ppm
Si
ppm
K
pH
ppm
Al
Muscovite
7.5
15
4.5
5.0
10
4.0
2.5
5
3.5
0
0
3.0
7.5
5.0
2.5
0
pH
Al
Si
K
pH
Si
Al
K
0
500
1000
1500
2000
2500
3000
Volume (cm³)

Fig. 2a

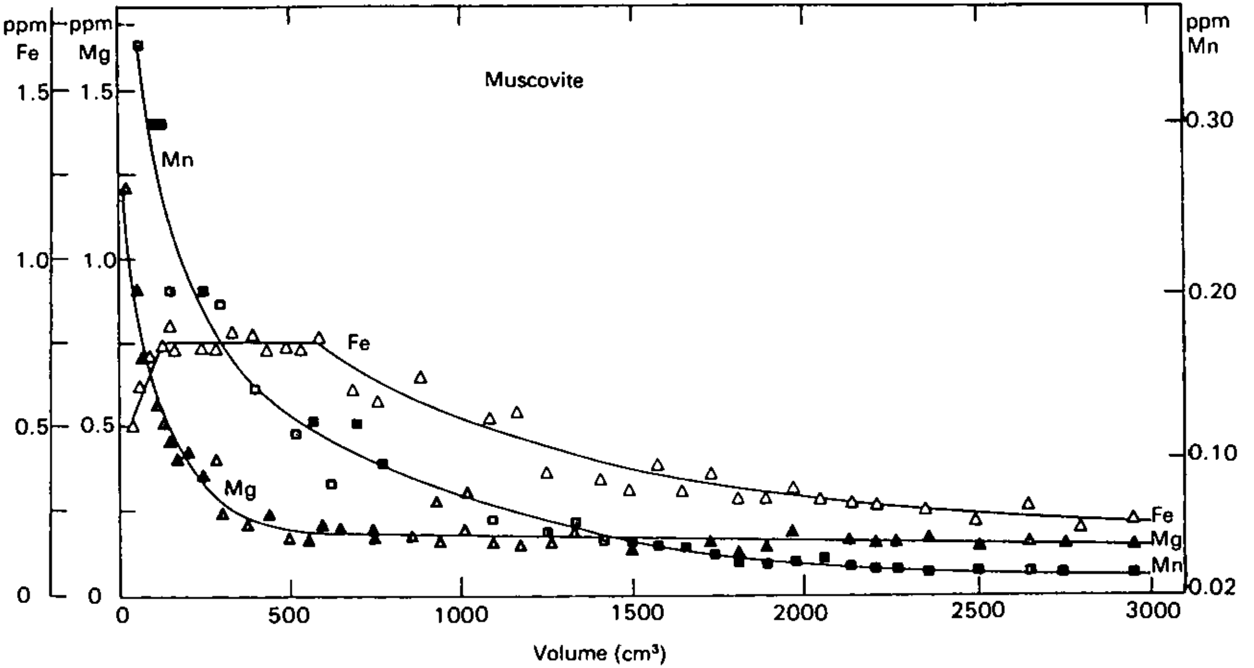

Fig. 2b

Figs. 2a+b. Potassium and structural cations concentrations in the effluent of muscovite leached with 0.001 M HCl solution.

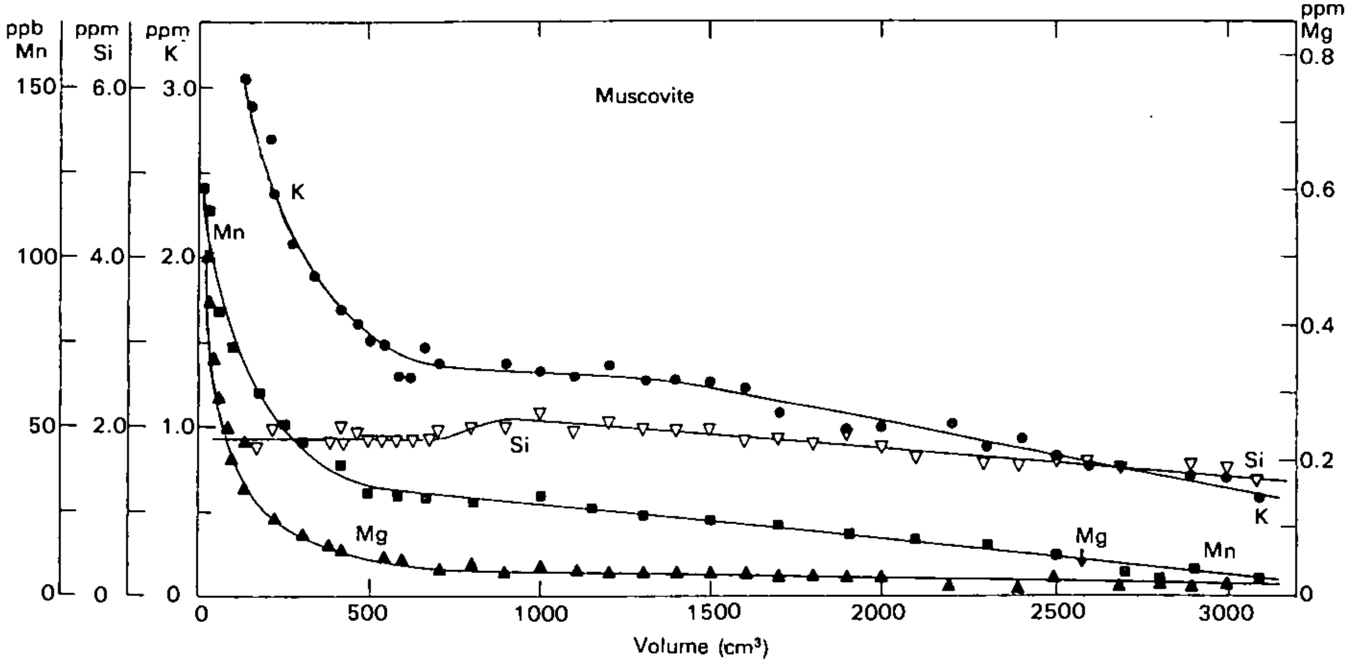

Fig. 3. Potassium and structural cations concentrations in the effluent of muscovite leached with 0.0005 M $CaCl_2$ solution.

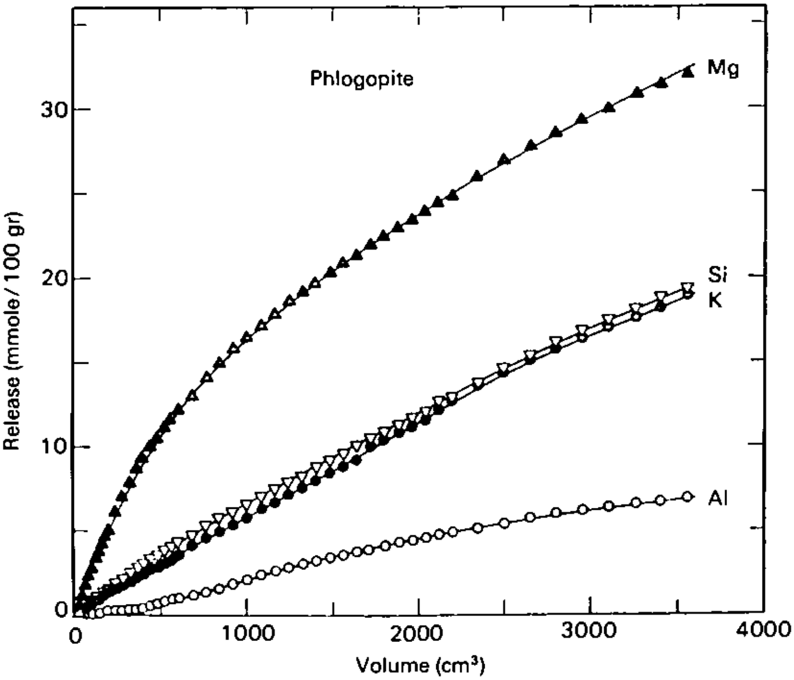

Fig. 4. Cumulative release of K and structural cations for phlogopite as a function of the volume of the acidic effluent.

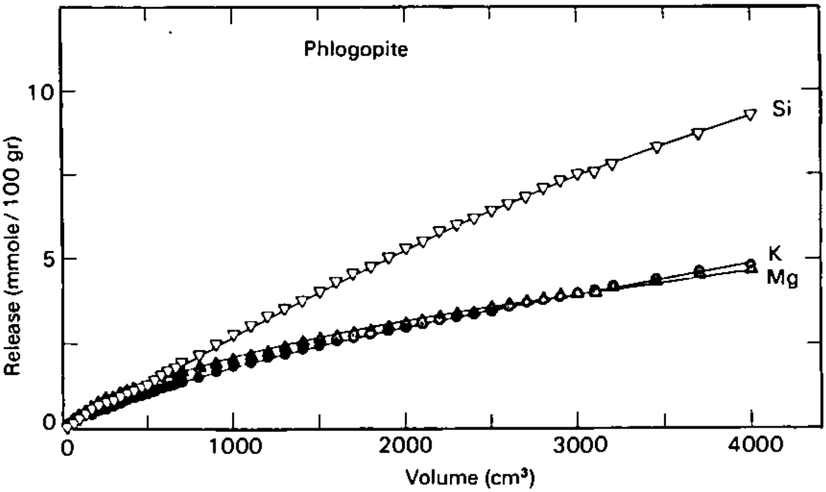

Fig. 5. Cumulative release of K and structural cations for phlogopite under neutral conditions as a function of the volume of the effluent.

Table 2. Cations released into 3.0 l of leaching solution in a) mmole/100 g; b) percent of the cation content in the mineral and c) the ratio, R, between the fraction of the cation and the fraction of K

Mineral	Treatment	K			Mg			Fe			Mn			Si			Al		
		$\frac{\text{mM}}{100\ \text{g}}$	%	R	$\frac{\text{mM}}{100\ \text{g}}$	%	R	$\frac{\text{mM}}{100\ \text{g}}$	%	R	$\frac{\text{mM}}{100\ \text{g}}$	%	R	$\frac{\text{mM}}{100\ \text{g}}$	%	R	$\frac{\text{mM}}{100\ \text{g}}$	%	R
Biotite	acid	14.6	8.3	1.0	19.4	5.7	0.69	7.5	2.8	0.34	2.2	16.7	2.0	19.8	3.2	0.39	4.2	1.3	0.16
	neutral	7.3	4.1	1.0	4.7	1.4	0.35	–	–	–	0.3	2.3	0.56	7.9	1.3	0.32	–	–	–
Phlogopite	acid	14.8	7.4	1.0	26.9	3.7	0.5	–	–	–	–	–	–	15.4	2.3	0.31	5.8	1.7	0.23
	neutral	4.7	2.3	1.0	4.2	0.6	0.26	–	–	–	–	–	–	6.2	0.9	0.39	–	–	–
Muscovite	acid	14.3	5.7	1.0	1.8	22.7	3.98	1.3	3.0	0.53	0.3	29.2	5.12	20.9	2.8	0.49	23.7	3.6	0.63
	neutral	7.6	3.0	1.0	0.6	7.0	2.33	–	–	–	0.1	10.2	3.4	14.3	1.9	0.63	–	–	–

Table 3. Release of K and structural cations from the mica minerals in batch-resin experiments*. The release of the cations is expressed in mmole/100 g, percent of the cation content in the lattice and the ratio, R, between the fraction of the cation and the fraction of K released

Mineral	Treatment and duration (days)	K			Mg			Fe			Mn			Al		
		$\frac{\text{mM}}{100\ \text{g}}$	%	R	$\frac{\text{mM}}{100\ \text{g}}$	%	R	$\frac{\text{mM}}{100\ \text{g}}$	%	R	$\frac{\text{mM}}{100\ \text{g}}$	%	R	$\frac{\text{mM}}{100\ \text{g}}$	%	R
Biotite	acid, 7 d	169.6	96.9	1.0	365.1	106.6	1.10	229.0	85.5	0.88	13.8	103.8	1.07			
	neutral, 55 d	5.3	3.03	1.0	5.0	1.47	0.48				0.50	3.76	1.24			
Phlogopite	acid, 23 d	128.9	64.8	1.0	343.7	47.1	0.73	17.2	57.6	0.89	0.19	58.1	0.90	152.4	46.6	0.72
	neutral, 61 d	3.23	1.62	1.0	6.56	0.90	0.55	–	–	–	–	–	–	–	–	–
Muscovite	acid, 21 d	40.1	15.9	1.0	2.8	36.3	2.28	7.5	16.8	1.06				57.5	8.7	0.55
	neutral	–	–	–	–	–										

* From *Feigenbaum et al. [1981]*

3) In biotite, under acidic conditions, the release of the octahedral cations in the batch experiments was similar to that of K (R values being equal to 1.0). In the leaching experiments, only about 50% of the major octahedral cations and only 16% of tetrahedral cations (Al) were released to the solution. It is evident that the leaching experiments were not as effective in dissolving the biotite lattice. This, in spite of the fact that in leaching experiments dissolved K is removed efficiently from the equilibrium solution and small amounts of K in solution are known to retard or prevent the exchange and diffusion reaction *(Quirk* and *Chute [1968])*. It seems that the difference in pH between the two sets of experiments may explain the differences in the results. In our experiment, it took 6 days for the pH of the effluent to drop from pH 7.0 initially to a steady pH of 3.5. Moreover, in the leaching experiments, the pH never dropped below 3.5, whereas in the batch experiments the pH was maintained all the time between 2.8 and 3.0. The presence of exchangeable H^+ at the resin ensured constant and ample supply of H^+ to the mica and assured its fast dissolution.

4) Under neutral conditions, more K and structural cations are released in the leaching experiments compared with the batch experiments. For example, in the batch experiment with biotite, 1.47% of octahedral Mg was released in 55 days compared with 1.4% in 12.5 days in the leaching experiments. It is evident that the efficient removal of the dissolution products enhance the dissolution reaction.

5) The release of octahedral Mn from biotite in both acid and neutral leaching solutions (Table 2) was higher than that of the dominant cations in the octahedral layer (Fe and Mg). In acidic solution, more Mn even than K was released to the leaching solutions (Table 2). Similar observations were made by *Barshad* and *Foscolos [1970], Feigenbaum* and *Shainberg [1975]* and *Feigenbaum et al. [1981]* (Table 3), who found that upon the decomposition of montmorillonite, illite and micas preferential release of the cations which 'contaminate' the octahedral positions takes place. This phenomenon was explained by the possibility that wherever substitution of another cation takes place, distortion and weakness of the structure exist and the minor cation is more easily released.

6) Mg, Mn and Si release from biotite was more affected by raising the pH than was K release. The same observation applies also to phlogopite and muscovite, where the release of the structural cations was more affected by raising the pH than was K release. This phenomenon suggests that dissolution is more sensitive to changes in pH than is exchange.

7) The percentage of the octahedral cations (Fe, Mg and Mn) released from biotite, phlogopite and muscovite into the effluent exceeds that of the tetrahedral cation (Al). Similar observations were made by *Bar-On* and *Shainberg [1970]* and *Feigenbaum* and *Shainberg [1981]*. Two mechanisms may be responsible for the preferential release of Mg, Fe and Mn from mica.

a) The relatively big Mg and Fe ions do not fit comfortably into the octahedral cavity and the distortion produced weakens the structure.

b) the breaking of the Al-O bond in the Al-O-Si linkage demands more energy than the breaking of the Mg-O (or Fe-O) bond in the Mg-O-Si or Mg-O-Al linkages; thus, the Mg-O (or Fe-O) bond is attacked first by the protons and Mg ions or Fe ions are released preferentially into the solution and/or the adsorbed phase.

Whatever the explanation is, the fact that octahedral ions are released preferentially

from the mica further indicates that dissolution of the clay is the dominant mechanism which seems to be responsible also for the release of K.
8) The relative dissolution of the octahedral ions at low pH (relative to K dissolution – the R values) is twice the relative dissolution of the octahedral ions at neutral pH. These findings indicate that structural decomposition of the mica and the dissolution mechanism for K release are more dominant in acidic conditions and that the role of interdiffusion increases in neutral conditions.
9) The high R values for Mg and Fe and Mn release in muscovite is very striking. This preferential release of these minor octahedral cations was explained already by the structural weakness introduced by these big cations which 'contaminates' the otherwise stable Al-octahedral layer.

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Evaluation of Potassium Fixation and Release in Nutrient Balances

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Summary

Relative potassium = $\frac{\text{assimilable K} \times 100}{\text{crop uptake of K}}$ is measured by soil and crop analysis. Relative K is high when assimilable soil K is low and the crop depends upon reserve K. In this case the uptake by the crops are very low. Relative K is also high when assimilable K is high in spite of luxury uptake. The minimum of the curve for this relative potassium for a crop and a soil type indicates the sufficiency level of assimilable K. Using this method we have found critical levels for assimilable soil K appreciably lower than those usually recommended in fertilizer advice 1972 and 1974. For example, for barley, assimilable K_2O at 0.3 to 0.7 mg per 100 g soil is sufficient for the heavy Founex soil though official advice gives the level as 1.3–2.0 mg. Similarly official recommendations for the light Moudon soil are from 3 to 6 mg/100 g compared with our finding of 2–3 mg. On difficult soils rich in micas and very low in assimilable K, like that of Founex, one should avoid planting crops which are unable to exploit the less available forms of soil K.

1. Introduction

Depending on the reagent and technique of extraction used, it is possible to determine fractions of potassium which differ in their availability but it is not always easy to interpret the results for practical use. Usually the aim is to measure that portion called 'assimilable potassium', that is to say easily exchangeable to the crop. Sometimes even though the level of assimilable potassium may be thought insufficient, the productivity of the soil is actually quite acceptable and wheat yields of 6 t/ha are regularly obtained. In such soils root crops, on the other hand, often have problems in satisfying their potassium needs. The improvement of our understanding of soil fertility requires study of the liberation and fixation of potassium by soils and of the ability of different crops to take it up.

1.1 Forms of soil potassium

Essentially, there are three important categories of soil K:
- potassium extracted by water saturated with CO_2 (the official Swiss method) which we arbitrarily designate 'assimilable' according to *Dirks* and *Scheffer [3];*

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- 'exchangeable' potassium corresponding to the array of cations held electrostatically around the soil colloids. These cations can easily be exchanged in this work exchangeable K content was determined by exchange with a solution of barium triethylamine *(Mehlich [7]);*
- internally held potassium in which there are two portions – 'intermediate' held within certain clay minerals and a much larger fraction representing 80 to 95% of the total *(FNIE [4]),* the potassium contained in undecomposed parent material *Quémener [83]).*

2. Soil analysis

A nutrient element is easily liberated if it is dissolved in the soil water, less easily if it is adsorbed by the clay-humus complex and only with difficulty if it is fixed by the clay minerals or chemically combined in parent material. As the strength of the reagent is increased more potassium, less easily accessible to the plant is extracted. The total potassium content of a soil may amount to 6 to 130 t/ha for 4000 t soil. Measurement of exchangeable potassium will show 60 to 2400 kg/ha K, while the soil solution contains only 3 to 30 kg/ha K^+ ions. It is this last which is directly available to the plant and this is sufficient only for part of the needs of the plant. But the soil solution K is renewed by exchange with the clay humus complex. The agronomist has to choose between:
- Using an aggressive extractant which will reveal a K supply in the soil 10 to 20 times in excess of the needs of the crop without knowing whether this reserve K is accessible to the crop;
- using water which will reveal a very low content, of the order of a few kg without knowing whether the solution is replenished according to the respective crop requirement from K reserves or by microbiological activity;
- using an intermediate reagent, approximating to water which will not touch the large but useless reserve K but which might be expected to extract that part of K extractable by the plant, for example CO_2 saturated water.

The measurement of K should be accompanied by the determination of other factors which take account of the effect of soil type on the availability of K to the plant.

2.1 Soil analysis and removal of K by the plant

We have studied the evolution of assimilable potassium to crops in an experiment using *Mitscherlich* pots of 5 l capacity. Seven different soils were used at three fertility levels:

extensive: with no application of potassium
normal: K applied to balance removals by crops
intensive: heavy application of potassium

Plant uptake was compared with the indications of soil analysis by *Dirks* and *Scheffer's [3]* method, by determination of CEC according to *Mehlich* with $BaCl_2$, by extraction with double lactate and by extraction with ammonium lactate. The experiment ran for ten years from 1968 to 1978.

Table 1 shows the results obtained on the extensive (no K fertilizer) treatment and shows disparity between K as determined by different methods and K taken up by the crops.

Table 1. K removed by 10 years cropping in pots compared with K extracted by various reagents and total soil K (g per pot)

Origin	Soil K					
	Total	Ds 1	CEC 2	DL 3	AL 4	Crop uptake 10 years
Treycovagnes	26.6	0.61	0.93	1.88	1.85	5.54
Missy	99.4	0.11	0.27	1.05	1.17	5.42
Vouvry	118.4	0.09	0.14	0.50	0.50	3.24
Moudon	81.3	0.21	0.29	1.24	1.33	2.17
Founex	91.5	0.02	0.12	0.42	0.50	2.86
La Rippe	43.2	0.15	0.22	0.66	0.92	2.17
Pailly	81.9	0.07	0.14	0.61	0.61	2.44

[1] CO_2 saturated H_2O *(Dirks* and *Scheffer)*
[2] By $BaCl_2$ *(Mehlich)*
[3] Double calcium lactate methode
[4] Ammonium lactate method

2.2 Effect of fertilizer treatment on assimilable K values in soil sampled 2 months after fertilizer application

Applying K changes the assimilable K content of the soil, the extent of the change depending on soil type. Soils with high CEC show only a small change while those of low CEC are very sensitive to K application. Organic soils (Treycovagnes soil) react similarly to light textured soils though their CEC is very high. K adsorbed on organic matter is more easily released than that adsorbed on clay minerals (Table 2). Two months after appying K to uncropped soil, extraction by CO_2 saturated water is related to CEC as shown in Table 2. The relationship with CEC is not close and it would be important to study the effect of the various types of clay.

Table 2. Effect of K fertilizer on assimilable soil K

K_2O applied per pot		0.0	0.8	1.6	2.4	3.2
Origin	CEC (me %)	Assimilable K after 2 months cropping (mg %)				
Treycovagnes	122.7	0.8	1.8	4.8	9.8	20.0
Missy	33.3	0.4	0.7	1.4	2.1	2.9
Vouvry	12.0	0.5	0.8	1.7	5.8	19.0
Moudon	11.3	0.3	1.6	4.8	11.0	21.0
Founex	25.3	0.2	0.3	0.7	1.1	1.4
La Rippe	32.0	0.3	0.7	1.9	5.2	10.0
Pailly	12.0	0.4	1.0	3.2	9.9	13.0

2.3 Measurement of potassium release

Adsorbed K is released by exchange with barium in a solution of barium triethylamine *(Mehlich [7])*, with which the soil is shaken and K measured in the filtrate. By repeating the process several times it is possible to measure the extent to which adsorbed K can replenish the soil solution. Results for 6 different soils are given in Table 3. From the results obtained it can be seen that soils rich in expanding clays and organic matter liberate more potassium in the first exchange than those with less organic matter and non-expanding clays (*e.g.* Founex) (Tables 3, 4, 5). In subsequent exchanges, the former liberate only a little K as compared with the latter. However this result is not always confirmed and it is doubtful whether this technique can distinguish soils of high saturation capacity.

Table 3. Liberation of soil K by repeated exchange with barium triethylamine

Origin	K exchanged as % of total			Exchangeable K me/100 g
	1st exchange %	2nd exchange %	3rd exchange %	
Missy	72.4	17.4	10.2	0.490
Vouvry	72.1	14.0	13.9	0.215
Moudon	81.7	11.0	7.3	0.410
Founex	68.3	17.1	14.6	0.205
La Rippe	67.0	16.5	16.5	0.425
Pailly	79.7	15.8	10.5	0.190

Table 4. Characteristics of the experimental soils

Origin	Clay %	Organic matter %	CEC fine earth me/100 g	Mineral CEC me/100 g	Organic CEC me/100 g	S %
Treycovagnes	29,9	60.6	122.7	9.7	112.9	71
Missy	41.6	5.7	33.3	10.6	22.6	63
Vouvry	18.6	2.8	12.0	4.2	7.7	78
Moudon	11.3	2.3	11.3	4.5	6.7	40
Founex	44.9	4.7	25.3	13.3	11.9	87
La Rippe	26.2	6.6	32.0	14.2	17.7	56
Pailly	14.8	1.9	12.0	4.9	7.1	60

Table 5. Clay analysis of soils

Origin	Chlorite	Expanding clays	Mica (illite)	Kaolinite
	14 Å	10 to 14 Å	10 Å	7 Å
Missy	1	2 (Vermiculite)	3	1
Vouvry	2	0	3	2
Moudon	2	2 (Montmorillonite)	2	2
Founex	0	2 (Vermiculite)	3	1
La Rippe	3	2 (Vermiculite)	1	1
Pailly	1	2 (Vermiculite	3	1

0 trace or nil   1 low   2 average   3 high

3. Relative potassium and assimilable potassium

(Dirks and *Scheffer)*

From the behaviour of the treatment in which no potassium fertilizer was applied it is possible to deduce a relationship between soil K supply (assimilable K) and uptake by the crop. We use an expression 'relative K' which is defined:

$$\text{relative K} = \frac{\text{assimilable K}}{\text{K uptake}} \times 100$$

Relative K as applied to a particular crop enables us to express the potassium fertility of the soil in relation to that crop. The minimum of the curve for relative K indicates the level of assimilable K corresponding to sufficiency *(Ryser [10])*.
We have been working since 1980 on the determination for different soils and different crops of this (satisfactory) level of assimilable K. Figure 1 gives the general form of the curve relating assimilable and relative K, indicating zones of excess, deficient and satisfactory K supply. Figure 2 shows the relationship for barley on La Rippe soil, while the values determined (for barley) on other soils are indicated in Table 6. The *Dirks* and *Scheffer* values for sufficiency for the barley crop are given in Table 7. Similar work has been done with maize and potatoes, using the same method as applied to barley in 1980.

Table 6. Relative potassium – barley crop 1980

Origin	K level (in increasing order)*				
	I	II	II	IV	V
Treycovagnes	19	13	⑩	17	19
Missy	4	5	⑥	6	7
Vouvry	3	4	⑥	㉙	37
Moudon	13	17	⑬	48	68
Founex	4	3	③	4	4
La Rippe	6	⑥	7	21	28
Pailly	13	10	⑨	⑲	25

* *Encircled* values indicate sufficiency in assimilable K

Table 7. Assimilable K defined by relative K for barley 1980

Origin	Assimilable K *(Dirks* and *Scheffer)* mg K_2O/100 g soil	
	Results	Reference values
Treycovagnes (organic)	1.3–5.6	3–6
Missy	0.5–1.0	1.3–2
Vouvry	2.0	2–4
Moudon	2.0–3.0	3–6
Founex	0.3–0.7	1.3–2
La Rippe	1.0–1.5	2–4
Pailly	1.0–1.2	3–6

The relationship between optimum assimilable K and CEC for three crops is shown in Figure 3.

Our results are not surprising since the authors of the extraction method recognized that the critical level would vary with soil type and with crop *(Thun et al. [12])*. They gave 1.5 mg K_2O/100 g soil as the critical value for wheat, oats, rye, harley and potatoes and 2 mg/100 g for sugar beet.

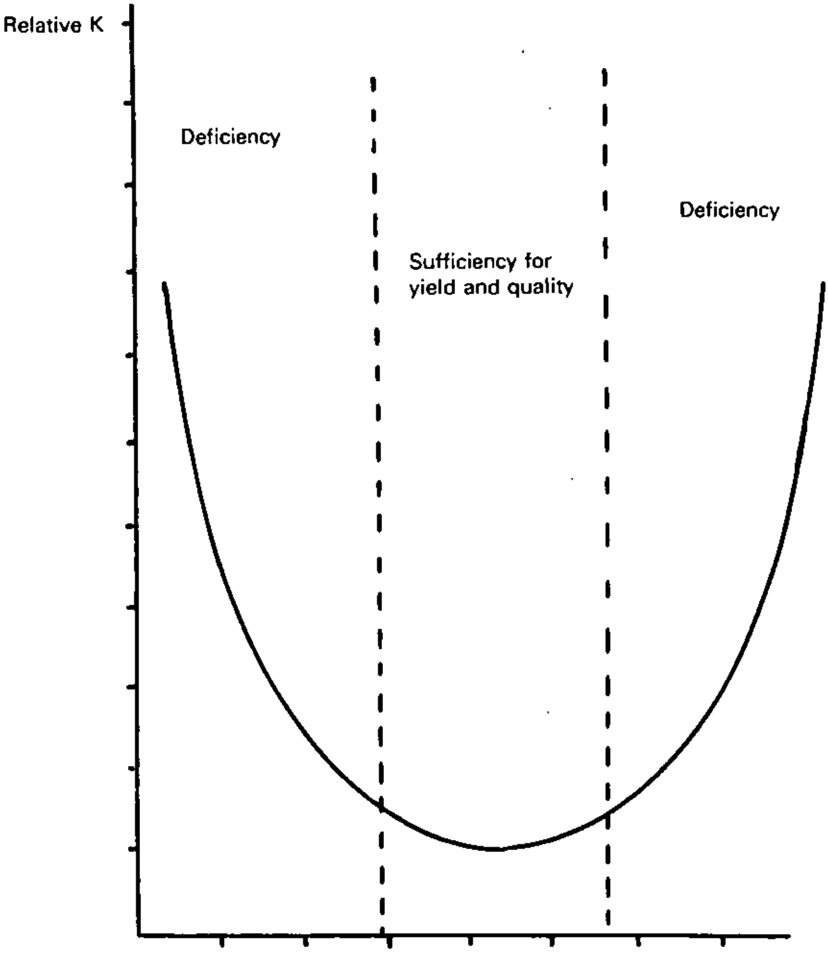

Fig. 1. Scheme for interpreting values of relative K as related to assimilable soil K.

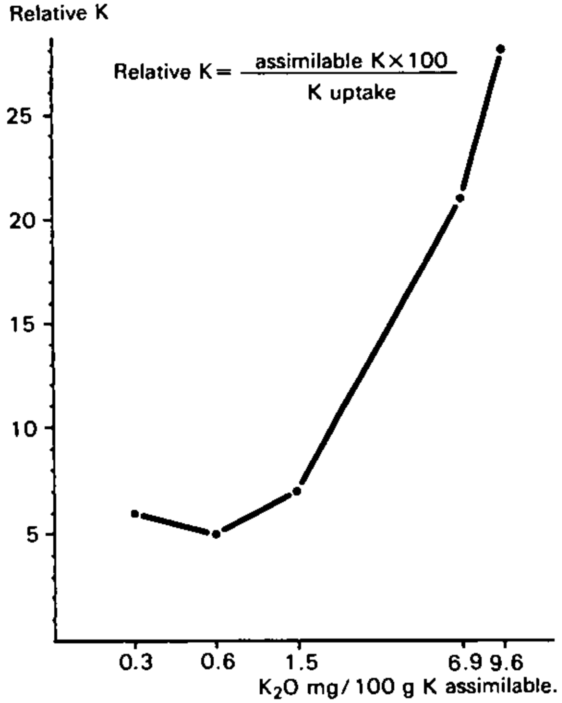

Fig. 2. Relationship between assimilable K and relative K (soil of La Rippe; barley; 1980)

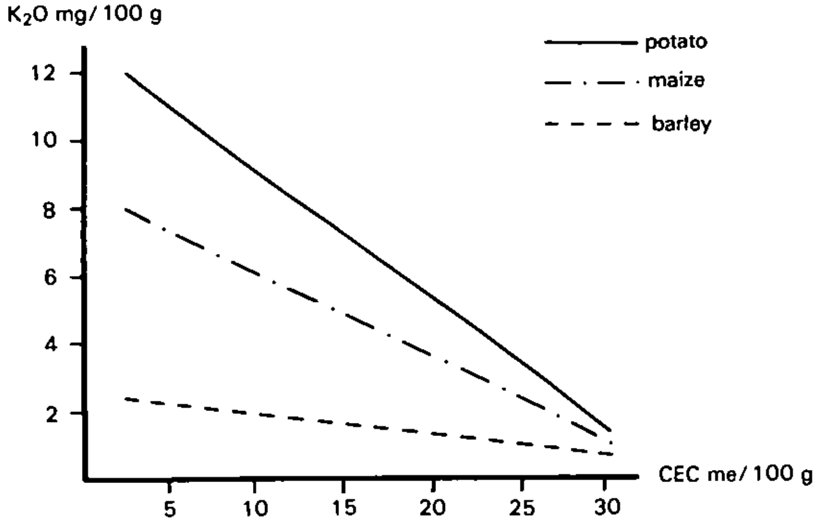

Fig. 3. Assimilable K related to CEC (no K fertilizer).

4. The interpretation of assimilable potassium values

(Dirks and *Scheffer)*

Using the concept of relative potassium improve the interpretation of *Dirks* and *Scheffer* values, but the interpretation must be related to the soil type. Classification of soils by cation exchange capacity can replace classification by pedology or texture. The importance of CEC and clay content has been stressed by various authors *(Loué [6], Addiscott [1], Quémener [8]).* Limiting values for assimilable soil K based on relative K are related to CEC. By limiting values we understand the range where the crop neither suffers from deficiency nor is subject to luxury consumption. For mineral soils of high CEC the values are low while for mineral soils of low CEC they are high. According to our reckoning the sufficiency values used for assimilable K in Switzerland *(Reckenholz, Liebefeld* and *Changins 9: Commission Romande des Fumures [2])* could be reduced for all soil types. Nevertheless allowance must be made for the crop being grown. Some crops can take up from the soil less easily available forms of potassium (interlayer and difficultly exchangeable K). This applies particularly to ryegrass, wheat and barley *(Steffens* and *Mengel [11], Keller [5]).* In contrast, other crops like maize, clover and tomato have little ability in this respect. In a rotation, the critical level to be adopted is that relating to the most K demanding crop. It has to be recognized that on some very high clay soils certain crops will present difficulties even though K fertilization is higher.

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Nutrient Losses by Leaching and Run-off and Possibilities of Their Control

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Summary

In this paper, experimental data are reported of nutrient losses by leaching, run-off and erosion. Agricultural practices are examined for the control of nutrient losses.

The selection of correct management practices appropriate to a given place will almost universally control nutrient loss from farmland caused by water transport. The aim in flat land should be to minimise water percolation. The rate of percolation depends mainly on the physical properties of the soil and it is high on coarse sands. On sands and on clays it is important to build up soil organic matter in order to improve water holding capacity. Fertilizer management is most important especially in the case of nitrogen. The use of organic N seems to offer advantages in gradual release and control of leaching.

So far as potassium is concerned leaching is hazard only where heavy applications are made on sandy soils.

The inclusion of long duration forage crops in the rotation is helpful in the control of nutrient losses by either leaching or run-off.

Practices recommended for sloping land generally aim to favour infiltration and to reduce the amount and velocity of run-off. However, a specific strategy should be developed for each field and agricultural system in a given environment since reducing the hazard in one respect may increase it in another.

1. Introduction

Leaching, run-off and erosion are natural processes influencing soil genesis and landscape evolution. As natural phenomena such processes are, in many ways, beneficial to soil renewal and landscape dynamics. However, when considering the nutrient turnover in the rhizosphere of a given land unit, the three water transport processes are factors responsible for irreversible nutrient loss and, consequently, for degradation of soil chemical fertility.

By taking up nutrients crops deplete the soil reserves. The maintenance or improvement of soil fertility depends on the restoration to the soil of crop residues and the application of fertilizers and manures. However, the effectiveness of the maintenance and improvement of fertility depends also on the farmer's skill in applying sound practices of soil and water management for the control of wasteful losses due to leaching, run-off and erosion *(Hudson [1971], Frere [1976], Novotny* and *Chester [1981]).*

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Another very important aspect of nutrient loss from farmland through water transport is the possibility of undesirable effects on the environment. Pollution of water bodies from cropland sources can be caused by massive application of fertilizer and manures without proper attention to good soil and water management practices.

Many authors have pointed out that the most important nutrients which are affected by water transport processes are nitrogen and phosphorus, either in relation to the degradation of soil fertility *in situ* or in relation to nonpoint pollution of water bodies *(Stewart [1970], Knisel [1980], Novotny* and *Chester [1981]).*

Frere [1976] reported the range of nitrogen and phosphorus concentrations in different water bodies (Figure 1), deducing the average spatial rates of nitrogen and phosphorus exportations in water and sediments from large areas (Figure 2).

However, considering a specific land unit, many factors affect the relative amount of nutrients carried away by the three water transport processes: a) rainfall amount, intensity and pattern during the year; b) soil matrix properties and horizon characteristics; c) land topography; d) vegetative cover; e) soil, water and crop management practices.

Due to the many factors involved, it is very difficult to forecast the amount of nutrient losses from a given cropland unit. Numerous efforts have been made to produce models to predict nitrogen and phosphorus nonpoint pollution from cropland *(Frere et al. [1975]* – Actmo, *Anon. [1975]* – Hsp, *Knisel [1980]* – Creams).

In this paper, some experimental data on the assessment of relative losses of nutrient by leaching, run-off and erosion are reported. Agricultural practices designed to control nutrient loss are also examined.

2. Nutrient leaching in relation to soil type, tillage practices and fertilizer application

Lysimeter experiments have been carried out at the *Istituto Sperimentale Agronomico, Sezione di Modena,* and several results have been published *(Spallacci* and *Boschi [1980], Spallacci* and *Lanza [1980], Spallacci [1981], Spallacci [1982]).*

The data on leaching presented here derive from these papers but also include some unpublished results.

The lysimeters (size 1 × 1 × 1 m) were filled using disturbed soil samples, but preserving the separation between the tilled layer and the subsoil layer. The lysimeters received both natural rainfall and irrigation water, the latter distributed according to the rainfall seasonal pattern, to cover the optimal water requirements of the cultivated crops.

2.1 Nutrient losses by leaching in relation to the use of fertilizer vs. FYM

The experimental lay-out can be summarized as follows:

a.1) Maize crop without fertilizer or manure
  2) Maize crop with fertilizers (300 kg ha^{-1} N; 150 kg ha^{-1} P_2O_5; 200 kg ha^{-1} K_2O)
  3) Maize crop with organic manure (50 t ha^{-1} FYM)
b. Cultivated fallow without fertilizer.

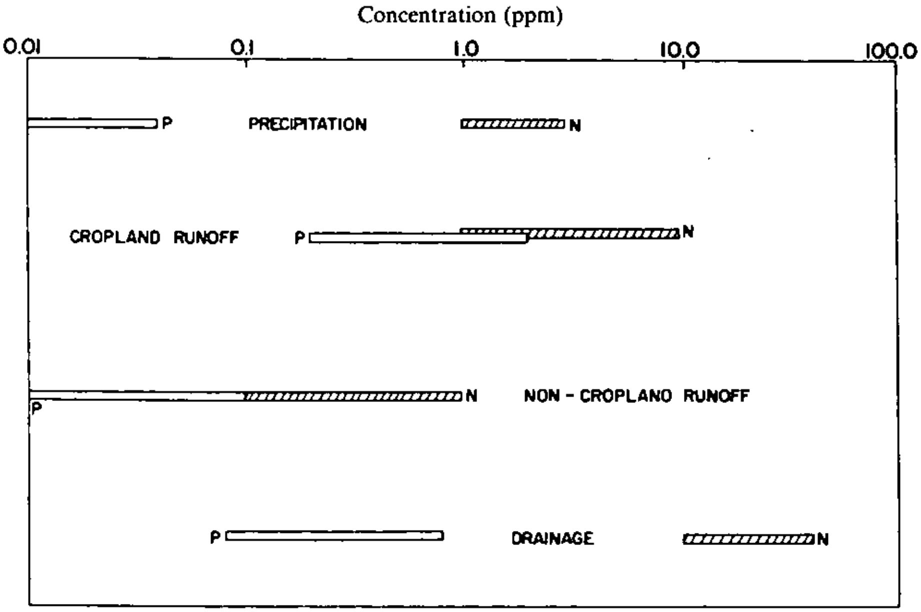

Fig. 1. Range of nitrogen and phosphorus concentrations in different waters (from *Frere [1976]*).

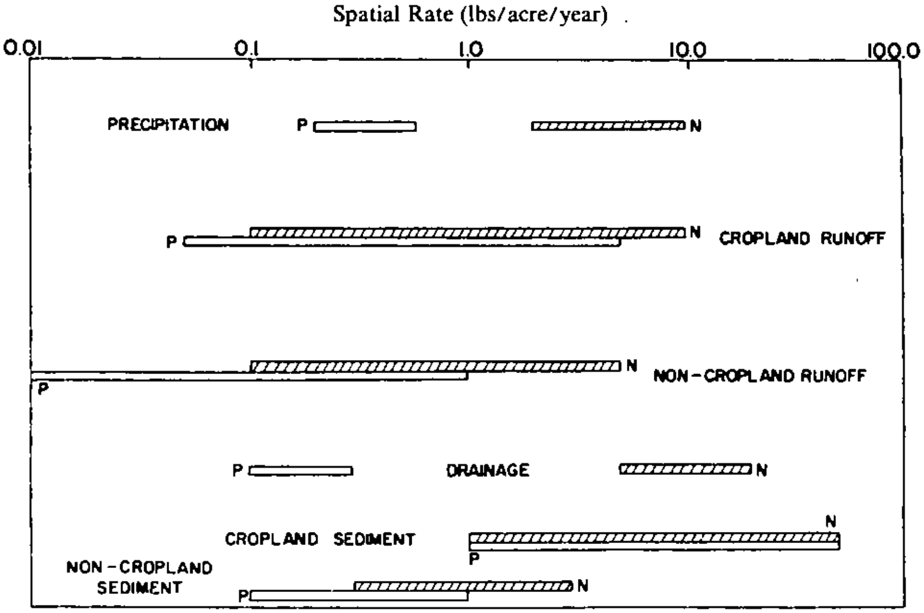

Fig. 2. Range of spatial rates of nitrogen and phosphorus in waters and sediments (from *Frere [1976]*).

Maize was grown continuously with uniform technique for the period 1970–1976. Nitrogen was applied in three split dressings. All data refer to the hydrologic year from the beginning of March.

The characteristics of the sandy loam soil *(Fluventic Eutrochrept)* used in this experiment are reported in Table 1.

The amount of water seepage and leached nutrients in relation to different crop-fertilizer treatments are reported in Table 2. The amount of percolation water from the fallow lysimeters was consistently higher than in the maize lysimeters (particularly in the first years of the experiment when both received the same amount of irrigation water). Transpiration by the maize crop was distinctly higher than evaporation from bare fallow. Applying fertilizer generally increased transpiration while reducing percolation through improving plant growth.

Nutrient losses were higher in the fertilized lysimeters, with some peculiar pattern in relation to specific chemical elements. The losses of total salts, Ca and Mg were higher in the fertilized lysimeters in comparison with the unfertilized lysimeters. Na, Cl and, to a lesser extent, SO$_4$ losses were lower in the fallow lysimeter than in maize lysimeters. K loss was higher from the FYM treatment than from fertilizer. It is interesting also to observe the greater leaching of HCO$_3$ in the unmanured lysimeters whether cropped with maize or fallowed.

The most interesting data are those relating to N leaching. This was higher from fallow than from cropped lysimeters. Between manurial treatments, N loss was minimum when no fertilizer was applied since all the available N was quickly taken up. Indeed, under these conditions, where water supply was optimal throughout the growing season, N supply would be the limiting factor for growth. FYM increased the supply of mineral N in the soil but the slow release by microbial activity reduced the leaching hazard. More N was leached from N fertilizer even though the dressing were split.

Amounts of percolation water and nutrients leached are listed in Figure 3. Percolation was in general related to annual rainfall but it also seems clear that it was also affected by crop and to a lesser degree by manurial treatment. Losses of soluble salts, Ca, Mg, SO$_4$ and Cl followed roughly the same pattern as percolation throughout the 7 year period but Na losses only for the last four years.

A more interesting aspect to underline is the decreasing loss of nutrients by leaching in the unfertilized fallow lysimeters advancing in the years, in comparison with the maize crop. The loss of K appears to be slightly higher from the FYM treatment and K is not affected as much as other nutrients by the amount of percolated water. On the other hand, N losses are strictly related to the amount of percolated water, with the exception of unfertilized and FYM treated maize, for which the pattern of losses appears very flat in the different years. An exception is observed in 1975 when a peak loss of N was recorded also for the FYM applications.

Table 1. Chemical and physical composition of the soil *(Fluventic Eutrochrept)* at the beginning of the lysimeter experiment on continuous maize in 1970, at the Ist. Sper. Agronomico, Sezione di Modena

Treatment combination*	Total N (Kjeldahl) ‰	Total P ‰ P_2O_5	Available P (1) ppm P_2O_5	Total K (2) ‰ K_2O	Exchangeable K (3) ppm K_2O	Organic matter (4) %	C/N	pH (in H_2O)
Tilled soil layer (0–30 cm)								
a.1	2.18	1.61	63	2.37	100	2.77	7.4	7.0
a.2	2.07	1.51	34	2.29	89	2.77	7.8	7.0
a.3	2.04	1.65	47	2.29	89	2.77	7.9	7.2
b	2.16	1.44	31	2.24	82	2.78	7.5	7.0
Subsoil (30–90 cm)								
a.1	0.73	1.17	–	2.62	109	0.81	6.4	7.6
a.2	0.69	1.08	–	2.66	98	0.78	6.5	8.0
a.3	0.73	1.24	–	2.68	98	0.78	6.2	7.6
b	0.62	1.06	–	2.66	98	0.67	6.3	7.4

Average textural composition of tilled soil layer: 53% sand, 35% silt, 12% clay.

* Explanation in the text.

(1) Na-acetate + acetic acid, pH = 4,8. (2) In concentrated HCl. (3) NH_4-acetate, pH = 7. (4) Dichromate oxidation.

Table 2. Amounts of percolation waters (mm $year^{-1}$) and nutrient losses (kg ha^{-1} $year^{-1}$) in lysimeters under continuous maize with different fertilizer treatments and under cultivated fallow (average of 7 years of trials at the Ist. Sper. Agronomico, Sezione di Modena)

Treatment combination*		Percolation waters	Total salts	K_2O	Na_2O	CaO	MgO	NO_3-N	Cl	SO_4	HCO_3
a.1	m̄	460.5	3827.5	5.4	272.4	1040.2	192.0	79.1	416.8	892.7	1207.4
	V.C.%	26.8	30.3	31.0	74.1	30.8	32.4	27.7	38.4	32.5	44.7
a.2	m̄	412.4	4758.9	6.3	280.4	1245.1	227.9	186.0	522.7	933.7	1008.6
	V.C.%	29.8	39.9	28.3	68.6	41.8	41.8	48.5	44.2	37.4	38.8
a.3	m̄	377.3	4500.7	8.3	289.8	1152.5	213.1	125.9	582.3	885.6	977.7
	V.C.%	28.5	40.9	47.6	78.0	40.7	41.5	50.2	44.2	37.6	38.2
b	m̄	527.4	3985.0	5.2	157.0	1088.3	196.6	208.4	202.4	685.3	1214.1
	V.C.%	28.8	40.2	57.1	42.2	42.4	49.6	36.9	81.7	43.4	32.7

* Explanation in the text.

m̄ = average over the period 1970–1976.

V.C.% = variation coefficient percent over the years.

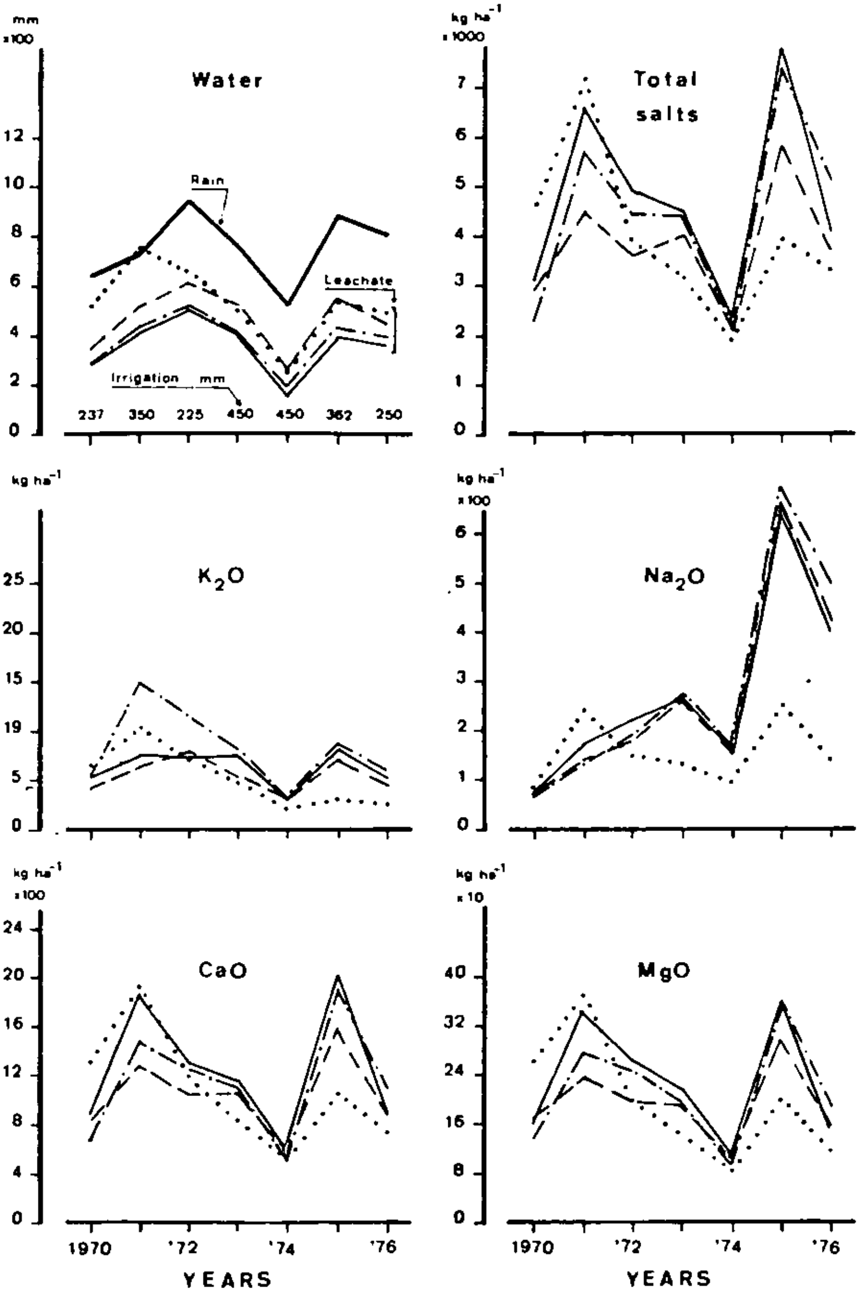

Fig. 3. Effects of the years on the amounts of percolation waters and nutrient losses in lysimeters under continuous maize at the Ist. Sper. Agronomico, Sezione di Modena.

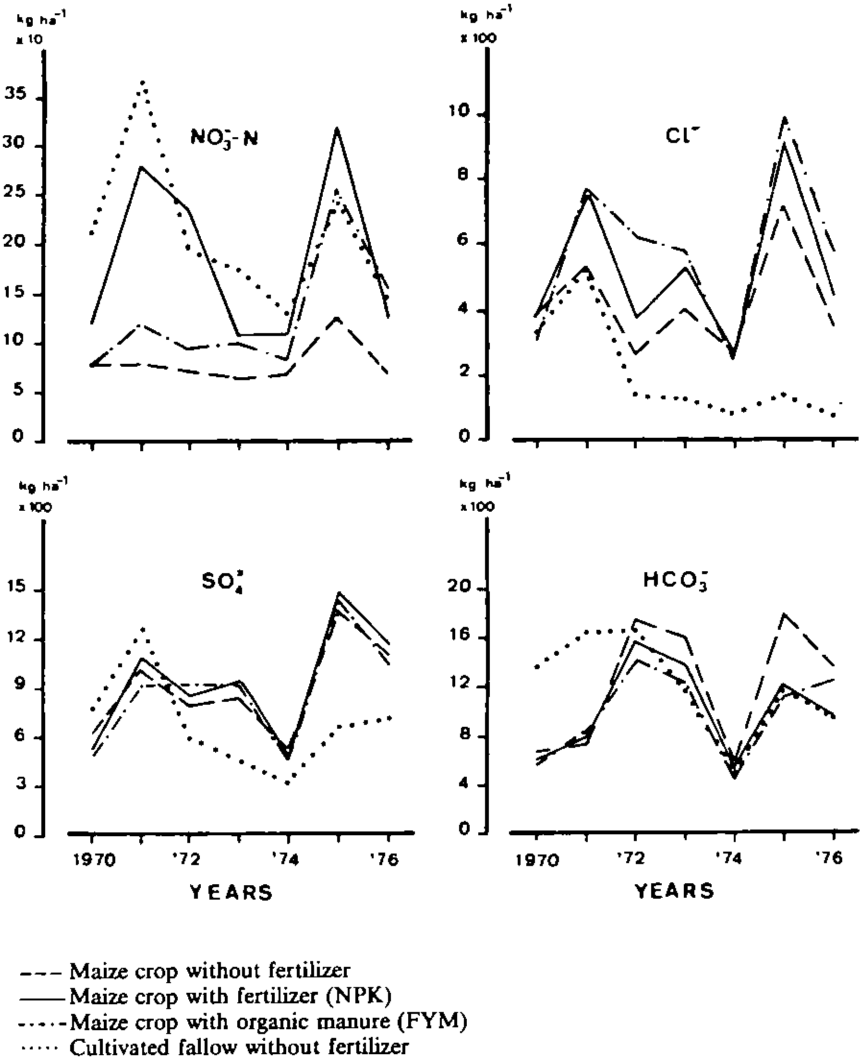

Fig. 3. (continued)

2.2 Nutrient losses by leaching in relation to soil type and rate of application of organic effluents

The experimental lay-out can be summarized as follows:

Soil type	*Manurial treatments (for each soil type)*
a) Coarse sand	0 = control
b) Sandy loam (unclassified)	1 = pig slurry at 355 kg ha^{-1} $year^{-1}$ N
c) Sandy clay *(Fluventic Xerochrept)*	2 = pig slurry at 710 kg ha^{-1} $year^{-1}$ N
d) Clay *(Vertic Xerochrept)*	3 = pig slurry at 1065 kg ha^{-1} $year^{-1}$ N

Pig slurry was applied at the beginning of the growing season of each crop of the rotation in split dressings.

Each lysimeter carried the same rotation of crops: 1976 – forage sorghum + Italian ryegrass; 1977 – grain maize; 1978 – wheat + silage maize; 1979 – grain sorghum. The hydrologic year was considered to begin with the month of April.

The physical-chemical composition of the four soils is reported on Table 3. The data concerning the average yearly rainfall plus the irrigation water (around 18% of total water applied), together with the amount of percolating water, are reported in Table 4.

Table 4. Annual input of water (rainfall + irrigation) and amount of percolating water in lysimeters with different soils (average of 4 years of trials at the Ist. Sper. Agronomico, Sezione di Modena)

Soil type	Percolating water	
	mm $year^{-1}$	%
a) Coarse sand	650.0	63.4
b) Sandy loam	352.0	34.3
c) Sandy clay	247.1	24.1
d) Clay	294.5	28.7

Total rainfall 867.3 mm $year^{-1}$
Irrigation water 157.7 mm $year^{-1}$

The amount of percolated water decreased consistently going from the coarse sand to the sandy loam and to the sandy clay soils, whereas it increased going from the sandy clay to the clay soil. This peculiar behaviour of the clay soil probably depends on the increase in macroporosity as the clay fraction increases.

The average annual amounts of N applied, taken up by crops and leached are listed in Table 5.

Crop uptake of N is affected by soil type being highest from the sandy loam and sandy clay soils and lowest from the coarse sand. It is clear also that the various soils have differing potentials for N release to crops. Apparent N recovery by crops decreased as the rate of slurry increased on all soils.

Leaching of NO_3 decreased with increasing fineness of soil texture, the highest losses being from coarse sand and the lowest from clay. For all soils the amount of N leached was positively correlated with rate of slurry applied. Apparent recovery by

Table 3. Physical and chemical composition of the different soils used in lysimeter experiments on pig slurry at the Ist. Sper. Agronomico, Sezione di Modena *[1]*

Analyses		Soil type			
		Coarse sand	Sandy loam (unclassified)	Sandy clay (*Fluventic Xerochrept*)	Clay (*Vertic Xerochrept*)
Physical analyses (2)					
Sand (2–0.02 mm)	%	97.6	56.5	63.7	10.9
Silt (0.02–0.002 mm)	%	1.2	32.6	20.5	47.5
Clay (<0.002 mm)	%	1.2	10.9	15.8	41.6
Bulk density	g/cm^3	1.45	1.32	1.26	1.25
Particle density	g/cm^3	2.58	2.50	2.48	2.62
Total porosity	%	43.8	47.2	49.2	52.4
Water infiltration rate	cm/h	201.0	20.7	16.1	19.0
Water retentivity pF 2.54 (2.01)	%	(2.3)	21.8	21.5	34.1
Water retentivity pF 4.19	%	1.4	12.2	13.1	22.1
Moisture of air-dry soil	%	0.16	1.71	1.68	3.35
Chemical analyses (3)					
pH (in H_2O)		8.0	7.2	7.9	8.0
pH (in KCl)		7.8	6.3	7.3	7.4
Conductivity at 20 °C (1:2.5)	mmho/cm	0.080	0.149	0.175	0.203
Total $CaCO_3$ *(Scheibler)*	%	5.5	0.6	14.4	14.6
Active $CaCO_3$ *(Drouineau)*	%	0.3	0.6	3.2	10.0
Total N *(Kjeldahl)*	‰	0.10	1.25	1.11	1.44
Organic matter *(Lotti)*	%	0.05	1.60	1.21	1.68
C/N ratio		3.1	7.4	6.4	6.8
Total P	‰ P_2O_5	0.61	1.26	1.18	1.34
Extractable P (0.5 N $NaHCO_3$)	ppm P_2O_5	11	36	12	16
Exchangeable K (1 N NH_4OAc)	ppm K_2O	9	127	177	350
Soluble K (1:2.5)	ppm K_2O	9	12	30	17
Exchangeable Na (1 N NH_4OAc)	ppm Na_2O	2	20	0	34
Soluble Na (1:2.5)	ppm Na_2O	6	18	21	30
CEC *(Cecconi-Polesello)*	meq/100 g	5.6	20.1	20.2	25.7

(1) sampled before the start of trials, at 0–25 cm depth

(2) data expressed on oven-dry basis

(3) data expressed on air-dry basis

Table 5. Amounts of nitrogen taken up by crops and lost by leaching in different soils treated with increasing rates of pig slurry (average of 4 years of lysimeter trials at the Ist. Sper. Agronomico, Sezione di Modena)

Soil type	Total N applied in slurry kg ha^{-1} yr^{-1}	Uptakes by crops		Losses by leaching	
		kg ha^{-1} yr^{-1}	% recovery	kg ha^{-1} yr^{-1}	% recovery
Coarse sand	0	35.0	–	22.8	–
	355	162.7	35.9	44.2	6.0
	710	227.0	27.0	152.8	18.3
	1065	302.6	25.1	192.8	15.9
Sandy loam	0	166.6	–	28.2	–
	355	296.5	36.5	59.5	8.8
	710	379.5	29.9	143.7	16.2
	1065	406.6	22.5	250.6	20.8
Sandy clay	0	204.6	–	29.7	–
	355	324.0	33.6	39.5	2.8
	710	374.1	23.8	99.4	9.8
	1065	459.2	23.9	158.6	12.1
Clay	0	112.8	–	12.3	–
	355	244.8	37.1	30.1	5.0
	710	330.0	30.5	56.2	6.2
	1065	371.3	24.2	111.8	9.3

leaching increased with increasing rates of slurry, confirming that the N leaching hazard increases exponentially with the rate of slurry used.

Data for P are reported in Table 6, where it is seen that P uptake like N uptake is influenced by soil type. P uptake increased only from the no manure treatment to the lowest rate of slurry, it did not increase further as the rate of slurry increased so that apparent P recovery in crop decreased with increasing rate of slurry.

Leaching of P was always small and only for the coarse sand did it exceed 1 kg ha^{-1} year^{-1}, as P_2O_5. In some cases high losses were also seen on clay soil probably due to cracking in this fine textured soil. There is only some hazard of P leaching on coarse sand and at high rates of slurry.

3. Comparative nutrient losses by leaching, run-off and erosion in a clay soil

A field experiment on soil hydrological behaviour and erosion assessment in relation to different crops and soil tillage systems was carried out for many years on a loamy clay soil *(Vertic Xerochrept)* formed on clay sediments of marine origin, at Vicarello (Pisa), in the hilly area of the central Apennines. The experimental layout was fully described in another paper *(Chisci et al. [1982])* and some results on soil hydrological behaviour and soil erosion have been published *(Chisci* and *Zanchi [1973], Chisci* and *Lodi [1974], Chisci* and *Tellini [1974], Chisci* and *Zanchi [1980]).*

Table 6. Amounts of phosphorus taken up by crops and lost by leaching in different soils treated with increasing rates of pig slurry (average of 4 years of lysimeter trials at the Ist. Sper. Agronomico, Sezione di Modena)

Soil type	Total P applied in slurry kg ha^{-1} yr^{-1} P_2O_5	Uptakes by crops		Losses by leaching	
		kg ha^{-1} yr^{-1} P_2O_5	% recovery	kg ha^{-1} yr^{-1} P_2O_5	% recovery
Coarse sand	0	22.9	–	2.82	–
	265	68.0	17.0	2.20	–
	530	82.2	11.2	6.19	0.63
	795	106.1	10.5	12.30	1.19
Sandy loam	0	94.8	–	0.92	–
	265	113.2	6.9	0.78	–
	530	122.6	5.2	1.35	0.08
	795	126.7	4.0	0.98	0.01
Sandy clay	0	95.5	–	0.53	–
	265	124.9	11.1	0.57	0.02
	530	117.3	4.1	0.89	0.07
	795	140.7	5.7	1.95	0.18
Clay	0	60.2	–	0.85	–
	265	106.3	17.4	1.01	0.06
	530	111.6	9.7	2.13	0.24
	795	115.7	7.0	1.15	0.04

The water discharged by drains and in run-off was sampled for analysis. Some results for drainage losses have been published by *Barbari [1980]* and *Bruno et al. [1982]*. Here we attempt to point out the peculiar behaviour of heavy clay soil in regard to nutrient loss through different water transport processes and we examine the effects of different crops and management systems.

The matrix characteristics of the soil are reported in Table 7. The average hydrologic parameters calculated for several years for different crops are reported in Table 8. The average nutrient losses by leaching, runoff and erosion are reported in Table 9. From the data, it appears that while the nutrient losses are generally low in the average year, either by leaching or by runoff and erosion, the environmental hazard in this soil is much higher for the nutrients lost by leaching than by runoff and erosion. This is probably due to the peculiar hydrological behaviour of the given soil, where there is a high seepage through the crack system, as reflected in the drain discharge coefficients, whereas the amount of surface runoff is low. Consequently, soil loss due to sheet and rill erosion appears relatively small under normal agricultural practices and the resultant amounts of nutrients exported by such processes are also small.

When comparing different crops and tillage practices, the data show that N leaching would be consistently reduced under a grass sward. In relation to wheat cultivation it seems that N leaching may increase consistently where minimum-tillage is applied. The main hypothesis for such behaviour may be the increase of the drain discharge coefficient (28.46%) in minimum-tillage plots, as compared to wheat on

Table 7. Matrix average characteristics for the layer 0–80 cm of a loamy clay soil *(Vertic Xerochrept)* at Vicarello (Pisa)

Clay (<0.002 mm)	%	42
Silt (0.002–0.02 mm)	%	37
Sand (0.02–2.0 mm)	%	21
Total N	‰	1.03
NH_4-N	ppm	7.18
Total P	‰ P_2O_5	1.75
Available P	ppm P_2O_5	64.1
Total K	‰ K_2O	1.50
Exchangeable K	ppm K_2O	182.7
Organic matter	%	1.32
$CaCO_3$	%	11.15

Table 8. Average hydrologic parameters for a loamy clay soil at Vicarello (Pisa)

Hydrologic parameters	Grassland	Wheat on minimum tillage	Wheat on ploughed soil
Rainfall, mm	700	700	700
Runoff, mm	4.3	26.2	33.0
Runoff coefficient, %	0.61	3.80	4.70
Soil loss, t ha^{-1} $year^{-1}$	0.02	0.20	1.40
Drain discharge, mm	148.0	199.3	168.9
Drain discharge coefficients, %	21.14	28.46	24.13

Table 9. Nutrient losses (kg ha^{-1} $year^{-1}$) by leaching in the tile-drain system and by runoff and erosion for a loamy clay soil at Vicarello (Pisa)

Nutrients	Grassland	Wheat on minimum-tillage	Wheat on ploughed soil
Leaching in tile-drain system			
N (NO_2, NO_3, NH_4 forms)	1.16	6.77	2.25
P_2O_5	1.43	1.17	2.15
K_2O	9.22	9.61	15.69
*Exported by runoff and erosion**			
Total N	0.05	1.09	1.87
Total P_2O_5	0.08	0.50	2.87
Total K_2O	0.30	1.56	5.16
Organic matter	0.26	2.64	18.48
$CaCO_3$	2.23	22.30	156.10

* The data are calculated indirectly from matrix soil composition and amount of sediment.

ploughed plots (24.13%). On the other hand the two different practices had no detectable effect on ammonification and nitrification of soil organic matter *(Arcara [1972a, b])*.

Losses of P by leaching appear very low in the different crop-tillage systems due to the well known capacity of the clay soil to keep P very strongly. However, such losses are approximately doubled on ploughed soil plots. It seems possible that some P may be leached in particulate forms through the macropores formed by ploughing the soil. The same hypothesis can be suggested in relation to K leaching, which is also consistently higher in the ploughed soil.

Nutrient losses in runoff and erosion seem strictly related either to the runoff coefficients or to the amount of soil loss by different crop-tillage systems. It is sufficiently clear that wheat on ploughed soil is responsible for the highest losses, while in grassland the nutrient losses are very small.

4. Comparison of nutrient losses by run-off and erosion on different clay soils

The influence of different clay soil characteristics on nutrient losses by run-off and erosion can be assessed from experimental data concerning three different locations in the central Apennines area: Vicarello (Pisa), Fagna (Firenze) and Guiglia (Modena). The main soil characteristics at the three locations are reported in Table 10.

These soils, in relation to their physical-mechanical characteristics, can be classified as clay or clay loam soils. Nevertheless, they are very dissimilar in relation to structural characteristics, as seen by comparing the particles size distribution with the microaggregate distribution (Figure 4: *Torri* and *Sfalanga [1980])*.

The following structure index has been used:

$$I_s = \frac{A_t - A_s}{A_t}$$

where: A_t = Area under the texture cumulative particle size curve between 63 μ and 8000 μ: A_s = Area under the structure cumulative grain size curve between 63 μ and 8000 μ. The range of such index is: $0 < I_S < 1$.

The value of the structure index calculated for the three soils is consistently higher for the Guiglia *Vertic Eutrochrept,* intermediate for the Vicarello *Vertic Xerochrept* and shows the lowest value for the Fagna *Typic Udorthent.* Such variation in soil structure index seems to be correlated with the different erodibility on the three soils, under rainfall of increasing intensity as it is shown in Table 11.

In laboratory trials, the Vicarello soil would seem to be easily subject to sheet and rill erosion, when the soil is saturated, if the amount of overland flow is high enough. However, we have found that this is not the case under field conditions, as discussed below.

Table 10. Some physical-chemical characteristics of matrix soils

Location	Soil type	Clay <0.002 mm %	Silt 0.002–0.02 mm %	Sand 0.02-2 mm %	Total P_2O_5 ‰	Total K_2O ‰	Total N ‰	O.M. %	$CaCO_3$ %
Vicarello	*Vertic Xerochrept*	42	37	21	1.75	1.50	1.03	1.32	11.15
Fagna	*Typic Udorthent*	44	43	13	1.09	1.56	0.99	1.90	23.90
Guiglia*	*Vertic Eutrochrept*	51	26	23	0.62	4.85	1.31	1.92	6.50

* Trials carried out in collaboration with the Ist. Sper. Agronomico, Sezione di Modena.

Table 11. Soil erodibility of disturbed samples obtained using a laboratory rainfall simulator *(Torri* and *Sfalanga [1980])*

Locations	Rainfall intensities					
	15 mm $hour^{-1}$		38 mm $hour^{-1}$		60 mm $hour^{-1}$	
	Splash erosion g cm^{-1} $hour^{-1}$	Sediment in suspension g m^{-2}	Splash erosion g cm^{-1} $hour^{-1}$	Sediment in suspension g m^{-2}	Splash erosion g cm^{-1} $hour^{-1}$	Sediment in suspension g m^{-2}
Vicarello	0.17	84.2	0.83	921.0	2.35	1933.5
Fagna	0.30	19.0	1.51	332.0	1.94	557.0
Guiglia	0.30	9.0	1.98	129.0	2.73	247.0

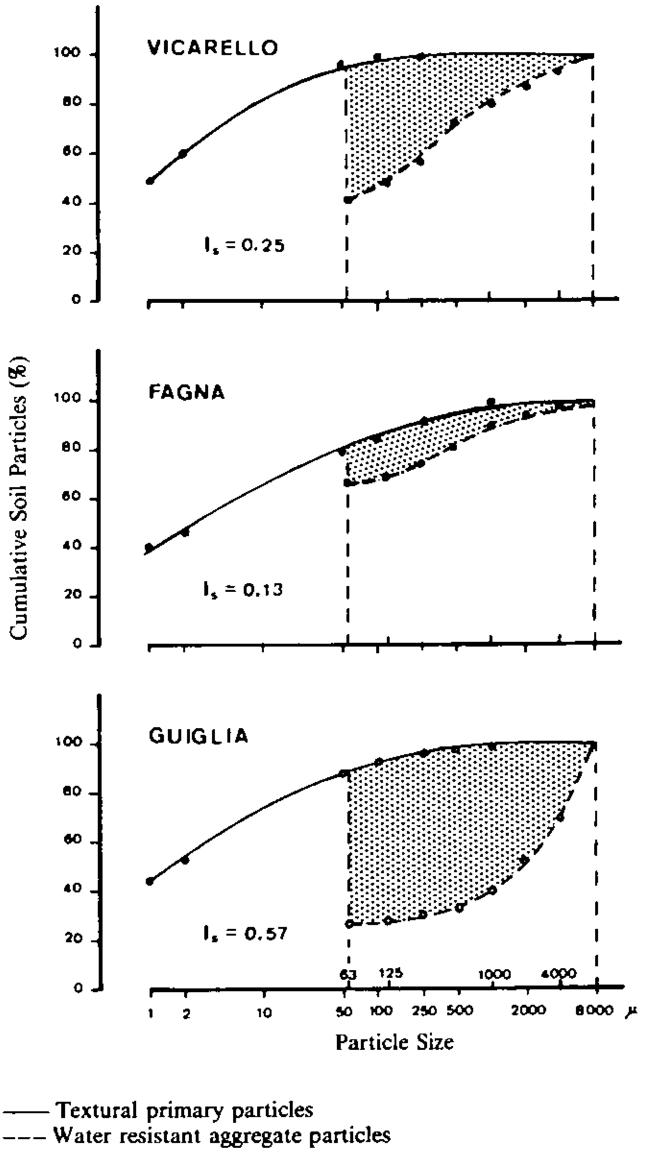

Fig. 4. Grain size distribution curves for clay soils at different locations in central Apennines hilly area (original data from *Torri* and *Sfalanga [1980]*).

For the other soils erosion in the field reflects textural and structural characteristics and soil loss in the field is well correlated with erodibility as measured on disturbed soil in the laboratory (Table 12).

Table 12. Runoff and soil loss on clay soils of different central Apennines hilly area (unit standard plots 22.1 m long having 9% slope, under continuous fallow)

Locations	Average rainfall mm year^{-1}	Runoff coefficient %	Average erosivity R-metric units	Average erodibility K per unit R	Soil loss t ha^{-1} year^{-1}
Vicarello	678.2	5	128	0.020	2.6
Fagna	1050.0	50	204	0.150	30.6
Guiglia	884.0	35	115	0.180	20.7

At Vicarello the run-off coefficient is very low so soil loss is also small. This soil has a high proportion of particles <50 μ and is much more liable to cracking than the other soils. The abnormally low value of the erodibility factor, K, calculated from field data, contradicts the erodihility index measured in the laboratory on disturbed samples. Probably because in the laboratory the soil is saturated, cracking does not occur. Cracking is much less intense in the other two soils under field conditions and their run-off coefficients are closely correlated with soil physical properties. The erodibility of such soils seems to be a function of splashability and overland flow capability.

Nutrient losses by run-off and erosion from these soils are listed in Table 13 and they are seen to be dependent on run-off coefficients and the amounts of soil loss. Regarding K, the very high K content of the Guiglia soil leads to losses high in comparison with the other soils.

Table 13. Nutrient losses (kg ha^{-1} year^{-1}) by erosion on clay soils of different central Apennines hilly areas (unit standard plots 22.1 m long having 9% slope, under continuous fallow)*

Locations	P_2O_5	K_2O	N	O.M.	$CaCO_3$
Vicarello	4.55	3.90	2.69	34.3	289.9
Fagna	33.35	47.74	30.29	581.4	7313.4
Guiglia	12.83	100.39	27.12	397.4	1345.5

* The data are calculated indirectly from matrix soil composition and amount of sediment.

In general, correct application of run-off and erosion control measures can minimise nutrient loss by water transport processes. In this connection, the data in Table 14 is of interest in showing the effects of cropping and cultivation methods on run-off and soil loss at the three locations. Grass and lucerne covers are effective in controlling nutrient loss by erosion and run-off and, thus, they play an important part in rotational cropping. Contour ploughing and the formation of contour ditches are effective measures.

Table 14. Estimated percent reduction of runoff and soil loss on slopes by the application of agricultural and mechanical practices at three locations in the central Apennines area*

Agricultural and/or mechanical practices	Amount of runoff	Amount of soil loss
VICARELLO		
Bare soil on slopes tilled up and down	100	100
Wheat on slopes ploughed up and down	88	67
Wheat on slopes prepared by minimum-tillage	77	20
Mixed meadow	45	3
Underground tile-drainage	68	80
FAGNA		
Bare soil on slopes ploughed up and down	100	100
Maize on slopes ploughed up and down	82	53
Wheat on slopes ploughed up and down	76	25
Mixed meadow	54	8
Rational pasture	44	1.2
Surcharged pasture	53	1.7
GUIGLIA		
Bare soil on slopes tilled up and down	100	100
Mais and/or sugar beet tilled on the contour with contour ditches	90	60
Wheat tilled on the contour with contour ditches	90	40
Lucerne ley with contour ditches	55	14

* The data have been desumed from the experimental findings of the following authors:
VICARELLO: *Chisci* and *Lodi [1974]; Chisci* and *Tellini [1974]; Chisci* and *Zanchi [1980].*
FAGNA: *Zanchi [1978, 1981, 1983].*
GUIGLIA: *Boschi* and *Chisci [1978]; Boschi et al. [1983]; Chisci et al.*, unpublished data.

5. Final considerations

Selection of correct management practices appropriate to a given land unit will almost universally control nutrient loss from farmland caused by water transport processes. As *Klingebiel [1972]* has pointed out, soil survey is an important basis for planning optimum use and management of each field.

Our data show that the risk of nutrient loss due to leaching, run-off and erosion differs between soils. Topography has a large effect; on flat land the main loss is by leaching, as the slope increases so does the risk of loss by erosion and run-off.

The aim in flat areas should be to minimise water percolation which we have shown to be the main factor in leaching. The rate of percolation for a given water input depends mainly on the physical properties of the soil; percolation is high on coarse sands and is progressively reduced on sandy loams and sandy clays. Percolation is higher again on clay soils due to cracking. It is important both on sands and on clays to build up soil organic matter content in order to improve water holding capacity and to improve soil structure.

In the shorter term, fertilizer management, especially in the case of nitrogen, is most important. Our experiments showed that the amount and timing of nitrogen application have important effects on N uptake by crops and on leaching losses, particularly in sandy soils. The use of organic N seems to offer advantages in gradual release and control of leaching.

Regardless of soil type, P is not mobile and very little subject to leaching. So far as potassium is concerned leaching is hazard only where heavy applications are made on sandy soil.

While in general the relative importance of leaching falls off as the slope increases and that of erosion increases, this does not hold for heavy clay soils in which cracking is of dominant importance so that even on the steeper slopes infiltration is high and erosion therefore relatively less important.

The inclusion of long duration forage crops in the rotation is helpful in the control of nutrient loss by either leaching or run-off. Reduced tillage is beneficial on sloping land but some reports in the literature mention that reduced tillage may limit yield especially on clay soils.

Many practices designed to reduce nutrient loss by water transport are described in the literature *(Frere [1976], Novotny* and *Chester [1981]).* Practices recommended for sloping land generally aim to favour infiltration and to reduce the amount and velocity of run-off. However, a specific strategy should be developed for each field and agricultural system in a given environment since reducing the hazard in one respect may increase it in another. Increasing percolation to reduce run-off may increase leaching and, conversely, attempts to minimise percolation may increase erosion and run-off.

Kreitler and *Jones [1974]* report examples of leaching of nitrate to the water table following terracing and other land and soil conservation measures. We have always to learn from previous experience and recommendations should always be checked for possible secondary effects.

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The Special Value for Crop Production of Reserves of Nutrients in the Subsoil and the Use of Special Methods of Deep Placement in Raising Yields

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Summary

Since 1974 a series of seven experiments on sandy loam and clay loam soils has tested the effects of thorough loosening of the subsoil either by hand cultivation, rotary cultivation or closely spaced tines with wings on crop production. Various amounts of P and K fertilizers singly and in combination have been incorporated into the subsoil. Nitrogen has been applied either at one amount or a range of rates tested.

Deep loosening alone increased yields. There have been additional benefits from incorporating P and K and the treatment, deep loosening plus P and K, has given yield increases as large as 45%, often 10 to 15% and only rarely have yields been decreased. These treatments appear to make water in subsoils more accessible during periods of water stress and improve the efficiency of nitrogen use, with particular benefit when small amounts are applied.

Deep loosening lessened subsoil strength as measured by a penetrometer. In all these experiments the lessening in strength and the increases in bicarbonate-soluble P and exchangeable K in subsoil were lasting effects which are still present.

1. Introduction

It has long been realized that soil conditions may be improved for plants by increasing the depth of soil through which roots may range. This paper describes Rothamsted work seeking to measure and explain benefits from deep loosening and fertilizer placement in subsoils. A series of experiments has been made on a silty clay loam and deep flinty loam at Rothamsted, a sandy loam and clay loam overlying heterogeneous subsoil at Woburn, and a sandy clay loam at Saxmundham. Results from these soils are related to others where possible.

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2. Early experiments, 1850 to 1970s

2.1 Experiments with subsoil loosening only

In the 1850s ploughing by horses was shallow, to about 12 cm deep, and at Rothamsted the effects of deepening this topsoil to 20 cm were measured from 1852 to 1855. Topsoil and subsoil were mixed but this lessened yields of wheat grain from 1.24 to 0.64 t/ha *(Lawes* and *Gilbert [15])*.

Later it was realized that subsoil should be kept below topsoil and this could be achieved by removing topsoil along a narrow trench, then loosening or inverting the exposed subsoil before replacing the topsoil. Bulky organic manures were often incorporated into the subsoil. Such trenching alone was without effect on the growth of fruit trees or on the moisture content of the soils at Rothamsted and Woburn *(Pickering* and *Russell [18])*.

Trenching was not feasible on a farm scale but subsoil could be disturbed by pulling a fixed tine through it and this was tested at Rothamsted from 1914 to 1918. Direct effects of subsoiling were measured on potatoes and residual effects on cereals. Potato yields were increased by 22% (14.7 to 18.0 t/ha) and those of cereals which followed by 15% (1.13 to 1.29 t grain/ha). Effects in subsequent years were negligible. These results suggested that the subsoil below the shallow surface soil (0–13 cm) was either naturally very compact or that even lightweight ploughs pulled by horses could smear soil at the interface between surface and subsoil with damaging effect on crop growth. In commercial practice subsoiling with widely spaced, fixed tines working at 40 to 50 cm became a common practice especially on soils where it was known that a compacted layer of soil, a pan, occurred within this depth. However, the benefits of subsoiling in terms of increased yields have often been small *(Swain [27])*.

The effects of tine-subsoiling, and deep ploughing, which mixed surface and subsoil, were measured on a range of arable crops and soil types *(Russell [24])*. Yields were increased on about 50% of experiments, on most of the remainder yields were unaffected whilst there were small losses on a few. Yield increases were sometimes large and varied with crop, soil type and season but no common soil factor could be identified for the soils on which yields were increased. Later work at Rothamsted showed how seedbeds varied considerably from year to year on deep ploughed land in which subsoil was brought to the surface *(Rothamsted Experimental Station [20])*. *Hull* and *Webb [6]* showed consistent small increases in yield from tine-subsoiling on arable crops and lucerne. This method of subsoil loosening increased barley yields at Woburn by 10 to 25% on sites known to have plough pans, but had little effect on yields of sugar beet, spring wheat or early potatoes *(Rothamsted Experimental Station [21])*. However cultivating all the subsoil (25 to 40 cm) by hand trenching increased yields of sugar beet by 11% *(Johnston* and *Warren [12])*. Similar thorough subsoiling on a not dissimilar soil at Wye increased barley grain yields by 14% and dry matter from a ryegrass ley by 33% *(Fisher, Gooderham* and *Ingram [3], El-Karouri* and *Gooderham [2])*.

2.2 Experiments with subsoil loosening and nutrient enrichment

There were few experiments in this period which tested subsoil enrichment and even fewer that distinguished between the effects of the nutrients and the loosening. Often nutrients were placed at depth in bands using widely spaced tines. In the United Kingdom yields of sugar beet, winter wheat and spring barley were not increased by either tine-subsoiling or injecting liquid NPK behind the tine. In the United States, however, yields of a range of crops were increased by 14% by tine-subsoiling and 24% by subsoiling and incorporation of NPK fertilizers. The responses, however, varied greatly with season and crop *(Kohnke* and *Bertrand [14])*. Complete mixing of P by hand digging to a depth of 35 cm increased yields of tea in Russia more than did subsoil disturbance alone *(Daraselia [1])*, but in the USA mixing together the top 90 cm of soil with or without additions of P did not increase yields of maize, sorghum or bahia grass *(Robertson* and *Volk [19])*.

2.3 Summary of early experiments

By the 1970s it had been shown that deepening topsoil by mixing a large amount of subsoil with existing surface soil was detrimental. However, subsoiling which loosened the subsoil whilst leaving topsoil on top was often beneficial. Increases in yield were sometimes obtained when the subsoil was enriched by placing bands of P and K into it behind widely spaced tines.

2.4 Leaching of P and K into subsoils

Subsoils from long-term experiments in which surface applications of fertilizers and farmyard manure (FYM) have been applied at Rothamsted and Woburn have been analyzed for their P and K content. On the silty clay loam at Rothamsted where fertilizers have been applied annually for more than 100 years to arable crops there was no detectable leaching of P into undisturbed subsoils *(Johnston [9])* but there was some movement of K *(Johnston [7])*. However, some P and much K had moved into subsoils where FYM had been applied for equally long periods. On the sandy loam at Woburn substantial amounts of both P and K had moved into subsoils below FYM-treated surface soils and also large amounts of K and a little P had moved where fertilizers were applied *(Johnston [8])*.

2.5 Benefits from P and K residues

As a consequence of the prolonged use of either FYM or fertilizers and only partial removal of the P and K they contained in the harvested crop, residues of these nutrients have accumulated in the topsoil often with beneficial effects on the yields of crops *(Johnston, Warren* and *Penny [13], Johnston* and *Poulton [11], Johnston, Mattingly* and *Poulton [10], Johnston [8])*. The FYM-treated soils, which contained more organic matter than soils given fertilizers only, often yielded more than fertilizer-treated soils. Whilst extra organic matter might explain part of the increase in yield of some crops on FYM-treated soils, part of the effect could have been caused by subsoil enrichment with P and K. To quantify the benefits of deep loosening and enrichment with P and K the series of experiments described below was started. In all the experiments seedbed dressings of P and K were applied to all plots each year at rates appropriate to the crop whether or not P or K treatments had been applied to subsoil or topsoil. Where N was not a treatment it also was applied to all plots at a rate appropriate to the crop. Throughout this paper the treatment referred to as 'None' is one without deep loosening or incorporation of P and K.

3. Subsoil loosening and incorporation of P and K by hand cultivation

This experiment was started in 1973 on a sandy loam (Cottenham Series), developed in drift over Lower Greensand, at Woburn. There was no readily recognizable soil pan on the site chosen. The results from the first four years when spring barley, potatoes, winter wheat and sugar beet were grown in rotation has been described in detail *(McEwen* and *Johnston [17])*.

3.1 The experiment

Four treatments were applied between mid-August and early October 1973: (i) none, (ii) subsoiled alone, (iii) subsoiled and PK incorporated into the subsoil, (iv) PK to the topsoil. Treatments (ii) and (iii) were done by trenching, as described above, topsoil being defined as 0 to 23 cm, subsoil as 23 to 46 cm. They were done only once in 1973, subsequently all plots were ploughed, cultivated and drilled by conventional farm machinery, but harvesting was by hand because plot sizes were small. The test dressings of P and K were 1930 kg P_2O_5/ha as superphosphate and 460 kg K_2O/ha as potassium chloride. These large amounts were intended to equalize readily-soluble P and K in topsoil and subsoil. In each subsequent year the amounts of NPK fertilizer applied to the topsoil were in accordance with standard farm practice at Woburn. Each treatment occurred once in a randomized block of four plots. The blocks were arranged in four strips of three so that each of the four crops was grown on one strip each year, the crops rotated annually.

3.2 Yields

During 1974–77 subsoiling alone increased the four-year mean yield of wheat by 20%, of barley by 26%, and of sugar from sugar beet by 10%, but potato yields were unaffected (Table 1). Incorporating P and K into the subsoil increased the mean yield of potatoes by 16% and further increased mean yield, in addition to the effect of subsoiling, of barley by 20% and sugar by 4%; mean yield of wheat was not further affected. Adding PK to the topsoil, equal in amount to that incorporated in the subsoil, did not increase the yield of any crop significantly except potatoes, where yields were increased by 7%.

Table 1. Effect of deep loosening by hand cultivation and incorporation of P and K in 1973 on the average yields of spring barley, winter wheat, potatoes and sugar from sugar beet during 1974–77, Woburn

Crop	Average annual N dressing to each crop kg/ha	Treatment				S.E. of a difference
		None	Deep loosened		PK to topsoil	
			alone	plus PK		
		Yields, t/ha,* and % increase in yield over None				
Spring barley grain	76	3.38	4.25 (26%)	4.94 (46%)	3.35 (−1%)	0.302
Winter wheat grain	100	4.32	5.18 (20%)	5.11 (18%)	4.06 (−6%)	0.182
Potatoes total tubers	242	45.4	45.5 (0)	52.5 (16%)	48.4 (7%)	2.00
Sugar beet sugar	160	4.62	5.09 (10%)	5.27 (14%)	4.68 (1%)	0.160

* Yields of grain in this and all subsequent Tables are at 85% dry matter

After the first four years barley was grown continuously on all plots. Between 1978 and 1980 subsoiling or subsoiling plus PK, done once only in 1973, continued to increase yields by between 5 and 14% whilst extra PK to the topsoil continued to have little effect (Table 2). Throughout these three years barley following potatoes or sugar beet in 1977 yielded more than barley following wheat or barley that year. This difference was thought to be because of soil borne pests and diseases and to test this, break crops were introduced on part of the experiment from 1982. Yields of barley in 1981–83, obtained only from the strip growing barley in 1977, were not increased by subsoiling or subsoiling plus PK, perhaps because of greatly increased nitrogen application (Table 2), (see later discussion). The effects of the subsoiling on barley following break crops are not yet available.

Table 2. Effect of deep loosening by hand cultivation and incorporation of P and K in 1973 on the average yields of spring barley, in 1978–80 and 1981–83, Woburn

Crop in 1977	Years	Average annual N dressing to barley, kg/ha	Treatment			
			None	Deep loosened		PK to topsoil
				alone	plus PK	
			Yields, t grain/ha and % increase in yield over None			
Potatoes or sugar beet	1978–80	96	5.48	6.17 (12%)	6.26 (14%)	5.54 (1%)
Barley or wheat	1978–80	96	4.20	4.42 (5%)	4.78 (14%)	4.33 (3%)
Barley only	1981–83	140	4.19	4.19 (0)	4.32 (3%)	4.80 (15%)

3.3 Nutrient uptake and concentration in dry matter

Data for N, P and K were given in detail for the 1974–77 period *(McEwen* and *Johnston [17])*. The concentrations of all three elements in grain and straw of wheat and barley were not affected by treatment. In potatoes and sugar beet roots only % P was affected by both deep and shallow PK. In sugar beet tops % N, P and K were all slightly increased by both deep and shallow PK but not by subsoiling alone. Wherever yield was increased by treatment, uptake of all three elements was also increased.

3.4 Available nutrients in soil

The fertilizer dressings applied to the subsoil were intended to equalize bicarbonate-soluble P and exchangeable K in topsoils and subsoils. At the first sampling after two cropping years it was evident that the calculated rate of P had been too large and that of K too small (Table 3); for the method of calculation see *(McEwen* and *Johnston [17])*. The annual seedbed dressings of P and K given to all crops each year maintained the initial levels of P and K in the untreated and subsoiled only soils. Subsequently the level of bicarbonate-soluble P changed little in either surface or subsoils except that some P moved into the subsoil where the large dressing had been applied to the surface soils. The amount of exchangeable K increased between the second and fourth years when generously-manured roots were grown. After 1977, when only cereals were grown, exchangeable K declined in all surface soils but especially from the heavily K fertilized soils, presumably because K was lost by leaching to depths greater than the 46 cm sampled.

Table 3. Effect of deep loosening and incorporation of P and K on the nutrient content, mg/kg, of the soil, Woburn

	P soluble in 0.5 M-$NaHCO_3$				Exchangeable K			
	Before treatment	years after treatment			Before treatment	years after treatment		
		2	4	10		2	4	10
Treatment and depth								
None								
Topsoil	81	86	87	83	160	137	154	108
Subsoil	56	60	52	64	80	91	105	102
Deep loosened								
Topsoil	81	83	82	77	160	135	153	101
Subsoil	56	58	53	63	80	84	98	101
Deep loosened plus PK								
Topsoil	81	92	86	85	160	144	155	111
Subsoil	56	114	114	103	80	121	131	114
PK to topsoil								
Topsoil	81	124	114	92	160	167	185	105
Subsoil	56	69	64	80	80	103	121	108

3.5 Effect of treatment on cone resistance

A measure of soil strength, and the effect of treatment on it, has been determined using a *Bush Recording Soil Penetrometer.* Readings, taken at 3.5 cm intervals to 50 cm depth, are expressed in bars and referred to as cone resistance. In 1981, seven and a half years after the treatments were done, there was still an appreciable decrease in cone resistance on subsoiled plots (Figure 1).

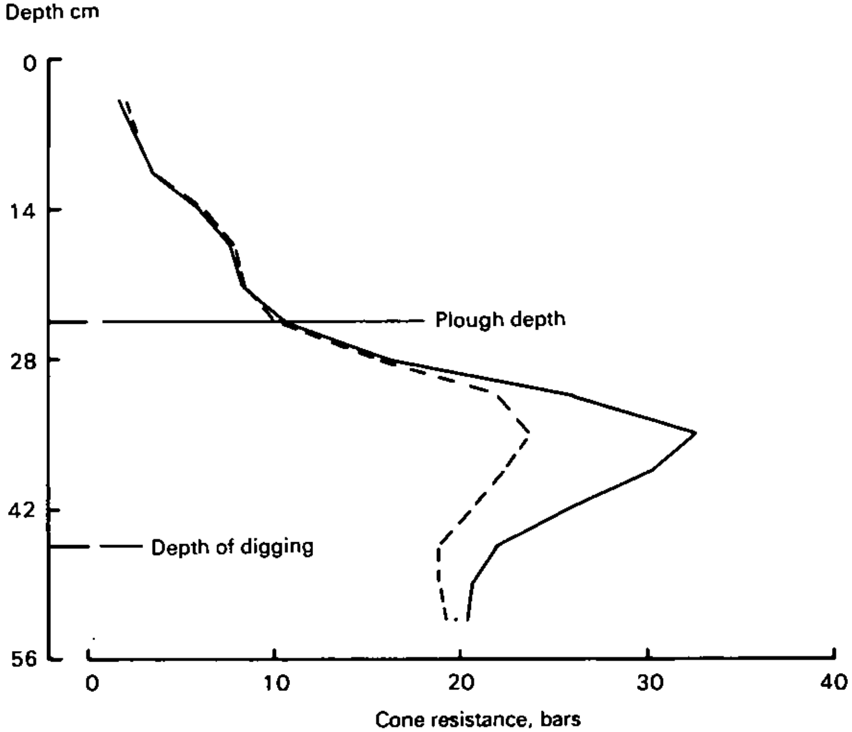

Fig. 1. Effect of hand digging the subsoil at Woburn in 1973 on cone resistance in 1981. —— without hand digging; --- with hand digging.

3.6 Conclusions

A single subsoil loosening and enrichment with P and K appreciably benefited yields of four arable crops in the following four years and of barley grown continuously in the subsequent three years. Soluble P and K levels in enriched subsoils were increased and these resulted in additional uptake not only of P and K but also of N. Subsoil loosening lessened soil strength, as measured by a penetrometer, and this effect persisted for at least seven and a half years.

The subsoil treatments in this experiment were done by hand on small plots, 4.3 m × 2.6 m, and this method could not be tested on a field scale. However in the mid-1970s two novel machines were being developed to have a much greater capacity for loosening subsoil than those currently available. The *Wye Double Digger,* built at Wye College *(Warboys et al. [28]),* could mechanically simulate the action of hand trenching. The other had closely spaced fixed tines, each with winglike attachments, working at various depths and was developed at *Silsoe College (National College of Agricultural Engineering) (Spoor* and *Godwin [25]).* To both it was possible to add fertilizer hoppers so that P and K could be added to the subsoil. Both were tested at Rothamsted and Woburn and the *Wye Double Digger* was used in other experiments at Rothamsted, Woburn and Saxmundham. The winged subsoiler was set to work at about 46 cm, the *Wye Double Digger* to plough to about 23 cm and rotary cultivate the subsoil between 23 and 38 cm. Subsequent ploughing was to 23 cm at Rothamsted and 25 cm at Woburn. The results are summarized in the following sections.

4. A comparison of two machines for deep loosening and incorporation of P and K

4.1 Description of the experiments

Two identical experiments, one at Rothamsted on silty clay loam (Batcombe Series), the other at Woburn on sandy loam (Cottenham Series) were started in autumn 1977. Besides evaluating the *Wye Double Digger* and a winged subsoiler, both capable of causing major disturbance in the subsoil, a conventional single tine unwinged subsoiler working at 50 cm intervals at Rothamsted, 70 cm intervals at Woburn was also included. Deep loosening with the *Wye Double Digger* and incorporation of P and K, 1930 kg/ha P_2O_5 and 460 kg/ha K_2O, by both machines was done only once in autumn 1977. The amounts of P and K were large but were chosen to facilitate comparisons with the previous experiment (Section 3). Subsoiling with the single-tined and winged subsoilers was repeated in autumn 1979. Spring barley was grown in 1978, and each year from 1980, spring beans *(Vicia faba)* in 1979.

4.2 Yields

Bean grain yields from untreated plots were 3.6 t/ha at Rothamsted but only 1.4 t/ha at Woburn and were increased appreciably, by 14% and 35% respectively, only by the *Wye Double Digger* plus PK treatment. Average yields of barley grain in 1978 and 1980 were larger at Rothamsted (6.13 t/ha) than at Woburn (4.85 t/ha). The effects of major soil disturbance varied (Table 4). On the heavier soil, three treatments increased average yields: the *Wye Double Digger* alone (11%), the *Wye Double Digger* with PK (16%) and the winged subsoiler with PK (6%). On the lighter textured soil only the *Wye Double Digger* with or without PK increased yields, by about 16%. The single fixed tine subsoiler increased yield more at Woburn (12%) than at Rothamsted (5%).

Table 4. Effect of deep loosening and incorporation of P and K by machine on the yield of spring barley, grain t/ha, 1978–1983, Rothamsted and Woburn.

Site	Period	Average annual N dressing kg/ha	Treatment					
			None	Single tine subsoiler	Wye Double Digger		Winged subsoiler	
					without PK	with PK	without PK	with PK
Rothamsted	1978 1980	89	5.81	6.09	6.46	6.77	5.48	6.16
	1981–1983	135	4.49	5.01	4.25	5.46	4.61	4.38
Woburn	1978 1980	89	4.62	5.20	5.31	5.36	4.45	4.18
	1981–1983	136	4.20	4.54	4.37	4.45	4.31	4.34

In the second period, 1981–83, average yields were less than in the first, by 23% at Rothamsted and 10% at Woburn even though N dressings had been increased by about 45 kg/ha. At both sites yields were increased by the *Wye Double Digger* plus PK, by 22% at Rothamsted and 6% at Woburn. The single tine subsoiler treatment gave the best yields at Woburn and next to the largest at Rothamsted.

The performance of the winged subsoiler was disappointing on both soils and in all years even though the subsoil loosening was repeated. This may be because the plots were initially traversed more than once in an attempt to get uniform fertilizer incorporation, and this may have caused some recompaction. Subsequently, the configuration of the tines has been changed and more uniform distribution of fertilizer can be achieved now at a single pass *(Godwin* and *Spoor [4]).*

4.3 Composition of green barley

In June 1978 ears were fully emerged in the crops at both sites and all plots were sampled, care being taken to seal the samples quickly in polythene bags to determine fresh weights accurately. Dry matter yield, % dry matter and % N, P and K in dry matter were determined (Table 5). At Rothamsted, treatment with the *Wye Double Digger* alone or with both machines incorporating P and K, increased dry matter yield and this benefit persisted to harvest. At Woburn, treatment with the single tine subsoiler and the *Wye Double Digger* with and without PK increased yields of barley at anthesis and here also the effect persisted to maturity. Percentage dry matter in the crops from the *Wye Double Digger* plus PK treatment at Rothamsted and the *Wye Double Digger* with and without PK at Woburn was appreciably less than from other treatments. Percentage N was little affected by treatment, but with one exception, both % P and % K were larger at both sites in crops grown on subsoils enriched with P and K by either machine.

Table 5. Effect of deep loosening and incorporation of P and K by machine on the dry matter yield and nutrient composition of green spring barley in June, 1978, Rothamsted and Woburn

Site	Factor	Treatment					
		None	Single tine subsoiler	Without P and K		With P and K	
				Wye Double Digger	Winged subsoiler	Wye Double Digger	Winged subsoiler
Rothamsted	Dry matter, t/ha	3.67	3.71	4.63	3.81	5.33	4.46
	% dry matter	22.9	22.7	23.1	22.7	20.8	22.1
	% N	1.67	1.67	1.63	1.56	1.67	1.80
	% P	0.22	0.24	0.22	0.24	0.28	0.27
	% K	1.91	2.00	1.92	1.98	2.40	2.12
Woburn	Dry matter, t/ha	4.26	5.01	5.65	3.96	5.69	3.16
	% dry matter	30.2	28.5	25.6	30.1	26.2	31.0
	% N	1.30	1.30	1.28	1.22	1.44	1.13
	% P	0.25	0.26	0.28	0.25	0.30	0.27
	% K	1.63	1.65	1.91	1.64	1.88	1.63

Table 6. Effect of deep loosening and incorporation of P and K by machine on soluble P and K in surface and subsoils, Rothamsted and Woburn, 1979

Site	Depth cm	Treatment					
		None	Single tine subsoiler	Without P and K		With P and K	
				Wye Double Digger	Winged subsoiler	Wye Double Digger	Winged subsoiler
Sodium bicarhonate-soluble P, mg/kg							
Rothamsted	0–23	19	22	16	15	44	20
	23–46	2	3	4	3	33	37
Woburn	0–25	70	74	71	74	81	72
	25–46	45	51	48	49	123	98
Exchangeable K, mg/kg							
Rothamsted	0–23	113	116	120	109	140	124
	23–46	118	120	121	123	139	139
Woburn	0–25	124	126	117	128	137	127
	25–46	88	89	86	88	132	107

4.4 Soil analyses

Bicarbonate-soluble P and exchangeable K were determined in both surface and subsoils from the two experiments eighteen months after the treatments were applied (Table 6). Both were increased in subsoils to which P and K had been added, and the increase was proportionally larger in the lighter textured soil. Increases in exchangeable K in the clayey subsoil at Rothamsted were quite small, the K presumably being held in non-exchangeable forms. Where the *Wye Double Digger* was used to incorporate P and K at Rothamsted not only the subsoils, 23–46 cm, were enriched with soluble P and K, but also the topsoils. This was because of the difficulty of maintaining working depth on this soil, which for many years had been ploughed to about 20 cm and which had very compact subsoil and an abundance of flints. On the lighter soil the depth of penetration was greater than at Rothamsted but there was still some enrichment of the 0–25 cm depth of surface soil. The winged subsoiler worked to the required depth at both sites.

4.5 Cone resistance and treatment

Both experiments were conventionally mouldboard ploughed each autumn. In May 1981, soil strength at each 3.5 cm interval within the plough layer was similar on all treatments, and between sites (Figure 2). Maximum cone resistances in undisturbed

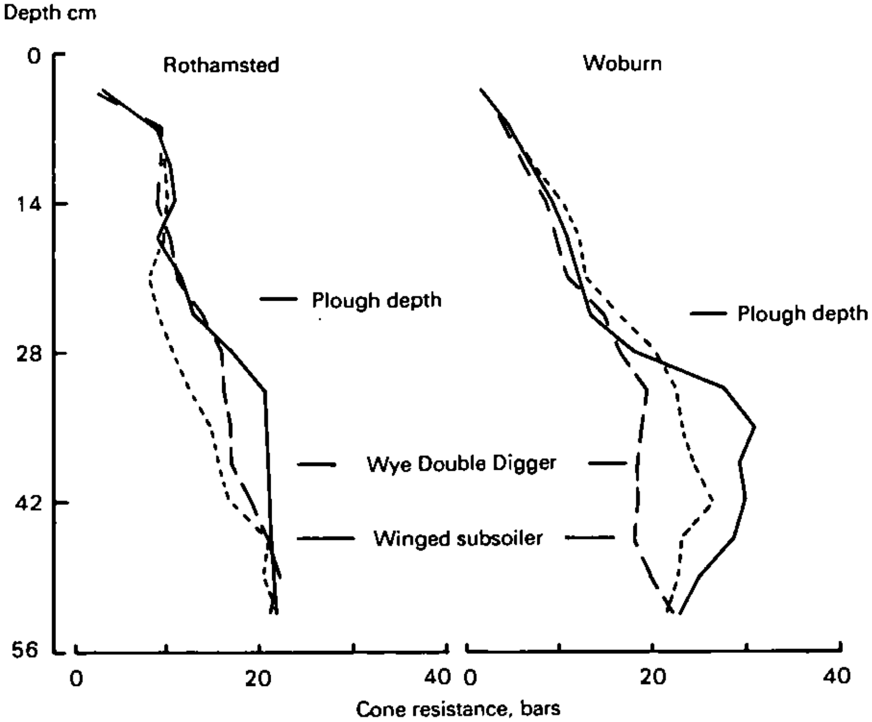

Fig. 2. Effect of using the *Wye Double Digger* in 1977 and a winged subsoiler in 1977 and 1979 on cone resistance in 1981 at Rothamsted (Figure 2a) and Woburn (Figure 2b). —— without deep loosening; – – – with *Wye Double Digger;* ---- with winged subsoiler.

subsoil were much larger at Woburn (about 30 bar) than at Rothamsted (about 20 bar). Almost four years after applying the treatments, cone resistance at Woburn was less with the *Wye Double Digger* than with the winged subsoiler even though the latter treatment had been repeated in autumn 1979. At Rothamsted, using the winged subsoiler on two occasions had decreased cone resistances a little more than had the *Wye Double Digger* used only once four years before.

5. The effects of deep loosening and incorporation of P and K with different seedbed cultivation methods

Ploughing as a preliminary to establishing a seedbed ensures that previous seedbed applications of P and K are distributed at least to the depth of ploughing. The increasingly common practice of minimum cultivations localizes these dressings in the 0 to 5 cm depth. Both subsoil loosening and enrichment with P and K may be particularly beneficial prior to starting, or as an occasional change from sequences of minimum cultivation. This is being tested at Woburn on a clay loam soil overlying a heterogenous subsoil of a mainly sandy loam texture in turn overlying Oxford clay at depth.

5.1 Description of the experiment

Cultivation treatments are being tested in conjunction with treatments designed to distinguish between the effects of cultivation and possible interactions with disease. Treatments include: (i) Deep loosening with and without incorporation of P and K. (ii) Continuous minimum cultivation, minimum cultivation broken by ploughing every third year and annual ploughing and seedbed preparation. (iii) Standard and enhanced pathogen control. (iv) Winter wheat and winter barley each grown continuously, and in the rotation: oilseed rape, winter barley, winter wheat. (v) Three amounts of N, 75, 150, 225 kg/ha. Deep loosening was first done in autumn 1979 and all plots were then ploughed. In the following year, 1980, spring sown cultivars of wheat and barley were grown as appropriate to the future cropping of each plot; the first crops with minimum cultivation were drilled that autumn.

5.2 Yields

All treatments are not yet in phase but some comparisons can be made. Average yields, during 1981–83, of winter wheat and winter barley grown continuously with the two seedbed cultivation methods and three amounts of N are in Table 7. There are 12 possible comparisons between treatment None and subsoiling with and without PK for both ploughing and minimum cultivation. Subsoiling plus PK yielded more than without subsoiling in all but one comparison, which was where winter barley was drilled following minimum cultivation. Subsoiling alone depressed yields in five comparisons four of which were with minimum cultivation. Averaged

Table 7. Effect of deep loosening and incorporation of P and K on yields of winter wheat and winter barley drilled following ploughing and conventional seedbed preparation and minimum cultivation during 1981–83, Woburn

N rate kg/ha	Ploughed			Minimum cultivation		
	None	Deep loosened	Deep loosened + PK	None	Deep loosened	Deep loosened + PK
	Winter wheat, grain, t/ha					
75	5.66	5.91	6.44	5.47	5.87	5.98
150	6.79	7.06	6.95	6.81	6.28	7.06
225	6.66	7.09	7.03	6.80	7.78	7.49
	Winter barley, grain, t/ha					
75	6.02	6.08	7.90	5.59	5.33	5.80
150	7.15	7.06	7.71	7.37	6.60	6.95
225	7.20	7.56	7.93	7.48	7.15	7.54

over both crops and seedbed preparation methods the effect of deep loosening plus PK was much larger (15%) at the lowest rate of N (75 kg/ha) than at the two larger rates where the average increase was only 6%.

6. The effects of incorporating different amounts of P and K singly and in combination

6.1 Description of the experiment

All previous experiments tested the combined effect of one rate each of P and K. The experiment described here was started in the autumn of 1980 and tested 5 rates of P and K, 0, 63, 125, 250, 500 and 1000 kg/ha P_2O_5 and 0, 31, 63, 125, 250 and 350 kg/ha K_2O singly and a selection of these rates of P and K in combination. The larger rates of P and K were incorporated only once, the lower rates, together with subsoiling alone, are being repeated annually. In addition the largest amounts of P and K incorporated into the subsoil were also applied as a single dressing to the surface soil in autumn 1980. The soil is a deep flinty loam, on loamy, gravelly or clayey substrata (Charity Series) at Rothamsted. The test crops, grown in rotation, and the average amount of N given to each in 1981–83, were: spring beans, none; winter wheat, 153 kg/ha; potatoes, 196 kg/ha; spring barley, 90 kg/ha.

6.2 Yields

During 1981–83 all crops yielded about average for comparable crops on Rothamsted Farm, winter wheat yields being a little less, probably because the deep loosening treatments applied annually delayed sowing beyond the date considered best for large yields. Effects of the treatments were very small but deep loosening and incorporation of the largest amounts of P and K always gave larger yields than subsoiling alone or none (Table 8). Plots given the largest amounts of P, 1000 kg P_2O_5/ha, and K, 350 kg K_2O/ha, once only to the surface soils gave yields only a little different from those where the same rates of P and K were incorporated into the subsoil.

Table 8. Effect of deep loosening and incorporation of five amounts each of P and K singly and in several combinations on the yields of spring beans, winter wheat, potatoes and spring barley grown in rotation during 1981–83, Rothamsted

Crop	Treatment				
	None	Deep loosened			P plus K to the topsoil
		No P or K	P plus K at the low rates applied annually	P plus K at high rates applied once only	
Spring beans grain, t/ha	4.27	4.45	4.33	4.78	4.53
Winter wheat grain, t/ha	7.66	7.58	7.52	7.83	7.72
Potatoes total tubers, t/ha	53.0	53.0	52.7	54.9	55.5
Spring barley grain, t/ha	6.88	6.88	6.93	7.25	7.36

7. Effects of deep loosening on a sandy clay loam

7.1 The experiment

This experiment was started in 1979 at Saxmundham on a sandy clay loam overlying a sandy clay subsoil (Beccles Series). Unlike the sites at Rothamsted and Woburn already described, the soil at Saxmundham is artificially drained with moles and tiles. This deep loosening experiment had to be accommodated on an existing experiment where contrasted manurial treatments to the surface soil had been tested since 1899. Both the number of new treatments and plot size were constrained by the existing experiment. In a simple test, deep loosening without and with incorporation of P and K, 860 kg P_2O_5, 860 kg K_2O, were compared with none. The treatments were applied in July 1979 on plots in grass, the *Wye Double Digger* ploughing out the grass on deep loosened plots and a single furrow plough on the others. Winter wheat sown that autumn was attacked badly by wheat bulb fly, despite spraying with insecticide, and the crop was accordingly destroyed with herbicide the following spring and then sown late with spring barley which yielded little. Wheat and barley have been grown since.

7.2 Yields

Winter wheat given either 80, 120, 160 or 200 kg N/ha was grown in 1981 and 1982 and spring barley given either 30, 60, 90 or 120 kg N/ha in 1983. Yields of wheat in 1981 were large and well above average in 1982. Spring barley yielded much less than the wheat but yields were about the average from many experiments on this soil. Rates of N and P to the topsoil affected yield but there was no interaction with either subsoiling treatment. Yields in Table 9 are averaged over rates of N, P and K to the topsoil. Effects of deep loosening were very small, but positive in all but one comparison, even at the largest yields of winter wheat.

Table 9. Effect of deep loosening and incorporation of P and K on the yields of winter wheat and spring barley grown on a sandy clay loam, 1981–83, Saxmundham

Year	Crop	Treatment		
		None	Deep loosened	Deep loosened plus P and K
1981	Winter wheat grain, t/ha	9.84	9.79	9.92
1982	Winter wheat grain, t/ha	7.84	7.94	8.08
1983	Spring barley grain, t/ha	4.46	4.63	4.69

8. The single and combined effects of incorporating P and K

8.1 The experiment

Treatments for this experiment on a silty clay loam (Batcombe Series) at Rothamsted were applied in autumn 1979. It is simpler than that described in Section 6, only one rate each of P, 1000 kg P_2O_5/ha, and K, 500 kg K_2O/ha are tested singly and in combination. Spring barley is grown each year, with a cumulative test of N at 0, 40, 80, 120 kg/ha. In addition PK equal in amount to that incorporated into the subsoil was applied in one dressing only to the topsoil in autumn 1979. This treatment was tested in the first hand-dug experiment (Section 3) but was without effect on the yields of barley, wheat and sugarbeet but did increase those of potatoes. It was therefore omitted from the next two experiments with cereals started in autumn 1977 (Section 4) but was tested again in this and other experiments started in 1979 (Section 5) and 1980 (Section 6).

8.2 Composition of green barley plants in 1980

Green barley was sampled on three occasions in 1980, 47, 68 and 96 days after sowing and % N, P, K, Ca, Mg and Na in dry matter determined. The treatments sampled were: None, deep loosened with and without PK and PK to the topsoil, all had received N at 80 kg/ha. At each sampling crops grown on treatments None or deep loosened only had concentrations of P and K which were not appreciably different from each other, and were always less than in the other two treatments (Table 10). Crops grown on soils enriched with P and K always contained more of both, but whereas P declined between the first and second sampling where P was applied to the surface soil it increased where P was incorporated into the subsoil suggesting that subsoil-P was beginning to contribute to P uptake.

At the first and third sampling, % N was larger in the crop grown on deep loosened and PK enriched soil compared to that on None by 15% and 3% respectively. This crop therefore continued to get more N from the soil at least until this final sampling.

Percentage Ca, Mg and Na were not affected by treatement except that crops grown on soils to which extra K was added tended to contain less Na.

Table 10. Effect of deep loosening and incorporation of P and K or of PK to the topsoil on the composition, % in dry matter, of green barley on three occasions in 1980, Rothamsted

Element	Date of sampling	Days after sowing	Treatment			
			None	Deep loosened		PK to topsoil
				without PK	with PK	
Nitrogen	21. 4. 80	47	4.25	4.48	4.90	4.74
	12. 5. 80	68	4.75	4.74	4.36	4.34
	9. 6. 80	96	1.69	1.55	1.74	1.77
Phosphorus	21. 4. 80	47	0.424	0.444	0.502	0.636
	12. 5. 80	68	0.434	0.414	0.540	0.570
	9. 6. 80	96	0.240	0.240	0.252	0.278
Potassium	21. 4. 80	47	4.02	4.18	4.80	5.18
	12. 5. 80	68	4.88	4.60	5.16	5.82
	9. 6. 80	96	2.04	2.06	2.54	3.28

8.3 Yields

Yields of barley grain averaged over 1980–83 are in Table 11. Compared with normal ploughing, deep loosening with incorporation of P and K gave the larger yields and the percentage increase varied with the amount of N applied: 35% with no N, 24% with 40 kg N, 12% with 80 kg N, 1% with 120 kg N. All yields with 120 kg N were similar.

Yields from deep loosening with P and K were always larger than from deep loosening alone or deep loosening with P only or K only. Differences between deep loosening with either 'P only' or 'K only' are interesting. With no applied N the 'P only' treatment yielded more than the 'K only' by 0.85 t/ha. However, with applied N, the 'K only' treatment always yielded more than the 'P only' and the difference (deep loosening plus K *minus* deep loosening plus P) was 0.87, 0.08 and 0.11 t/ha when the N applied was 40, 80 and 120 kg/ha respectively. This suggests that extra K in the subsoil possibly aids NO_3-N uptake by providing readily available K to balance anion uptake by the roots.

Table 11. Effect of deep loosening and incorporation of P and K singly and in combination, and of PK to the topsoil, on the yield of spring barley grown continuously at four amounts of nitrogen, 1980–83, Rothamsted

Amount of N tested kg/ha	Treatment					
	None	Deep loosened				PK to topsoil
		without PK	with P only	with K only	with P and K	
0	2.46	2.48	2.98	2.13	3.33	3.40
40	4.15	4.30	3.75	4.62	5.14	4.78
80	5.29	5.77	5.66	5.74	5.91	5.61
120	6.31	6.35	6.36	6.47	6.37	6.48

In this experiment the single large PK dressing to the topsoil increased yields (Table 11), and there were interesting differences between yields given by additional PK to topsoil and subsoil. The yield difference (deep loosened plus PK *minus* PK to topsoil) was −0.07, +0.36, +0.30, and −0.11 t/ha when the N applied was 0, 40, 80 and 120 kg/ha respectively.

Thus there appears to be an interaction between the benefit of deep loosening, the incorporation of P and K and the amount of N applied, with the benefits being larger at the lower rates of N.

8.4 Nitrogen in barley grain at harvest

This has been determined for three years, 1980–82 (Table 12). Straw analyses were not included but about 80% of the total N in grain plus straw is found in the grain alone and therefore the following observations would not be greatly affected if N in straw had been included. In the absence of fertilizer N, grain from 'ploughed only' plots contained 35 kg N/ha and this was increased to 48 kg N/ha where P and K were applied either to the surface or subsoils (Table 12). This increase in N in grain, 37%, was the same as the average % increase in grain yield.

Table 12. Effect of deep loosening and incorporation of P and K singly and in combination, and of PK to the topsoil, on the amount of N, kg/ha, in barley grain at harvest, 1981–83, Rothamsted

Amount of N tested kg/ha	Treatment					
	None	Deep loosened				PK to topsoil
		without PK	with P only	with K only	with P and K	
0	35	37	44	31	48	48
40	51	57	44	59	69	61
80	71	76	76	77	87	76
120	95	93	94	94	100	95

At each level of applied N, there was always more N in grain where PK was incorporated than where PK was applied to the topsoil but the difference diminished as applied N increased. The extra N, compared to that in grain from ploughed plots, for the deep loosened plus PK and PK to topsoil was, respectively, 45 and 25% at 40 kg N/ha; 20 and 6% at 80 kg N/ha and 4 and 0% at 120 kg N/ha.

9. General discussion

The results of this series of experiments clearly show that deep loosening of the subsoil, below either sandy loam or clay loam surface soils, by either hand cultivation, rotary cultivation or winged subsoiler, can lessen soil strength as measured by a penetrometer. The benefits have lasted for at least seven years following hand cultivation or four years following rotary cultivation.

Large amounts of P and K fertilizers added to the subsoil gave measurable increases in bicarbonate-soluble P and exchangeable K. Ten years after application to a sandy loam subsoil there was still much soluble P and some extra K. On sandy loam soil equally large dressings of P and K fertilizers to the surface soil resulted in much K and some P moving into the subsoil. Analysis of green crop samples growing on land with enriched subsoil has shown that P and K are taken up from this depth.

Barley at anthesis (Section **4.3**) and beans sampled in June the following year, had lower % dry matter in plants grown on deep loosened soils. The increased volume of tissue water per unit dry matter in these plants must have been accommodated in larger cells. At the whole plant level this would be reflected in the production of larger and thicker leaves per unit of dry matter, which, in turn, would result in higher relative growth rates and hence increased yield *(Leigh* and *Johnston [16]).* These plants were from treatments which did produce the largest grain yields. However, the factor to which the crops responded is not yet known.

Our large increases in yields of spring barley, winter wheat, potatoes and sugar from sugar beet from deep loosening was in contrast to earlier work at Rothamsted and elsewhere *(Russell [24], Swain [27])* and suggests that the degree of subsoil loosening is an important factor. Thorough subsoil loosening was also a feature of experiments where yields of vegetable crops were increased *(Rowse* and *Stone [22], Stone [26]).* It is possible that the degree of loosening achieved by hand cultivation, or the *Wye Double Digger,* reorientates soil structural units and produces a more stable structure than can be achieved by fixed tines *(Hartge* and *Sommers [5]).* Our yields have been increased further by intimately mixing large dressings of P and K into the subsoil.

Since 1978, increases in yield from deep loosening with or without incorporation of P and K have not been as large as they were in 1974–77 (Section 3) although they have often been between 10 and 15% for cereals. Only in very few comparisons have yields been less than those on plots without deep loosening. The years 1974–77 included two very dry years, 1975–76, and not since then has any year had consistently dry springs and summers. Benefits for deep loosening were small in 1983, notable for a dry period from June to harvest, but in early June soils were still at or near field capacity following a very wet spring. This suggests that one benefit of deep loosening may be that roots are able to extract water from a larger volume of soil in periods of water stress. *Rowse* and *Stone [23]* also considered that one benefit of deep loosening subsoils was enhanced water extraction from depth. However, the importance of the availability of this subsoil water will depend on the total water balance during the growing season.

Deep loosening may improve drainage of water from surface soils and in the experiment comparing minimum cultivation and ploughing (Section 5) surface water was often seen standing on minimum cultivated plots without deep loosening after periods of prolonged rain.

Deep loosening and incorporation of P and K appear to improve the efficiency of uptake of nitrogen, especially when applied at low rates. This may, in part, explain the decreasing effects on yield of hand cultivating the subsoil (Section 3) and rotary cultivation (Section 4) in recent years in which nitrogen dressings applied uniformly to all treatments have been increased.

Further work must now identify soil types on which deep loosening and incorporation of P and K will predictably benefit yields of crops so that the cost effectiveness of the treatment can be assessed.

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Potassium Balances in a Series of Field Experiments

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Summary

The potassium balance was determined annually on a series of 40 field experiments with uniform crop rotation (75% cereals) to which annual K dressings averaging 0, 86, 172 and 345 kg/ha K_2O were applied over a period of four years. On the average, annual application of 143 kg/ha K_2O maintained the K balance when total crop including residues was removed from the field, while if all residues were returned an annual application of 48 kg sufficed. Increases in K uptake caused by increases in K fertilizer application were largely confined to the crop residues (straw, beet tops and potato haulm), and thus remained in the cycle when residues were returned. Comparison of K balances with CAL/DL soil K content indicated the importance of the soil's buffering capacity. Supply of K to the crop from non-exchangeable sources in surface soil and from reserves at depth amounted to up to 124 kg K_2O per hectare and year. Positive K balances considerably increased non-exchangeable and subsoil K.

1. Introduction

A long history of fertilizer use in developed agricultures has had the result that, generally speaking, soil fertility has been improved to the extent that corrective (supplementary) fertilizer dressings are now seldom required. Current fertilizer policy aims to maintain fertility at the desirable level and for this purpose the input-output nutrient balance assumes increased importance.

The nutrient cycle includes the soil, which is a buffer system, and which, through weathering, brings additions to the nutrient pool, so that a complete description of the nutrient balance must include as well as nutrient additions through fertilizers and manures and nutrient removals by the crop, changes in the nutrient status of the soil over the relevant period, as was the main of a series of 40 field experiments over a period of four years carried out under the auspices of the *Federal Experimental Station for Agricultural Chemistry,* Vienna.

The experiments were sited predominantly in dry areas so that possible losses of K by leaching were not sufficiently large to affect the balances appreciably. Lysimeter experiments by *Vömel [1966, 1974]* and *Pfaff [1963]* indicated losses of 0–13 kg/ha K on loess, clay and loamy soils and of up to 22 kg/ha on sandy soils. Inputs of K via precipitation, estimated by *Ulrich et al. [1979]* at 2–3 kg/ha per year, can be neglected.

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2. Experimental

The series of experiments covered the most important farming areas and the main soil types of Lower Austria:

21 experiments in the northeastern plain and hilly area (annual rainfall 560 to 590 mm, annual mean temperature 9.1–9.4 °C); chernozems, moist chernozems and brown earths from loess;

11 experiments in the prealpine hills (850 mm rainfall, mean annual temperature 8.5 °C); brown earths and pseudogleys from alluvium and loam;

8 experiments in the 'Waldviertel' (670 mm rain, 6.8 °C); brown earths from crystalline material.

Medium and heavy textured soils predominated (34 locations of which 4 were 'very heavy'); clay contents from 6 to 46% (20 sites over 26% clay), silt and clay (60 µm) 42 to 98%, median value 87%. K fixation capacity (wet) remained within limits with a maximum of 45 mg K_2O/100 g soil. Available K supply ranged from 7 to 43 mg K_2O/ 100 g (CAL, DL) (mean 19.14). *Schüller's* calcium acetate lactate method was used for soils with pH of 6 and above and the *Egner-Riehm* double lactate method for soils below pH 6.

A uniform rotation (spring barley, winter wheat or winter rye, sugar beet or potatoes, spring barley) was used throughout. Potash was applied at 0, 75, 150 and 300 kg/ha K_2O to cereals and at 0, 120, 240 and 480 kg/ha to root crops. Adequate N and P fertilizers were applied to obviate limitation of yield response to K.

3. Results

3.1 Yields and response to K fertilizer

Mean yields under the various treatments for crops and crop residues are given in Table 1.

Yields were on a medium level. Rainfall and its distribution are generally yield limiting in this dry region suited to quality wheat production. Irrigation is usually confined to sugar beet and farms, which lie within the area of low terraces with groundwater in usable depth. Potatoes responded to K fertilizer but cereals and beet did not, but the lack of response by beet would seem to be exceptional as indicated by a later series of trials not included in this report. In Table 2 cereal results are

Table 1. Mean yields t/ha of grain, sugar beet roots and potato tubers with dry matter yields of leaves

Kg/ha K_2O applied		Cereals (n = 120)		Sugar beet (n = 28)		Potato (n = 12)	
Cereal	Roots	Grain	Straw D.M.	Roots	Leaf D.M.	Tubers	Leaf D.M.
0	0	4.10	3.46	46.41	6.59	32.48	1.85
75	120	4.13	3.52	47.04	6.61	32.93	1.95
150	240	4.15	3.47	46.15	6.74	33.52	1.82
300	480	4.10	3.51	46.33	6.86	34.04	1.89

grouped according to soil K content where it is seen that response to K increases as soil K content declines though even at < 15 mg K_2O/100 g the response is very slight.

Table 2. Effect of K fertilizer on grain yield (kg/ha) as related to soil K content

Soil class mg K_2O/100 g	kg K_2O/ha/year applied			
	0	75	150	300
<15	4100	+34	+78	+20
15–25	4100	+24	+40	−12
>25	4100	+19	+ 0	−32

3.2 Potassium balance

Dry matter yields of crop and crop residue (cereal straw, potato and beet leaves) were determined for all 160 harvest (40 experiments × 4 years) and K content determined. All crops and crop residues were removed from the field and total removals of K_2O are listed in Table 3 together with additions by way of fertilizer.

Table 3. Average potash balance under a four crop rotation (75% cereals)

		kg/ha K_2O			
Spring barley	Supply	0	75	150	300
	Removal	90	97	100	104
	Balance	− 90	− 22	+ 50	+196
Winter-wheat Winter-rye	Supply	0	75	150	300
	Removal	38	39	40	39
	Balance	− 38	+ 36	+110	+261
Bi-annual intermediate	Balance	−128	+ 14	+160	+457
Sugar beet potato	Supply	0	120	240	480
	Removal	327	343	359	387
	Balance	−327	−223	−119	+ 93
Tri-annual intermediate	Balance	−455	−209	+ 41	+550
Spring barley	Supply	0	75	150	300
	Removal	78	81	83	86
	Balance	− 78	− 6	+ 67	+214
4 years final	Balance	−533	−215	+108	+764
Mean annual	Supply	0	86	172	345
	Removal	133	140	145	154
	Balance	−133	− 54	+ 27	+191

The table demonstrates two main features:

- K removal by root crops is very much greater (about 4 times) than that by cereals.
- Net removal in the absence of K fertilizer at the end of 4 years amounts to 533 kg/ha K_2O; there is still a negative balance (−215 kg/ha K_2O) at the lowest rate of K fertilizer and a very substantial positive balance (764 kg/ha) at the highest rate of K fertilizer (300 kg/ha K_2O to cereals and 480 to roots).

Average annual K removal from all treatments was 143 kg/ha K_2O with the soil supplying 133 kg/ha under the treatment with no K fertilizer; this being 21 kg/ha less than removal under the heaviest (excessive) K treatment.

3.2.1 Distribution of K removal between crop and crop residue

This is shown in Figure 1.

Thus, approximately one third of total removal is attributable to crop and two thirds to crop residues. If all the residues were left in the field, average removal would be only about 50 kg/ha/yr K_2O, and this figure is scarcely affected by fertilizer treatment. On the other hand, removal in residues is so affected, but in practice these residues would normally be returned to the soil. K removals are also affected by soil K level as demonstrated in Figure 2.

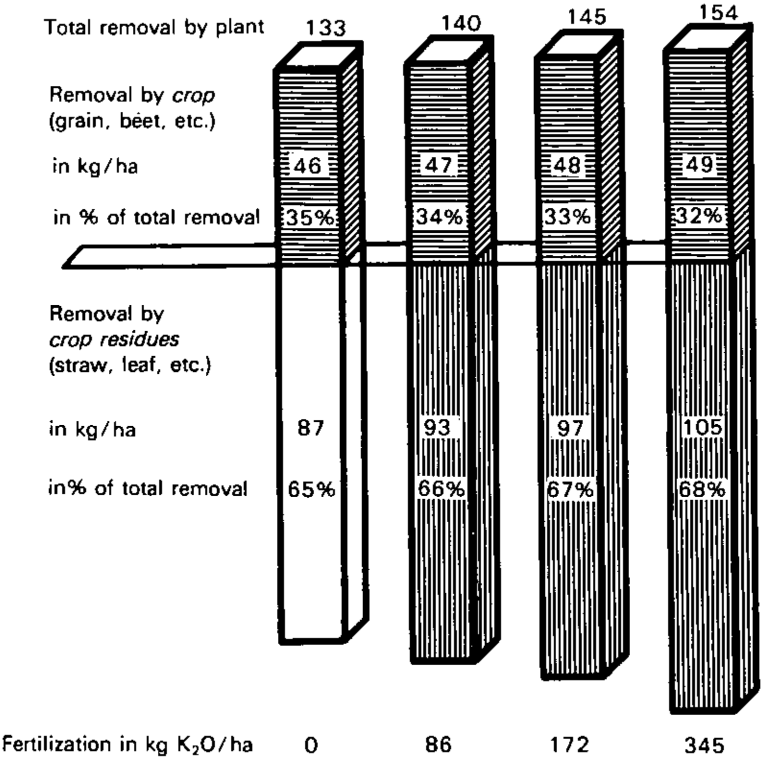

Fig. 1. Effect of K fertilizer on removal of K_2O by crop and crop residues. Mean of 40 sites over 4 years (crop rotation with 75% cereals share; all data are in kg K_2O/ha/year).

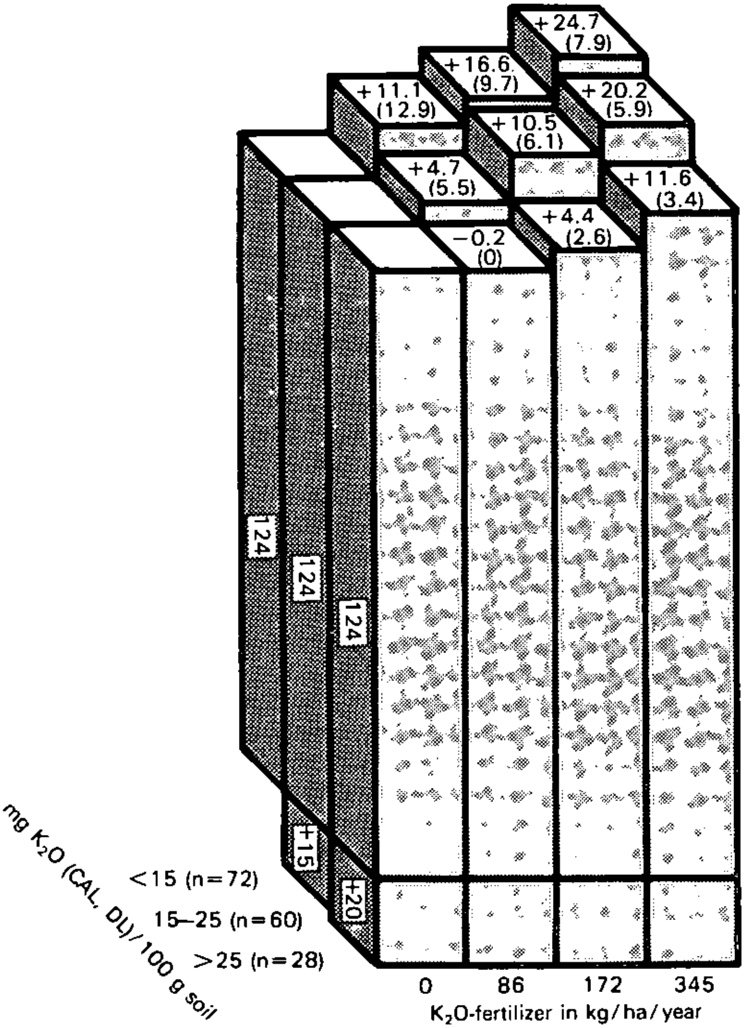

Fig. 2. K removal (kg/ha K_2O) as affected by K fertilizer and soil K content; figures in parentheses indicate % K_2O from fertilizer).

When soil content is below 15 mg K_2O/100 g the soil contribution is reduced to 124 kg/ha K_2O/yr. On low K content soils, uptake of K_2O is more affected by K fertilizer than on high K soils and the marked reduction in the effect of fertilizer on K removal on high K soils demonstrates that luxury consumption remains within limits.

3.2.2 Relative importance of yield and nutrient content in assessing removals

In practice, total K removals by a crop are often estimated from grain (or root) yield using constant K removal units for every ton grain (or root) yield to be found in the textbooks. But we have seen that total removal by the whole crop is largely determined by the variable removal in crop residues. As Table 4 shows, total K removal is poorly correlated with grain yield ($r^2 = 0.43$) while K content of straw is well correlated ($r^2 = 0.85$). In other words K content of straw is the decisive factor for total removal. Straw yield is poorly correlated ($r^2 = 0.13$) while variation in K content of grain has only a slight effect on K removal ($r^2 = 0.34$).

Table 4. Relationship (expressed as r^2) between yield, content and K removal parameters, based on 120 experimental results

	Total removal	Removal by		Grain yield	Straw yield	K-content in grain
		grain	straw			
Grain yield	0.43	0.71				
Straw yield	0.13		0.17	0.11		
K content in grain	0.34	0.53		0.07	0.11	
K content in straw	0.85		0.81	0.27	0.00	0.56

On the other hand, if we are concerned only with net removal by grain or roots, removal estimated from yield of grain or roots and using the following equations obtained by regression analysis is well correlated with actual net removal determined experimentally:

1. K_2O removal in grain (kg/ha) = grain yield (t/ha × 6.34) − 4.22
   giving for 4 t/ha net removal of 21 kg/ha K_2O
   giving for 5 t/ha net removal of 27 kg/ha K_2O $r^2 = 0.71$
   giving for 6 t/ha net removal of 34 kg/ha K_2O
2. K_2O removal in beet (kg/ha) = root yield (t/ha × 2.944) − 35.39
   giving for 40 t/ha net removal of 82 kg/ha K_2O
   giving for 50 t/ha net removal of 112 kg/ha K_2O $r^2 = 0.83$
   giving for 60 t/ha net removal of 141 kg/ha K_2O

3.3 Effect of balance on soil K content

Soil K content was determined annually on all plots of all experiments (16 samples per 30m² plot) by CAL ($pH \geqslant 6$) or DL ($pH < 6$) methods and the results related to annual changes in K balance, as shown in Figure 3. The change in K_2O content of topsoil (25 cm) as indicated by K balance agrees with change shown by soil analysis only at the point where 185 kg/ha K_2O is applied annually. As the rate of K application decreases below this value the discrepancy between theoretical (balance) K content and the actual value shown by soil analysis increases in favour of the actual value *i.e.* change in K content of surface soil is less than would be expected, while when more K is applied the reverse applies. In the former case K is taken up by the crop from non-exchangeable sources and the subsoil while in the latter case non-exchangeable and subsoil K is increased. This demonstrates the large buffering capacity of the soil.

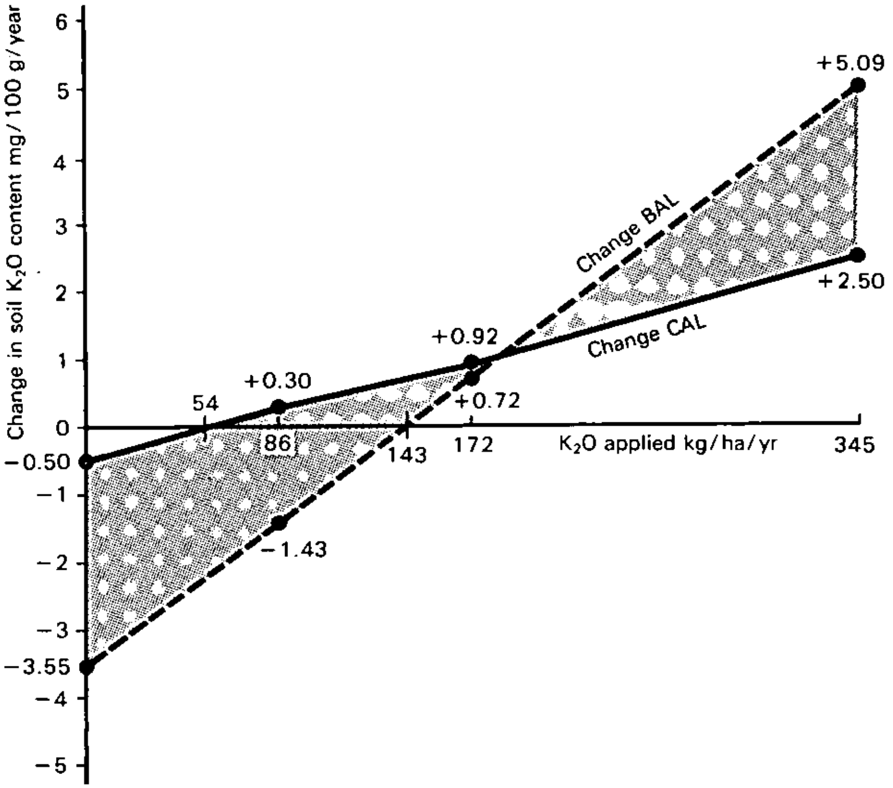

Fig. 3. Annual changes in soil K_2O content (CAL, DL) in topsoil (25 cm). BAL = theoretical value derived from K balance; CAL = actual value by soil analysis, 40 experiments over 4 years.

As to the ability of the soil to deliver K from the above mentioned reserves, in the case of the control treatment (no K fertilizer) this amounts to 114 kg K_2O per hectare per year (133 − 19, corresponding with the reduction in soil K content of 0.5 mg K_2O/100 g per year). Stabilization of soil K content (on the average of all experiments at 19.1 mg/100 g) requires annual application of 54 kg/ha K_2O; in this case the soil delivers 84 kg/ha/yr K_2O. This value depends not only on the rate of K manuring but also on the soil K content as shown in Figure 4. Utilization of reserve K, not identified by the usual methods of soil analysis reduces as the CAL/DL K content increases. In the soil class 'over 25 mg K_2O' actual change in soil K content closely follows the change indicated by the balance. This means that generous K dressings are required not only to achieve high soil K levels but also to maintain them, otherwise the annual decrease in soil K content will be greater than that on lower K soils. Thus the opinion that having achieved the desired soil K content it can be maintained merely by replacing K removed in crops is not confirmed. This circumstance gives special weight to the question concerning the profitability of stockpiling targets.

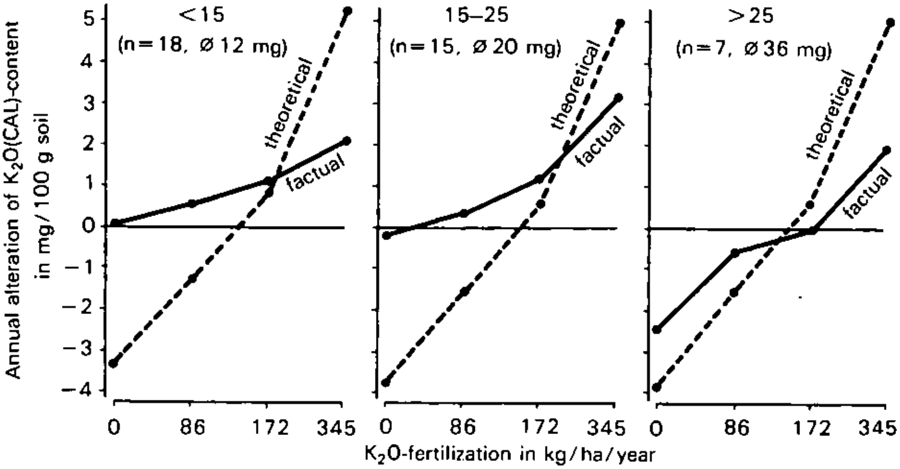

Fig. 4. Theoretical and factual K_2O (CAL, DL) content alteration of the soil by potassium fertilization within different classes of supply (mg K_2O/100 g soil).

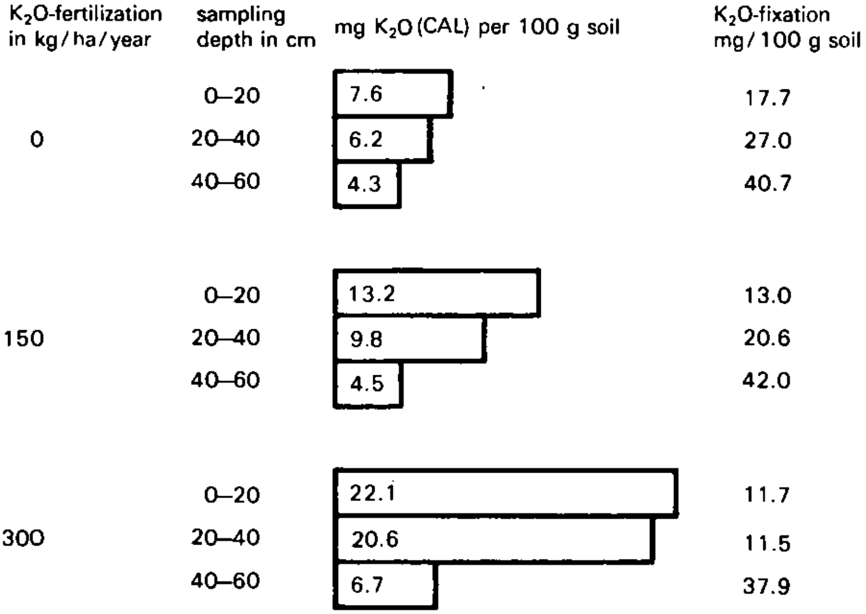

Fig. 5. The influence of potassium fertilization on K_2O concentration of soil in different sampling depths (potassium long-term experiment Fuchsenbigl).

3.4 Migration of potassium to depth

Positive K balances are only partly accounted for by changes in CAL/DL K_2O in the topsoil and the question arises as to the importance of changes in non-exchangeable K content and in K content of the subsoil. The present series of experiments gives no information on movement of K to depth but some information is available from a long-term experiment at Fuchsenbigl on chernozem from loess, a deep fine-sandy loam, with annual rainfall 560 mm illustrated in Figure 5.

This shows that applying K fertilizer greatly increases the K content of the surface (0–20 cm) soil and also increases the K content of the subsoil (20–40 cm). Variation in the depth of ploughing doubtless makes a contribution to this. There is only a small change in K content of soil below 40 cm and that only at the highest rate of application (300 kg/ha K_2O per year). To the extent that K enrichment down to 40cm depth overcomes restriction of K uptake from surface soil in dry areas it must be welcome. The increase in K fixation with depth points in the same direction and confirms the potassium distribution pattern of the soil by way of the CAL-values.

4. Conclusion

Fertilization to replace crop K removal (by total crop) requires annual application of about 150 kg/ha K_2O to a practical rotation comprising 75% cereals. If all crop residues are returned to the land this annual requirement reduces to about 50 kg. Such a fertilizer programme – as indicated by results from long-term experiments – corresponds in every case to economically optimum K usage and in many cases is more generous. In making recommendations the soil's ability to supply K must be taken into account. Only when the rotation includes a higher than average proportion of K demanding crops (potatoes, sugar beet, legumes, etc.) or when special conditions result in high K fixation, will higher dressings be required.

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Co-ordinator's Report on the 2nd Session

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Evaluation of Nutrient Balances

Several factors determine soil fertility; some of them, *i.e.* soil depth and texture, can hardly be modified; on the other hand, others can be more or less corrected, *i.e.* humus content, soil structure, available nutrients, biological and sanitary state of soil. Nutrient availability is very important to soil fertility. However, this factor can only express itself as long as there are no other limiting factors, such as water shortage or unsatisfactory soil structure.

The nutrients taken up by plants, lost by leaching, run-off, or possible fixation in the soil can be compensated by appropriate fertilization. The aim of fertilization is to maintain a sufficient nutrient level, while avoiding excesses, in order to meet crop requirements and to ensure the quality of the products. Different methods can be used to determine the optimal fertilization:

– the first consists of setting up field trials with increasing amounts of fertilizers for various crops and types of soil under various environmental conditions. These methods have been widely used to determine optimum rates of nitrogen fertilizer. The response of the crop to nitrogen fertilizers is rapid and valid information can easily be collected. Regarding other nutrients, such as phosphorus and potassium, for instance, the problem is a little different. Prof. *Beringer* showed in his paper that only long-term experiments can give useful indications. Consequently these methods are expensive and must be used primarily to calibrate and adjust the methods of soil or plant analysis.

– a second method is to return to the soil the amount of nutrients which has been removed from the field by the crop. This method appears to be very useful and can be a basis for fertilizer recommendations. However, it is insufficient to obtain the best economical efficiency of the fertilizer input and to ensure the maintenance of soil fertility in the long term. In his very interesting communication, Prof. *Chisci* referred to losses by leaching and erosion, which can be important according to the types of soils and crop management. So, this method would be an inadequate guide to nitrogen fertilization. Furthermore, Dr. *Edelstein* has shown the importance of potassium, which can be released in young mica-rich soils. Finally, we have to mention the fixation of potassium and phosphorus. All these factors are to be taken into consideration and can lead to important mistakes in the long run. Furthermore, a fertilizing technique based essentially on a balance sheet does not take the level of available nutrients in the soil into account. In fact, it is advisable to reinforce or limit fertilization to compensate for poor or high nutrient levels in the soils.

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– Due to the deficiencies of the above mentioned methods, chemical soil or plant analyses are necessary in order to set up optimal fertilization and to maintain the nutrient balance sheet in soil in the long-term. As Prof. *Beringer* pointed out, ideal methods do not exist: all represent an approach to reality and need interpretation. Relations between yield and available nutrients are not always obvious in crop trials. Other factors, such as for instance water shortage over a few weeks, soil-borne diseases, effects of soil depth and structure and crop management can interfere. Pot experiments allow us to neutralize these effects: the available nutrient status becomes the only limiting factor. Furthermore, the response of plants to the amount of applied fertilizers will also be more evident and clearer as compared with field trials. Results of pot experiments allow us to establish more easily correlation with soil analyses and are very useful for calibrating and adjusting the methods. They should, however, be confirmed by field trials. Dr. *Ryser's* paper has given a good example of the work, which must be done to adjust the interpretation of the results when using a mild extracting agent. The results show how important it is to take the effect of texture and cation exchange capacity into account for their interpretation; the different sensitivities of crops to nutrient levels must also be considered.

Concerning soil analysis, an improvement of the methodology is desirable. So, in some difficult cases, it would be advisable to use two extracting agents, a mild one and an aggressive one. It would then be possible to get better information not only on the easily available nutrients but also on the reserve of nutrients. However, according to *Viets,* as Prof. *Beringer* emphasized, soil and plant testing will probably always remain empirical because of the great complexity of the soil water-plant system. Nevertheless, such methods as those using electroultrafiltration (EUF) offer interesting prospects for improvement. The operation costs could limit its use for routine soil analyses. Prof. *Beringer* has also pointed out the interest of plant analysis in the case of perennial crops and showed the limits of these techniques for annual crops. These methods could supply a very useful complement to soil analysis. The nutrient balance in the plant is much more sensitive than in the soil. However, we must not forget that plant analysis can be influenced by the weather and general growth conditions. Furthermore, these data do not give information about the nutrient reserve in the soil. Therefore, they are to be considered as a complement to soil analysis.

The importance of the nutrient reserve in the sub-soil has been underestimated. This problem deserves more attention, especially in deep soils. Levels, which are to be maintained in the sub-soil, should be defined. To our knowledge, the nutrient level in the sub-soil has only been taken into consideration for perennial crops, such as grapes and fruit trees. According to the results of *Johnston* and *McEwen*, annual crops also seem to react positively to good supplies in the sub-soil, particularly during dry periods.

In conclusion, we should like to point out that soil analyses are often blamed for their imprecision; various factors can interfere, such as season of sampling or soil moisture at the time of sampling; furthermore, the interpretation should be able to take into account texture, soil depth, content of stones and gravel, etc.

Knowledge of these complementary factors should allow us greatly to improve the quality of results' interpretation. The conception of an efficient but economical agriculture also calls for better definition of the nutrient levels to be maintained in the soil in order to satisfy crop requirements, provide the highest economical yields, ensure quality of the products, and avoid excessive fertilization with risks of pollution.

In spite of its limitations, soil analysis remains a useful tool for the management of reasonable and economical fertilization in most of our soils.

Chairman of the 3rd Session

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3rd Session

Building Yields by Fertilizer Input in Temperate Agricultural Systems

Site-specific Yield Potentials in Relation to Fertilizer Use

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Summary

Field experiments traditionally measure the difference between applied treatments. Modern multidisciplinary studies instead compare yields with the yield potential of a given site. The yield potential of a crop with a given genetic constitution at any site is limited by radiation, which controls photosynthesis, and temperature, which controls plant development. A variety of additional factors then combine to diminish yields, and give the observed normal distribution of yields around the mean value. The distinction between site factors and management factors is discussed. Some of these factors are nutritional, and can be controlled by the use of fertilizers, though their exact use may be complicated. The relative importance of different factors on different soil types is considered. This situation is illustrated with results from the *Yield Variation Programme* of the *Agricultural Research Council,* which concentrated on winter wheat.

1. Introduction

Ever since the invention of artificial fertilizers by *John Bennett Lawes* of Rothamsted around 1840, their effective use has been controlled and tested by field experiments, in which different rates or forms are compared with each other or with no fertilizer at all. The original idea behind field experimentation with fertilizers was thus to test the improvement in yield by applying them, *i.e.* the reference point was the unfertilized crop. The response was given in absolute units or in percent, and one has occasionally the feeling that the absolute level of yield in such work was of almost secondary interest.

An important change in point of view was the seemingly minor point suggested by *Bray [8],* of stating the fertilized yield as 100%, and the unfertilized yield as a percentage of this. This emphasized that a healthy, fertilized crop is the normal one, and that the standard or reference crop should be regarded as one which is fully supplied with nutrients. As our thinking has become more multidisciplinary, we now are starting to consider other targets as our point of reference. Thus an ideal crop, in an ideal climate, without any disease or deficiency, is one in which the genetic potential of the crop is fully utilized. According to this way of thinking, the response produced by any factor or treatment is measured in terms of the degree to which it assists in attaining this ideal crop. This focusses attention on the definition of the yield potential of the crop, and the way in which the environment prevents this from being attained.

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2.1 Yield Variation Programme

This idea underlay the research programme on Yield Variation started by the *Agricultural Research Council* in 1977, as a co-operative venture by four Institutes *[35]*. It started from the fact that the mean national yield of winter wheat was at the time little over 5 tonnes ha^{-1}, whereas there were already well-substantiated cases of farmers' yields of over 10 tonnes ha^{-1}. The purpose of the programme was to investigate the reasons for this wide span of yields, which could certainly not be accounted for by obvious and simple errors on the part of farmers. The main thrusts of research which developed were as follows:
a) Studies on the structure of yields throughout the country.
b) Multidisciplinary, multi-factorial field trials to determine the levels of yields obtainable with the best combination of treatments.
c) Comparison of crops on different soil types, to identify constraints operating on particular soils.
d) Detailed physiological studies of very high-yielding crops, and the acquisition of good data sets on them.
e) Construction of a whole-crop model of the winter wheat crop.
The work under d) and e) will not be described here; reports on the modelling work are given in *[38]* and *[39]*. Informally, the aim of the programme was stated as 'to be able to grow 10 tonnes ha^{-1} wheat on any site, or to be able to state the reasons why it was not attained'. This last point is important; there is never any shortage of opinions on the reason for unsatisfactory yields, but it is only in the rarest cases that such opinions are supported by facts. If the programme were started now, this target of 10 tonnes ha^{-1} would almost certainly have to be increased.
This approach is related that of *Maximum Yield Research* or *'Blueprints' [11, 15, 24, 25]* but has clear differences. The latter programmes mainly aim to develop high-input systems that are sufficiently effective on average over large areas. Yield Variation is a wider concept, in that it tries to determine the causes of the variation, whether these are immediately correctable by adjustment of existing inputs or not. By implication, it aims for more site-specific advice, the more exact adjustments of inputs to expected yield, the systematic identification and correction of constraints to yield, and hence more regular, predictable and profitable yields.

2.2 Yield potentials

This rather confused topic requires some definitions first. The 'genetic potential' is the largest yield obtainable if all the environmental conditions and agronomic decisions were perfect. The actual yield obtained is reduced below this by deficiencies in the conditions and by errors in decisions or in their execution (Figure 1). The distinction between *site factors,* which determine the site potential, and *management factors,* which determine the actual yield, is not always clear. Thus some factors, such as fertilizers, are clearly 'management', whereas some such as soil texture are clearly 'site', but others such as drainage or crop rotation systems, are less easily classified. Water supply is particularly difficult, as it is a 'site factor' when it is rainfall or stored soil water, but 'management' when applied as irrigation. For the purposes of this discussion, I define management factors as those which are under the experimenter's or farmer's control *in that growing season.* These are the immediate decisions relating to that particular crop; longer-term decisions (e.g. relating to drainage systems) are regarded as influencing the site potential.

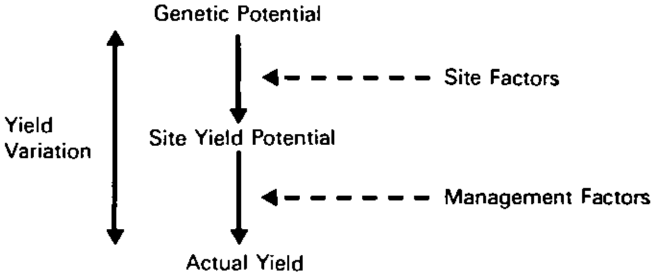

Fig. 1. Relation of genetic potential, site potential and actual yield, as used in this paper.

2.3 Genetic potential

This is difficult to determine. For a crop well adapted to the climate, such as winter wheat in Britain, there are three sources of evidence;

a) Physiological calculations of leaf area and photosynthetic capacity *[2].*

b) Reports of the maximum yield obtained on farmers' fields, on the assumption that a few fields out of very many will have almost perfect site conditions and management by chance.

c) Highest plot yields obtained in multi-factorial experiments on good sites.

For high-yielding winter wheats all three agree reasonably well, and point to a genetic potential, in the British climate, of 12 to 14 tonnes ha^{-1} grain at 85% dry matter *[2].*

2.4 Site potential

This is much more difficult to decide, because of the difficulties of definition discussed above. One thinks at first of land capability classifications, but these are of rather little help. In the British system *[7]* the yield level is considered very little, capability being defined in terms of the range of crops which may be grown on a site. Some attention to sustained production rate is given in the bulletins now accompanying the 1:250 000 soils map of England and Wales, as it is also in the recently published land capability classification system for Scotland *[6].* There are other systems which base assessment of capability on yield, but these will tend to be too inexact or empirical for our purposes, being designed for use on extensive areas rather than single sites. The general principles used in this type of approach are outlined by *McRae and Burnham [21].*

In practice, the only way to determine a site potential is to carry out a multifactorial experiment testing different levels of all those factors which cannot be predicted with certainty. The best yield in the experiment is then the site potential. This is clearly open to error if an important management factor has been omitted, or the range of treatment levels wrongly selected. Examples of results of such experiments are in Table 1. More details of experiments in this series are given in *[26, 28]*. Such experiments are expensive, and clearly only a limited number of sites can be tested in this way. Much depends upon the size of interactions between treatments; on average these were not large, the most marked being between nitrogen and leaf fungicide sprays. Another series of smaller factorial experiments *[28, 41]* tested only nitrogen treatments and fungicides. Where there are no interactions, treatments can be tested singly, in much simpler trials. Most of the yield responses found in these factorial experiments were fairly small, except where zero levels of N were tested. This is of course a consequence of setting the treatments near to the known optima; these experiments are in a sense an attempt to fine-tune agronomic treatments. They also demand that many other treatments or decisions shall be made correctly, if they are not included as variables. This implies that this approach is most effective where there is a large body of existing information on a crop.

2.5 Yield sensitivity

So far we have discussed yield potentials as though they were the only characteristic of particular sites. However, of comparable importance is the *sensitivity* of a particular site to management decisions. As an example, Table 1 gives results from multifactorial trials on two contrasted soil types, in which yield was nearly always altered more on the sandy loam at Woburn than on the clay loam at Rothamsted by any given difference in management. Multifactorials thus give information about the best possible yields, and also on how likely this is to be attained. Experiments can test many combinations of treatments, and the experimenter can select the best, but a farmer has to make one set of decisions for a single field. All of them are unlikely to be exactly correct, and the penalty for the resulting errors will be larger on a site such as Woburn than a site such as Rothamsted. Two soil types could thus have the same site potentials, but the range of yields, and hence the mean yield obtained in practice, could be very different.

In Table 2 are listed the maximum yields obtained (as averages of at least four plots) for particular combinations of treatments on all our six sites over four years. All sites except Maulden achieved over 10 tonnes ha^{-1} in at least one year; the reasons for the relative failure at Maulden are discussed below. On this measure, the sandy loam at Woburn (with irrigation) is little worse than most of the clay soil sites, which are normally regarded as far superior for wheat. However, good yields at Woburn depend upon very exact control of the nitrogen level and timing. In addition, from Table 2 it can be seen that some sites are more dependable from year to year than others in attaining over 10 tonnes ha^{-1}, but this yearly variation in maximum yield on the same soil and farm does not appear to be related to the sensitivity to treatment differences in one year, as the Woburn maximum yields are relatively stable. The total variation in maximum yields, between 6.7 and 11.4 tonnes ha^{-1}, is large and the reasons for it are discussed below.

Table 1. The effect of six factors on grain yield (tonne h^{-1}) of Hustler winter wheat at Rothamsted (clay loam) and Woburn (sandy loam) in 1981 [42]. Means over all other treatments. Differences in parentheses *[32]*.

Factor tested	Rothamsted	Woburn
(1) Sowing date		
15/16 September	9.45	9.40
30/31 October	8.79(−0.66)	7.84(−1.56)
(2) Total N kg ha^{-1}		
(R) 80 (W) 150	9.15	8.43
(R) 150 (W) 220	9.09(−0.06)	8.81(+0.38)
(3) N Division		
Single	9.18	8.38
Divided	9.07(−0.11)	8.86(+0.48)
(4) N Time		
Early	9.03	8.70
Late	9.21(+0.18)	8.54(−0.16)
(5) Irrigation		
None	9.28	8.25
Full	8.96(−0.32)	8.99(+0.74)
(6) Aldicarb (5 kg ha^{-1}) to seedbed		
Without	8.96	8.23
With	9.28(+0.32)	9.01(+0.78)

Table 2. List of maximum yields determined with best treatment combination, on 6 farms on different soil types. (*Widdowson and Darby,* private communication; Rothamsted Annual Reports for 1980 to 1983).

	tonne ha^{-1} grain			
Year	1980	1981	1982	1983
Rothamsted – clay loam	10.92	9.74	8.71	10.36
Woburn – sandy loam	9.09	10.02	8.97	9.26
Saxmundham – clay loam	10.14	10.91	10.66	11.36
Hexton – clay	10.51	11.41	10.17	9.58
Billington – clay	8.62	10.16*	7.63*	10.06
Maulden – clay	6.73*	8.60*	8.21*	8.12*

* preceding crop wheat or barley

2.6 Yield distribution and soil series effects

There is remarkably little information about the statistical distribution of yields between different fields for major crops, but this could be of great value. *Church and Austin [10]* considered the evidence available for winter wheat in Britain, and concluded that the variance between single fields was around 24%. Very useful data have also been obtained from the 'Ten-Tonne Club' operated by *Imperial Chemical Industries [18].* Over three years this provided measured field yields from many farmers. These were of course selected, in the sense that the farmers were very competent, the fields chosen were the best, and inputs are aimed at maximising yields. From the point of view of a discussion on site potentials, these factors are a positive advantage, in that simple errors of management are less likely than in a random sample, hence underlying site factors are more likely to be detectable. The mean yields in the survey were indeed 1.5 to 2 tonnes ha^{-1} greater than the corresponding national average. The conclusions about yield distribution (Figure 2) *[33, 35, 40]* were:

1) The *variance* of the yields was not greatly reduced from the value of 24% given above even though the mean yield was greater. Larger and better controlled inputs do not therefore give a markedly lower yield variation. This suggests that the variation arises from site factors, and from many decisions which are not greatly in error, but are not the best possible.

2) The form of the distribution of yields was very close to normal with virtually no skewness (Figure 2). This implies that there is no biological barrier to increased yields, *i.e.* the genetic yield potential is well above the yields recorded in the survey. It also implies that farmers recorded poor as well as good yields correctly.

3) A normal distribution is usually a sign that the variation is due to a number of causes, rather than a very few dominant factors. The fraction of fields with very high yield must be very small, showing the small chance of getting all the many site factors and management decisions just right.

Weir, Rayner and Catt [40] also investigated the effect of different variables on yields. Rather surprisingly, they found that the largest fraction of the total variance

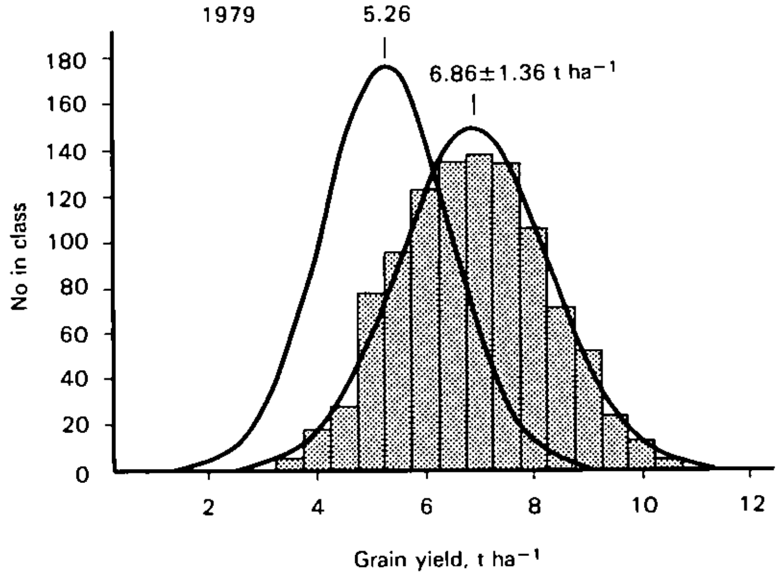

Fig. 2. Frequency distribution of grain yields in 1979. Histogram is for Ten-Tonne Club yields, with smooth curve of best-fit Gaussian distribution for the same data with a standard deviation of 20%. The other curve is for a mean of 5.26 t h^{-1}, as found in the national crop in that year, with a standard deviation of 24% *[10]*. (after *[40]*).

was associated with soil series (Table 3). Soil texture alone accounted for very little of the variance. Major factors such as crop cultivar or preceding crop were important, but less so than soil series. This is one of the first pieces of evidence that soil series definitions have a specific ability to predict yield capability.

Table 3. Percentage of total variance of field yields in Ten-Tonne Club survey accounted for by different site conditions and varieties (after *[42]*).

Factors	1979	1980
Soil series	18.3	18.7
Crop variety	5.5	15.3
Previous crop	7.8	5.3
Sowing date	3.0	1.2
Original Ten-Tonne Club soil classification	2.9	4.0

3. Factors affecting site potential

3.1 Radiation and temperature

The potential yield will vary with radiation and temperature at a particular site and season. The intercepted radiation is closely related to the total dry matter formed by large and healthy crops *[22]*, and changes in incoming photosynthetically active radiation will thus affect dry matter. Intercepted radiation also depends upon the development of leaf area, and hence on plant development; this is always a function of temperature, and both shoot *[17]* and root *[4]* development are controlled by accumulated thermal time. The rapid development of leaf area is vital, though it is perhaps less important for a crop such as winter wheat, in which canopy closure occurs early, than in spring-sown crops such as sugar beet. It has been suggested *[2]* that typical differences in the radiation intercepted have relatively little effect on final yield.

Temperature and radiation are the two environmental factors over which there is little control (except in part by changes in sowing date), but they define the yield potential of a crop at a given site in the most basic terms. However, neither is likely to vary much over short distances, and they are unlikely to explain large differences in yield potential between sites near together. Computer simulation models of winter wheat growth as affected by temperature and radiation have been constructed *[38, 39]*, and it may be possible to use these to determine just how important changes in these variables are over the main wheat-growing areas of Western Europe.

3.2 Water supply

Shortage of water is due to both climate and soil, which is why rainfall was not included in discussing the climatic variables in 3.1. In experiments it can be controlled by irrigation, but in practice this is rarely possible for cereal crops. In a given climatic zone, the demand for water is mainly dependent upon the intercepted radiation, *i.e.* upon ground cover. Thus in Eastern England winter wheat normally requires about 350 mm of water between spring and harvest. If the rainfall in this period, plus the stored available water in the profile, can deliver this water at the necessary rate, then drought will not decrease yield. The real question – and a very long standing one – is to what depth, and to what suction, water can be extracted before yield is affected in practice. Water can be extracted at Rothamsted by wheat to a 'limiting deficit' of 150 mm, before yield is affected. However, this result was obtained by direct measurements on a single site – we still need a complete model of water extraction on different soils which would allow us to predict this limiting deficit from soil observations. *Innes and Thomasson [19]* showed that the effective potential soil moisture deficit for winter wheat in Eastern England was normally 100 to 125 mm, and that yield reductions could be expected when this value exceeded the computed 'available water' in the rooted zone (which should be the same as the limiting deficit), with the effect becoming marked when the difference exceeded 50 mm. This profile available water was calculated by assuming that the fraction of the available water (defined by the usual soil moisture suction criteria) which could actually be extracted, decreased with increasing depth. There is also the question of whether timing of drought is important; according to the work of *Day et al. [14]* with spring-sown barley, the total water supply was the important factor, rather than the time at which the drought began. The loss in yield is around 1.2 to 2.0 t ha^{-1} for each 100 mm of water which is required but not available *[3]*.

The average response of winter wheat in England to irrigation is small or even negative unless the soil is lighter than a sandy loam, or the year is one of exceptional drought. The limiting water deficit of a given soil and crop combination is thus a most important site limitation to yield, but in practice with wheat on typical, heavy soils in Britain, this limit is rarely reached *[16]*. The analysis of the Ten-Tonne Club records *[40]* suggested that lack of water was rarely a constraint on yield, because there was a positive correlation between maximum potential water deficit and yield.

When drought does restrict yields, the consequences for fertilizer use are clear. The potential yield of the site is decreased, and the demand for nutrients lessened. Whereas this may matter less for potassium and phosphorus – in which availability matters more than quantity – it is crucial for nitrogen and sulphate. The efficiency of use of nitrogen fertilizer has been reviewed by *Cresswell and Godwin [12]*, who found that the factor which most limited efficiency of use was water shortage.

3.3 Waterlogging

This factor is highly site specific, but also depends upon rainfall, and can be altered by artificial drainage. Recent work at Letcombe Laboratory has shown that wheat is very sensitive to waterlogging at germination and emergence, but later it is surprisingly tolerant. Yield increases of around 10 to 20% can be obtained by artificial drainage of heavy soils under moderate rainfall *[9, 31]*.

3.4 Texture and structure

These are also components of water relations. It is often taken as axiomatic that a soil with 'good' texture and structure must have a higher yield potential than one where these are poorer, but this depends closely upon how far inherent disadvantages can be overcome by careful agronomy. In trials during 1978 to 1982 we have had yields of up to 10 tonne ha^{-1} of grain from a light sandy loam, a clay loam and heavy clay soils (Table 2), though this required careful matching of nitrogen demand with supply *[35]*, irrigation on the light soil, and fungicide sprays in all cases. In data from the ICI surveys *[18]* very little correlation between yield levels on farmer's fields and soil texture was found.

This is not necessarily so when a structural factor is involved. Soil texture will determine the ease with which compacted layers are formed, and their strength and duration. The actual effect of pans and compacted layers on crop yields is very poorly defined in quantitative terms *[29, 32]*, probably because the effect of a pan is so strongly dependent upon other growing conditions. Thus at Woburn in 1982/83 a plough pan on sandy loam prevented root penetration until April, and the crop was consequently nitrogen deficient and stunted compared with that on soil where the pan had been broken. Despite this, when N fertilizer was applied in spring, the roots penetrated the pan, and at harvest there was only about 5% difference in the grain yields *[37]*. However, the site at Maulden, on a heavy soil with a compacted layer, consistently gave the lowest yield of any of the six sites (Table 2). There is an urgent need to be able to predict reliably whether a particular soil pan is depressing yield or not.

There is probably no site factor with which management interacts more strongly than with soil structure. The soil at the Saxmundham site (Table 2) is of the Beccles series, and is generally accepted as being difficult to cultivate successfully, and showing serious structural problems. Originally yields from plots on this site were no greater than the national average yield, but over a period of some ten years the yields have gradually increased to the levels shown, which are now attained consistently. A major factor in this is undoubtedly the increasing experience of cultivating this soil (Widdowson, personal communication).

3.5 Soil-borne diseases

The presence of take-all disease *(Gaeumannomyces graminis)* is a serious impediment to high yield. It is not a constant factor acting on yield potential, as in any one year it depends upon weather and preceding crop, and there is little agronomic action which can be taken to combat it. In comparisons of multidisciplinary tests at Rothamsted after potatoes or oats (little take-all) or barley (much take-all) the effect

Table 4. Yield of wheat grain, t ha^{-1}, following different crops, in two experiments at Rothamsted in the same year on the same soil type, averaged over sowing date (for plots receiving fungicide sprays) (after *[23]*).

Previous crop	Oats	Barley	Potatoes
N rate		N applied early	
N_1	8.25	4.96	7.51
N_2	8.80	6.22	7.82
		N applied late	
N_1	7.78	4.81	7.26
N_2	8.35	4.60	7.92

of the preceding crop was larger than any other factor (other than total absence of nitrogen), at nearly 3 t ha^{-1} *[23]*. Apart from the large difference in mean yield, sharp differences in the effect of extra N, and of timing of N, both depended upon the preceding crop (Table 4). In the trials listed in Table 2, most followed break crops, except on the low-yielding Maulden site. Current work is aimed at determining whether rotations or soil physical conditions, or both, are the cause of low yields at this site.

3.6 Machinery accessibility

The carrying out of operations, particularly preparation of a seedbed and seed drilling, at appropriate times is clearly an aspect of management that depends upon soil texture. In most experimental fields this can be optimized without too great difficulty in most years, and this factor may thus not be serious. However, in farming practice this is much more difficult, and the ease with which machinery can get access to the land (machinery work days) is important *[30]*. This is consequently a factor in the assessment of average site yield under practical conditions, in that it determines how easily management can be optimized. It cannot be further considered here.

4. Management factors

4.1 Effects of fertilizer rates

The aim of farm management is to attain the best economic result from a field. In current circumstances, that normally means attaining as near to the site potential as possible, because of the relative costs of fertilizer and grain. In most circumstances nutritional problems can be cured by appropriate fertilization (soil or leaf-applied) in the year of cropping. However, the existing availability of nutrients in the soil determines how essential the addition of fertilizer is, and this assessment is thus crucial to the attainment of the yield potential at a site. This is particularly so in farming practice, where a single decision on rates has to be made. In an experiment, a series of rates can be tested so that the best level is certain to be found.

It is essential to have appropriate levels of phosphate and potassium in the soil. The levels will vary with the crop, but for cereals there are well-established soil analysis values which are normally adequate. There is little difficulty in monitoring these for a proper fertilizing programme, and as any surplus causes no damage for cereals, there is no pressing need for great precision. The most important point is that if yields close to the site potential are being removed regularly, the offtake of phosphate and potassium may be greater than normal, and this must be allowed for. Thus a 10 tonne ha^{-1} crop of wheat will remove about 35 kg P ha^{-1} and 250 kg K ha^{-1}, with a very high demand at times of rapid growth (Figure 3).

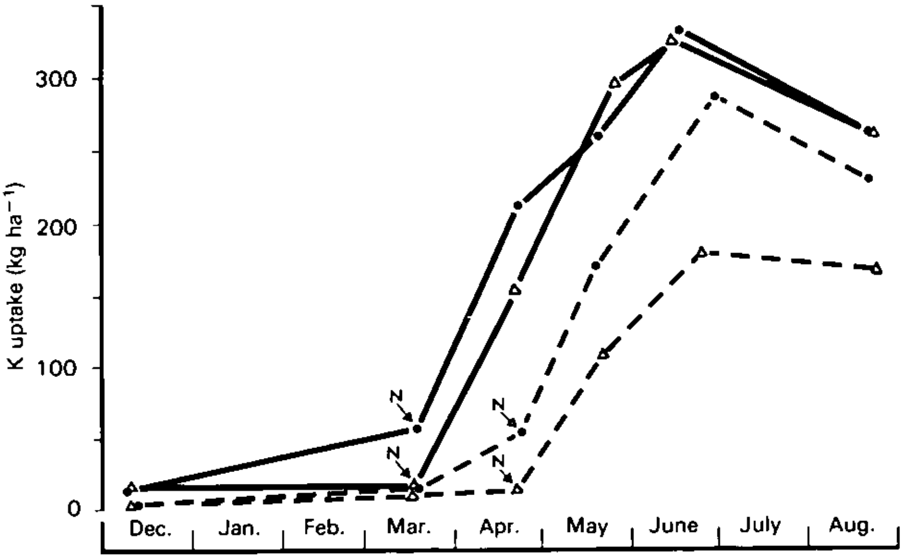

Fig. 3. Potassium content in high-yielding wheat crops in 1981. O at Rothamsted; Δ at Woburn; —— sown early; – – – sown late. N marks point at which spring nitrogen top dressing was applied. (*P. Barraclough*, private communication).

For nitrogen the situation is different. The demand depends critically upon the size of the crop, the nature of the preceding crop, the soil type and the weather. The first of these then depends upon how far other constraints upon yield have been corrected. If this is known, the demand can be estimated, and for a 10 tonne wheat crop this will be over 200 kg N ha^{-1}. This leads to one form or other of the 'Balance method' *[27]*, in which inputs are balanced against outputs and the difference indicates what needs to be supplied as fertilizer nitrogen.

There are difficulties in assessing the inputs, the main one being the amount of mineral nitrogen stored in the soil profiles in the spring (N min). This is measured by direct sampling to one meter depth in some systems now being used in Europe *[5, 36]*. Whilst this has been shown to increase the precision with which nitrogen is used, it seems possible that the method is not cost-effective because of the labour-intensive sampling prodecure. Instead, modelling methods are now under development *[34]* which predict nitrogen need from soil and weather data. Some loss of precision is probably acceptable for lower costs, and the measurement of N min is in any case open to experimental error. Recent tests of the accuracy of such a computer method at Rothamsted has shown a correlation coefficient of 0.93 between the predicted and measured mineral N (NH_4 plus NO_3) levels to 90 cm depth, on thirty sites, over four years and several different soil types *[1]*. This, allied to the clear relationships between soil nitrate level and stem nitrate level in winter wheat and the apparent success of the 'Balance method' on our own experiments *[35]* leads us to believe that useful predictions of nitrogen need can be made for winter wheat. Presumably the same principles can be applied to other crops.

4.2 Timing of fertilizer application

The timing of application of potassium and phosphorus is not normally very important, unless the soil is extremely deficient or extremely prone to leaching loss. In contrast, the time of application of nitrogen can be critical for cereals. There are many questions which are constantly asked about how much nitrogen should be applied at various times during the ten months or so when winter wheat is in the ground. In particular there is argument about whether autumn or winter nitrogen is needed, and how many separate applications are needed in spring. Our view is that there is no single answer to any of these questions, because of differences in soil and weather and crop. Some soils have ample nitrogen for growth until April, others have almost no mineral nitrogen present from February on *[35]*, and it is essential for these to receive an early nitrogen dressing (Table 5).

Table 5. Effect of added winter nitrogen, in relation to soil nitrate nitrogen, on crop weight and grain yield (after *[35]*).

	40 kg N ha^{-1} as urea in winter	
	Without	With
Nitrate to 90 cm (avg. Feb. and March) (kg N ha^{-1})		
Rothamsted	26	n.d.
Woburn	8	n.d.
Crop dry weight at anthesis (kg m^{-2})		
Rothamsted	1.07	1.11
Woburn	0.99	1.21
Grain yield at harvest (t ha^{-1})		
Rothamsted	10.4	10.0
Woburn	10.5	11.4

The factors which determine such a need can be of two types. There is the simple lack of nitrogen, as above, which depends mainly upon soil physical and microbiological factors and the weather. There are also more complex problems arising from effects of nitrogen on crop physiology, *e.g.* tiller formation and survival, which are less clearly understood.

There seems to be a real possibility of using computer simulation to control timing of nitrogen, in addition to rate. The simulation of soil and crop changes from weather data *[34]* can generate warnings of when the nitrate level in the profile falls so low that added nitrogen is advisable, and this could be confirmed by measurement of stem nitrate-N if desired. *Jenkinson and Powlson [20]* have shown that considerable losses of fertilizer nitrogen occur in the month after it is applied, probably by denitrification, and that the loss is related to the rainfall. This opens the possibility of also predicting the need for late additions of N if losses are unacceptably large, and thus achieving accurate control over the whole procedure of nitrogen fertilization at reasonable cost.

4.3 Need for accurate assessments of inputs

If our interest is solely in the maximum yield potential for a site, then the approach will depend upon whether there is a clearly marked optimum level for an input, or whether a maximum yield is reached beyond which a higher level of input has no effect. If the latter is true, then exact estimates of input level are not needed, and the yield potential will be obtained if any level of excess is used. If the former is true, then several levels of input must be tested to ascertain the best one in experimental work, and it makes the attainment of high yields in normal farming practice much more difficult. The best example is with nitrogen fertilizer; in many experiments we find that the response curve of wheat grain to nitrogen has a peak if no leaf fungicide is used, but reaches an asymptote if leaf sprays are applied (Table 6). Thus it may or may not be necessary to determine exactly the optimum level of an input for the measurement of yield potential, though it is of course always essential to determine the best level of input for maximum economic return.

Table 6. Yield of grain at 85% DM (t ha^{-1}) on three experiments on clay soils in 1982. *[13].*

Experiment	Hexton		Billington		Maulden	
Aphicide/Fungicide N (kg Ha^{-1})	None	Sprayed	None	Sprayed	None	Sprayed
Nil	8.26	8.59	3.53	3.78	4.43	4.55
70	9.07	9.80	–	–	–	–
100	9.16	9.93	–	–	6.68	7.57
130	9.19	10.08	6.63	6.93	6.83	7.71
160	9.05	10.15	6.57	6.89	6.85	7.84
190	–	–	7.00	6.89	6.76	8.00
220	–	–	6.97	7.50	–	–

5. Conclusion

If great care is taken to examine levels of inputs and types of management, it is possible to define the yield potential of a particular site in a particular season with some degree of confidence, though one can never be certain that some untested input or management choice would not in fact have produced a still higher yield. The experience within our Yield Variation programme, which is still limited, is that given skilled agronomy most reasonable sites can produce yields of around ten tonnes ha^{-1} of winter wheat (at 85% moisture). If this is correct, it suggests that the basic differences in site yield potentials, as defined by soil type, may be less than is suggested by the variation found in commercial yields, which also depends upon the sensitivity and responsiveness of the site to management decisions, and upon factors which are under long-term management, such as crop rotation, drainage, subsoiling, etc.
Much of this variation between fields in normal farming must be due to accidents or unavoidably poor timing of operations. Much will also result from incorrect decisions on timing or input level, which can be avoided or tested for in experimental

work. The between-field variance has been shown to be around 24% *[10]*. *Austin [3]* has calculated that this variation could be produced by six two-level factors, each of which affected yield by only 10% plus one three-level factor affecting yield by 25%. This idea of the variation in commercial fields being produced by a fairly large number of different factors varying independently is supported by the normal distribution of field yields about the mean, even when the latter is high *[33]*. The practical attainment of the maximum potential yield at a site thus demands both the corrections of long-term constraints on the site potential, and excellent management in each year. If this is correct, yield variation can only be decreased, and the mean national yield thus brought closer to the genetic potential of the crop, by more exact and site-specific advice. Whole crop modelling, which is part of the Yield Variation programme, should be of value in this context.

Acknowledgments

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Nitrification Inhibitors and Nutrient Uptake by Plants

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Summary

The effect of nitrification inhibitors (NI) on nutrient uptake by plants is a complex subject depending on the mode of action, and factors affecting persistence and effectiveness of these compounds in soil. Factors such as pH, temperature, type of fertilizers, nitrifying activity, type of crop and urease activity have to be carefully considered before using NI. Possible benefits to be obtained from inhibiting nitrification may be counteracted by increased losses by ammonia volatilization, especially in alkaline soil. In a grass-legume association under a Mediterranean climate, spring-applied urea-N is rapidly hydrolyzed, nitrified and eventually immobilized by microorganisms or taken up by plants. Where N losses by leaching and denitrification are low and limited to a short period of time the use of NI should be discouraged.

Nitrate is the most mobile N compound in the soil-plant system since it is not adsorbed by the negatively-charged soil colloids and although easily taken up by plants can therefore be leached by water; denitrification is a further pathway involving nitrate by which N can be lost through the production of gaseous compounds such as N_2O and N_2. The nitrification process thus commands a central role in the soil N cycle. Soil scientists have speculated that if nitrification could be controlled, man might gain greater control over the ultimate fate of N and thereby improve N utilization by plants. Several compounds that slow or stop nitrification have been developed on a commercial basis.

The aim of this paper is to present the effects of nitrification inhibitors on nutrient uptake by plants. A correct presentation of this problem requires the consideration of the modification in the soil nutrient status caused by the addition of inhibitors. Contradictory results have been obtained regarding the influence of nitrification inhibitors (NI) on nutrient uptake by plants and this is dependent on the fact that the mode of action and factors affecting persistence and effectiveness of these compounds in soil have not been properly taken into consideration. In addition, the aim in reducing leaching and denitrification losses has often caused agronomists to overlook the fact that the use of nitrification inhibitors can also present severe limits. An exhaustive examination on the effects of NI on nutrient plant uptake has to consider advantages and limits of this use, the mode of action of these compounds as well as the factors affecting their persistence in soil.

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1. Advantages and limits in the use of nitrification inhibitors

Potential for loss from the soil-plant system is greater with nitrogen than with any of the other plant nutrients. The use of NI has been advised to delay the nitrification rate and decrease N losses, especially where NO_3-N is highly susceptible to leaching and denitrification.

However, the crop efficiency in the presence of NI can be also improved through a different use of metabolic energy *(Sequi* and *Pagliai [15])* which can be shifted from the reduction of nitrate to increase, for example, the protein content. It is well known that ammonia uptake is preferred and, when nitrate and ammonia are present in hydroponic solution, nitrate reductase is inhibited (*Rotini et al. [13]).* Crop yield can also be increased by avoiding possible high nitrate concentration causing a 'nitrogen stress'.

Research has shown that the efficiency of utilization of applied N varies with time of application, soil type and location. The use of NI may increase the efficiency of fall-applied N fertilizers *(Touchton et al. [16])* decreasing N losses in wet conditions. It may also permit the use of a single application avoiding the need to split the required fertilization rate thus reducing labour, agricultural machinery and fertilizer storage costs.

However, NI have some limitations which have to be considered before deciding on their use. In neutral, and particularly in alkaline soils, ammonia volatilization may represent a serious N loss when ammonifiable forms of N are applied to soil; delay

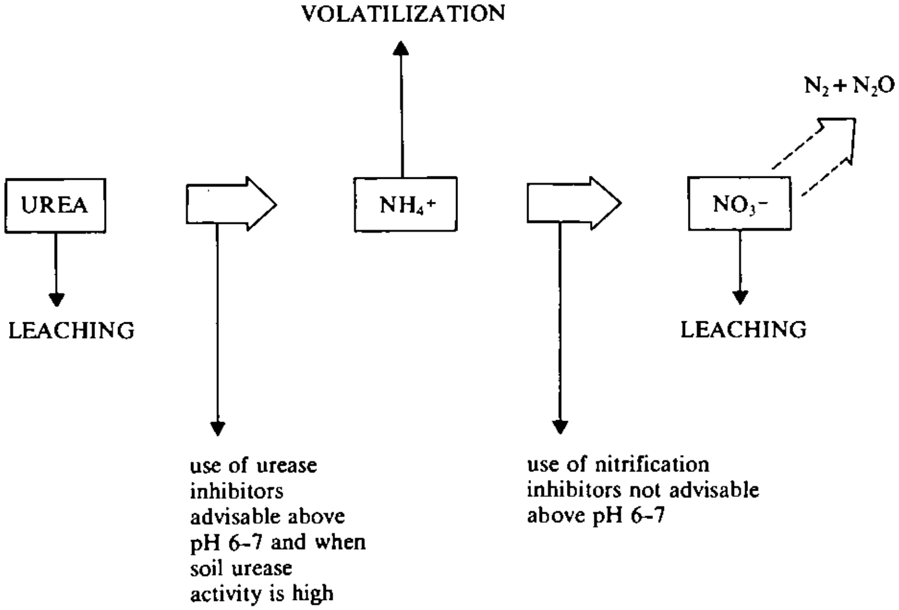

Fig. 1. Ureolysis, nitrification and N losses.

of nitrification increases volatilization losses (Figure 1). Possible benefits to be obtained from inhibiting nitrification by the application of dicyandiamide may be counteracted by increased loss of ammonia by volatilization even in slightly acid soils *(Rodgers [11])*. When urea is applied as N fertilizer in alkaline soil it is more convenient to use urease inhibitors than NI. However, even in the case of urease inhibitors some caution is required, especially when soil urease activity is low; in the presence of unhydrolyzed urea we must assess the risk of N losses due to leaching and toxic effects, *e.g.* on earthworms.

Other factors besides pH affect ammonia volatilization from soils *(Nelson [10])*. Losses increase with temperature and cation exchange capacity and when N fertilizers are applied on the surface. All these factors have to be carefully considered before using NI.

In some cases plant growth is depressed by high levels of NH_4^+ relative to NO_3^- resulting from NI application *(Hendrickson et al. [5])*. This depression may be a result of the inability of plants to effectively assimilate abnormally high levels of NH_4^+ or of nutrient imbalances such as the negative interaction of high NH_3 and low K *(Dibbs* and *Welch [3])*.

2. Mechanism of action

Nitrification is the process by which ammonia is oxidized to nitrate by chemosynthetic autotrophs which derive from it the energy needed for their metabolic activities (Figure 2). Fixation of carbon occurs by the pathway of the Calvin reductive pentose phosphate cycle. Since in the oxidation of hydroxylamine to nitrite there is a net transfer of four electrons, the presence of another intermediate, the unstable nitroxyl (NOH) has been hypothesized; so far, however, there is no direct evidence of its presence in the reaction sequence. Ammonia hydroxylation is a step requiring energy and is catalyzed by an oxygenase; the oxidation of hydroxylamine is cataliz-

oxygenase hydroxylamine oxidoreductase nitrito oxidase

$$NH_4^+ \ 2\ e \rightarrow NH_2OH - 2\ e \rightarrow NOH - 2\ e \rightarrow NO_2^- - 2\ e \rightarrow NO_3^-$$

Chemoautotrophic nitrifiers present in soil
oxidize NH_4^+ to NO_2^-

Nitrosomonas europea
Nitrospira briensis
Nitrococcus nitrous
Nitrosolobus multiformis
Nitrosovibrio tenuis

oxidize NO_2^- to NO_3^-

Nitrobacter winogradski

Fig. 2. Reaction sequence for the oxidation of ammonia to nitrate and list of chemoautrophic nitrifiers present in soil (modified from *Schmidt [1982])*.

ed by a hydroxylamine reductase in the presence of suitable electron acceptors such as cytochrome a_2 whose chemical structure is characterized by the presence of heme with a copper atom (Figure 2).

The biochemistry of the nitrification process is far from being fully understood and the development of NI for use in agriculture has proceeded, for the most part, independently of biochemical studies. As a result, there is a large gap in our knowledge of the mechanism of action of these compounds.

A perfect inhibitor should be effective in inhibiting the oxidation of ammonia but not that of nitrite which is toxic to plants, animals and microorganisms *(Keeney [7])*. Therefore, in this presentation we consider as specific nitrification inhibitors those compounds which slow or block the oxidation of ammonia. Nonspecific inhibitors are not considered here. Many compounds affect the activities of soil microorganisms, including nitrifiers. Nonspecific nitrification inhibitors are compounds interfering with the growth and activity of nitrifiers through changes in the cell ultrastructure or interference in the respiratory metabolism.

Nitrapyrin and dicyandiamide act as copper chelating agents of the cytochrome oxidase component which is involved in ammonia oxidation (Table 1). Allylthiourea and thiourea inhibit ammonia oxidation but not the associated cytochrome oxidase and this inhibition can be partly reversed by the addition of Cu^{++} *(Hauck [4])*. Compounds, such as KN, MBT and ST, whose structure is characterized by their heterocyclic thiazole substituent, inhibit ammonia oxidation. It has been suggested that thiazole is structurally related to the pyridin ring of nicotinamide and may interfere with nicotinic acid or coenzymes derived from it *(Hauck [4])*. A possible action of the derivates of triazole, such as ATC and MT, might be to repress a catalase-like enzyme *(Hauck [4])*.

Table 1. Commercial and chemical name and site of action of nitrification inhibitors (Modified from *Hauck [1980]*).

Commercial name	Chemical name	Site of action
Dd, DNDN, Dycian	Dicyandiamide	Cytochrome oxidase
Nitrapyrin	2-Chloro-6-(trichloromethyl) pyridine	Cytochrome oxidase
Thiourea, Tu	Thiourea	Heme copper in the prostetic group of cytocromes
ST	Sulfathiazole	Structurally related to the pyridin ring of nicotinamide
MBT	2-Mercapto-benzothiazole	Structurally related to the pyridin ring of nicotinamide
KN, KNE	2-Benzothiazole-sulfane-morpholine	Structurally related to the pyridin ring of nicotinamide
Etridiazole	5-Ethoxy-3-trichloromethyl-1,2,4-thiadiozole	Structurally related to the pyridin ring of nicotinamide
MAST	2-Amino-4-methyl-trichloromethyl triazine	Unknown
ATC	4-Amino-1,2,4-triazole HCl	Unknown
MT	3-Mercapto-1,2,4-triazole	Unknown
CS_2	Carbon disulphide	Unknown

3. Effectiveness of nitrification inhibitors

The effectiveness of NI, defined recently as bioactivity *(Keeney [7])*, depends on many factors. A compound may persist in soil for a long time but not be bioactive because it is adsorbed by soil colloids (Figure 3). On the contrary, a compound may have a high bioactivity only for a short period of time since it is rapidly degraded. Environmental factors supporting adsorption, hydrolysis and volatilization of NI decrease the bioactivity of these compounds. Usually, we are in the presence of complex interactions; soil temperature influences volatilization and degradation of inhibitors as well as the intrinsic nitrifying activity of a soil which is often forgotten as a factor in the examination of the bioactivity of nitrification inhibitors. A certain concentration of an inhibitor can block or slow nitrification activity in some soils but it may be ineffective in soils characterized by a high activity. It is well known that the optimal pH for ammonium-oxidizers is the neutral to slightly alkaline range *(Schmidt [14])*. Fertilizers such as anhydrous NH_3 and urea rapidly increase pH and these N forms often nitrify faster in acid soils than does a salt such as $(NH_4)_2SO_4$. As a rule when the soil nitrifying activity increases the effectiveness of the inhibitor tends to decrease. Also the manner of application of inhibitors is very important since, for example, surface-applied compounds will have low effectiveness due to photolysis, volatilization losses and minimal penetration into soil.

Another aspect to be considered is that relative to the different response of nitrifying bacteria to nitrification inhibitors (*Belser* and *Schmidt [1]*). Soils with different nitrifying populations behave differently when treated with NI.

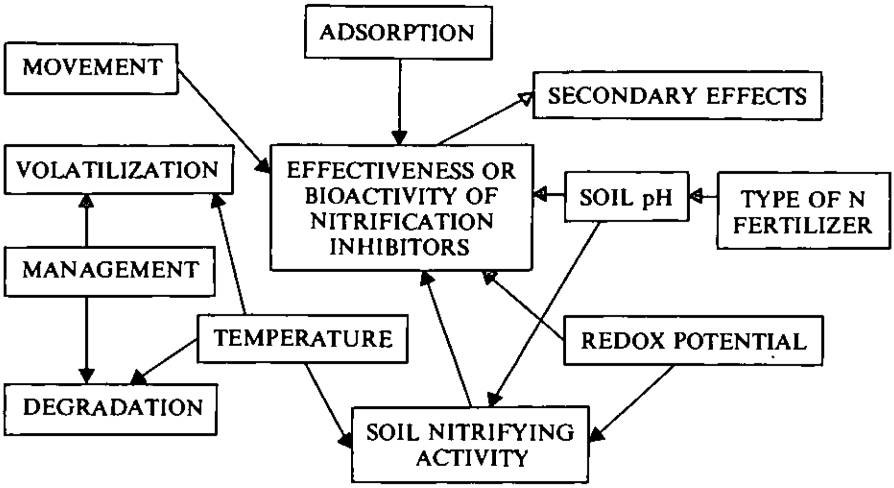

Fig. 3. Factors affecting the bioactivity of nitrification inhibitors.

4. Nitrification inhibitors and nutrient uptake

Spring-applied urea is rapidly hydrolyzed in the field in the Mediterranean climate (Table 2). The sequence of reactions involves, besides ureolysis, nitrification and, eventually, microbial immobilization and N uptake by plants *(Nannipieri et al. [9])*. In experiments with urea enriched in ^{15}N we have shown, in a clay-loam soil in Central Italy, that such a reaction is rapid and microbial immobilization largely prevails over plant uptake and N losses, so that a large proportion of fertilizer N is immobilized in soil in organic forms. It is evident that in these conditions the risk of consistent leaching or denitrification losses is limited to a short period of time. Previous knowledge of climatic conditions, particulary a forecast of rainfall, might be more useful and economical in deciding the time of fertilizer application than resorting to the use of nitrification inhibitors to limit N losses.

Table 2. Nitrogen reactions of spring-applied urea in a grass-legume association under Mediterranean conditions (from *Nannipieri et al. [1984])*.

Intensive ureolysis from 0 to 5 days after N fertilization
Intensive nitrification from 2 to 6 days after N fertilization
Microbial immobilization from 5 to 18 days after N fertilization
Mean minimum daily temperature 5 °C
Mean maximum daily temperature 21 °C
Rainfall in the 0–20 period following urea fertilization 43 mm

Nitrification inhibitors generally increase N uptake by the crop. Both rates of dicyandiamide increased nitrogen uptake at both levels of spring-applied nitrogen (Table 3). When no N fertilizer was applied, dicyandiamide at a lower rate increased, but not significantly, N uptake by wheat *(Rodgers* and *Ashworth [12])*. Where 0 or 35 kg of N fertilizer were applied both rates of nitrapyrin increased grain yields and N uptake; a decrease was observed at higher N rates. The lower rate of etridiazole increased grain yields and N uptake with 35 or 70 kg N/ha.

Table 3. Effect of inhibitors on nitrogen uptake by winter wheat of spring-applied 'Nitro Chalk' *(Rodgers and Ashworth [1982])*.

Treatment	Inhibitor rate (kg/ha)	N uptake (kg/ha)		
		Fertilization rates (kg/ha)		
		0	35	70
No inhibitor		65.1	89.4	112.5
Dicyandiamide	5	71.8	104.2	119.0
Dicyandiamide	20	81.1	100.2	118.6
Etridiazole	0.5	63.9	95.6	129.7
Etridiazole	2	77.7	89.1	115.7
Nitrapyrin	0.5	74.2	97.1	105.8
Nitrapyrin	2	72.2	96.7	108.7
L.s.d. (P=0.1) between inhibitor rates 9.8				

As has been mentioned previously the method of application has to be considered. For instance, dicyandiamide, unlike etridiazole or nitrapyrin, is non-volatile so that soil incorporation immediately after application is unnecessary. Besides it is also a slow N-source.

However, the use of nitrification inhibitors does not always cause an increase in wheat N uptake *(Juma* and *Paul [6])*. When 4-amino-1,2,4-triazole (AT) was applied under field conditions, there was a greater recovery of fertilizer N in the soil-plant system (95 vs 80%) but no changes in wheat N uptake (37%). Five to eight percent of fertilizer N was recovered in the non-exchangeable NH_4^+ fractions of the A horizon of ATC-treated soils compared with about 1% in non-AT treatments.

Nitrification inhibitors can have marked effects on other soil reactions. Carbon bisulphide and 4-amino-1,2,4-triazole hydrochloride (AT) applied at 22 kg/ha in the field reduced the ammonification rate as well as nitrification of NH_4^+ *(Malhi* and *Nyborg [8])*. The use of inhibitors that reduce both ammonification and nitrification could be a way of reducing volatilization, leaching and denitrification losses.

5. Conclusions

The decision whether or not to use NI is not simple and easy owing to complex interactions among factors affecting the bioactivity of these compounds and to the complexity of N reactions in soil. Factors such as soil pH, temperature, type of fertilizer, soil nitrifying activity, type of crop and soil urease activity have to be carefully considered before using NI. Possible benefits to be obtained from inhibiting nitrification may be counteracted by increased losses by ammonia volatilization especially in alkaline soils. Where the aim to reduce N losses by applying these compounds is achieved, a careful examination of the economic costs should be carried out. Costs of labour, of use of agricultural machines and NI may be so high that the resultant reduction of N losses from the soil-plant system may not be profitable.

More biochemical studies are needed on the way in which many compounds currently in use inhibit nitrification. To understand the effects of these inhibitors on other soil nitrogen reactions further experiments, both in the laboratory and in the field are also required. Moreover, in research using nitrapyrin, which is the most commonly used inhibitor, there are factors which, if not recognized, can vitiate these experiments. Nitrapyrin is readily dissolved in several organic solvents but it is difficultly soluble in water *(Bremner et al. [2])*. In laboratory and field research it is necessary to apply nitrapyrin as an aqueous solution because organic solvents can affect N transformations. Secondly, aqueous solutions of this compound become less effective when stored before use because nitrapyrin is hydrolyzed to 6-chloropicolinic acid. Thirdly it is advisable to use aluminium foil to close flasks used for the incubation of soils treated with nitrapyrin since rubber stoppers tend to sorb the volatilized compound *(Bremner et al. [2])*.

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Response of Grain Yield of Wheat to Potassium as a Function of Nitrogen Dynamics in the Soil

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Summary

Pot experiments with increasing rates of N and K supply to spring wheat and winter wheat on three soils low in K (exchangeable K: 4.0–6.4 mg/100 g) and with different contents of Kjeldahl-N (45–250 mg/100 g) gave the following results:
Regardless of the soil Kjeldahl-N content increasing the N supply from 2 to 4 g/pot in treatments which had also received K increased grain yield on all three soils during the years 1981 to 1983. Increasing K supply improved grain yield (especially the thousand grain weight) at the lower N rate on all three soils but the highest grain yield (higher number of grains/ear) was obtained at the higher N level (4 g) with K at 1.5–3.0 g/pot on all three soils and in all three years.
In the low N treatments ear emergence and maturity were accelerated by addition of K, whereas maturity was delayed by increasing K in the high N treatments. The extended grain filling period is probably the reason for higher grain yield by addition of both K and N.
Soil analyses carried out during the vegetation period showed that the EUF-extractable organic and inorganic N fractions in March characterize the rate of N mineralization of the investigated soils better than the NO_3-N values in spring can do.
The N contents of the grains were closely correlated with the Σ EUF-N contents in March ($r = 0.86$; $n = 12$). Straw N content on the contrary was more closely correlated with the EUF-N-org contents ($r = 0.89$) than with the Σ EUF-N ($r = 0.80$). There was also a close relationship between the grains + straw N content and the Σ EUF-N contents (0.89). Thus Σ EUF-N content appears to be a good indicator of soil N supply status.

1. Introduction

Pot experiments with different cultivars of spring wheat have shown that increasing levels of K fertilization considerably affected chlorophyll content and water status of the flag leaves *(Forster [1])*. This resulted in a prolongation of the physiologically active period during grain filling. Both single grain weight and number of grains per ear were improved. However, in miniplot experiments conducted at the Büntehof with spring wheat on 8 different soils it has been observed that depending on the soil the duration of the grain filling period was either extended or retarded by increasing levels of K fertilization *(Németh [4])*. Similar findings are reported by *Rex [6]*. It was therefore investigated which soil properties had an influence on the duration of the grain filling period and how these properties can be determined.

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2. Material and methods

Pot experiments were conducted with increasing levels of N and K to spring wheat (1981) and winter wheat (1982 and 1983) on three soils low in K (exchangeable K: 4 to 6 mg/100 g) and different N reserves (Kjeldahl-N contents: 45–250 mg/100 g).

Soils:	pararendzina	13.0 kg/pot
	alluvial soil I	12.6 kg/pot
	alluvial soil II	12.0 kg/pot
Test plants:	spring wheat ('Kolibri')	24 plants/pot
	winter wheat ('Vuka')	24 plants/pot
Basal treatments:	1 g P ($CaHPO_4$), 0.5 g MgO ($MgSO_4$); 50 mg Fe as Fetrilon; each 40 mg Mn and Cu as sulfate, 2 mg B as H_3BO_3; 1 mg Mo and 1 mg Co.	
Fertilizer treatments:	2 g N/pot (1 g before planting) 4 g N/pot (2 g before planting)	
K treatments:	spring wheat: 0, 1.25 and 3.75 g K/pot winter wheat: 0, 0.75, 1.5 and 3.0 g K/pot	
Yield analysis:	grain yield, 1000-grain weight, ear number, grain number/ear, N contents in grain and straw	
Soil analysis:	exchangeable K (NH_4 acetate) Kjeldahl-N EUF-nutrient fractions at 20 °C and 200 V ($\leqq$ 15 mA) and 80 °C and 400 V ($\leqq$ 150 mA)	

3. Results

3.1 EUF-N contents in unplanted pots during the vegetation period

The three experimental soils were analyzed for their contents of EUF-extractable nitrogen before and after N fertilization. The results are exhibited in Table 1. This table shows that the EUF-NO_3 contents were low (1.0–1.4 mg N/100 g) in all three soils before N fertilization. The contents of EUF-N-org increased with increasing Kjeldahl values. N fertilization increased both the contents of EUF-NO_3-N and EUF-N-org, these increases being, however, different in the individual soils.

The greatest increase of the EUF-NO_3-N contents was observed in the pararendzina and the smallest in the alluvial soil II rich in N. The sum of the EUF-N contents was also more increased by N fertilization in the pararendzina than in the alluvial soils. In the N treatment of 2 g/pot, i.e. of 2 g/12–13 kg soil, it was expected that the sum of the EUF-N contents would rise by 15–16 mg/100 g soil provided no immobil-

Table 1. EUF-N fractions (mg N/100 g) of experimental soils before and 10 days after fertilization (February 1981)

Soils and N treatments	$EUF\text{-}NO_3\text{-}N$	EUF-N-org	EUF-N	$\frac{EUF\text{-}N\text{-}org}{EUF\text{-}NO_3\text{-}N}$
1. Pararendzina (Kjeldahl-N: 45 mg/100 g)				
0 g N/pot	1.0	0.4	1.4	0.40
2 g N/pot	14.0	2.4	16.4	0.17
2. Alluvial soil I (Kjeldahl-N: 145 mg/100 g)				
0 g N/pot	1.0	1.2	2.2	1.20
2 g N/pot	11.4	3.0	14.4	0.26
3. Alluvial soil II (Kjeldahl-N: 250 mg/100 g)				
0 g N/pot	1.4	2.9	4.3	2.0
2 g N/pot	10.8	5.0	15.8	0.46

ization of the fertilizer-N has taken place in the soil. Table 1 clearly shows that immobilization of nitrogen is practically nil in the pararendzina. In the alluvial soils, on the contrary, only part of the fertilizer-N (75–80%) could be recovered by EUF extraction. This suggests that part of the fertilizer-nitrogen had been incorporated into the biomass of the soil. The extent of N immobilization increased with increasing quotients of

$$\frac{EUF\text{-}N\text{-}org}{EUF\text{-}NO_3\text{-}N}$$

(pararendzina: $EUF\text{-}N_Q = 0.4$; alluvial soils II: $EUF\text{-}N_Q = 2.0$).

The composition of the EUF-N fractions was repeatedly investigated during the vegetation period in the unplanted pots. Table 2 shows EUF-N contents of the experimental soils in which the soil moisture was kept almost constant at 80% field capacity throughout the vegetation period. In the pararendzina without N fertilization no nitrogen had been mobilized in the course of the vegetation period by mineralization. In alluvial soils, on the contrary, the Σ EUF-N September values without N fertilization are considerably higher than those measured in May (Table 2) or February (Table 1). This indicates that N was released in these soils by mineralization. N release was greater with higher EUF-N-org contents in February (Tables 1 and 2). The February values of $EUF\text{-}NO_3\text{-}N$, on the contrary, do not give indications of the different N replenishment potential of these soils.

Equal N fertilization (2 g N/pot) had a very different effect on the EUF-N contents of the individual soils during the vegetation period. No N release was observed during this period in the pararendzina where no N immobilization had occured after N fertilizer addition. In the alluvial soils part of the nitrogen had been subject to immobilization immediately after N fertilization. These quantities of fertilizer-N were, however, released during the months of May to September.

Table 2. EUF-N contents of experimental soils in unplanted pots (1981)

Soils	a) without N 28.5.	28.7.	10.9.	b) 2 g N/pot treatment 28.5.	28.7.	10.9.
Pararendzina						
EUF-NO$_3$	0.5	0.3	0.5	16.4	14.0	19.2
EUF-N$_{org}$	0.7	0.6	0.3	1.0	2.8	2.7
EUF-N$_Q$	1.4	2.0	0.6	0.06	0.2	0.14
Alluvial soil I						
EUF-NO$_3$	1.7	2.7	2.6	16.4	18.3	19.0
EUF-N$_{org}$	1.5	1.5	1.0	2.2	4.0	3.5
EUF-N$_Q$	0.88	0.55	0.38	0.13	0.21	0.18
Alluvial soil II						
EUF-NO$_3$	5.8	10.2	10.7	25.5	28.2	31.2
EUF-N$_{org}$	3.3	4.0	3.3	3.5	6.6	5.2
EUF-N$_Q$	0.56	0.39	0.30	0.13	0.23	0.18

3.2 EUF-N contents and yields in pot experiments with spring wheat

Table 3 gives the N contents of experimental soils (K fertilization: 1.25 g/pot) for pots planted with spring wheat.

In the 2 g N/pot treatments the EUF-N contents of all soils were remarkably decreased. The values indicate moreover the different N replenishment potential of the soils. In the alluvial soil II the considerably higher EUF-N-org contents prevent the EUF-NO$_3$-N contents from declining to the low level of the pararendzina. A certain N mobilization can be observed after harvest (August 25) probably due to decaying root residues.

Table 3. EUF-N contents (mg N/100 g) of soils in pot experiments with spring wheat (K$_2$ treatments, 1981)

		Time of sampling				
		26.5.	9.6.	7.7.	10.8.	25.8.
Pararendzina						
2 g N	EUF-NO$_3$-N	12.2	1.6	0.59	0.22	0.58
	EUF-N-org	1.1	0.9	0.9	0.9	1.3
4 g N	EUF-NO$_3$-N	17.5	10.6	9.0	6.6	9.6
	EUF-N-org	1.5	2.7	3.7	2.5	2.4
Alluvial soil I						
2 g N	EUF-NO$_3$-N	10.5	2.3	0.6	0.5	0.6
	EUF-N-org	1.8	1.7	0.8	0.8	0.8
4 g N	EUF-NO$_3$-N	17.8	6.8	2.1	2.1	4.2
	EUF-N-org	2.0	1.8	1.9	1.4	1.5
Alluvial soil II						
2 g N	EUF-NO$_3$-N	8.7	3.5	0.8	1.0	1.3
	EUF-N-org	3.0	3.0	2.4	2.4	2.7
4 g N	EUF-NO$_3$-N	20.9	17.7	6.6	3.0	7.0
	EUF-N-org	4.0	5.2	6.1	2.7	3.0

The EUF-N contents in the 4 g N/pot treatments declined less than in the 2 g N/pot treatments. This resulted in a substantial increase of grain and straw yields. Table 4 clearly shows that the grain yields in the K_2 and N_2 treatments are considerably higher than in K_2 and N_1. The highest grain yield was found in the pararendzina in which the EUF-NO_3-N contents had remained on the highest level of all soils throughout the months of July and August (Table 3). In this soil only a small part of the fertilizer-nitrogen had been incorporated into the biomass of the soil. In the alluvial soil, the processes of mobilization and immobilization are more accentuated. The greater decline of the EUF-N contents in the alluvial soils is, however, also due to the considerably higher straw yields.

K fertilization had a distinctly positive effect on all three soils and in both N treatments which was to be expected, as the K contents of the soils were low (EUF-K-20°C = 2–3 mg/100 g).

Table 4. Grain and straw yields of spring wheat at different levels of N and K fertilization per pot (1981)

Soils and fertilizer treatments	Yields g/pot)			
	K_1		K_2	
	grain	straw	grain	straw
Pararendzina				
N_1	45.7	39.5	63.0	66.5
N_2	37.3	30.5	74.6	65.8
Alluvial soil I				
N_1	45.8	55.0	59.2	76.0
N_2	45.0	54.0	71.9	87.3
Alluvial soil II				
N_1	45.8	58.8	46.2	72.0
N_2	52.1	79.5	68.0	90.8

3.3 EUF-N contents and yields in pot experiments with winter wheat

Table 5 shows that the EUF-NO_3 contents in the 2 g N treatments were already very low on May 11. The major part of the EUF-N-org contents are also used up in the course of June, July and August, so that the EUF-NO_3 contents continue to decline. Due to the easily mineralizable higher EUF-N-org contents in the 4 g N treatments the EUF-NO_3 content remained sufficiently high throughout the vegetation period which led to substantial extra yields (*cf.* Table 6). The pattern of the EUF-N contents for the pot experiment with winter wheat in 1983 is similar to the results exhibited in Table 5 and will therefore not be discussed here again. The same applies to the yields of 1983.

Table 6 indicates that K fertilization alone substantially increased grain yields on all soils and in both years. This result is not surprising, as the contents of available K (EUF-K-20°C) were low (about 2 mg/100 g).

Although the N reserves of the experimental soils were very different, the highest grain yields were obtained with the highest N levels, when adequate amounts of K fertilizer were given at the same time.

Table 5. EUF-N contents of soils (mg/100 g) in pot experiments with winter wheat (K_3 treatments, 1982)

		Time of sampling	
		11.5.	19.8.
Pararendzina			
2 g N	EUF-NO_3-N	0.84	0.48
	EUF-N-org	1.38	0.71
4 g N	EUF-NO_3-N	13.8	1.40
	EUF-N-org	2.00	1.12
Alluvial soil I			
2 g N	EUF-NO_3-N	0.41	0.20
	EUF-N-org	2.0	0.64
4 g N	EUF-NO_3-N	18.5	2.85
	EUF-N-org	4.2	1.42
Alluvial soil II			
2 g N	EUF-NO_3-N	1.32	0.97
	EUF-N-org	2.28	1.62
4 g N	EUF-NO_3-N	11.49	2.95
	EUF-N-org	3.90	2.55

Table 6. Grain yields of winter wheat at different levels of N and K fertilization (1982 and 1983)

		Pararendzina			Alluvial soil I			Alluvial soil II		
		K_1	K_3	LSD 5%	K_1	K_3	LSD 5%	K_1	K_3	LSD 5%
1982	N_1	37.1	76.5		54.8	77.6		37.0	86.0	
	N_2	60.5	99.5	7.6	54.2	89.8	5.4	39.4	100.3	10.3
	LSD 5%	10.2			7.2			13.8		
1983	N_1	50.3	72.0		6.7	74.8		15.1	73.0	
	N_2	63.6	88.6	7.2	5.3	88.3	5.8	6.2	82.5	5.7
	LSD 5%	9.6			7.7			7.6		

3.4 Influence of N/K interactions on the individual yield components

Analysis of the yield components like number of ears, number of grains per ear and thousand grain weight (TGW) gave the following results:

TGW and grain number per ear increased with increasing K fertilization for the two N levels during the two years under investigation (the data are given in Tables 7 and 8). In contrast, ear number decreased with increasing K fertilization, again for both the two N levels and years. At equal K fertilization the number of ears is higher for the higher N level. Different levels of K fertilization can, however, produce a different effect on grain yield at equal number of ears, as K fertilization increases the

Table 7. Influence of N/K interactions on the yield components of winter wheat (1982)

	Thousand grain weight (TGW)				Grain number/ear				Ear number				Grain yields (g/pot)			
	K_1	K_2	K_3	K_4	K_1	K_2	K_3	K_4	K_1	K_2	K_3	K_4	K_1	K_2	K_3	K_4
Pararendzina																
N_1	26	40	45	46	33	46	47	48	44	41	36	36	37	76	77	78
N_2	34	43	46	47	36	46	47	50	49	47	47	40	60	92	99	92
Alluvial soil I																
N_1	35	40	45	47	39	45	44	43	40	41	40	38	55	75	78	75
N_2	30	42	43	47	37	39	46	44	49	47	46	41	55	78	90	85
Alluvial soil II																
N_1	22	39	42	41	30	46	46	44	57	48	45	47	37	85	86	85
N_2	24	38	42	42	28	39	46	43	60	53	53	51	39	78	100	91

Table 8. Influence of N/K interactions on the yield components of winter wheat (1983)

	Thousand grain weight (TGW)				Grain number/ear				Ear number				Grain yields (g/pot)			
	K_1	K_2	K_3	K_4	K_1	K_2	K_3	K_4	K_1	K_2	K_3	K_4	K_1	K_2	K_3	K_4
Pararendzina																
N_1	30	42	43	42	32	40	46	50	50	38	35	32	50	63	72	69
N_2	30	36	41	42	37	42	50	47	56	50	43	41	63	78	88	80
Alluvial soil I																
N_1	9	41	42	42	22	37	45	45	37	44	40	42	7	66	74	80
N_2	8	32	38	40	16	43	48	50	47	52	46	44	5	71	88	88
Alluvial soil II																
N_1	14	37	39	41	30	40	42	46	35	44	45	43	15	66	73	82
N_2	7	27	34	37	19	41	47	46	45	53	51	47	6	59	83	78

number of grains per ear and TGW. This increase of grain number/ear and single grain weight at equal numbers of ears is most probably due to an extension of the active grain filling period which was very pronounced during the two years of investigation.

The number of ears generally decreased with increasing K fertilization in all soils as well as in the two treatments. As the number of ears remained higher at higher levels of N fertilization, K application had a more pronounced effect on yield than in the lower N treatments.

The N contents of grain in the treatments well supplied with K (K_3 and K_4) closely correlate with the Σ EUF-N contents in March ($r = 0.86$; $n = 12$). The N contents in straw, on the contrary, show a closer correlation with the EUF-N-org contents ($r = 0.89$) than with Σ EUF-N ($r = 0.80$). This means that the quantities of nitrogen released from the EUF-N-org fraction have a more pronounced effect on straw yield. The N contents in grain + straw closely correlate with the Σ EUF-N contents (0.89). When assessing the N supply status of a soil, it is therefore expedient to take the Σ EUF-N contents into account.

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Effect of Potassium Fertilizers on Take-all of Wheat

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Summary

The effect of potassium fertilizers on the growth and yield of healthy and take-all infected spring wheat was studied in pot experiments. The effect of K was related to N nutrition. Neither higher K nor higher N application increased yields of take-all infected plants when the other nutrient was in insufficient supply, but balanced nutrition minimized yield losses. The effect of higher K application depended on the severity of take-all. Very high infection density (ID) overrode the effect of plant nutrition. In a range of moderate ID yield depression due to take-all was significantly reduced by adequate K supply. Comparing potassium chloride with potassium sulphate the beneficial effect of Cl on grain yield was confirmed, but only under water stress. Flag leaves of take-all infected plants showed a consistant tendency of higher transpiration with KCl than with K_2SO_4. It is assumed that plant nutrition by increasing the tolerance to water stress has a favourable effect on take-all infected plants.

1. Introduction

Take-all *(Gaeumannomyces graminis* var. *tritici* [Ggt]) is worldwide a most serious disease of wheat and barley. Increasing attention has recently been given to the significance of plant nutrition in minimizing yield depressions caused by the pathogen. This paper summarizes published and unpublished results of pot experiments using artificial infection. Pot experiments are more suitable than field experiments for comparing yields of healthy and infected plants. This comparison allowed conclusions on the influence of fertilization measures on yield depressions caused by Ggt. Estimation of yield depression as indicator of the significance of the disease seems to be a more reliable parameter than measurements of disease ratings like number and extent of root lesions. *Weigert* and *Weizel [1936]* and *Garrett [1948]* have shown that disease incidence and yield are not necessarily linked with each other.

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2. Experimental

The experiments were done in 'Ahr'-pots with spring wheat cv. Kolibri as described earlier *(Trolldenier [1981])*. The pots contained in the first three experiments 13 kg of a low nutrient sandy soil, amended with adequate rates of major and minor nutrients, except K, which was applied at various rates between 0.75 g and 3 g K_2O as KCl. Nitrogen was applied as NH_4NO_3 at 6 g N per pot in split doses. The first experiment also included a treatment with 3 g N per pot. The fourth experiment was conducted with 14 kg of a nutrient rich loamy soil per pot. Nitrogen was applied as $Ca(NO_3)_2$ at 10 g per pot. The pots received 2 g K_2O either as KCl or as K_2SO_4.

The Ggt inoculum constituted of mycelium grown on sterilized cereal grains. The inoculum density (ID) was varied by placing different amounts of infected kernels between the seeding rows. In each pot 24 wheat seedlings were left after germination. The soil was kept at 60% waterholding capacity (WHC) if not otherwise stated.

3. K effect in relation to N nutrition

In an experiment with two N levels (3 and 6 g N) and two K levels (0.75 and 3 g K_2O) the interaction between N and K in respect to yield depression caused by take-all was evaluated.

First symptoms of take-all were yellowing of older leaves at the end of tillering in the treatments with low N application (N_1). Later yellowing also occurred with higher N application (N_2). At both N levels higher K supply (K_2) reduced symptoms of take-all. The severity of the disease increased during booting and anthesis mainly in the N_1 treatments. Near maturity differences in disease severity were still visible between treatments (Figure 1). Differences between fertilizer treatments were much more pronounced in plants infected by Ggt than in healthy control plants.

Straw yields (Figure 2) corresponded to the performance of plants. In both K treatments the response to higher N application was greater with infected plants. In the highest fertilizer treatment (N_2K_2) depression of straw yield caused by take-all was only 15%, while in the other treatments yield was reduced by 35 to 45%.

The number of ears per pot showed similar tendencies (Table 1). At the highest fertilizer treatment (N_2K_2) there was no significant difference between infected and non-infected plants.

Take-all affected grain formation more than straw yields. The progressing spread of the fungus hampered grain filling considerably as indicated by the thousand grain weight (TGW) which was up to 50% lower due to take-all (Table 1). When K application was low the TGW of healthy plants was depressed by higher N. The highest TGW was obtained at the highest N and K rate.

Grain yield of non-infected plants was decreased by high N application at low K level, while at high K level higher N increased yield (Figure 2). Yields of Ggt infected plants were generally low and significantly increased only at the highest fertilizer rate (N_2K_2). The experiment confirmed that balanced nutrition minimized yield loss.

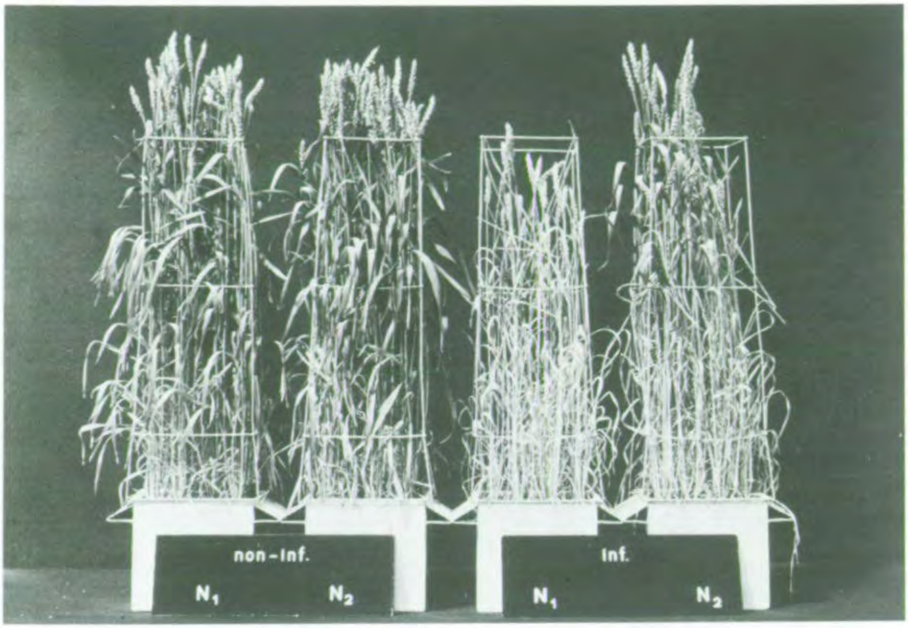

Fig. 1. Effect of nitrogen nutrition at high K supply on non-infected and take-all infected (high ID) wheat.

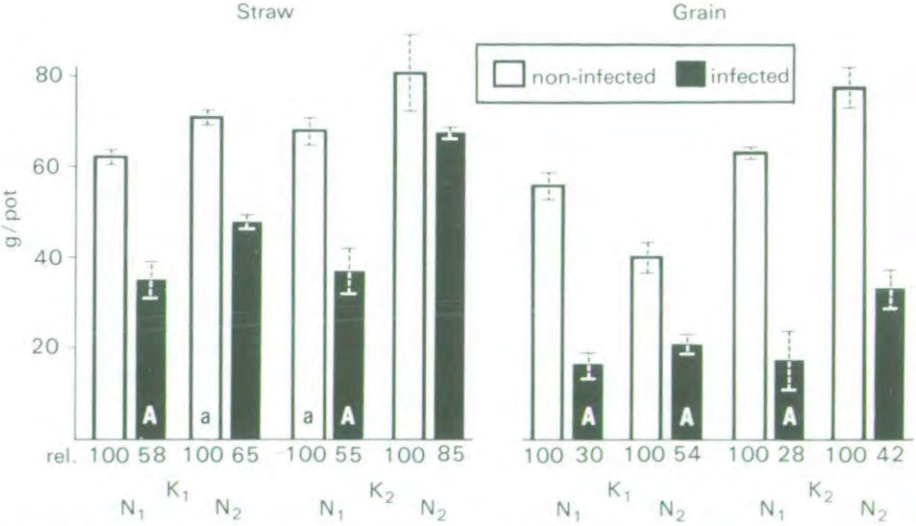

Fig. 2. The relation between yields, NK nutrition and take-all. Bars signify the standard error. Small 'a' indicates no significant differences between non-infected treatments, capital 'A' no significant differences between infected treatments at 5% level.

Table 1. The effects of take-all and NK nutrition on ear number/pot and thousand grain weight (g)

	K_1		K_2	
	non-infected	infected	non-infected	infected
	Ear number			
N_1	57.5	36.3	60.0	37.8
N_2	71.0	43.0	69.0	61.5
LSD at 5%	Infection: 8.4, Fertilization: 5.4			
	Thousand grain weight			
N_1	45.5	23.0	52.2	26.3
N_2	31.7	24.0	52.8	27.1
LSD at 5%	Infection: 5.8, Fertilization: 3.7			

4. K effect in relation to inoculum density

Hassebrauk [1930] showed with cereal rusts that fertilizer application had the greatest effect with moderately susceptible varieties. Highly resistant and highly susceptible varieties were not affected by the nutritional status. Though extensive screening of cultivars (e.g. *Mielke [1974])* revealed that all cultivars are highly susceptible to take-all, in nature disease severity may vary over a wide range. In experiments with artificial infection a very high infestation is often overriding differences which occur at moderate infestation. It seemed opportune, therefore, to study nutrition in relation to disease severity.

4.1 Experiments with two K levels and 5 infection densities

As the experiments were done over several years the absolute yields are hardly comparable but the relative numbers given on the abscissa in Figures 3 and 4 allow comparisons between the experiments. At very low to medium ID infestation with take-all was generally low and the only visible sign was earlier senescence of leaves in the K_1 ($=0.75$ g K_2O) treatment. At high and very high ID the height of plants and the tiller number were also considerably affected when K nutrition was inadequate. At very low to medium ID the straw yield was not reduced (Figure 3). High ID reduced straw yield of K_1 plants by 35, of K_2 plants ($=3.0$ g K_2O) by only 15% as compared to healthy plants. At very high ID the percentage of straw yield loss was still higher but similar for both K levels.

The number of ears reflected the straw yields.

Grain yield reduction at low ID was similar in K_1 and K_2 plants (Figure 4). At medium ID, yield of K_1 plants was more depressed than of K_2 plants. Very high ID caused severe damage in both K treatments and K nutrition had no yield improving influence on the diseased plants. As found in the first experiment take-all decreased TGW. Infested plants responded best to better K nutritional status at medium ID.

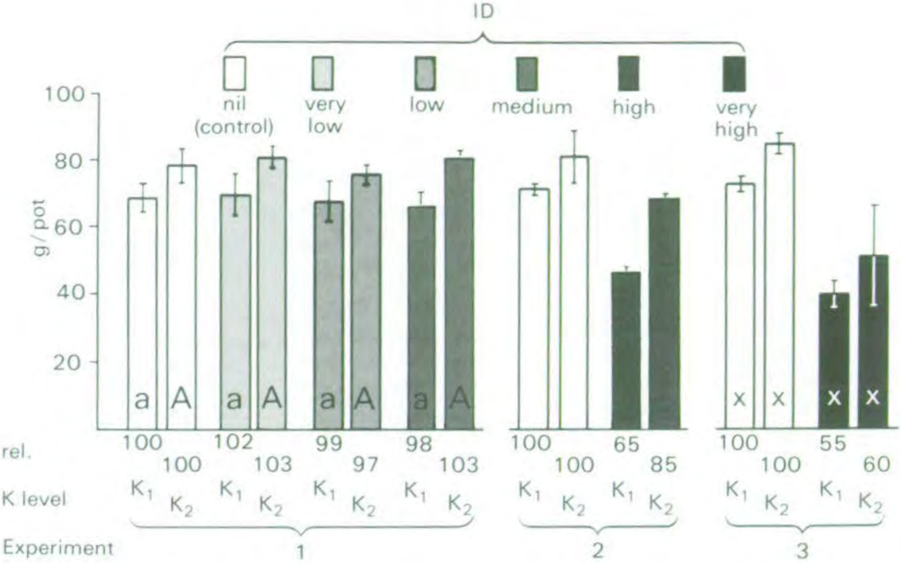

Fig. 3. Straw yields in relation to K nutrition and infection density by Ggt. Bars signify the standard error. Small letters indicate no significant differences between K_1 treatments, capitals indicate no significant differences between K_2 treatments, and × indicates no significant differences between K_1 and K_2 treatment of the same ID at 5% level *(Trolldenier [1982])*.

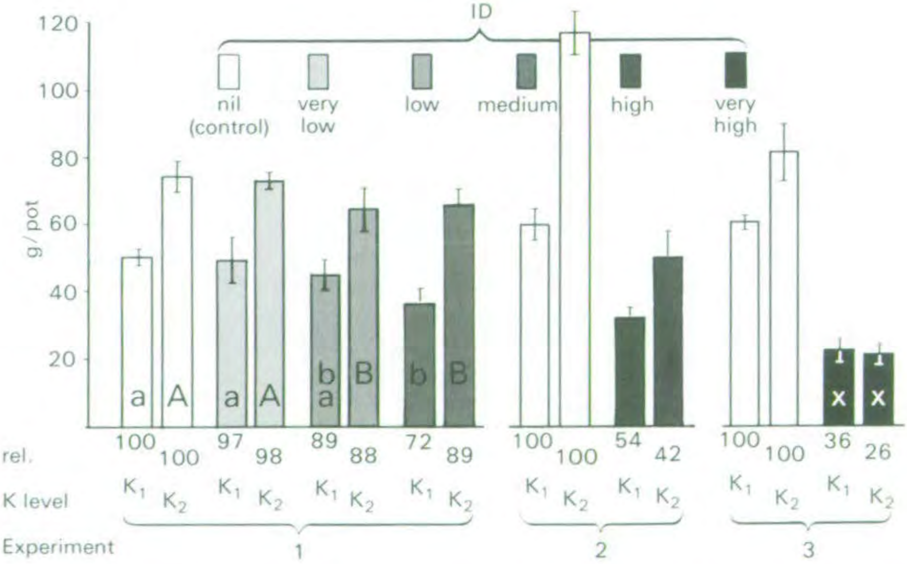

Fig. 4. Grain yield in relation to K nutrition and infection density of Ggt. For further explanation see Figure 3 *(Trolldenier [1982])*.

4.2 Experiment with three K levels and three infection densities

A further experiment included an intermediate K level of 1.5 g K_2O per pot and in addition to non-infected control pots those with low, medium and high ID. As shown in Figure 5 for medium ID decreasing K application affected growth of infected plants more than that of healthy control plants. At milk ripening stage on a warm sunny day transpiration and diffusive resistance of flag leaves were measured in plants of the lowest and the highest K treatment (Table 2). These were negatively correlated. Transpiration of flag leaves of take-all infected plants was much less and diffusive resistance much higher than that of healthy plants. At low K application transpiration seemed to be more decreased. Correspondingly diffusive resistance of infected low K plants was highest.

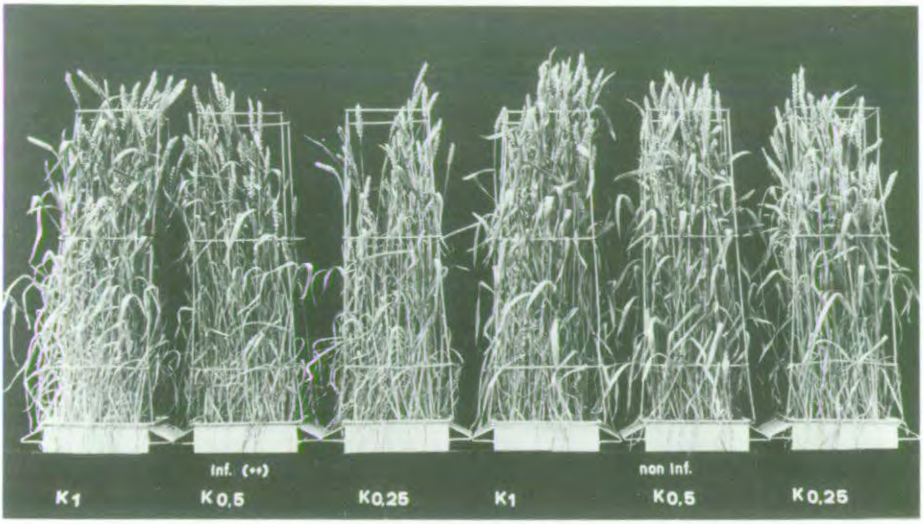

Fig. 5. Effect of potassium nutrition on non-infected and take-all infected (medium ID) wheat. $K_{0.25} = 0.75$ g K_2O, $K_{0.5} = 1.5$ g K_2O, $K_1 = 3.0$ g K_2O.

Table 2. The effect of take-all and KCl nutrition on transpiration and diffusive resistance of flag leaves

Treatment	g K_2O pot^{-1}	Transpiration ($\mu g\ cm^{-2}\ sec^{-1}$)		Diffusive resistance ($sec\ cm^{-1}$)	
		non-infected	infected	non-infected	infected
K_1	0.75	11.4	4.4	1.8	5.7
K_3	3.0	12.4	5.8	1.6	3.9

LSD at 5% Infection: 1.5, K level: 1.3
Leaf temperature 30.3–33.7 °C, rel. humidity 50%

The lower transpiration and the higher diffusive resistance of infected plants at low K application may be caused by restricted water uptake due to root damage. The lower transpiration seemed to be associated with reduced metabolic activity resulting finally in yield depression.

Straw yields and number of ears per pot decreased with rising ID (Table 3). While in healthy plants lower K nutrition did not decrease the number of ears, the greatest depression was found at the highest ID. Increasing ID depressed straw weights more at insufficient than at adequate nutrition.

Table 3. Yields and yield components in relation to ID and KCl nutrition

g K_2O pot^{-1}	Infection density				Infection density			
	nil	low	medium	high	nil	low	medium	high
	Straw (g)				Grain (g)			
0.75	61.1	52.7	45.7	45.1	47.3	36.7	37.2	38.5
1.5	62.9	56.1	53.5	45.5	71.1	40.0	43.9	39.0
3.0	68.5	63.7	61.2	53.7	73.2	55.2	55.4	56.0
LSD at 5%	Fertilization: 3.4, ID: 2.2				Fertilization: 6.0, ID: 4.0			
	Number of ears pot^{-1}				Thousand grain weight (g)			
0.75	60	55	44	44	29.4	23.2	29.6	29.2
1.5	62	51	52	39	39.4	27.9	29.2	30.1
3.0	62	58	56	51	40.6	34.2	36.2	37.4
LSD at 5%	Fertilization: 5, ID: 3				Fertilization: 2.7, ID: 1.8			

Grain yields of healthy plants were not significantly different at high and intermediate K level. However, infected plants yielded much less at intermediate than at high K supply. Though the lowest yields were found in all treatments with low K supply the effect of take-all was proportionally less than at moderate K level. This may be ascribed to the unusual fact that grain weights were not reduced at higher ID. The explanation could be a decrease of soil pH during growth reducing the spread of the pathogen in the generative phase. The soil pH measured at harvest was 4.6, in a range where take-all had only little effect on yield as found in earlier experiments *(Trolldenier [1981])*.

Analysis of straw showed that K and Cl content increased significantly with higher KCl fertilization (Table 4).

In both sets of experiments from low to very high ID, grain yields were always more affected than straw yields. At very high ID different potassium levels did not affect grain yields. Significant effects of high K nutrition compared to healthy control plants were obtained in the range of moderate ID. Similar results were found in respect of N and P *(Trolldenier,* in press [a]). So far the experiments were conducted with potassium chloride as K source.

More recently it was reported that chloride fertilizers reduce take-all. The beneficial effect of Cl is ascribed in part to reduction of osmotic potential and increase of turgor potential in wheat leaves *(Christensen et al. [1981])*. Similar effects are known to occur with higher K nutrition *(Mengel* and *Arneke [1981])*. As with higher KCl fertilization both K and Cl content of dry matter increased (Table 4), it is conceivable that both components contribute to the beneficial action of the salt. To elucidate the role of Cl a further experiment was conducted.

Table 4. Potassium and chloride contents of straw (mg g DM^{-1}) as related to ID and KCl nutrition

g K_2O pot^{-1}	Infection density			
	nil	low	medium	high
	Potassium			
0.75	2.1	3.4	4.1	4.0
1.5	6.0	7.6	8.2	8.8
3.0	14.8	15.3	16.1	15.5
LSD at 5%	Fertilization: 1.4, ID: 1.5			
	Chloride			
0.75	2.0	1.9	2.4	2.4
1.5	3.5	3.1	2.6	3.8
3.0	5.1	5.1	5.4	4.7
LSD at 5%	Fertilization: 1.0, ID: 1.1			

5. Significance of the K source

The role of potassium, a major osmotic agent in plant cells, and of chloride is related to the water status of the soil. Therefore, the effect of KCl and K_2SO_4 on yields of take-all infected plants was studied at varying soil moisture content.

The experiment included non-infected, low and medium ID plants.

Soil moisture was kept at 60% WHC until the beginning of stem elongation. It was then reduced to 40% in one half of the pots. Restricted growth was observed in pots with lower soil moisture. During milk ripening curling of the flag leaves was observed on hot summer days in the K_2SO_4 treatments at both moisture levels. The curling was more pronounced on leaves of plants with medium infection than in less diseased plants. No curling was found in healthy plants. With KCl flag leaves of more diseased plants (medium ID) at 40% WHC remained in a green state for a longer period of time than with K_2SO_4.

Measurements of transpiration of flag leaves were made during a warm weather period. Transpiration was highest in leaves of healthy plants and decreased with infection (Table 5). It was restricted by low soil moisture. The KCl treatments showed a tendency to higher transpiration, particularly in the more infected plants. It may be deduced from the transpiration measurements that, with higher incidence of take-all, the flag leaves remained metabolically active for a longer period of time when plants suffering from water stress had received chloride. This conclusion is supported by the yields (Table 6). Though straw weight of plants at medium ID was only slightly increased by KCl application at 40% WHC, grain yields showed a significant increase and were as high as at 60% WHC.

Table 5. Transpiration of flag leaves as related to ID, soil moisture and K source (*Trolldenier,* in press [b])

Growth stage	Treatment		Transpiration ($\mu g\ cm^{-2}\ sec^{-1}$)		
	Soil moisture (% WHC)	K source	Infection density		
			nil	low	medium
Milk ripening	60	SO_4	7.5	5.7	3.2
		Cl	9.1	6.6	4.0
	40	SO_4	4.0	4.0	2.1
		Cl	6.4	2.6	3.7
	LSD at 5%	Soil moisture and K source: 3.7, ID: 3.4			
Dough ripening	60	SO_4	7.4	3.3	1.8
		Cl	7.5	4.2	2.6
	40	SO_4	5.6	2.5	1.3
		Cl	5.5	2.0	2.1
	LSD at 5%	Soil moisture and K source: 2.6, ID: 2.4			

Milk ripening stage Leaf temperature 33.1–35.1 °C, rel. humidity 30%
Dough ripening stage Leaf temperature 25.6–28.0 °C, rel. humidity 35–40%

Table 6. Yields and yield components as related to ID, soil moisture and K source (*Trolldenier,* in press [b])

Treatment		Infection density			Infection density		
Soil moisture (% WHC)	K source	nil	low	medium	nil	low	medium
		Straw (g pot^{-1})			Grain (g pot^{-1})		
60	SO_4	117.0	106.6	92.8	69.7	62.4	42.7
	Cl	114.6	96.2	96.4	71.9	64.9	48.3
40	SO_4	92.4	78.5	70.7	64.3	56.4	35.0
	Cl	85.0	75.3	76.9	58.7	55.3	46.9
LSD at 5%		Soil moisture and K source: 9.0 ID: 8.2			Soil moisture and K source: 7.3 ID: 6.6		
		Number of ears pot^{-1}			Thousand grain weight (g)		
60	SO_4	58.3	53.8	44.8	35.7	35.3	27.4
	Cl	58.8	50.5	49.8	37.7	36.4	29.6
40	SO_4	50.8	43.3	41.8	42.1	35.5	35.5
	Cl	47.8	45.5	44.0	40.5	36.4	36.4
LSD at 5%		Soil moisture and K source: 4.9 ID: 4.4			Soil moisture and K source: 3.8 ID: 3.4		

Analysis of straw for chloride and potassium revealed very high K contents but no consistent difference between SO_4 and Cl treatments (Table 7). The Cl content was, however, considerably higher after Cl application. Interestingly chloride had no effect on yield of infected plants when soil moisture was optimal (60% WHC). At the lower soil moisture plants were subjected to water stress as indicated by the generally lower yields. According to *Trolldenier [1981]*, water stress affects diseased plants more than healthy plants. It may therefore be assumed that since balanced plant nutrition increases tolerance of water stress it should have a favourable effect on take-all infected plants. Besides potassium, chloride also plays a definite role in the water status of plants *(Mengel* and *Kirkby [1982])*. Other aspects of the chloride effect are discussed by ***Powelson et al.*** [in press]. Increased tolerance of infected plants to water stress seems to be an important factor in explaining the beneficial affect of Cl in minimizing yield depression by take-all.

Table 7. Potassium and chloride contents of straw (mg g DM^{-1}) as related to ID, soil moisture and K source *(Trolldenier*, in press *[6])*

Treatment		Potassium Infection density			Chloride Infection density		
Soil moisture (% WHC)	K source	nil	low	medium	nil	low	medium
60	SO_4	31.1	35.5	55.8	1.2	<0.1	1.3
	Cl	34.9	33.8	52.0	6.1	3.5	3.1
40	SO_4	35.6	38.1	48.4	1.4	<0.1	1.0
	Cl	50.2	35.3	52.9	2.4	5.0	3.4

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The Influence of Mineral Nutrition on Plant Susceptibility to Pathogens

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Summary

Results of experiments in which container grown carnation and cupressus received varying rates of calcium and potassium in the nutrient solution are summarized. Calcium supply had a marked influence on resistance to *Fusarium oxysporum* in carnation and to *Coryneum cardinale* in cupressus; it did not affect vegetative growth of carnation but increased growth of cupressus. Increasing potassium applied to cupressus increased susceptibility to coryneum up to the optimum rate for growth; beyond this point, though there was no further increase in growth, increasing potassium supply decreased the susceptibility to the pathogen. The importance of disease resistance as affected by nutrient balance is discussed.

1. Introduction

The rather general title of this communication is not intended to signify that we intend to deal here with the whole of the subject to which a whole colloquium of the *International Potash Institute* in 1976 at Izmir was devoted. On that occasion there were some thirty papers which dealt exhaustively with results on the effects of fertilizer treatment on plant health available at that time. However, we think our general title is justified because after surveying collaborative work in which agronomists and plant pathologists have collaborated we have tried to develop a general scheme concerning the effect of a particular element in the reaction of the plant to a pathogen, using for our investigations particular pairs of host and parasite and various nutrient elements.

While not offering any explanation of the mechanisms which may be involved, this method does offer irrefutable proof of the roles of two elements, calcium and potassium, in the reaction of the host plant to infection. It also suggests some explanation of the extreme heterogeneity of findings reported in the literature of the subject which was emphasized by *Perrenoud [5]* in his exhaustive review on '*Potassium and Plant Health*'.

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2. Material and methods

The research reported here is concerned with two host-parasite associations:
- carnation – fusarium *(Dianthus caryophyllus – Fusarium oxysporum f. dianthi* (Pril del. Snyder-Hansen) *,
- cupressus – coryneum *(C. sempervirens – Coryneum cardinale* WAG.) **

The same agronomic and phytopathological techniques were used in both cases. The plants were grown in containers in an inert medium and supplied with nutrient solutions varying in their content of a single nutrient, which, in the case of the work reported here was either potassium or calcium. The plants were grown in this way until tissue differentiation, as judged by analysis, was judged to be sufficient. They were then subjected to infection and grown on the same nutrient solutions until the end of the experiments. Observations were made on:
- the effect of treatment on growth (elongation or biomass production, etc.)
- chemical analysis of samples taken before infection to indicate the stage of tissue differentiation and at the time of infection
- development of pathogenesis (qualitative and quantitative recognition of symptoms).

The methods used in each experiment are described in detail elsewhere *(D. Blanc et al. [1, 2]; J. Ponchet et al. [7])*. Here, in each case, we shall only briefly summarize the treatments.

3. The models and their behaviour

3.1 Model 1: Carnation – fusarium – calcium

Differential calcium treatments (4, 6, 8, 10, 12 and 14 me Ca l^{-1} in the nutrient solution) were applied to young mother plants. A reasonably uniform production of cuttings (about 1100 g) was obtained on each treatment, the Ca content being respectively 0.88, 0.96, 1.08, 1.24, 1.40 and 1.48%. After rooting, the various lots of cuttings were infected by soaking in a suspension of *F. oxysporum sp. dianthi* conidia and then replaced in media identical to those used in the pre-infection phase.

The effect of Ca level in the tissues was followed by weekly counts of mortality. Mortality was considerably reduced by increasing Ca level (Figure 1). These results obtained with *cv* Scania were confirmed with *cv* Sacha.

3.2 Model 2: Cupressus – coryneum – calcium

Young plants derived from clonal cuttings were planted in May 1980 on media with 5 levels of Ca (4, 6, 8, 10 and 12 me l^{-1}). After analytical confirmation of varying Ca levels in the tissues, two inoculations of the trunk in March and July 1981 were effected using *Ponchet's [6]* technique.

Work in collaboration with phytopathologists: *R. Tramier* * and *J. Ponchet* **, INRA, Antibes/France

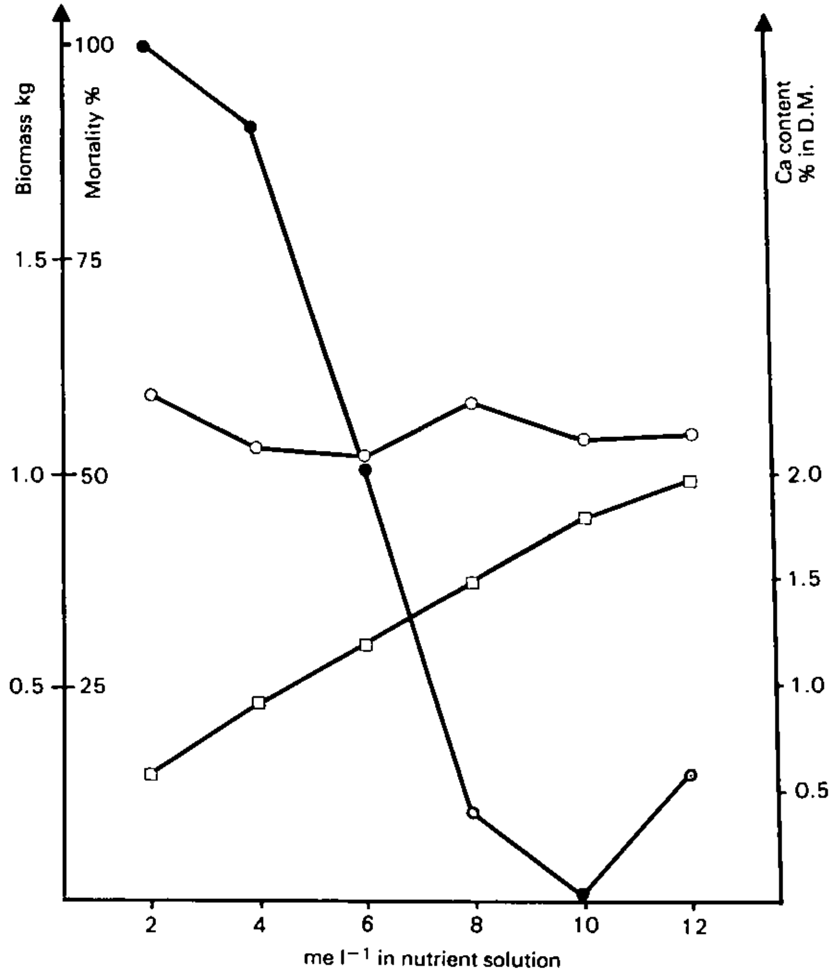


Fig. 1 Model Carnation – fusarium – calcium. Effect of calcium on dry matter production (○), plant Ca content (□) and susceptibility to fusarium (●)

In the preliminary phase, calcium had a pronounced and immediate effect on the growth of the young trees; after 6 months the mean length of the ten upper internodes was closely correlated with the Ca content of the growing medium. Later this effect became less marked and eventually it was only the lowest rate of calcium that had a marked negative effect on shoot growth and trunk diameter measured at the point of infection.

Chemical analyses of the branches around the point of inoculation showed a significant positive effect of treatment on Ca content, while increasing Ca reduced N content (dilution effect).

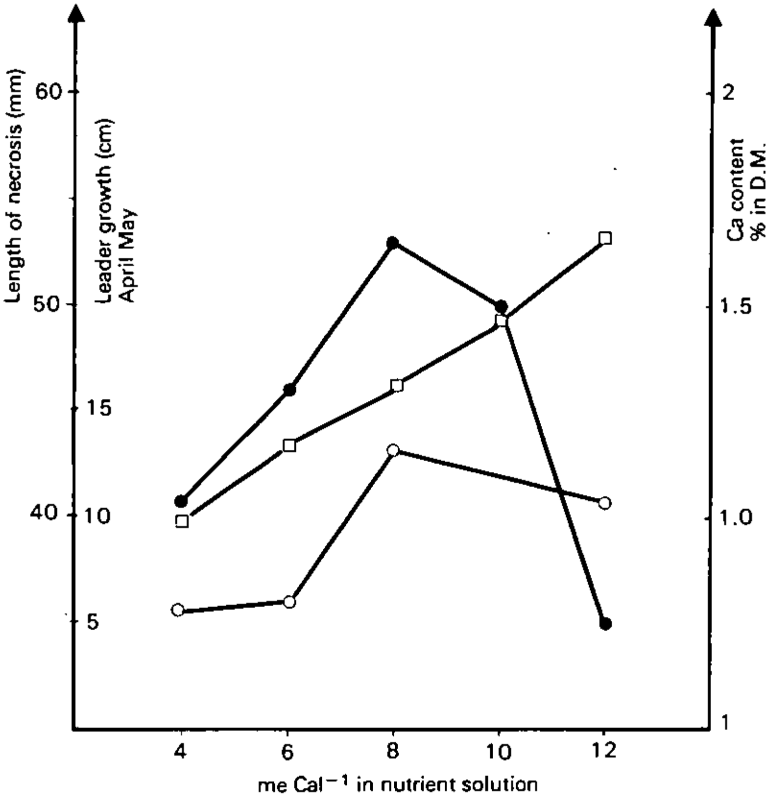


Fig. 2 Model Cupressus – coryneum – calcium (1st inoculation). Effect of Ca on leader growth (○), on length of necrosis on trunk (●), and Ca content of adjacent branch (□)

The effect of calcium on the susceptibility of the host to the pathogen was assessed by various measurements during growth and at the end of the experiment. The two inoculations on the trunk gave comparable results, *i.e.* maximum susceptibility to *C. cardinale* at the medium rate of Ca with minimum susceptibility at the highest and lowest rates and the start of wound-healing at the highest rate of calcium applied (Figures 2 and 3).

3.3 Model 3: Cupressus – coryneum – potassium

Uniform clonal cuttings were grown on artificial media with nutrient solutions containing 1.8, 3.6, 5.4 and 7.2 me l^{-1} K together with 11 me l^{-1} nitrate N and 8 me l^{-1} Ca. After allowing one year for differentiation the trunks were inoculated. Tree growth which was minimum at the lowest rate of K reached a maximum at 3.6 me K l^{-1} and declined markedly at higher rates.

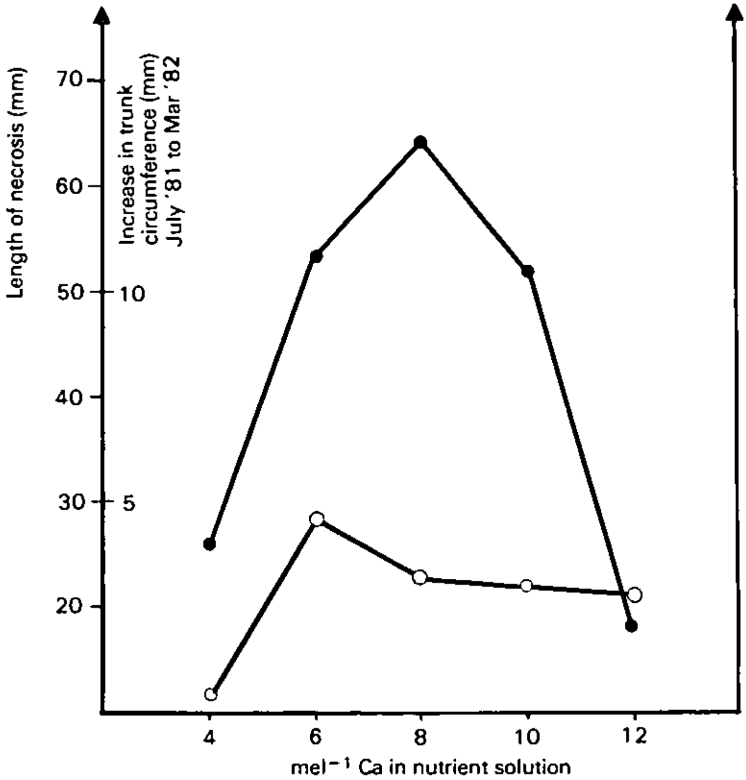


Fig. 3 Model Cupressus – coryneum – calcium (2nd inoculation). Effect of Ca on length of necrosis on trunk (●) and trunk diameter at point of inoculation (O)

Potassium content of the plants increased regularly with K content of the nutrient solution; Ca content reached a maximum at 3.6 me K l^{-1}. Susceptibility to the pathogen was maximum at 3.6 me K l^{-1} whether measured by length of necrosis, girdling of wood or bark, etc. (Figure 4).

4. Discussion

There is not room here to discuss each case in detail; the results are discussed more fully elsewhere *(loc. cit.)*. Nevertheless we can say that in each of the experiments described here the relevant nutrient had an unambiguous effect on the course of the disease. The specific action of calcium is well evidenced by the two models in which it was involved. This fact should be emphasized since, in the literature, calcium is generally said to have an indirect effect via its influence on soil pH *(Pergola et al. [4])*

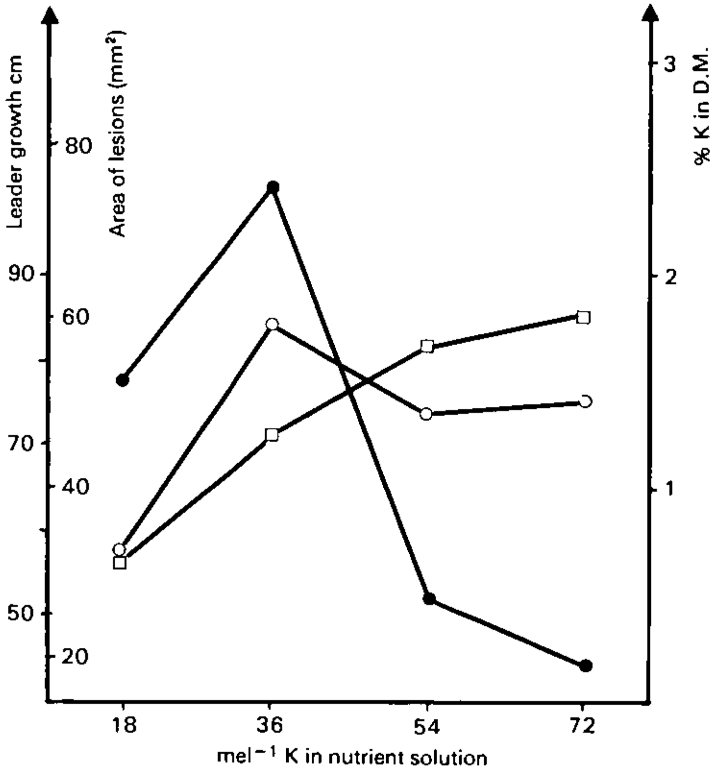
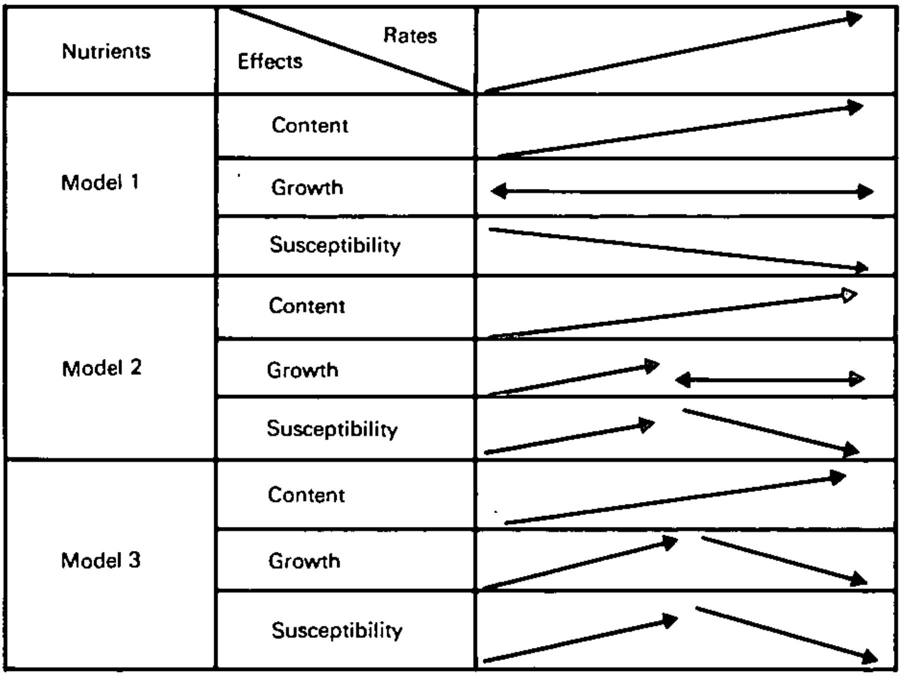


Fig. 4 Model Cupressus – Coryneum – Potassium. Effect of K on tree growth (○), plant K content (□), and area of lesions caused by the pathogen (●).

or via effects on trace element availability *(Jones et al. [3])*. In hydroponic culture with control of pH and ample supply of minor elements, it can only be the direct effect of Ca which is involved. Its dominant role in effects on the cell wall would suggest that it would be of great importance in host-parasite relationships, but up to now, experimental proof has been lacking.

On account of diversity in the models, in the species, in the pathogens and in the nutrients under test, the results should be treated with very much reserve. However, since the methodology was uniform and the individual experiments dealt each with a single cation nutrient applied at numerous concentrations with minimum risk of interference by induced effects and included simultaneous observation of effects on growth, on mineral composition and development of the disease, it is reasonable to consider the results as a whole. Table 1 gives a general picture of the observed effects.



Nutrients	Effects \ Rates	↗
Model 1	Content	↗
	Growth	↔
	Susceptibility	↘
Model 2	Content	↗
	Growth	↗ ↔
	Susceptibility	↗ ↘
Model 3	Content	↗
	Growth	↗ ↘
	Susceptibility	↗ ↘

Table 1. Diagrammatic representation of results.

1. The two nutrients each have direct effects on host-parasite relationships. However, the effect varies with the initial level of the relevant nutrient. In models 2 and 3 the plant is less susceptible at the extremes of the range. It follows that according to the initial level of the nutrient in the growing medium, increasing the rate can either increase or decrease susceptibility to the pathogen and this would explain the contradictory results mentioned by *Perrenoud.*

2. The concentration of the element in the plant, positively correlated with supply over the whole range, does not appear to be a determinant factor in the reaction to the pathogen. This concerns the total plant content of the elements. In the case of calcium the study of its distribution between the various structures and of the forms in which it occurs might be expected to throw light on its role in the mechanisms of resistance and recovery from damage (enzymatic lysis and neoformation of tissue).

3. In the ranges of deficiency or latent-deficiency, where any increase in supply of the element results in improved growth, there is a close relationship between growth and susceptibility to the pathogen. When the increase in supply is above the needs of the plant and no longer improves growth there is no such connection. Then, in every case, there is a very rapid increase in resistance which can only be attributed to direct effects of the element, potassium or calcium, on host-parasite relationships. It should be pointed out that in the case of carnation where calcium had no effect on growth, resistance to fusarium increased steadily as calcium supply increased.

5. Conclusion

Though they may be imperfect, these preliminary studies allow us, albeit with some caution, to distinguish certain general tendencies.

If the potassium and calcium effects which we have studied should be confirmed for other models and thus assume a more general character, the concept of nutrient balance in fertilizer use takes on added meaning. This concept must be extended beyond the traditional NPK trilogy, for example to include calcium. Among other things, it cannot be excluded that the generally observed tendency to increased disease susceptibility at excessive rates of nitrogen fertilizer is due to induced deficiency on certain soil types in other nutrients such as potassium or calcium. Whether or not in the light of these results susceptibility of the plant to disease is increased at the maximum of productivity, there is an urgent necessity to develop a joint approach by agronomists and pathologists. Traditional experimentation aims to define optimum fertilizer treatment taking into account both plant production and plant health but, beyond this, cooperative work should aim to study the mechanisms through which the nutrient elements may be concerned in modifying host-parasite interactions. It is not inconceivable that in the near future a nutrient element may come to be regarded not merely as a factor in production but also as an important factor in integrated plant protection.

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Co-ordinator's Report on the 3rd Session

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Building Yields by Fertilizer Input in Temperate Agricultural Systems

It was in the temperate and humid climatic zone of the earth that chemical fertilizers were invented about 150 years ago and it was also in this zone of Europe – and only there – that the fertilizers were used as a real factor of agricultural production before 1950.

That these things happened just there was not by mere chance.

To understand the development we will have to go back to the general features of soil formation and the great zonal soil groups. As you well know the general soil-forming factors are the following five:

Climate
Vegetation
Parent material
Topography
Time

These factors are listed and discussed in most pedology textbooks.

The climate of the humid temperate zone provides a good supply of water to the vegetation but makes the soils poor in nutrients and acid in reaction because of the leaching process. Precipitation exceeds evaporation.

The poor and acid soils need fertilization and liming more than anything else. Water supply does not greatly limit plant growth and fertilizers and lime give remarkable effects. The well-fertilized soils of the humid temperate region are among the highest-yielding in the world.

When vegetation is given as the second soil-forming factor I do not fully agree. Instead of just vegetation this factor should include the living organisms as a whole. In that way man, from the farmer to the soil scientist, will be included in this factor. This is not unimportant because the arable soils – strongly affected by man as a soil-forming-factor – comprise 10% of the land surface of the earth and thereby constitute a widespread intrazonal type of soils. In addition, the plant pathogens and pests should be included in the factor. Often they will modify the soil-forming effects of vegetation. Agriculture and forestry represent the interaction between climate, soil, vegetation, and man. If we combine climate and soil, we can simplify the scheme and talk about site, vegetation, and man.

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Within this simplified scheme a large number of individual growth factors are working, related to the site, to the vegetation and to the farmer which all interact and build up yield potentials.

As already stated, the use of fertilizers is an important way to build up and maintain a high yield potential in the temperate climatic zone.

In his paper Dr. *P.B. Tinker* dealt with two kinds of yield potentials, the yield potential of the crop and the yield potential of the site. The former is high, determined by leaf area, duration and efficiency of photosynthesis. It is said not to be measured directly. However, I may mention that already *Mitscherlich,* at the beginning of the present century, in his efforts to find a mathematical expression for crop production tried to determine an approximate crop potential by the use of pot experiments. In repeating his type of experimentation and calculating the results on hectare basis, we have found crop potentials for cereal grain of about 20 tonnes.

The site potential is normally clearly lower than the crop potential and thereby also limits production. It is built up of a large number of partial factors and of interactions between them.

Tinker divides these environmental factors into two groups:

1. Site factors, uncontrollable by the farmer.
2. Management factors.

There are, of course, the uncontrollable factors that really determine the site potential.

Undoubtedly historical development has from time to time changed the situation. Factors which earlier were uncontrollable have now been turned into management factors. This applies to the many nutritional factors, nowadays managed by fertilization and having a great influence on crop productivity.

From our long-term soil fertility experiments in Sweden – started in 1957 – I have drawn the conclusion – somewhat simplified – that there are no really bad sites, only bad farmers or, maybe, bad agricultural scientists and advisors. The experimental material given by Dr. *Tinker* seems to corroborate this conclusion.

However, the conclusion is founded on average figures for several years. The individual yields show a considerable annual variation caused by variations in the so far uncontrollable factors, tbe climatic factors (briefly the weather) and the biotic ones (attacks by pathogens and pests).

Increased constancy and reliability in crop production is urgently wanted all over the world. There is great interest in research on this point but this interest is mostly rather superficial. In this respect the problem is also related to the weather: Everyone is talking about it but no one is doing anything about it.

The *British Yield Variation Programme* is apparently an exception to this. It looks ambitious and realistic. The preliminary results given by Dr. *Tinker* are promising and very interesting. We await further results with great expectations!

In addition to the main paper given by Dr. *Tinker* the session included four contributions, all dealing with nutritional factors of our crops and extending the main paper on special points.

Drs. *P. Sequi* and *P. Nannipieri* have given a valuable review of the nature of nitrification inhibitors used so far and their effects on nutrient uptake by crops.

However, in my opinion the really interesting aspect of this kind would be to stop nitrification in the soil completely and definitely. The materials now available are not suitable for this purpose; they are not specific enough, not long-lasting enough.

In spite of some risks of increased ammonia evaporation and delayed plant availability of soil nitrogen considerable advantages with regard to the nitrogen balance of the soil and to the control of nitrate pollution of the environment would be attained.

The contribution by Dr. *K. Németh* illustrates the importance of regulating the balance between potassium and nitrogen in the soil for the yield of wheat.

The contributions by Dr. *G. Trolldenier* and Dr. *D. Blanc* illustrate the importance of a proper nutrient balance in the crop for its resistance against fungal diseases and point at possibilities of eliminating yield variations along this line.

It has often been stressed that the purpose of agriculture is to produce optimum yields, a statement that could have many aspects. One line is that optimum yields mean high yields, even very high yields, full utilization of the yield potential of the agricultural site. This line is illustrated by the 'blue print' farming of, for example, England and Schleswig-Holstein of West Germany. Another line is that optimum yields mean optimal environment protection. This line means low yields, the potential of the agricultural land cannot be fully utilized or it may even mean no agriculture at all. This line is best represented by the agriculture of Sweden, the paradise of environmentalists.

In my opinion the realistic way will be some kind of compromise between these two extreme lines. Agriculture in the humid and temperate climatic zone must work on a high level of production, utilize its favourable yield potential, though aspects of environment protection must not be neglected. Regardless of the line chosen, the annual yield variation must be defeated. This is an urgent task of future research in which the different production lines can unite and participate.

Chairman of the 4th Session

Prof. Dr. *O. Steinbeck,* Director, Institute of Crop Management and Crop Breeding, Agricultural University, Vienna/Austria; member of the Scientific Board of the International Potash Institute

4th Session

Fertilizer Needs in Temperate Ecosystems

Levels of Fertilizer Input and Soil Nutrient Status in European Agriculture

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Summary

Overall nutrient balance sheets have been calculated for the various countries, for regions and at the farm and field levels. Account was taken of nutrients added on fertilizer and products sold off the farm, forage being assumed to be consumed on the farm. Generally speaking the balances are positive: for the EEC (10 countries) removals account for only 51, 68 and 32%, respectively of N, P and K applied in fertilizers. The balances would be even greater were nutrients contained in purchased feeds to be added and, eventually, if account were taken of urban and industrial wastes. In most countries nutrient ratios of fertilizer have moved in favour of nitrogen the more so the more intensive the farming system. In some areas, where the balance is positive and where soil analysis indicates satisfactory levels, some economy could be made in phosphorus application without ill-effects, but a reduction in potassium could result in soil K values declining to below the desirable level since the balance sheets may make insufficient allowance for losses and fixation. On grazed land, returns through the animal are extremely uneven, resulting in high leaching losses on some soils and fixation on others where analysis indicates a satisfactory level.

Introduction

While fertilizer use was an important factor in increasing yields in the first half of this century in an agriculture which was primarily concerned with subsistence, subsequent changes have given us an agriculture which is more commercially orientated, in which fertilizer usage has become an absolute essential for the realization of the full potential of the environment and the improvements in other production techniques (plant breeding, plant protection, etc.). The growth in fertilizer usage has depended upon the mastery of techniques which allow us to aim for high yields. Nevertheless, fertilizer usage shows great variation between the countries of Western Europe and, in almost all countries, there is great variation between, and even within, regions.

The situation is affected on the one hand by the advisory services who aim to provide advice appropriate to present day farming and, on the other, by the fertilizer manufacturers and distributors motivated mainly by market considerations.

This paper aims to examine the developments in farming which have affected fertilizer consumption and to try to find out whether the overall balances exhibited in

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different sectors and various systems justify present consumption patterns. We shall also be concerned with the part that soil analysis has to play in establishing the significance of nutrient balances.

1. Farming conditions

1.1 Changes in land use

Of the 224 million hectares of agricultural land (UAL) in Europe (excluding the USSR) 150 million (1980) were in W. Europe of which 92 million were found in the countries of the EEC *(FAO [11])* (Table 1).

The agricultural area has reduced in almost all European countries; in the west, with three exceptions (Finland, Greece, Ireland) by 1.3% (Sweden) to 9% (Italy).

There are three main utilization patterns:

1. Predominantly arable (over 80%): Denmark, Finland, Norway, Portugal, Sweden.
2. Arable land from 37 to 70%: Austria, Belgium, France, Federal Germany, Greece, Italy, Netherlands, Spain, United Kingdom.

Table 1. Agricultural used area (AUA), percent of arable land (AL) and fertilizer consumption in Europe, 1980 *(FAO)*

	AUA(1000ha)	%AL	N(1000t)	P_2O_5(1000t)	K_2O(1000t)
Austria	3 675	44.5	159.7	99.4	143.8
Belgium + Lux.	1 585	55.4	193.7	102.4	142.0
Denmark	2 905	91.3	374.1	111.0	142.2
Finland	2 563	93.6	196.7	151.4	143.2
France	31 526	59.1	2146.5	1774.0	1689.2
Germany FR	12 248	61.2	1550.8	837.5	1144.1
Greece	9 181	42.8	333.3	157.3	36.0
Ireland	5 802	16.7	275.1	144.7	181.1
Italy	17 601	70.8	1028.5	752.6	385.4
The Netherlands	2 021	42.6	482.8	82.8	112.3
Norway	938	86.6	102.5	61.8	80.1
Portugal	4 080	87.0	136.1	81.3	41.3
Spain	31 530	65.0	900.3	475.1	284.6
Sweden	3 704	80.4	243.9	123.0	116.9
Switzerland	2 021	19.6	65.6	47.8	68.7
United Kingdom	18 469	37.9	1240	404.0	414.0
Bulgaria	4 533	67.6	450.0	291.0	88.7
Czechoslovakia	5 335	49.0	675.0	495.0	560.0
Germany DR	4 827	80.3	751.8	388.7	496.5
Hungary	5 592	80.5	536.8	390.2	472.2
Poland	15 312	78.6	1313.0	968.0	1354.3
Romania	10 521	70.1	609.0	476.0	101.0
Yugoslavia	8 205	55.1	439.8	214.6	205.0

3. Arable land less than 20%: Ireland, Switzerland.

The area and proportion of permanent grass has remained stable or diminished slightly but a major part of the arable area is devoted to forage production. Thus, *van Burg et al. [20]* estimate that 60% of the agricultural land of the EEC is devoted to permanent grass and the growing of forage.

The area under leguminous crops has been decreasing in many countries over a long period and where rainfall is sufficient these have been replaced by grass (Italian ryegrass or fescues) and to a large extent by forage maize. Between 1968 and 1980 the area of maize has increased 3.5 times in France, 8 times in Western Germany and by almost 35 times in the Netherlands. The protein supply for livestock is in many cases assured by the purchase of concentrate feeds.

1.2 The increase in yield

Generally speaking, the availability of improved crop varieties, improved knowledge of the physiological requirements of crops and increased mastery of the use of other inputs have enabled us to come nearer to the realization of the full potential of the environment. This is particularly striking in the case of cereals. The production of all cereals (including maize) has increased from 124 million t at the beginning of the seventies to 160 million in 1980, that is by about 30%. Yield per hectare increased by about 0.1 t/ha per annum and the rest of the increase is due to increase in area planted. In the zone between the 48th and 53rd parallels, some fields are now yielding somewhere near the potential for the climate at a little above 10 t/ha. However, general yield levels on the better farms are some 2 t/ha less while regional averages are 4 t/ha less.

Similarly, sugar beet yields have increased by 10 t/ha in the EEC over the past 20 years. In contrast, potato yields have remained static, except in the United Kingdom where they have doubled, though total production has declined.

Changes in stocking rates are important in the context of this discussion owing to the importance of the recycling of animal wastes. Between 1970 and 1980, cattle numbers increased by 7% (39.2% in the Netherlands), pig numbers by 42.2% (over 50% in Belgium and Finland, and about 80% in the Netherlands, Spain and Portugal), sheep have increased by 5.7% (48.2% in the Netherlands and 62.5% in Austria).

This increase, particularly in countries with little utilizable land, has resulted in an increase in industrial-type livestock husbandry. While energy needs in the ration are met by forage maize or substitutes (cassava, etc.), bought in protein is adding to the nitrogen content of residues.

FAO indices of agricultural production for European countries in 1980 (1969 to 1971 = 100) vary from 110 (Finland) to 143 (Spain and Ireland), countries which were more productive in the reference period showing the lesser increase (the Netherlands occupy a prime position: 130). In eastern Europe the indices have increased by 21% on the whole, especially in Hungary (140) and Romania (159). Comparative figures for the USSR and USA are 11 and 22% respectively.

On the face of it one must conclude that outputs of nutrients must have increased by some 20% for the whole of Europe.

2. Development of fertilizer usage

2.1 General situation

Figure 1 shows how fertilizer consumption has progressed in the 20th century. In the case of nitrogen, the rate of increase was regular but slow up to the fifties and since 1960 growth has been rapid and linear. In regard to phosphate and potash consumption, there was a first increase between 1950 and 1968 and a second steeper increase 1968 to 1980; since than consumption of both nutrients stagnated somehow. Consumption in W. Europe is shown in Table 2 *(IFA [14])* where one sees a regular increase up to 1979/80 with the interruption of 1974/75 (oil crisis) and some stagnation over the last three years. P and K reached a maximum in 1973/74 followed by a drop in 1974/75 then slight recovery followed by stagnation. In 1980/81 total consumption was 9.5 million t N, 5.4 million t P_2O_5 and 5.3 million t K_2O. Against the increase of crop nutrient uptake of 20% the increase in nutrient consumption since 1969/70 has been 59% for N, 15% for P and 20% for K (Figure 2).

Table 2. Fertilizer increase in Europe as kg of nutrient per ha of AUA *(FAO)*

	Arable land % in 1980	N		P_2O_5		K_2O	
		1969–71	1980	1969–71	1980	1969–71	1980
Austria	44.5	33	43	35	27	41	40
Belgium + Lux.	55.4	105	122	88	65	108	89
Denmark	91.3	98	129	43	38	62	49
Finland	93.6	64	77	67	59	51	55
France	59.1	43	68	55	56	42	54
Germany FR	61.2	87	127	71	68	92	93
Greece	42.8	22	36	13	17	2	4
Ireland	16.7	15	47	31	25	26	31
Italy	70.8	31	57	27	42	12	21
The Netherlands	42.6	178	239	49	41	59	56
Norway	86.6	83	109	57	66	71	85
Portugal	87.0	21	33	12	20	3	10
Spain	65.0	19	29	13	15	6	9
Sweden	80.4	59	66	39	33	35	32
Switzerland	19.6	17	32	22	23	29	34
United Kingdom	37.9	42	67	27	22	26	22
Bulgaria	67.6	60	73	43	47	6	14
Czechoslovakia	49.0	59	98	49	72	73	82
Germany DR	80.3	83	120	63	62	99	79
Hungary	80.5	55	81	31	59	34	71
Poland	78.6	43	69	33	45	58	72
Romania	70.1	26	43	12	32	2	7
Yugoslavia	55.1	21	29	12	15	10	14

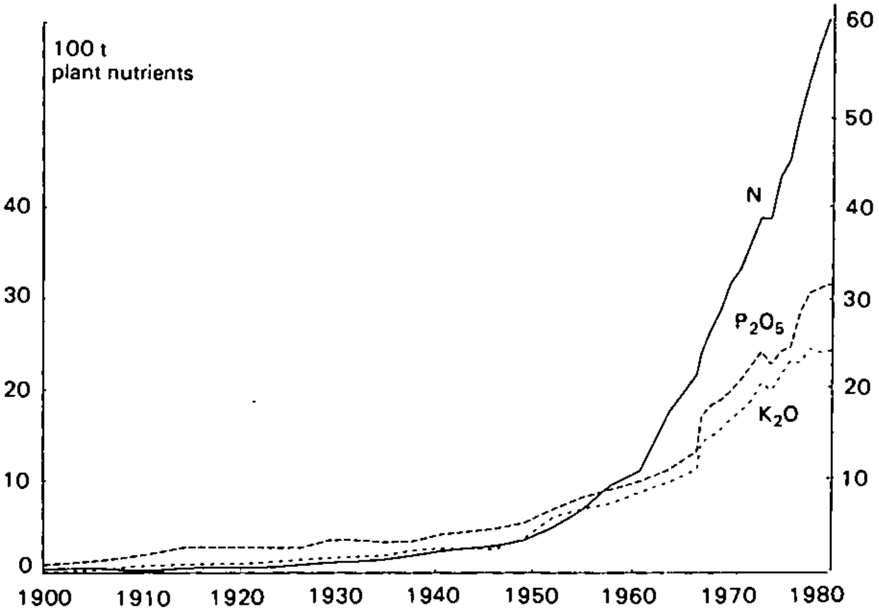

Fig. 1. Fertilizer consumption since 1900.

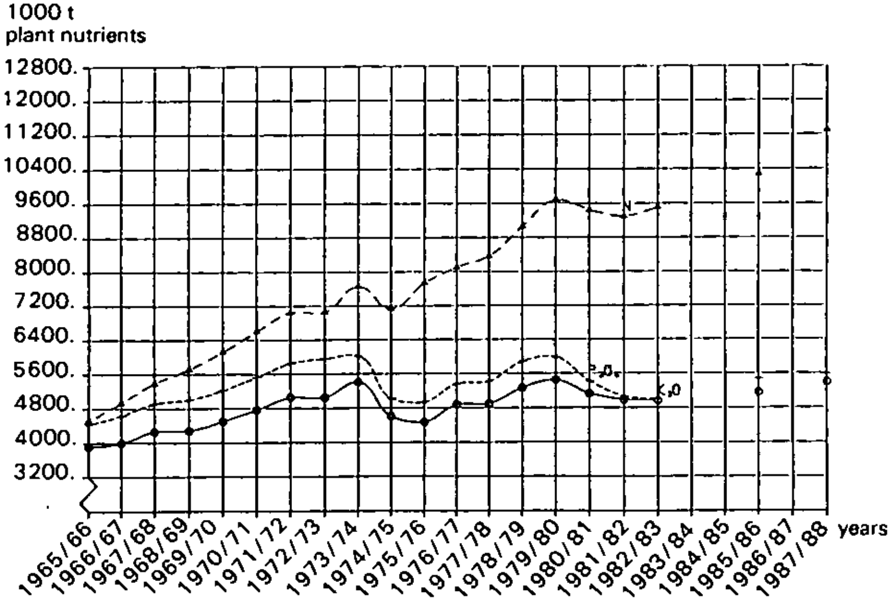

Fig. 2. Fertilizer consumption (West Europe).

2.2 Change in consumption per hectare and in nutrient ratio

Consumption per hectare of utilizable agricultural land (UAL) is shown in Table 2. Statistics which give a better picture are those based on '*fertilizable* agricultural area' in which fallow land and rough grazings are disregarded. When countries are arranged in decreasing order of N consumption per hectare, they fall roughly into three groups:

– Six countries using more than 100 kg/ha N. Rates of P_2O_5 vary between 40 and 70 kg and of potash, always higher than P_2O_5, between 49 and 93 kg/ha K_2O. Over 10 years N rates have increased, those of P and K have tended to decrease (except in

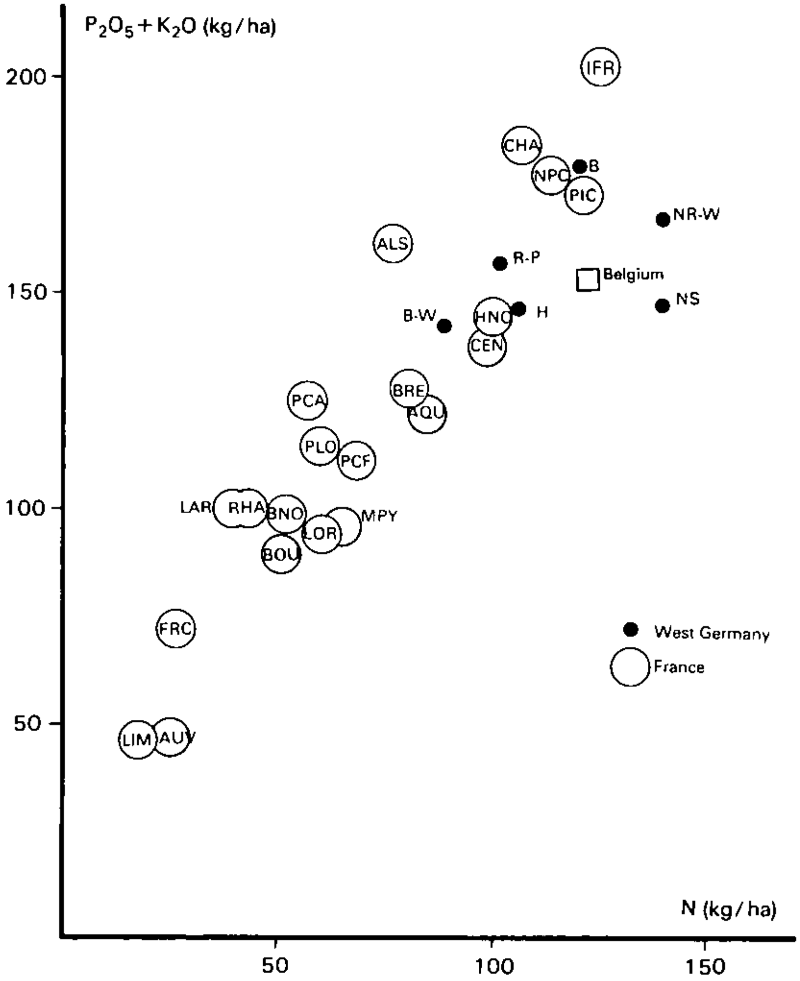

Fig. 3. Relationship between nitrogen and phosphorus + potassium in fertilizers in Federal Republic of Germany, Belgium and France.

Czechoslovakia). The Netherlands have a very wide nutrient ratio (1:0.2:0.2) on account of the very high N usage (239 kg/ha).

– Seven other countries using 29 to 67 kg/ha N favour N at the expense of P and K, the last often being lower than P. The countries of southern Europe on the whole consume less fertilizer because of the unfavourable conditions for non-irrigated crops. Here the usage of potash is very low with nutrient ratios like 1:0.6:0.3. If there is much permanent grass P and K consumption is low (recycling), but if conditions for intensification are good nitrogen usage may be high. Nutrient ratios range from 1:0.7:1 in Switzerland to 1:0.3:0.3 in Great Britain.

France is intermediate between the two groups, using 68 kg/ha N but having the nutrient ratio 1:0.8:0.8. Here we can see the effect of two kinds of farming: intensive arable mainly in the Parisian basin and the other, operating under more difficult conditions in dry or hilly areas, using less nitrogen.

In many countries, nitrogen consumption for long remained below that of the other elements (Austria, Belgium, Denmark, Finland, France, Federal Germany, Ireland,

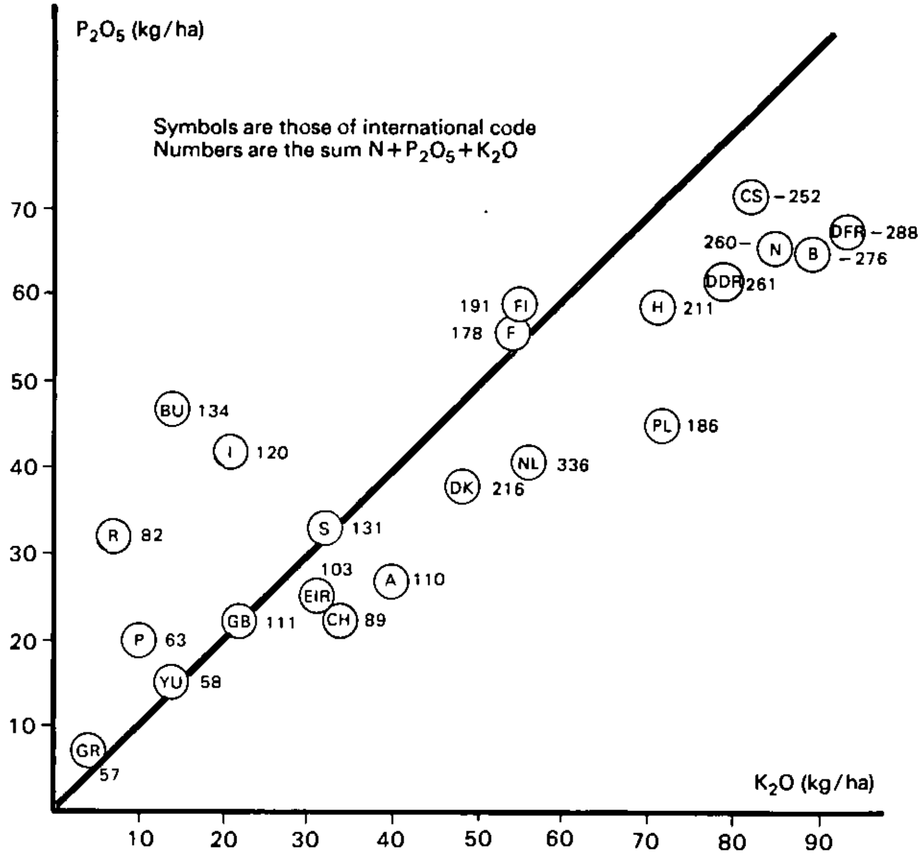

Fig. 4. Phosphorus and potash relationship in Europe.

Switzerland) but became higher in all by 1980. In certain countries, as Ireland and France, this only took place from 1975/76.

Figure 3 shows the relationship between P + K fertilization and N usage for regions of the Federal Germany Republic and France. Most show a similar N:P:K ratio but North Rhine-Westphalia, Lower Saxony and Schleswig-Holstein depart from this pattern, indicating the high intensity of farming in these areas. The other German states compare with the intensive French regions (mainly north of the Loire). Belgium occupies an intermediate position. The influence of soil and climate is quite evident. Farming systems used in the Netherlands make this country exceptional.

In general, in countries using more than 180 kg N + P + K the K_2O:P_2O_5 ratio is about 0.7 (Figure 4). For France and Finland it is 1. Countries using less nitrogen use these two elements in equal amount or with a higher proportion of P (Italy, Romania, Bulgaria) except France which favours K.

3. Nutrient balance sheets

Fertilizer balance for countries or regions can only be made very approximately. It is assumed that offtakes are made up from all the grain (cereals and oil crops), sugar beet roots, potato tubers with meat and milk. It is supposed that home consumed vegetables are very nearly compensated by removals in other crops marketed. In such calculations no account is taken of some very intensive crops receiving high rates of fertilizer but, on the countrywide scale, the area occupied by such crops is not great, and removals of N, P and K are usually much below applications. In any case, their inclusion would make little difference to the national picture.

The basis for the following calculations for the countries of the EEC are, in tonnes per 1000 t:

Cereals 17-8-5; sugar beet 2.5-1.2-3; potatoes 3.2-1.6-6.0; oilseeds 37-15-10; milk 5.5-2.2-1.7; meat (including bone and skins) 30-40-3.

3.1 National balances

For the 10 countries of the EEC removals amount to only 50.9, 67.8 and 32% of application for N, P and K, respectively. Reasons for the low recoveries may be leaching losses or fixation but the excess of applications over removals should lead to improvement in soil fertility which might be confirmed by soil analysis. True, also, the last kilogrammes of a nutrient (applied by the farmer because he still obtains a return) have a very low efficiency. Though the balances may not be accurate, they do reflect the differences in production systems between countries (Figures 5, 6 and 7).

In the case of nitrogen, for example, both the Netherlands and Greece show poor recoveries of N but for very different reasons:

- In the Netherlands we may underestimate removals by very intensive crops which are not accounted for, but the main reason is that nitrogen is used at very high rates, from 200 to 350 kg/ha in intensive forage growing. Though removals in milk and meat are high (68%) they only account for a small part of the application.
- In Greece, where the proportion under arable is much higher, it may be assumed that drought is the main cause of poor nitrogen utilization.

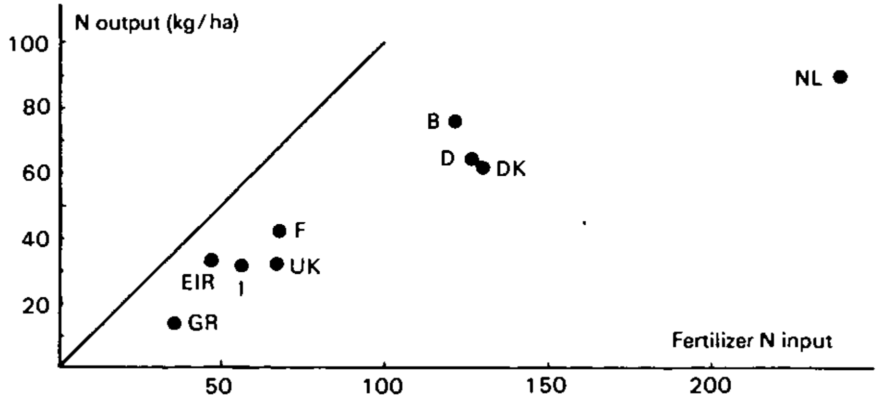

Fig. 5. Nutrient balances between fertilizer applications and production offtakes: Nitrogen.

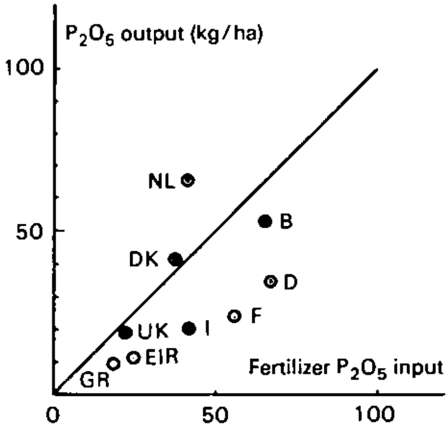

Fig. 6. Nutrient balances between fertilizer applications and production offtakes: Phosphorus.

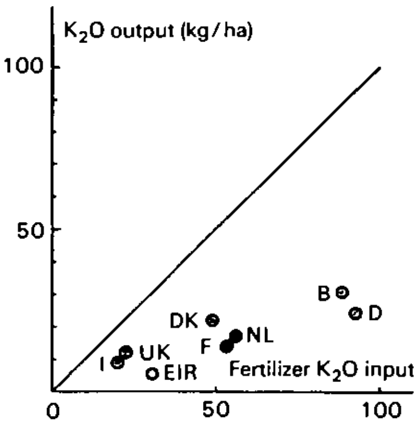

Fig. 7. Nutrient balances between fertilizer applications and production offtakes: Potassium.

Phosphorus recoveries are higher but with rather large differences between countries. The United Kingdom, Belgium, Denmark and the Netherlands utilize P very efficiently, over 100% for the last two. P applications per hectare are relatively low in comparison with production, a great deal of the removal being in meat and milk. Thus the UK uses only 22 kg/ha P_2O_5. Such low rates are justified by the high returns in animal droppings. In the case of the Netherlands, one might wonder about the apparent P utilization efficiency of 161%, at 66 kg/ha P_2O_5 removed since P_2O_5 returned in animal excreta is estimated at 85 kg/ha P_2O_5 *[17]*.

Apparent recovery of potash is very low (32%) especially for Ireland (16.6%), a low consumer. Belgium, France and Federal Germany also show mediocre recoveries, though with high rates of application on account of the importance of rotation crops.

The balance in the Netherlands between offtakes in animal products and returns in animal manures is as follows (in million t):

	N	P_2O_5	K_2O
Production	124.6	105.7	24.0
Returns	276.7	170.7	258.0

It is estimated that 125 kg N, 56 kg P_2O_5 and 149 kg K_2O are applied to pastures via cattle, while calves, pigs and poultry supply 158 kg N, 127 kg P_2O_5 and 98 kg K_2O to arable land. This explains why grazed grass in the north only receives 20–30 kg P_2O_5 and 7–45 kg K_2O whether they are on clay or sand, nitrogen remaining at a very high level (300 kg). Rates of fertilizer application on farms with mainly arable crops in the Netherlands are about 190-65-85 and where animals dominate nitrogen is increased by about 80 kg/ha while P and K are reduced by only 30 and 50 kg/ha, respectively. The apparent excess of application over removal poses questions as to the fate of fertilizer nutrients.

The situation in the UK is quite different. The intensity of farming is also relatively high but much less fertilizer is consumed (67-22-22). There is a large area of hill land which receives 25% less N than other areas but much the same rates of P and K. However, the annual statistics of fertilizer usage on farms *[9]* which show much higher rates of usage per hectare allow us to calculate separate balances for arable and grassland (temporary + permanent) – Table 3.

Table 3. Theoretical nutrient balances for arable and grassland in the United Kingdom

	Tillage			Grassland		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
Applied	121	49	54	119	27	26
Removed	55	26	24	17	15	3
Balance	66	23	30	102	12	23

This balance, probably subject to error because some crops are used as forage and, in the other sense, because it takes no account of animal returns nevertheless shows positive balances, particularly for nitrogen. More than 75% of the tillage area receives more than 50 kg/ha N, but 17% receives less than 25 kg P_2O_5 and 19% less than 25 kg/ha K_2O. This pattern approximates to that in Denmark.

3.2 Regional balances

Where we find regions where cropping systems are reasonably homogeneous and adequate statistics are available, the construction of balance sheets can be revealing. We have taken examples from several regions of France, using 'fertilizable' area as the basis of calculation and present the results in Table 4.

Table 4. Fertilizer balance for some French Departements (as kg/ha of Fertilizable Agricultural used area)

Departement	FAUA 1000 ha	% arable		Outputs			Fertilizer inputs	Balance	Low soils after SCPA
				Crops	Milk and meat	Total			
Seine et Marne	352.2	94.9	N	96	8	104	150	46	—
			P_2O_5	45	4	49	116	67	17.6
			K_2O	42	2	44	108	64	58.8
Aisne	513.3	74.6	N	71	7	65	113	48	—
			P_2O_5	34	5	39	86	47	18.
			K_2O	42	2	44	90	46	57.4
Isère	296.0	46.0	N	34	10	44	57	13	—
			P_2O_5	16	7	33	65	32	34.0
			K_2O	11	2	13	70	57	75.7
Pyrenées Atlantiques	284.3	45.2	N	33	13	46	130	84	—
			P_2O_5	15	10	25	113	88	36.2
			K_2O	10	3	19	98	79	66.9
Manche	500.2	26.4	N	4	22	26	69	43	56
			P_2O_5	2	12	14	69	55	—
			K_2O	1	6	7	61	54	67

In Seine et Marne, where arable crops predominate, fertilizers supply one and a half times the nitrogen removal, twice the phosphate and potash. In Aisne, with some areas under grass, fertilizer usage is not as high but the ratio between removals and application is similar. In Isère with much mixed farming and where animal products account for much of the nutrient removal, applications are 130%, 200% and 538% of removals for N, P and K, respectively. In Pyrènèes Atlantique, a region with a favourable climate and where recently there has been much intensification particularly with the maize crop, fertilizer usage is similar to that in Seine et Marne but removals are only one third for N, and about a quarter for P and K. In La Manche, essentially a grassland area, removals are covered by three times for N, 5 times for P and almost 9 times for K.

3.3 Balance studies on individual farms and in experiments

3.3.1 Large stockless arable farm (Soissonais)

Fertilizer application and nutrient removals are shown in Table 5. If allowance is made for moderate losses in drainage, we see that removals account for all of the nitrogen applied (possibly applications to wheat are on the low side), 75% of the P and 58.8% of the K applied. It should be noted that for a number of years insufficient potash was applied on this farm (and the same applies to other farms in this area) and this is reflected in soil analysis.

Table 5. Nutrient balance for a stockless farm (Soissonnais)

Crop	Acreage (ha)	N		P_2O_5		K_2O	
		Input	Output	Input	Output	Input	Output
Winter wheat	115	12 650	13 800	0	5520	0	3 795
Sugar beet	75	11 250	8 250	10 050	4125	18 750	10 312
Can peas	28	840	−1 176	3 752	1176	7 000	823
Corn	8	1 200	832	1 072	364	2 000	260
Losses			4 520		0		1 130
$\frac{\text{Output}}{\text{Input}} \times 100$		101		75.2		58.8	

3.3.2 Long-term arable experiment (Omiecourt, Somme)

This experiment, jointly run by SCPA and INRA makes possible the construction of nutrient balance sheets for a succession of crops over a period of 23 years *[16]*. In the calculation we have used for each year the rates of nitrogen and potash which gave the highest yields. P rates were deliberately set high as the soil was low in P at the outset. N rates were similar to those commonly used in the area. Crop residues were ploughed in. The balance can be summarized as follows, in kg/ha:

	N	P_2O_2	K_2O
Application	130	128	179
Removal	98	47	112
Losses	20	1	5
Difference	+12	+80	+62
Difference as % application	9.2	62.5	34.6

Here again we find efficient utilization of N and the accumulation of considerable amounts of P and K. It should be pointed out, however, that the more potash responsive crops were still giving good responses to the high rates of K fertilizer after 20 years generous application.

The experiment confirms that the basis for national balance sheets has been correct allowing for the other crops not included here.

3.3.3 Intensive animal husbandry with pig lot (Brittany *[3]*)

40 milking cows and thirty followers utilize 26 hectares and the enterprise includes a fattening house for 364 pigs (Table 6). The nutrient content of purchased feeds represents the following percentages of total nutrients applied: 53.8% for N, 51.8% for P_2O_5 and 34.2% for K_2O. Theoretically, at least, this covers the total nutrient requirement for production, as is the case for most similar holdings with intensive pig fattening.

Table 6. Nutrient balance for a livestock farm with pig breeding (Britanny)

		N	P_2O_5	K_2O
Feeding stuffs	for pigs	5 768	3 343	2 000
	for cattle	2 009	1 621	614
Fertilizers		6 672	4 612	5 040
Total inputs		14 449	9 576	7 654
Milk		1 499	625	750
Meat		1 889	1 261	397
Leaching losses		780	26	520
Total outputs		4 168	1 912	1 667
Balance	Total	10 281	7 664	5 987
	per hectare	395	294	230

3.3.4 Animal husbandry (Maine et Loire *[17]*)

The farm consists of 28 ha of which 7 are in permanent pasture. All of the crop production is used in the production of 300 t milk and 9.3 t liveweight. Fertilizer purchases amount to 127 kg/ha N, 54 kg/ha P_2O_5 and 81 kg/ha K_2O. Bought in feed supplies 64 kg/ha N, 61 kg P_2O_5 and 25 kg/ha K_2O, resulting in positive balances of 129 N, 86 P_2O_5 and 94 kg/ha K_2O. Farm manures are applied to the arable area which results in positive balances for that area of 196 kg/ha N, 96 P_2O_5 kg/ha and 80 kg/ha K_2O (Table 7).

Clearly the accumulation of such balances should affect the fertilizer policy. Research is needed to establish the nutrient efficiency in the year of application of farmyard manure and slurry, especially so far as concerns nitrogen and where supplies of manures are very large it may be necessary to limit their use.

Table 7. Nutrient balance for a livestock farm (Maine-et-Loire)

		N	P_2O_5	K_2O
Crops balance				
Immature winter wheat		− 30	− 50	− 110
Italian ray grass		+ 270	+ 200	+ 90
Silage corn		+ 350	+ 140	+ 260
	Rotations	+ 590	+ 290	+ 240
	On arable 21 ha	+4 130	+2 030	+1 680
	Permanent grassland (7 ha)	− 105	+ 245	+ 245
Farm balance				
Inputs	Fertilizers	3 560	520	2 280
	Feeding stuffs	1 800	1 700	700
	Straw	300	100	600
	Total	5 650	3 320	3 580
Outputs	Milk	1 800	750	900
	Meat	230	150	50
	Total	2 030	900	950
Balance		+3 620	+2 420	+2 630

In summary, it seems that in cash cropping systems, the farmers have good control of nitrogen fertilizer rates but that apparently P and K are applied in excess. In livestock systems, the positive balances appear on the whole to be excessive.

4. Nutrient status of soils

4.1 Concept of nutrient status

The conventional character of the usual soil tests implies that their practical value in making fertilizer recommendations must be based on the accumulation of much experimental evidence. *Balland* and *Quémener [2]* have given an example to illustrate the difficulties in interpretation. Norms must be modified according to soil type. In applying results to large areas we have recourse to simplified classification and to adopt a limited number of soil classes, usually three or five. The soil nutrient level called 'satisfactory' is taken to be that where the aim of using fertilizer is to maintain the *status quo* and, even for a given soil type this does not have a constant value since it must also depend upon the level of crop yield attainable. The financial loss which results from applying too little fertilizer is usually much more serious than that which results from applying too much. So there is every incentive to obviate such risk by making sure that soil nutrient status is kept at a sufficiently high level. If fertilizer policy aims for 'sufficiently high' soil nutrient status even the more demanding crops will seldom give a visual response to the relevant fertilizer; then soil tests attempt to reflect 'nutrient potential'.

So far as concerns nitrogen and sulphur, the availability of which in most cases depends on the soil content of organic matter and its character, and on biological activity, classical methods of analysis are of little practical use for fertilizer advice. We have to rely on consideration of the nutrient balance in which the terms, particularly for mineral N in spring, vary greatly from year to year.

4.2 Nutrient status of soils in various countries

Little has been published in international scientific reviews. Usually the information can only be found in internal reports of laboratories and advisory services. The situation in various countries has been reviewed by *Ansiaux [1]*.

4.2.1 Federal Republic of Germany

Wiechens [19] has described the evolution of analytical results for P, K, Mg and lime status, using 3 classes between 1973 and 1978.

For P in arable soils, the proportion of low soils has remained fairly constant at 13%. While rich soils amounted to 60% by 1974, there has since been some decline with an increase in medium. The picture on permanent grass is similar, the rate of disappearance of low soils slowing down as the proportion decreases (20%).

For K, 10% of arable soils are low. Enrichment was regular and continuous from the fifties and there was a spectacular increase in rich soils from 1960, perhaps indicating over generous usage but since 1966 the tendency has reversed, medium soils increasing at the expense of rich. The same holds for grassland but for the past ten years low soils have remained at 24%.

Some 16% of arable and 26% of grassland are low in magnesium. There has been little change in calcium status of arable soils in the past 20 years with 25% of soils having a lime requirement; grassland soils have adequate lime status to the extent of 85%.

The changes described take good account of the P and K balance of the FRG despite the change in nutrient ratio of fertilizers from 1:1:1 to 1:0.5:0.7. It should be noted that the reduction in soils rich in P since 1974 can be explained by the moderate reduction in application rates. However, the proportion of soils rich in K has reduced despite an increase in K usage and this might be explained by the increase in yield levels.

4.2.2 The Netherlands

The theoretical balance sheet shows a deficit in P (66 kg removals and 41 kg/ha fertilizer usage). This is the only country in this situation. In fact, because of the P input via purchased feeds, in this heavily stocked country the P balance is positive and by 1977 only 11% of soils were low while 50% of soils were rich in P.

There are precise statistics for K in relation to soil type based on analysis of 90000 samples per year *[16]*. For the period 1973–1980 the most noticeable trend is that of an increase in low K soils; the proportion of medium soils has remained constant while there is a decrease in high K soils. This tendency is not so marked on grassland soils.

Because the national balance is positive, it is difficult to explain this decline; this is a subject to be examined in the discussion. Whatever may be the reasons, the advisory services are now revising their potash recommendations. According to *Kroon [15]* it should be possible to raise the low K soils to the satisfactory level within 4 years by increasing present application rates (1983) by 1.8 times. For soils up to now reckoned to be sufficient in K, the corresponding increase should be by a factor of 1.6, pending revision of the advisory norms.

4.2.3 United Kingdom

The theoretical balance for the UK shows approximate equilibrium for P and a large excess for K if we refer to survey results (*cf.* 3.1). Even so an investigation of 1969–70 *[8]* shows that supplementary P and K should be applied to 30% of rootcrops but only to 10% of cereal grass rotations. 16% of permanent grass was low in P and 8% low in K but the recent increase in N usage increases the incidence of low P and K.

4.2.4 Belgium

According to statistics from the Louvain laboratory *[4]*, medium to low P status is found in 25% of soils except in Upper Belgium where the figure is 63.5%. Except in that area, P status improved up to 1975 and since then has stabilized with ⅔ at optimum status.

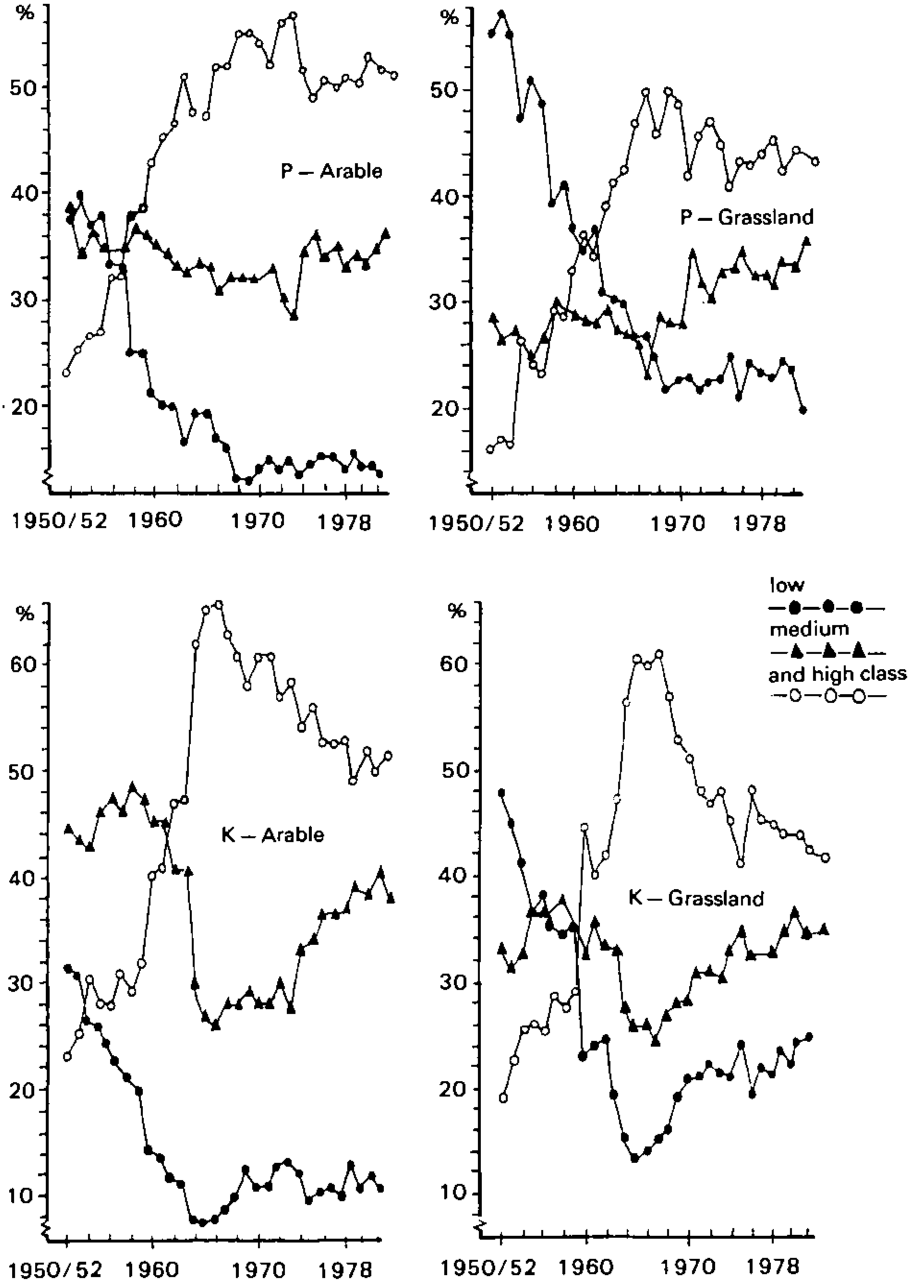

Fig. 8. Supply of arable and grassland soils with phosphorus and potassium, respectively, in Federal Republic of Germany (after *E. Wiechens*).

For potash the position is quite variable. In Polders, the sands of Flanders and Campine, soils are low in K while in Upper Belgium most of the soils are satisfactory. The loamy area is about equally divided between low and satisfactory and everywhere the proportion of high K soils is low. In general there has been an increase in low to moderate K soils since 1975 except in sandy areas.

4.2.5 Switzerland

Bovay [5] discussing the use of organic manures in conjunction with fertilizers, gives the following information on P status derived from *Siegenthaler.* Low P values are found in 35% of natural grassland soils, in 22% of leys, 20% of arable crops, 28% of fruit areas, 32% of vineyards and only 7% of garden soils. On the average 20% of grassland and arable soils are very high in P.

4.2.6 France

According to *Calvet [6]* for France as a whole, soil P is slightly low (but not far removed from satisfactory) and soil K is low. Between 1960 and 1970 there was improvement in P status but only slight improvement in K. In the seventies, 32.8% of soils were low in P and 57.3% low in K.

Such overall averages conceal large interregional differences. Data for the Departements mentioned in 3.2 are as follows according to the results of *SCPA* and *GESA:*

– *Seine et Marne:* In this area of arable crops 17.6% of soils are low in P and 58.8% low in K. There has been a general improvement in P status since the sixties but only a modest improvement in K status.

– *Aisne:* There was a marked improvement in P status between 1960 and 1975 the average Dyer value moving from 0.24 to 0.34 with a reduction in low P soils to only 18%. The picture for K is similar to that in the former Departement with 57.4% of soils still low.

The situation in these two Departments is similar despite there being much more permanent grass in Aisne. One is led to believe that much of the grassland receives little fertilizer, is seldom analyzed and is somehow self-sufficient.

– In *Isère* the soils have been markedly enriched in P over the past ten years and there is quite a high proportion of over fertilized soils. In contrast, K status has been little improved (from 134 to 143 ppm exchangeable K_2O).

– In *Pyrénées Atlantiques,* thanks to a large positive P balance, low P soils have decreased from 58 to 36% in 5 years, the decrease being even greater on arable crops. High P soils increased from 8 to 29%. Improvement in K status has been less, but still appreciable, low K soils changing from 75 to 67%. Improvements were the largest on the valley soils which have a high cropping potential, while grassland has remained poor on the whole.

In the *Manche* 56% of soils are low in P and 67% low in K and there has been improvement in P and K levels over fifteen years. It is possible that acidity, which is general in the area, masks the improvement in available P.

4.3 Observations on farms

On the stockless farm (*cf.* 3.3.1) manures contribute to a positive N balance, taking account of losses which are difficult to minimize on the present farming system. The soils are all high or rich in P and somewhat low in K. This would suggest that P fertilization (now 65 kg/ha P_2O_2) might be slightly reduced while K fertilization should be maintained (at 122 kg/ha K_2O).
The Breton farm (*cf.* 3.3.3) with a large surplus of nutrients has seen its soils change from 'poor' in 1975 to 'rich' in 1981 as regards both P and K. Clearly the fertilizer policy should be modified and surplus manures transferred to other farms. On the Maine et Loire farm (*cf.* 3.3.4) P_2O_5 in many fields has increased by 200 ppm (Dyer) within 5 years, while, in contrast, K in the surface soil appears to have changed little but there is definite K enrichment at depth.

5. Other Elements

5.1 Nitrogen

The response of soil nitrogen to fertilizer treatment in terms of the nitrogen balance really demands deeper consideration than can be given here. In a general way we can say that the nitrogen balance is to some extent automatically regulated not only by inevitable losses but also by the farmer's quick reaction in correcting apparent deficit or excess. Storage of a part of the surplus depends essentially on the carbon balance.

5.2 Sulphur

Sulphur needs are more difficult to detect. While in some areas considerable sulphur enters the soil from the atmosphere, additions in fertilizers have decreased with the increasing concentration of N, P and K in fertilizer materials. In Europe, potassium and magnesium sulphates are used primarily to supply K and Mg rather than to add sulphur, and for crops with special requirements. The sulphur content of soil declines as organic matter content is reduced. Also it seems that sulphur deficiency has been increasingly seen as the S/N ratio of fertilizers has decreased. However, it would be thought that the sulphur used in manufacture of soluble P fertilizers remains in the nutrient cycle.

5.3 Magnesium

Additions of magnesium to the soil are not always known and data on Mg status of soils is of recent origin. It is known that soils which have received no magnesium may have very different Mg status, this being often related to the parent material of the soil. Some soils can supply sufficient to support high yields over a long period of time, at least up to 100 years. Thus for the French Departements cited in 4.2.6, exchangeable MgO content is above 0.1% in 60% of soils in Aisne, 64% in Isère, 86% in Pyrénées Atlantiques, 65% in La Manche. Low Mg soils can apparently be corrected rapidly and crops like maize or sugar beet which well indicate deficiency are useful aids in suggesting when action is needed.

5.4 Trace elements

The situation regarding trace element status of soils is not very clear. The policy followed up to and around the sixties was only to correct identified deficiencies which would thus be quite severe. Deficiencies were often limited to regions in relation to soil type (*e.g.* podzols, soils derived from granites, strongly calcareous soils). In sugar beet growing areas the risk of boron deficiency is obviated by regular use of B containing fertilizers, taking precautions to avoid levels which would be toxic to cereals.

However, research into very high yields has led agronomists to consider two points:

- the possibility of the occurrence of short term temporary deficiency (at periods of maximum growth)
- the possible need for maintenance dressings (of the order of tens up to hundreds of grammes per hectare) to compensate for removals by higher crop yields.

This has resulted in the appearance on the market of trace element mixtures either incorporated with solid compound fertilizers, or as solutions for spray application.

There are yet few data on the profitability of such measures. Application to high yielding winter wheat in N. Germany has given interesting results, but it appears responses in the Parisian basin have been less marked. In contrast application of copper to wheat on the chalk soils of Champagne have been useful. It is believable that we are concerned in both cases with slight deficiencies related to soil type (a tendency to leaching in north Germany, the effect of high pH in Champagne).

Generally speaking, the trace element problem needs very detailed investigations. Soil tests are probably not the most appropriate for the detection of possible deficiencies. In practice soil physical conditions are more frequently limiting factors than trace element supply.

6. Conclusions and perspectives

The conventional sheets which have been established at various levels to indicate the nutrient status of soils, with few exceptions, give evidence of two facts:

1. Applications greatly exceed removals, particularly so in the case of potassium. Nutrients introduced through animal feeds should be added to this surplus.
2. There is evidence of some soil enrichment in the case of phosphorus. Enrichment is much more difficult and may even be negative in the case of potassium.

We have, then, to ask ourselves about possible losses from and immobilization of nutrients in the system, the immobilized nutrient not being apparent in soil analysis.

6.1 Defects in the nitrogen balance

Considerable losses are involved in livestock systems. These comprise gaseous losses from manure in the stable and in storage, losses at pasture caused by uneven distribution and leaching and gaseous and leaching losses on arable land.

Storage losses may amount to from 30 to 90% of ammonium N depending on the process of fermentation. Ammonium N may represent 90% of N for cattle urine, 50% for cattle slurry, 70% for pig slurry and 15% for fermented stable manure. Scarcely more than 60% of N in animal droppings is likely to reach the soil. Balances which include forage among the removals and organic manures among the additions may more nearly approach the truth for farms or regions but are very difficult to establish for the latter.

Localization of droppings at pasture is an important source of loss. It is estimated *[7]* that nutrient rates under cowpats are equivalent to 1100 to 1700 kg/ha N, 400 kg P_2O_5 and 600 to 2500 kg/ha K_2O. At a stocking rate of 2 LGU/ha, 7% of the surface receives much manure and is enriched, while the rest is impoverished. The nitrogen is highly susceptible to leaching while losses by volatilization are also considerable. At the same time the untouched part of the field should receive fertilizer to compensate for the normal losses by leaching and denitrification.

On arable land, the main N loss is by volatilization during application of materials high in ammonium N while that part which is nitrified (applied at the end of summer) is subject to leaching over winter and denitrification in spring. It is also known that part of the organic nitrogen is mineralized during the growing season so that what is a necessary application of fertilizer N in spring becomes excessive by the end of the season of growth.

So far as losses from fertilizer N are concerned, these are better known and estimated at between 10 and 20 percent for volatilization and between about 10 kg/ha N and almost the whole of the residual N by leaching depending on soil and climatic conditions.

6.2 Defects in the phosphorus balance

There are similar problems in the case of animal droppings at pasture but drainage losses are negligible.

In cultivated soils losses are generally slight but soil enrichment is a slow process on account of fixation. In very calcareous soils, the conversion of P residues to insoluble forms means that soil enrichment must be a very slow process inasmuch as the soil test is relevant. *Fardeau [13]* has said that a decline in organic matter content is accompanied by reduced P availability as indicated by soil tests. Even so one is aware that fixed P plays some part in the pool of labile phosphorus.

6.3 Defects in the potassium balance

The potassium balance appears to be the most positive, particularly in animal systems. Potassium in stable manure arrives more or less intact on the arable field and behaves similarly to that in fertilizer. In contrast, on grazed grass, the high concentrations particularly in urine patches are conducive to heavy leaching losses, which are even more severe than those of nitrogen. This applies particularly on light textured soils. There are also losses by fixation on clay soils. The former type of loss is permanent, fixed K is recoverable in time. In experiments, K recoveries have not exceeded 50% and may be as low as 2.5%. Thus the application of K fertilizer is justified.

On cultivated soils it may be that insufficient account has been taken of leaching losses on light and shallow soils.

6.4 Soil tests and fixation problems

While the interpretation of analytical results for fertilizer advice is straightforward if the contents indicated are at the high or low extremes, it is much more difficult to forecast the rate of fertilizer needed and the chances of profit when soil values are intermediate. Different countries follow varied policies in this respect. Some advise soil testing at regular intervals (2 or 3 years) and attempt to advise on fertilizer treatment for immediate profit. Others plan fertilizer treatment over the medium term based on the results of analysis, the effect of the treatment being judged by the results of analysis after 5 or 10 years. Under many conditions soils exhibit only maintenance of fertility or a slight decline despite apparent positive nutrient balance. It seems more account should be taken of movement towards the subsoil and of fixation.

On this latter point, in the absence of convenient tests for fixation soils appear to behave very differently. Thus long-term experiments (18) have shown in some cases a nil balance to be accompanied by maintenance or even increase in exchangeable K in the plough layer while in others, exchangeable K has declined despite more or less large positive K balance.

The Omiecourt experiment (*cf.* 3.3.2) is particularly interesting (Figure 9). In this originally poor soil, increasing fertilizer dressings were immediately translated into increase in exchangeable K_2O (though this varied from year to year). But the difference between K treatments has remained constant in later years.

The change from 0.11‰ of exchangeable K_2O to 0.20‰, still regarded as on the low side in spite of the enrichment, demands an application of about 6 t K_2O (K_3) which left a positive balance of 4500 kg/ha K_2O, the annual rate of usage being 196 kg/ha with removals at about 112 kg/ha by the optimum yields. The potassium excess should correspond to more than 12 times the change in exchangeable K_2O. For practical purposes it would appear to be best to adopt the most immediately profitable rate of application (K_1 for cereals and usually K_2 for the other crops) rather than to go for a policy of enrichment which will only achieve the aim very slowly.

This illustrates the importance of experimental work to adapt fertilizer policy to suit soil conditions and that further work is needed to be able fully to describe the nutrient potential of the soil.

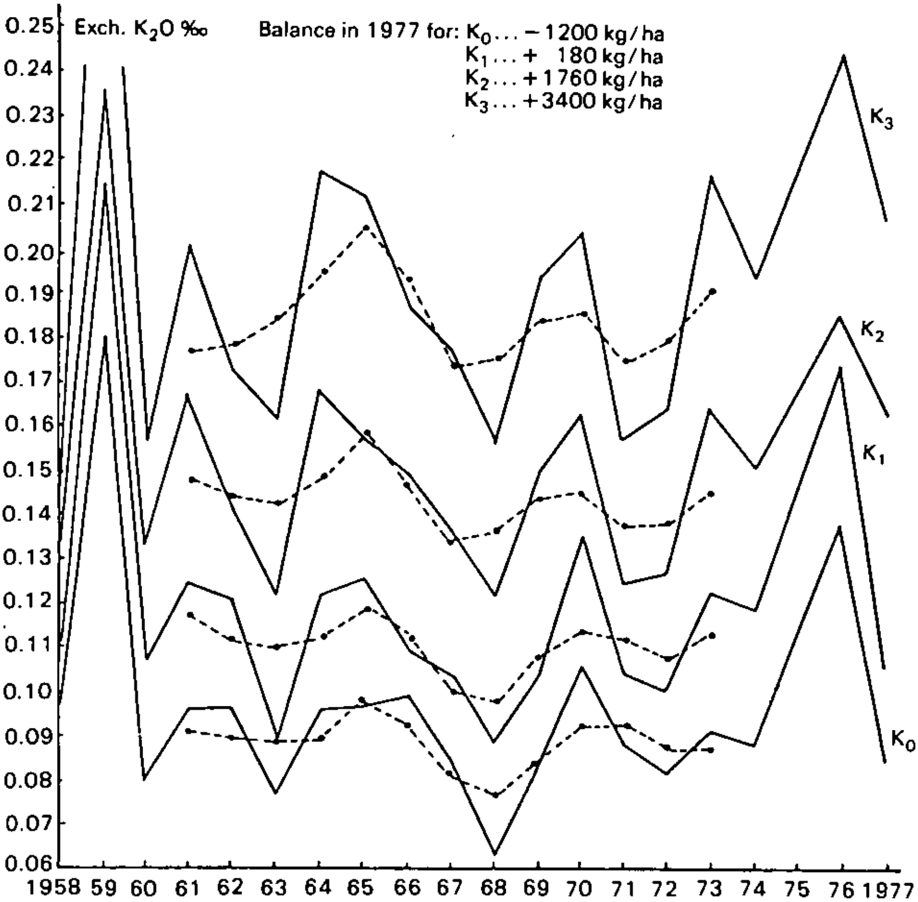

Fig. 9. Changes in exchangeable potassium in the long-term experiment at Omiécour *(Loué [18]).*

6.5 Prospects

Positive nutrient balances indicate that:

- in some situations the farmer has not mastered high yield techniques,
- in others, while making reservations as to the availability to crops of nutrients in manures, application rates are sufficient if not excessive.

Nevertheless even in countries where the overall balance is the most positive, there remains a larger or smaller proportion of low nutrient status soils. In some cases one can foresee some reduction in application of fertilizers especially where recycling of farm manures, industrial or town wastes is possible. Equally one can foresee some change in distribution.

In the search for higher productivity and to economize on inputs, the aim is to arrive at a sufficiently high level of fertility. On the one hand we know that rational fertilizer use enables us, due to interactions, to grow high yields even on poor soils. On the other hand it is easier to resolve the practice of fertilizer use, which has not been touched upon here: refinements may be needed in the use of various types of fertilizer (straights, binaries and compounds) and in timing of applications. Nitrogen fertilizers need special attention.

Recommendations will remain imprecise unless some points are clarified:

1. We need soil analytical methods more closely related to the actual plant availability of soil nutrients,
2. We need more simple experimental work to buttress the recommendations. Considerable work has been done in some countries, more is needed in others. In view of the cost of such work it is suggested that international cooperation could be very fruitful.
3. We need better understanding of the concept of nutrient balance on the field scale. Soil analysis alone is insufficient basis for medium term fertilizer recommendations. The subsoil is also important in crop nutrition but it would be costly to extend soil analysis to the subsoil. Therefore we have to attempt:
   - more precise estimation of nutrient losses,
   - more precise estimation of the part of nutrients which does not participate in the nutrient pool due to fixation and precipitation.
4. We need better evaluation on the availability of nitrogen over time in organic manures (farmyard manure, compost and urban wastes).

There can be no doubt that data processing through modelling and simulation will make rapid progress in this area. But that will only hold insofar the farmers and their advisers are well enough educated to put the findings to good practical use.

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Fertilizers, Soil and Crop Management – Evaluation of Long-Term Field Experiments (1953–1983)*

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Summary

Results from extensive experimental work carried out at the Agricultural Research Centre in Gembloux between 1953 and 1983 have shown that the evaluation of the amount of available nutrients in the cultural profile, in order to determine the N, P and K requirements, depends on the cultivation practices adapted to each situation and especially on the organic matter regime, the crop sequence and the soil tillage.

Foreword

This communication results from a panel discussion between several researchers from the *Agricultural Research Centre of Gembloux.*

The following have participated in the research work and drafting of the present note:

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*** *A. Crohain, M. Frankinet, J. Guiot, L. Rixhon.*

This synthesis relates exclusively the results of numerous experiments carried out in the two above mentioned departments between 1953 and 1983. Almost all these experiments were conducted on a deep, well-drained, and fertile loess soil, in a temperate humid climate.

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1. Introduction

Fertilizer studies centre on three major nutrients namely nitrogen, phosphorus and potassium. These elements should be considered separately owing to their fate in the soil and their impact on crop production: nitrogen on the one hand, phosphorus and potassium on the other *(Droeven [34]; Laloux et al. [60]; Rixhon [79])*.

Most of the nitrogen found in the soil is organic N which is progressively transformed into soluble and highly available nitrate N. The influence of nitrate N on crop development is very strong; the least excess or deficiency is made visible. Improper distribution can also lead to disturbances in crop development or exacerbate the susceptibility of the plant to certain parasitic diseases *(Parmentier* and *Rixhon [62])*.

Nitrogen is the most important fertilizing element conditioning mostly the maximum possible yield. It should be applied annually and be adapted to the plant needs as well as to the soil and climatic conditions, and this generally requires the splitting of the fertilizer dressing.

On the other hand, phosphorus and potassium are intercepted in the soil by physicochemical bonds or go through a series of complex chemical reactions which lead to reversion and fixation of these nutrients. These phenomena are reversible, the velocity of the equilibrium reactions depending on the degree of immobilization and on the soil and climatic conditions. Once back into the soil solution both nutrients are made available to the plant. Leaching losses are negligible except for potassium in light soils. The effect of both elements on crop development is slight and they do not induce disturbances in plant growth nor aggravate parasitic diseases. A shortage is not easily detected and there are no visual symptoms of excess uptake ('luxury' uptake) resulting in practice in waste *(Lacroix [56]; Demortier* and *Droeven [27]; Darcheville [17])*. Therefore long-term experiments are necessary to evaluate the effect of P and K dressings on crop yields and on the evolution of P and K reserves in the soil which are particularly important in most of the Belgian soils *(Destain [29, 31])*. It follows that soil fertility is linked to the fertilizer history of the crops as far as P and K nutrients are concerned. From a practical point of view the problem of P and K fertilizing is to provide adequate supplies to the soil corresponding to the actual uptake by the plants over, say, a complete crop rotation and by making up for possible losses by fixation or leaching.

Cultivation techniques as a whole and especially the organic matter regime, the crop sequence, and the soil tillage should be considered in order to evaluate the amounts of available nutrients in the soil and hence, the level of the N, P and K dressing.

2. Nitrogen

2.1 Crop needs

Nitrogen fertilizers should be applied annually and be well adapted to crop needs, as well as to soil and climatic conditions.

Crop needs can be defined as the adequate amount of available nitrogen ensuring continuous and smooth growth of the plant leading to the economically optimum yield.

It is obvious that natural soil N supplies are generally insufficient to meet the needs of a crop. So, additional dressings of fertilizer N are necessary to make the amount up to the level needed at each stage of plant development. The number of splits as well as the amount of N delivered at each split depends on the particular crop species *i.e.* on its needs and tolerance to high ion concentrations in the soil solution.
Nitrogen timing depends also on the soil and climatic conditions *(Riga, Fischer* and *van Praag [70]; van Praag, Fischer* and *Riga [82])* on the one hand, on the general crop management practices as the organic matter regime, the preceding crop, the soil tillage *(Lacroix et al. [57, 58]; Delhaye [26]; Crohain et al. [15])* and the use of anti-lodging chemicals, on the other *(Rixhon* and *Crohain [71, 72, 73]; Rixhon [74]; Crohain et al. [12]).*
It is difficult to predict the precise needs of a crop, for this assumes knowledge of the amount of nitrogen supplied by the soil at any moment of plant development, and of the ideal amount of complementary fertilizer nitrogen. It is, however, possible to get a rough idea of the evolution of these needs by following nitrogen uptake by the plant at different stages of its growth. The curve of Figure 1 illustrates N uptake by winter wheat given an optimum N dressing *(Guiot [45]).*

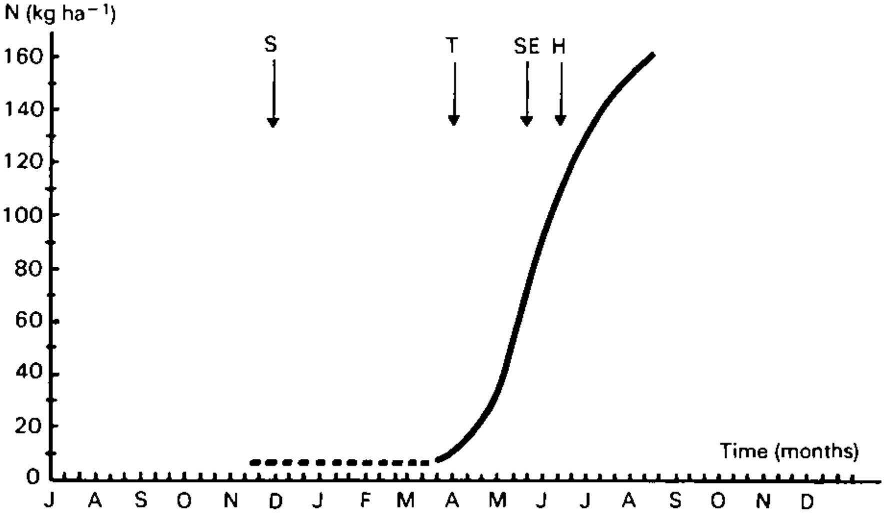

Fig. 1. N uptake by winter wheat. S = sowing (20 kg N/ha^{-1}); T = tillering (60 kg N/ha^{-1}); SE = stem elongation (40 kg N/ha^{-1}); H = heading (20 kg N/ha^{-1}.

2.2 Availability of soil nitrogen

Almost all soil nitrogen reserves are organic N unavailable to the plant. To be made available this nitrogen has to go through a series of microbial transformations called 'mineralization' leading to the production of highly available nitrate N. The factors which enhance the growth of the soil microflora will also increase the intensity of the mineralization process: air and water which should be held at an optimum ratio as resulting from good structural stability, temperature and pH. This last factor should be controlled regularly.

The evolution of the amount of mineral N in a loamy soil, bare fallowed without fertilizer application after the crop harvest (oats), is shown under I in Figure 2 *(Guiot [47])*.

After harvest the level of mineral N in the soil profile is low: some fifteen kg ha^{-1} which is an indication of a good uptake of soil and fertilizer nitrogen by oats. Soil temperature is high at this time of year and favorable to mineralization, which leads to a rapid increase in mineral nitrogen in the soil profile.

This mineralization process is slowed down in the fall and practically stops with the first frosts.

The amount of mineral nitrogen generally remains constant during the winter period with a possible small increase if soil temperatures are positive. On the other hand some of the nitrate may be leached down below 1.50 m if winter rainfall is heavy *(Guiot [46])*.

In the spring the amount of mineral nitrogen in the soil profile increases more or less as a result of the rise in soil temperature. Wide differences are found between years as far as resumption of mineralization is concerned; a 6-week range has been observed in Gembloux *(Guiot [50])*.

The amount of mineral N reaches its maximum value in the summer and is over 120 kg ha^{-1} in the whole profile at the end of August.

No significant difference is found between fallowed plots and plots sown to winter wheat until the end of the winter period. When plant growth resumes in early spring (curve II, Figure 2), uptake exceeds the amount of nitrogen released by the soil and mineral N decreases in the cultivated plots. The moment at which the two curves diverge is also weather dependant, especially as far as soil temperature is concerned,

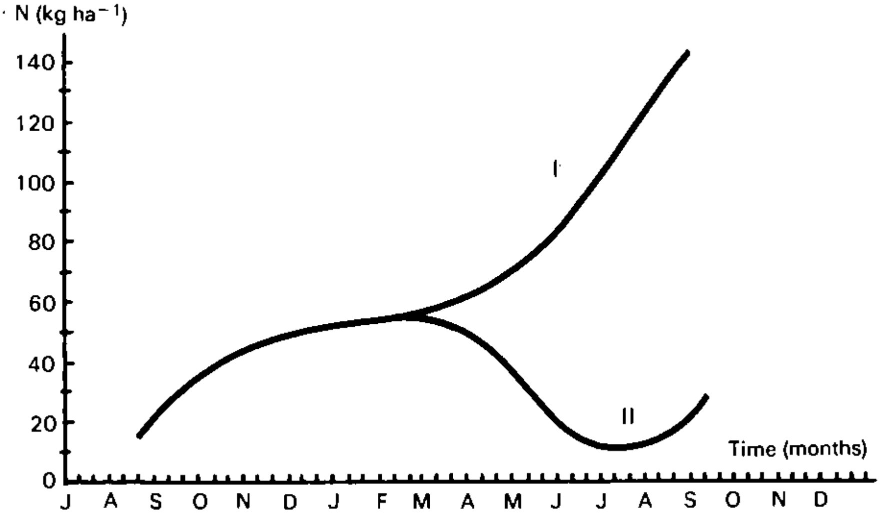

Fig. 2. Evolution of mineral N in the soil profile after the oat harvest. No N fertilizer added. I = bare soil; II = soil sown to winter wheat.

and differences between farming years are of the same order of magnitude as those recorded for the resumption of mineralization *(Guiot [50])*. Nitrogen uptake by the plants increases rapidly with a concomittant decrease of mineral nitrogen in the soil, with a minimum value of 10 kg/ha^{-1} in the whole profile (1.5 m) in the middle of July. Two or three weeks before barvest plant uptake decreases sharply and becomes smaller than the amount mineral nitrogen released by the soil; the amount of mineral nitrogen in the soil profile increases once more.

The difference between the levels of mineral N in bare soil on one hand, and plots sown to wheat on the other hand, gives an indication of the amount of soil N taken up by the crop. This difference reaches its maximum value – 90 kg/ha^{-1} in the present example – when the amount of mineral N is at its lowest level in the cropped soil.

Other factors such as soil type and the cropping system adopted on the farm influence the amount of soil nitrogen released to the crop. Among these, organic matter returns, crop sequence and soil tillage should be mentioned.

The influence of soil type on soil nitrogen mineralization has been mentioned above; this factor is also to be considered as far as nitrogen uptake by the plant is concerned which depends on depth of the cultural profile. As an example let us mention the important amounts of mineral N found in the lower layers of some sandy soils – some 10 to 15 kg/ha^{-1} per 15 cm-thick layer – and made unavailable to the roots of cereal crops which do not go deeper than 80–90 cm in these soils *(Guiot et al. [54])*.

2.3 Evaluation of the nitrogen dressing as related to added organic materials, crop sequence and soil tillage

2.3.1 Added organic materials

In order to determine correctly the nitrogen dressing to be applied to a crop under different kinds of organic matter regime it is necessary to evaluate the nitrogen value of each type of organic matter supply *(Lacroix et al. [59]; Demortier and Droeven [28]; Crohain and Raimond [10]; Raimond [65]; Droeven et al. [35])*.

This can be done in three ways. The first two are based on the evaluation of *mineral nitrogen released or immobilized* by the organic matter ploughed in or turned under:

- either from a *theoretical calculation* involving the isohumic coefficient of this organic matter and its total nitrogen content,
- or from the *periodical determination of mineral N* under a bare fallow with or without addition of organic materials *(Guiot [44])*.

The third method leads to the evaluation of the '*N effect*' of organic matter in terms of amounts of mineral fertilizer nitrogen resulting from field experiments carried out on a test crop. This 'N effect' results not only from the nitrogen released from the organic matter but also from any beneficial effect as *e.g.* the improvement of soil structure, the general stimulation of plant metabolism by humic substances... *(Crohain [8])*.

Example: Determination of the nitrogen value of straw according to the three above-mentioned methods

Weight of straw: 5 500 kg/ha^{-1}
Dry matter: 4 700 kg/ha^{-1}
Total N in straw: 22 kg/ha^{-1}

First method: theoretical calculation
Isohumic coefficient of straw: 0.10 to 0.25
Humus produced: 470 to 1 170 kg/ha^{-1}
N immobilized by humus (5%): 23.5 to 59 kg/ha^{-1}
N value of straw: *−1.5 to −37 kg/ha*$^{-1}$

The N value calculated according to this method is very approximate as it depends of the value chosen for the isohumic coefficient. On the other hand, if the total amount of nitrogen ploughed in with external organic matter as FYM is easily calculated, it is much more difficult to evaluate when the organic materials are produced *in situ* by the underground parts and returned to the soil as green manure.

Second method: periodical soil analysis	Amount mineral nitrogen (kg/ha^{-1}) in the soil profile *with straw*	 *without straw*
mid-August before straw manuring	11.4	10.7
mid-November after straw manuring	26.2	39.5
mid-March after straw manuring	53.7	62.1

Determination of the nitrogen value of straw:

at mid-November
Mineralized N in soil without straw: 39.5 − 10.7 = 28.2 kg
N added as fertilizer N before straw manuring: 28.0 kg
N value of straw: 26.2 − (11.4 + 28.2 + 28) = *−41.4 kg*

at mid-March
Mineralized N in soil without straw: 62.1 − 10.7 = 51.4 kg
N added as fertilizer N before straw manuring: 28.0 kg
N value of straw: 53.7 − (11.4 + 51.4 + 28) = *−37.1 kg*

This technique enables one to determine the N value of added organic material. Its main object however is the precise determination of the amount N in the soil actually available to the crop for any organic matter regime. It allows the adjustment of nitrogen fertilizer dressing to the crop but unfortunately it should be repeated during plant development and is of little practical value on the farm.

Third method: 'N effect' of straw as calculated for a sugar beet crop

Total mineral nitrogen dressing in kg ha^{-1}	Root yields in kg ha^{-1}		'N effect' of straw	
	without straw	with straw	difference	
90	47 890			
110	51 390			
130	52 910	48 030	4 880	*−44*
150	54 580	50 530	4 050	*−37*
170		52 430		
190		54 750		

Increase coefficient as calculated in linear regression: 109 kg sugar beet roots per kg N.

As climatic conditions influence the 'N effect' of organic materials added to the soil, a valid estimation of this value with the above-mentioned technique requires repeated experiments over several years and, if possible, with different kinds of crops. For instance our trials have shown that the 'N effect' of sugar beet tops turned under, which has an evaluated average value of 40 kg ha^{-1}, amounts only to 25 kg during fall and winter wet periods due to a slowing down of N mineralization in waterlogged soils *(Crohain* and *Rixhon [5])*.

On the other hand adverse climatic conditions may reduce the crop yields and hence the efficiency of nitrogen dressings. The results of two experiments carried out in two years with contrasting weather conditions, in order to evaluate the resultant 'N effect' of the return of barley straw and vetch turned under as green manure for a sugar beet crop, are given hereunder as an example *(Crohain* and *Rixhon [7])*.

N dressing kg/ha^{-1}	Root yields in kg/ha^{-1}	
	1st experiment	*2nd experiment*
80	47 940	36 600
100	51 270	37 100
120	52 600	37 400
140	54 730	37 600
σm	600	400
d 0.05	2 080	n.s.

In the second experiment the small differences between root yields are not statistically significant and make it impossible to calculate any 'N effect' of straw and green manuring.

As already mentioned the calculation of the 'N effect' may lead to different values depending on the kind of plant and on the level of the nitrogen dressing. For instance the 'N effect' of sugar beet tops is always higher when evaluated for a winter crop which lasts 10 months as compared with a 5-month spring crop. In the same way the 'N effect' values measured with low N dressing are always higher than the figures obtained with higher N applications.

'N effect' of various organic materials

The evaluation of the practical fertilizing value of various organic materials has been based on data collected from field experiments, some of them extending up to twelve consecutive years *(Crohain* and *Rixhon [5, 7]; Crohain [9]; Lecomte et al. [61]; Couvreur et al. [4])*. These values are given hereunder in kg N/ha^{-1}.

	1st year after ploughing in	2nd year after ploughing in
FYM (40 t/ha^{-1})	+30/40	+25/15
Slurry: pig (35 t/ha^{-1}) or cattle (55 t/ha^{-1}) or poultry (25 t/ha^{-1})	+85	+20
Vetch: green manuring (2 t DM/ha^{-1})	+40/50	+20/15
Cruciferae with 100 kg N/ha^{-1} dressing, as green manuring	+15/20	—
Sugar beet tops (40–45 t/ha^{-1})	+25/40	+20/10
Carbonate of lime as waste from beet sugar factories (40 t/ha^{-1})	+30/35	+10
Straw (5 t/ha^{-1}) infrequently ploughed in	−35/40	+10
repeatedly ploughed in	−20/25	+10

2.3.2 Crop rotation

Apart from the above-mentioned organic materials and by-products from crops, the mineral N in the soil profile available to the following crop originates from several possibles sources *(Guiot [48, 51, 53])*. Let us mention the residue of fertilizer N applied to the preceding crop *(Riga et al. [70])*, the nitrogen produced by biological activity in the soil during the fallow season or fixed by the Rhizobium of a preceding legume.

Variations in mineral N reserves in the soil interact positively, or negatively with other factors. So the increase in soil N reserves due to the legume (direct effect of the Rhizobium) or to the flax (indirect effect of the mineralization during the fallow season) can be enhanced by the improvement of soil structure and of health conditions of the crop *(Rixhon* and *Parmentier [76]; Parmentier* and *Rixhon [63])*. The greater the botanical difference between the succeeding plants the higher this efficiency. On the other hand the nitrogen value can be reduced or even made negative by the parasitic effect resulting from the continuous cropping with the same crop *(Defosse* and *Rixhon [25]; Rixhon* and *Defosse [78]; Rixhon* and *Crohain [77]; Frankinet* and *Rixhon [41, 43])*. This extra soil mineral nitrogen is more readily taken up by a high-demanding crop such as a winter cereal with a well-developed rooting system in the fall, preventing any possible leaching during the winter period.

Results in Table 1 show the nitrogen value as calculated for twenty crop sequences. These values have been based on periodical soil analyses in order to apply a complementary amount of fertilizer N adapted to each situation and leading to the same level of mineral N in the cultural profile for each split of a 3-split dressing *(Guiot [52]; Guiot et al. [54])*.

These data show the inhibitory effect of single crop farming systems resulting from parasitic diseases as in treatment No. 13 (W-W-W) notwithstanding the relatively high fertilizer N dressing applied, namely 123 kg N/ha^{-1}. The N value can easily be measured by subtracting the amounts fertilizer N applied to the last crop of the crop sequences giving similar yields. For instance treatments 8 (W-O-Wb) and 16 (W-Hb-W) show a 39 kg N value for the horse bean turned under while the comparison between treatments 20 (W-Lu-Lu) and 6 (W-M-Sb) indicates an N value of, at least, 69 kg N for the two-year lucerne.

Table 1. N dressings, yields and amounts mineral N left over in 1980 for twenty different crop sequences (1980/79/78).

Treatment No.	Crop sequence 80/79/78	Adjusted N dressing* kg N/ha^{-1}	Yield kg/ha^{-1}	Mineral N left over after 1980 harvest kg N/ha^{-1}
20	W/Lu/Lu	70	6717	17
19	W/L/L	95	6504	15
5	W/Hb/Sb	100	6459	13
3	W/F/Sb	114	6450	10
6	W/M/Sb	139	6408	7
7	W/F/Wb	105	6402	15
9	W/Hb/Wb	101	6391	13
12	W/Rg/Wb	85	6354	10
11	W/M/Wb	115	6327	11
4	W/O/Sb	131	6295	13
10	W/Sb/Wb	120	6255	14
8	*W/O/Wb*	*128*	*6232*	*13*
16	*W/Hb/W*	*89*	*6226*	*14*
2	W/B/Sb	138	6107	10
14	W/F/W	114	6077	14
18	W/M/W	117	6063	9
1	W/W/Sb	114	5972	20
15	W/O/W	136	5968	12
17	W/Sb/W	130	5912	15
13	*W/W/W*	*123*	*5387*	*21*
Mean		113	6213	13.3

Symbols: W = winter wheat; Rg = ray grass; Wb = winter barley; Lu = lucerne; Hb = horse bean; F = flax; B = spring barley; O = oats; M = maize; Sb = sugar beet; L = ley.

* 3-split N dressing (see text).

2.3.3 Tillage

Results of annual experiments carried out in order to reduce the cultivation of soils sown to winter wheat after a sugar beet crop with no return of tops have stressed the importance of an extra N dressing in the case of reduced tillage *(Crohain [6])*.

These experiments have been repeated with sugar beet tops ploughed under and for three levels of N dressing *(Frankinet* and *Rixhon [42])*. The resulting data substantiate this assumption. It has, however, not been possible to evaluate separately the effect of soil tillage on the one band, and of the modification of the 'N effect' resulting from the turning under of sugar beet tops at various depths, on the other.

A medium-term experiment initiated in 1967 and including direct-drilled plots has lead to the same conclusions *(Rixhon [75]; Frankinet et al. [38]; Crohain* and *Frankinet [14])*.

The data show that the release of mineral N is approximately 20 kg N/ha^{-1} lower in direct-drilled as compared to traditionally drilled plots; however no statistically significant differences were found between deep (25 cm) and shallow (15 cm) cultivated plots.

In the same experiment plants reacted differently to reduced cultivation *(Frankinet [39])*. Spring horse bean is the only plant species which produced higher yields when direct-drilled. No difference was generally found between the cultivation systems in plots sown to winter wheat, with no need for an extra N dressing to the direct-drilled plants. On the other hand direct drilling depressed the yields of sugar beet, maize, spring barley and, to a lesser extent of oats, with no certainty of making up all the difference with supplementary N fertilizer.

Summing up what has been said above, it seems that supplementary fertilizer N should be applied below a certain level of soil cultivation. Next to this 'N effect' of soil tillage one should take into account the influence of the various cultivation systems on the physical soil conditions (structure, water, temperature, etc. . . .) *(Frankinet* and *Ben Harrath [36]; Ben Harrath et al. [1]; Frankinet [37]; Cordier et al. [2]; Cordier* and *Frankinet [3])* as well as on the biological soil conditions (soil fauna and soil flora) *(Hennuy et al. [55]; van Ormelingen et al. [81]; Stassart et al. [80])* without neglecting the special requirements of certain crops as *e.g.* soil temperature for maize, soil structure for sugar beet, . . .

3. Phosphorus and Potassium

3.1 P and K requirements for a complete crop rotation

Long-term field experiments have been conducted for nearly 20 years in order to determine the amounts of P and K fertilizers needed to produce the economically optimum yield for different kinds of soil and different cropping systems *(Darcheville [16, 17, 19, 21])*. Three- and four-course rotations have been investigated with sugar beet or maize, followed by two or three small-grain cereals and, occasionally, by a horse bean crop. Most of the conclusions drawn from the P and K experiments differ from those of the N trials. In a general way, yield increases resulting from P and K dressings applied in the experiments reported here, have been small or almost non-existent (Table 2) *(Darcheville* and *Destain [22])*. Moreover the evolution of P and K reserves in these soils has underlined the availability of P and K reserves in

Table 2. Influence of N, P and K mineral fertilizer dressings on crop yields in Gembloux (Hesbaye limoneuse) during the 1967–1983 period.

Crop	Number of crops	N		P		K	
		S	NS	S	NS	S	NS
Sugar beet	10	6	4	0	10	2	8
Winter wheat	9	6	3	2	7	1	8
Winter barley	7	6	1	2	5	1	6
Spring wheat	2	2	0	0	2	0	2
Oats	2	1	1	0	2	0	2
Spring barley	2	1	1	0	2	0	2
Horse bean	2	0	2	0	2	0	2
Total	34	22	12	4	30	4	30

S = Effect significant at the 0.05 probability level
NS = Effect not significant at the 0.05 probability level

the cultural profile, as well as the possibility for the plant to take up other chemical forms of these two nutrients, considered to be less available *(Destain [29, 31])*.

These results have made it possible to establish a fertilizer scheme for P and K, calculated on the plant requirements over a complete crop rotation and taking into account the actual uptake of the two nutrients by the crops (Table 3), the amounts brought in by mineral amendments and by organic material ploughed in or turned under, and the losses through leaching and fixation. These annual losses amount to 10 and 20 kg/ha^{-1} in terms of P_2O_5 and K_2O respectively *(Darcheville, Rixhon* and *Crohain [18]; Darcheville* and *Crohain [20])*.

The distribution of this P and K dressing between the succeeding crops of the rotation is made by adjusting, as well as possible, to the requirements of each crop on the one hand, and the kind of compound fertilizers and their economical broadcasting on the other *(Crohain* and *Darcheville [13])*.

Where much organic material, by-products and other amendments are applied, the amounts of P and K fertilizers to be applied are generally rather small and can be given to the first crop of the rotation as a 'periodic application' *(Darcheville* and *Destain [23])*. If the so calculated K dressing is greater than 300 kg K_2O/ha^{-1}, any amount in excess of this value should be distributed between the following crops. This in order to avoid any excess salts in the soil solution leading to possible magnesium deficiency.

Table 3. Means of P and K uptake by the principal crops (expressed as P_2O_5 and K_2O in kg ha^{-1}). Field experiments conducted from 1967 till 1982.

Crop	Number of samples analyzed	Roots or grain		Leaves or straw		Total	
		P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O
Sugar beet	822	43	133	32	189	75	322
Winter wheat	1404	51	32	10	46	61	78
Winter barley	436	47	38	3	47	50	85
Spring oats	464	36	26	10	86	46	112
Horse bean	392	48	42	6	31	54	73
Fodder maize	228	—	—	—	—	63	181

3.2 P and K dressing, added organic materials and soil tillage

3.2.1 Added organic materials

The application of the method described above requires knowledge of the amounts of P and K returned to the soil as by-products of crops turned under, or ploughed in as FYM, carbonate of lime as waste from beet sugar factories, slurries, . . . (Table 4) *(Droeven [32]; Crohain [11])*. One should also consider the rate of release of the nutrients by the decomposing organic material *(Droeven* and *Demortier [33])*. It is generally admitted that the P and K released by the FYM to the plants of the crop rotation should be distributed in the following way: one half to the first crop, one third to the second and one sixth to the third crop.

Owing to their origin and dilution the chemical compositions of slurries varies greatly *(Destain* and *Raimond [30])*. Unlike FYM, K in the slurry is completely soluble and is comparable with that in a mineral fertilizer.

Table 4. P and K content of several amendments (expressed as P_2O_5 and K_2O in kg T^{-1}). Analyses carried out between 1957 and 1982.

Amendment	Number of samples analyzed	P_2O_5	K_2O
FYM	22	6.95	7.42
Cattle slurry	82	2.27	5.78
Pig slurry	234	3.98	3.93
Carbonate of lime as waste from beet sugar factories	5	8.50	0.82
Carbonate of lime as waste from paper factories	2	0.43	0.15

Cereal straw, sugar beet tops and waste lime from beet sugar factories can be compared with FYM.

The rate of decomposition of sugar beet leaves is higher than that of FYM and straw; their effect is generally distributed as follows: 75% the first year and 25% the second.

Green manures do not receive any P and K dressing and are supposed to release their P and K in the year following turning under.

3.2.2 Soil tillage

While traditional tillage involves the more or less homogenous mixing of fertilizers and amendments within the ploughed layer, direct drilling leads to an increase in P and K concentration near the soil surface. Beyond the 30-cm depth P and K concentrations seem to be only slightly modified by the soil cultivation conditions in the top layer. These are findings from long-term field experiments conducted from 1967 up to 1983 *(Raymond [64, 66])*. If P and K are more or less diluted in the cultural profile depending on the soil cultivation system involved, the total available amounts of these two nutrients are practically the same for all treatments if one considers the soil layers explored by the roots *(Raimond [67])*.

Plant analyses show differences in P and K concentration at harvesting smaller than 5% between direct-drilled and tilled plots. These small differences are nevertheless significant as far as P is concerned. The great variability of the results as well as the marked influence of the climatic conditions should be stressed; the 'year effect' outweighs the 'soil cultivation' effect *(Frankinet* and *Grevy [40])*.

Field experiments with ^{32}P-labelled fertilizers have shown that the percent P derived from the fertilizer (% PDFF) represents only a small fraction of the total P taken up by the above-ground parts of spring barley and oats. These values are nevertheless higher for both cereals in direct-drilled plots as compared to traditional tillage namely: 9.5 and 6.4% for oats, 5.9 and 5.6% for spring barley *(Riga* and *Francois [68, 69])*.

In the same plots root development has been followed during plant growth. Root activity is more concentrated near the soil surface in direct-drilled plots especially if sown to spring barley *(Decocq* and *Riga [24])*.

It can be concluded in terms of 'balance sheet' that the differences in P and K concentrations observed between the cultural profiles under the various cultivation systems investigated, do not alter the total amounts of P and K nutrients and their availability to the plant.

4. Conclusion

The determination of the N, P and K dressing to be applied to a crop should be based on the history of the soil and crop management of the plot. The experimental work reported here shows clearly that the amount of available nutrients in the cultural profile are related to the conditions peculiar to each situation and especially, as concerns organic matter regime, crop rotation and soil tillage.
Consequently, each situation should be considered separately in a fertilizing scheme, the factors characterizing the crop environment being taken into account.

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Interactions Between Fertilizers and Irrigation with Reference to Nitrogen and Winter Wheat

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Summary

The profitability of irrigation in the temperate climate of France – supplementary irrigation – being somewhat problematical, farmers are uncertain as to whether it may pay to irrigate winter wheat. This is bound up with the question of response to optimum N dressings. If irrigation is available this is straightforward but if it is not there is always a risk that the crop will be short of water and the farmer does not know, particularly at the time when he has to apply N, what the chances are of rainfall being adequate. The problem is all the more difficult because of uncertainty as to the nitrate content of the soil.

The investigations reported here show that irrigation of winter wheat is profitable owing to the strong interaction between water supply and nitrogen fertilizer. When there is a risk of water shortage after shooting nitrogen application should not be reduced below the rate appropriate for a crop adequately supplied with water. The risk of pollution is the same in either case. If there is a great risk of water shortage before shooting – which is relatively rare in the temperate climate – reduction of nitrogen fertilizer should be considered with a view to lessening the risk of pollution.

Introduction – Irrigation in France

The areas in France where irrigation may be considered essential extend to an area of 700000 ha, or 54% of the total irrigable area, and are situated in the southwest and southeast, south of the line from Bordeaux to Montpellier *(RGA [79]),* see Figure 1. A further 600000 ha of irrigable land are found north of this line in the temperate zone. Here water shortage is not always a prime yield limiting factor. 46% of the irrigated area is under maize. Here irrigation is used to supplement water supply and profitability of irrigation is uncertain because:

- Mean water deficits are relatively slight (Figure 2) which means that the effects of irrigation on yield are limited.
- The frequency of occurence of summer drought is very variable.

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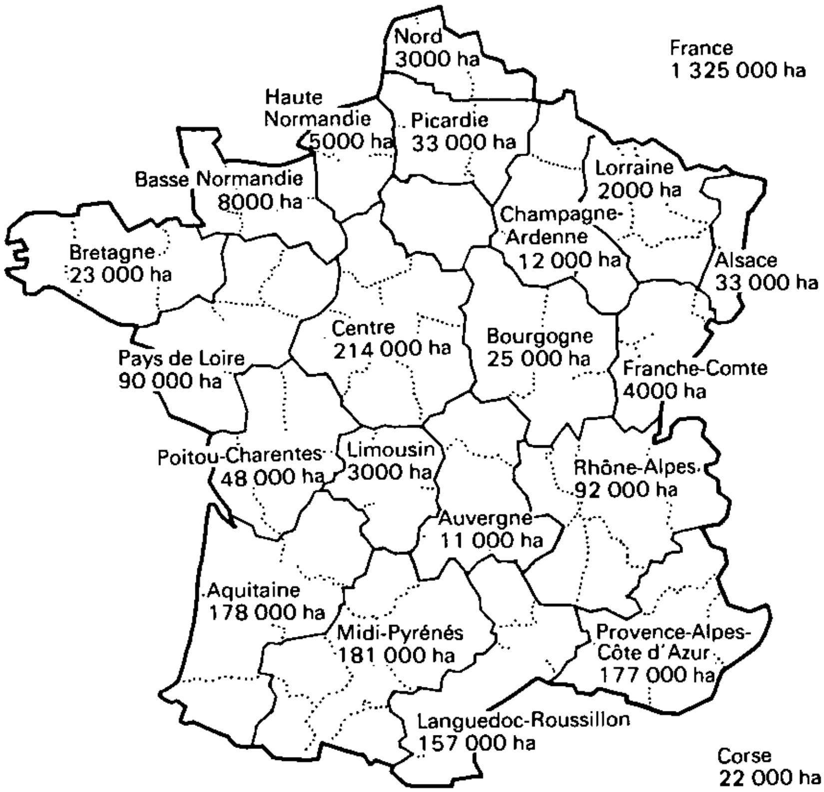

Fig. 1. Irrigated areas in France (after *RGA [1979]).*

1. The problems of temperate zone irrigation

1.1 Agronomic aspects – the response to water

Research has revealed a close connection between crop production and water consumption by crops. *Robelin* and *Mingeau [1970]* and *Maertens [1973]* found a linear relationship between total dry matter production and water requirement expressed in the ratio ETR/ETM which can be written:

$$\frac{\text{DMT (ETR)}}{\text{DMT (ETM)}} = a\,\frac{\text{ETR}}{\text{ETM}} \pm b \qquad (1)$$

where

DMT (ETR) = total dry matter production with actual evapotranspiration
DMT (ETM) = total dry matter production at maximum evapotranspiration
ETR = actual evapotranspiration by crop
ETM = maximum evapotranspiration by crop

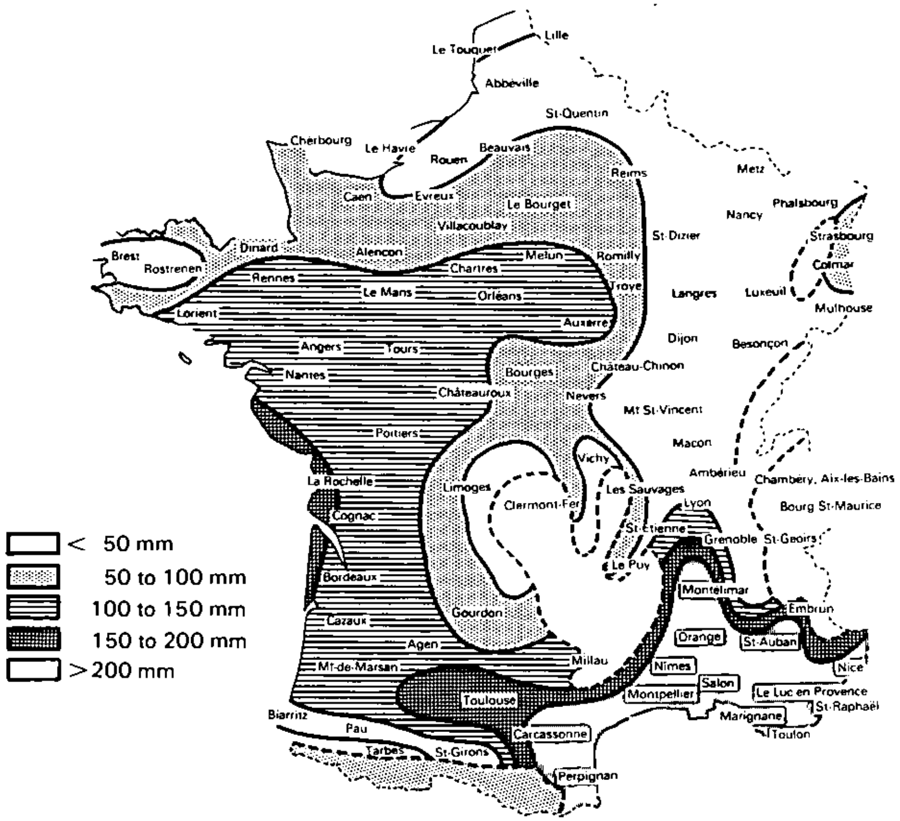

Fig. 2. Biennial water need – Crop: maize – RFU = 100 mm (after *Lecarpentier*).

Applied to the case of grain maize, the equation becomes *(Robelin [1958]; de Naurois [1973]; Thevenet* and *Couvreur [1978]):*

$$\frac{y}{Y} = 1.75\frac{e}{E} - 0.68 \tag{2}$$

where y = grain yield at ETR; Y = grain yield at ETM; other production factors being optimum; e = actual evapotranspiration of maize over the critical period (from apex height 10 cm to dough stage); E = maximum evapotranspiration of maize over this period.

Then, equation (2) means that the frequency of occurrence of water deficit (mm) can be transformed into frequency of economic deficit (in t/ha) *(Cabelguenne [1980]).*
In temperate France, as defined above, E can be considered constant at the order of 450 mm. Further, the average water deficit being 80 mm, e is therefore 370 mm. For a yield of 9 t/ha, the value of y calculated from equation (2) is 6.8 t/ha. Thus the average yield difference between irrigated and non-irrigated crops can be expected to be 2.2 t/ha.

1.2 Economic aspects – profitability of irrigation

A mean yield increase from irrigation of 2 to 2½ t/ha will cover the extra costs (write-off of installation cost and running costs of the equipment) *(IGER-BCMEA [1979]; de Bouvier [1980]; CTGREF [1980]). Thus, in the temperate area, irrigation of maize is just profitable.*

There are three possible ways of improving profitability:

- *Adjustment of quantity of water*: improvement of irrigation efficiency ($\frac{Y-y}{T}$, with 1 m^3 water applied) by improved understanding of actual water application essential *(Moutonnet et al. [1980]; Peyremorte [1983]).*
- *At the crop level*: improvement of the efficiency of water use $\frac{Y}{ETM}$. Here there are possibilities of limiting ETM, for instance by modifying crop morphology *(Morizet et al. [1982]; Robelin [1983]; Innes* and *Blackwell [1983]),* or by the effects of fertilizer treatment – potash in particular – *(Hudson [1958]; Blanchet* and *Studer [1962]; Höfner [1971]).* The results of 10 years work on maize monoculture by *ITCF* in collaboration with *SCPA (Balland* and *Drieu [1983])* illustrate this (Figure 3).

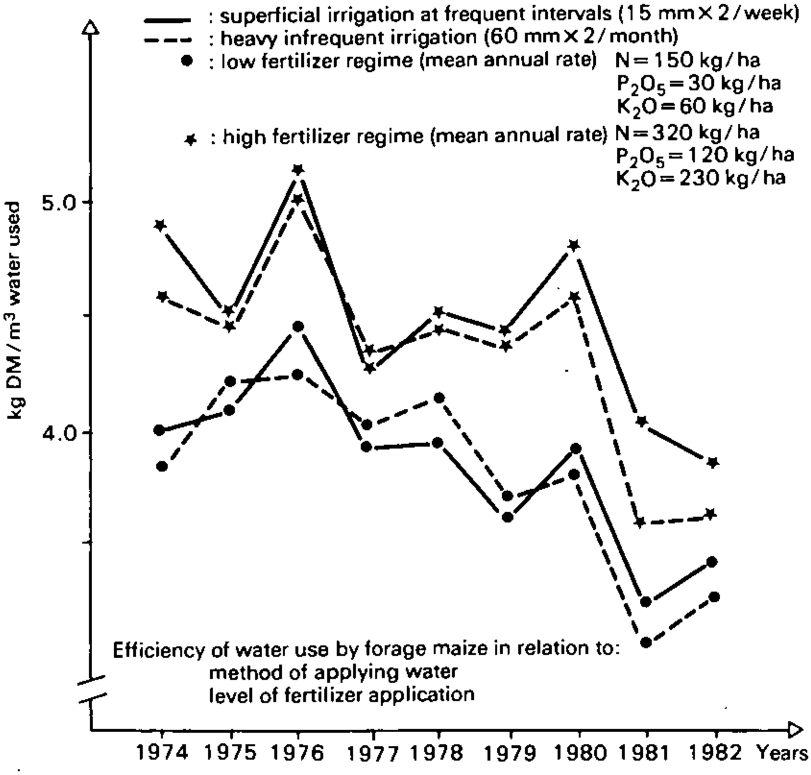

Fig. 3. Efficiency of water use by forage maize.

- *Management:* Elucidation of the best distribution of irrigations between the crops on the farm with the aim of producing an 'irrigation calendar' to assure the best economic return *(Cabelguenne [1982])*.

As regards the irrigation of winter wheat in France there are two problems. The first is relatively simple: what is the optimum rate of N for the irrigated crop. The second is more difficult: what is the optimum for the non-irrigated crop knowing that in some years there is sufficient water for the crop while in others there is drought. Here we have to consider the possibility of excess nitrate polluting the subsoil water *(Hénin [1980])*.

2. Utilization of nitrogen by irrigated and non-irrigated winter wheat

2.1 The problem

Hébert's [1971] method of predicting nitrogen requirement of wheat, as developed by *ITCF (Viaux [1980])* – the balance method – can be summarized in the equation:

$$bY + a = Nf + Ns \qquad (3)$$

where b = N uptake by wheat in kg/100 kg grain yield, Y = target yield in dt (100 kg), a = residual unavailable soil N after harvest, Ns = soil N after winter + mineralization of organic matter + residual effect of previous crop and Nf = requirement for fertilizer N. This relationship is true only in the region of maximum yield in conditions where N supply is the only limiting factor.

When other factors may limit yield (soil structure, disease, etc.) the pattern of response to N is modified (Figure 4). Then higher rates of N fertilizer are needed to achieve the same yield (reduced efficiency of applied N) and equation (3) can be rewritten *(Rémy* and *Viaux [1983])* thus:

$$by = (Nf + Ns)C \qquad (4)$$

where $C = ks \times km \times \ldots$ where ks, km ... coefficients of efficiency ($\leqslant 1$) of N in the presence of limiting factors: structure (s), disease (m), etc.

There is some danger in introducing such coefficients of increasing the risk of pollution should N remaining in the soil after harvest be unduly elevated. Where there is a risk of drought, should the terms of equation (4) for calculating Nf be modified?

2.2 Material and methods

2.2.1 Factors studied

Treatments applied to winter wheat (*cv.* Abo) in factorial combination in a split-plot layout with 3 replications were:

- irrigation at 2 levels, nil and irrigation to ETM by sprinklers (applied when the water balance: rainfall + soil water − k ETP = 0 *(Robelin [1968])* to main plots,

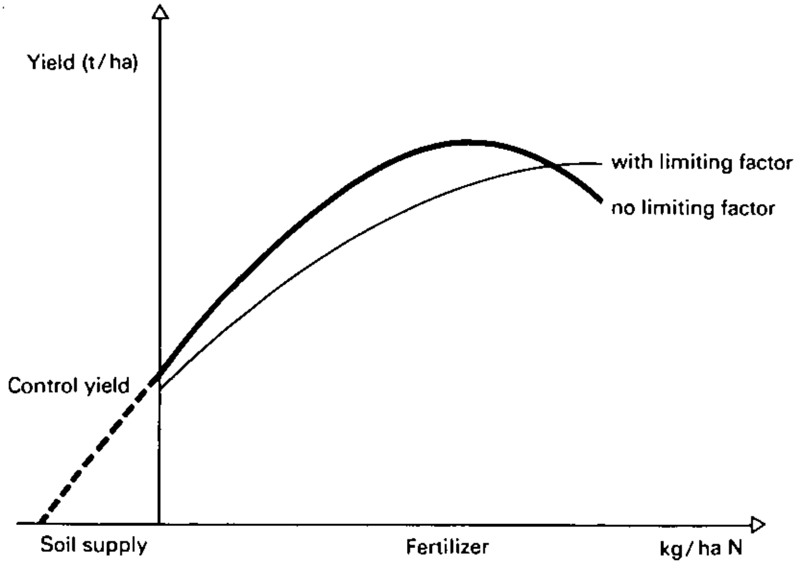

Fig. 4. Theoretical response of wheat to nitrogen with and without limiting factors.

Table 1. Nitrogen treatments (kg/ha/year) to dry and irrigated crops.

	Water Regime	
	Dry	Irrigated
kg N/ha	0	0
	–	$X_I - 80$
	$Xs - 40$	$X_I - 40$
	Xs	X_I
	$Xs + 40$	$X_I + 40$
	$Xs + 80$	$X_I + 80$
	$Xs + 120$	–

Xs = 1982; 100 kg/ha for yield 5.3 t/ha
1983; 160 kg/ha for yield 5.3 t/ha

X_I = 1982; 180 kg/ha for yield 8.0 t/ha
1983; 240 kg/ha for yield 8.0 t/ha

- N fertilizer at 6 rates (Table 1) the basal rates Nd (dry) and Ni (irrigated) being calculated by the balance method (see 2.1).

Other factors which would affect the efficiency of N were uniform (structure, plant population, date of application, disease control).

2.2.2 *Sites*

The experiments, on sandy soils of the Forez plain (6% clay, 60% coarse sand) well provided with organic matter (1.4%) and of good nutrient status (0.175, 0.09 and 0.45 mg/100 g for exch. K_2O, exch. MgO and Dyer P_2O_5 respectively) lasted for 3 years (1981, 1982 and 1983 harvests).

2.2.3 *Measurements*

Yields (harvested area 12.5 m^2) and yield components (three 2 m lengths of row) were recorded for each sub-plot. N content of straw and chaff (Np) and of grain (Ng) and the ratio ($\frac{\text{straw + chaff dry matter}}{\text{grain dry matter}}$ $\frac{P}{G}$) were determined at harvest on 1 m^2 samples, in order to know total N uptake by the whole plant per 100 kg grain yield: Nabs/100 kg = (Np × $\frac{P}{G}$ + Ng) × 1.3 (the factor of 1.3 allows for root N) *(Welbank et al. [1973]; Bordes [1981])*.

2.3 Results

Only the years 1982 and 1983 were dry (Table 2) before shooting in 1982 and post-shooting in 1983. All irrigations in 1981 were followed by rain.

Table 2. Weather and irrigation applied

Month	Decade	Year 1982		Year 1983	
		Rain (mm)	Irrigation (mm)	Rain (mm)	Irrigation (mm)
April	1	0		14	
	2	2	20 + 20	33	
	3	3		93	
May	1	14	30	25	
	2	13	25	119	
	3	0	20 + 25	34	ear emergence
June	1	36	ear emergence	4	
	2	2	20 + 20	4	20 + 25
	3	44		9	30

2.3.1 *N supplied by soil*

Soil N supplied to wheat (Ns) was 66.7 kg/ha (irrigated) and 64.8 kg/ha (dry) in 1982; 88.6 (irrigated) and 92.0 kg/ha (dry) in 1983. To all intents and purposes, thus, the values were the same for both dry and irrigated crops.

2.3.2 *Yield and yield components*

In both 1982 and 1983 there was significant positive interaction between irrigation and N supply (Ns + Nf). The interaction was more marked in 1982 when drought occurred before shooting (Figure 5) than in 1983 with post-shooting drought (Figure 6).

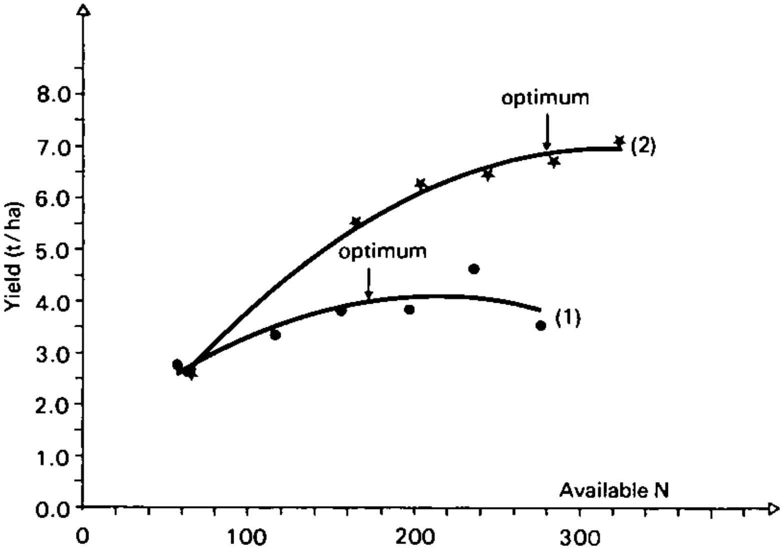

Fig. 5. Yield and available nitrogen
(1) with pre-shooting drought: $y = 12.7 + 0.269x - 0.00063x^2$ $r2 = 0.76$
(2) water not limiting: $y = 1.63 + 0.43x - 0.00068x^2$ $r2 = 0.99$

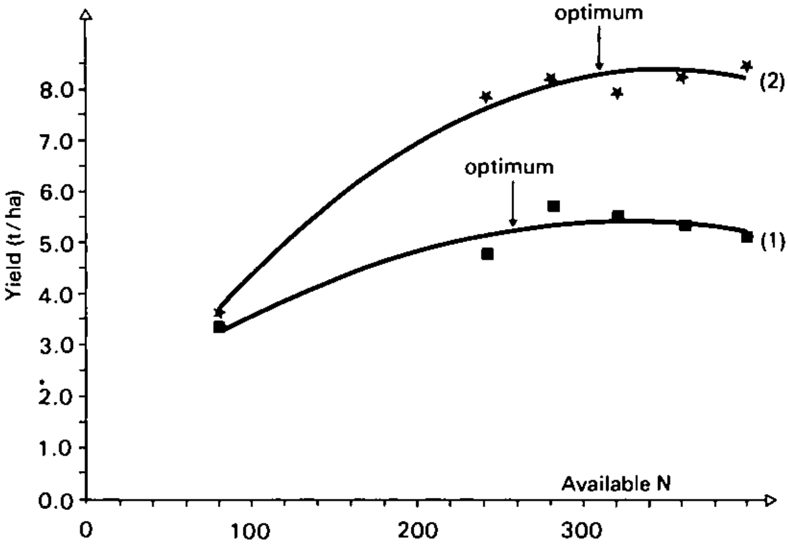

Fig. 6. Yield and available nitrogen
(1) with post-shooting drought: $y = 15.8 + 0.23x - 0.0035x^2$ $r2 = 0.93$
(2) water not limiting: $y = 5.07 + 0.448x - 0.00064x^2$ $r2 = 0.98$

Table 3. Yield components

Water regime	Year 1982										Year 1983											
	Dry					Irrigated					Dry						Irrigated					
Components \ Nrate	0	100	140	180	220	0	100	140	180	220	0	160	200	240	280	320	0	160	200	240	280	320
Plant population (pl/m^2)	290	290	290	290	290	290	290	290	290	290	333	333	333	333	333	333	333	333	333	333	333	333
Ears/m^2	331	442	488	481	463	310	509	565	510	637	354	657	677	648	638	731	351	677	640	689	746	713
Grain no./m^2 × 1000	6.5	8.6	8.6	10.8	7.9	6.3	12.8	13.6	12.6	15.6	8.7	17.0	17.8	16.7	15.1	18.9	9.2	17.9	17.8	17.4	18.8	19.0
1000 grain wt./(g) (16% moisture)	47.5	47.5	48.5	49.4	47.4	43.3	43.5	45.5	47.3	45.0	41.5	33.5	33.2	35.3	29.4	28.0	43.6	46.8	47.0	47.3	45.5	47.7

Table 3 shows significant effects on ears/m² and grain number/m² in 1982. There was positive interaction (N × I) in the case of the latter. Only 1000 grain weight was affected by both treatments, again with positive interaction, in 1983 (Table 3). These results confirm those of *Couvreur* and *Thevenet [1978], Musick* and *Dusek [1980], Christensen* and *Killhorn [1981], Grignac [1981], Decau* and *Pujol [1982]* and *Johnson* and *Kanemasu [1982]* so far as concerns the effect of water deficit and the greater susceptibility of winter wheat to preshooting drought.

The optimum economic yield (calculated on the basis of equivalence of 40 kg/ha N and 100 kg grain) was attained with:

- 279 kg/ha total N supply (of which 212 kg/ha from fertilizer) for a yield of 6.57 t/ha in 1982 with irrigation
- 174 kg/ha total N (113 kg/ha from fertilizer) for a yield of 4.04 t/ha by the dry crop in 1982.
- 311 kg/ha N of which 224 kg from fertilizer for a yield of 8.25 t/ha by irrigated wheat in 1983,
- 257 kg/ha N of which 165 kg from fertilizer for a yield of 5.18 t/ha by the dry crop in 1983.

2.3.3 *N uptake and apparent coefficient of utilization of fertilizer N*

In every case (no water deficit, drought pre- or post-shooting) there was a linear relationship between N applied and N uptake ($Nabs = N_o + \alpha N_i$)* $\alpha = \frac{Nabs - No}{Ni}$ is the apparent coefficient of utilization of fertilizer N. Its mean value in the absence of drought is of the order of 0.8 (0.767 in 1981, 0.749 in 1982 and 0.880 in 1983). Its value is little affected by post-shooting drought (0.84) but much reduced by pre-shooting drought; to 0.36 (Figure 7).

2.3.4 *Efficiency (productivity) of applied N and efficiency of N uptake*

The mean efficiency coefficients for applied N recorded in irrigated (0.43 and 0.45) and dry (0.23 and 0.27) conditions compare with values 0.33 (1/3) and 0.40 (1/2.5) calculated from the N requirements per 100 kg grain according to *Coïc [1956]* (2.5 kg/100 kg) and *Hébert [1969]* (3 kg/100 kg).

The efficiency of applied nitrogen – or productivity – $\frac{Yi - Yo}{Ni}$ (where Yi = yield at Ni and Yo = yield where no N is applied) evidently decreases as Ni increases and, at a given level of N input, with increasing dryness. This decrease seems to be greater and more rapid in pre-shooting drought (Figure 8).

The efficiency of N uptake ($\frac{Yi}{Nabs}$ in 100 kg grain per kg N taken up) is identical under irrigation and with pre-shooting drought. In contrast it is much reduced by post-shooting drought (Figure 9).

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* Nabs = N uptake, Ni = N input

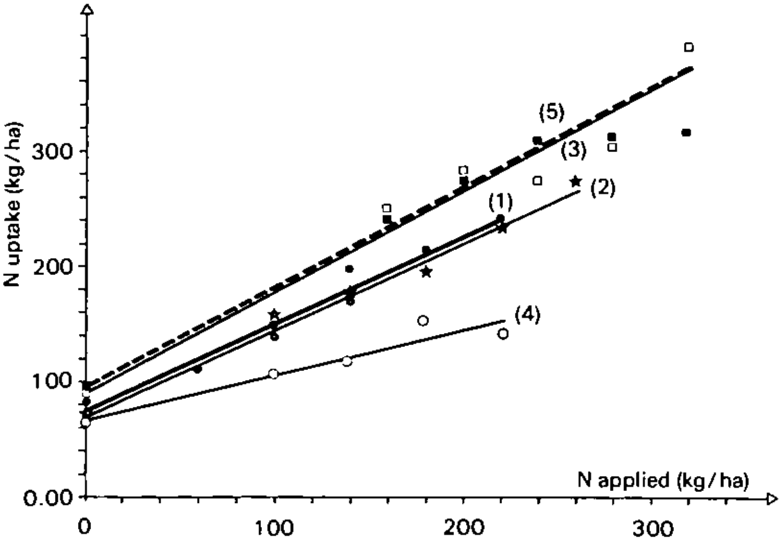

Fig. 7. Nitrogen uptake related to nitrogen fertilizer rate

(1, 2, 3) water not limiting:	y = 74.0 + 0.77x	r2 = 0.97	year 1981 (1)
	y = 66.3 + 0.75x	r2 = 0.99	year 1982 (2)
	y = 88.9 + 0.88x	r2 = 0.94	year 1983 (3)
(4) pre-shooting drought:	y = 67.7 + 0.36x	r2 = 0.90	
(5) post-shooting drought:	y = 94.1 + 0.84x	r2 = 0.93	

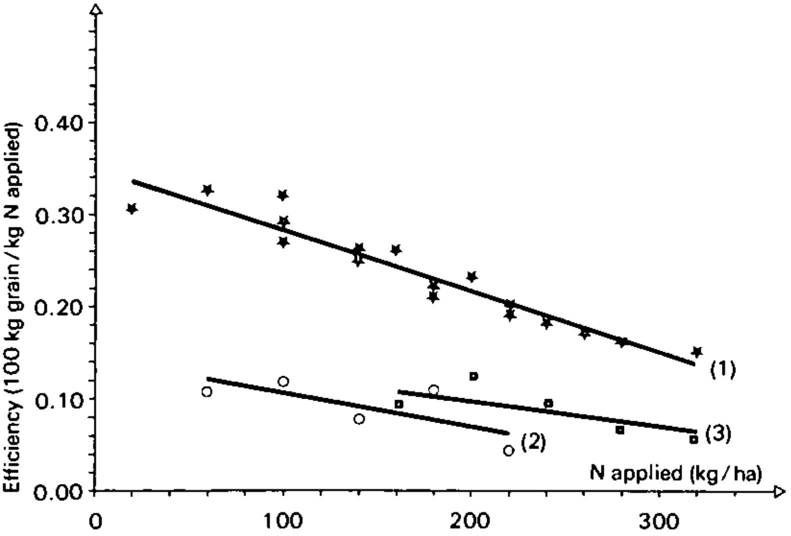

Fig. 8. Efficiency of applied N

(1) water not limiting:	y = 0.35 − 0.00066x	r2 = 0.90
(2) pre-shooting drought:	y = 0.145 − 0.00037x	r2 = 0.54
(3) post-shooting drought:	y = 0.152 − 0.00027x	r2 = 0.58

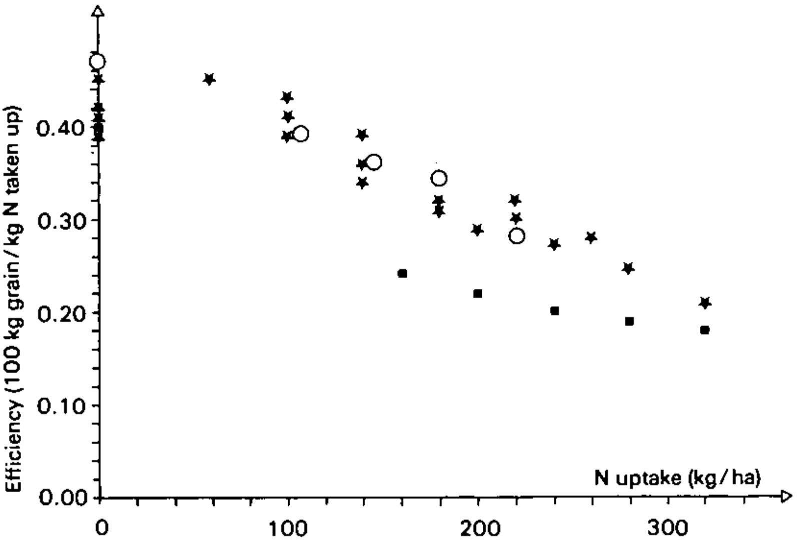

Fig. 9. Efficiency of nitrogen taken up
✶ water not limiting; ○ pre-shooting drought; ■ post-shooting drought.

2.4 Discussion

The results given assume that there is no interaction between soil N supply (Ns) and rate of N fertilizer applied. This hypothesis, discussed by *Hébert [1973]* among others, seems to have been confirmed by work with N-15 between 1978 and 1982 *(Recous [1983])*.

The linear relationship between N uptake and N applied at normal agricultural rates agrees with findings of *de Witt [1979]* and *Recous [1983]*. The apparent utilization coefficient for fertilizer N is therefore constant over the whole of the response curve. The N residue left in the soil is therefore proportional to the supply.

- The decrease in N efficiency under drought conditions and found in equations relating N supply to yield has two different origins:

● In the case of post-shooting drought, the apparent fertilizer efficiency is scarcely affected. This is in accord with the pattern of N uptake by wheat, which is practically completed by flowering under French conditions *(Rémy* and *Viaux [1983])*. On the other hand, the efficiency of utilization of N uptake is strongly reduced (accumulation of N in the straw). Overall, the quantity of N taken up by the crop is not changed so that the residual N left in the soil is the same as that found after a crop adequately supplied with water. There is therefore no increase in the risk of pollution in the short term.

● When there is drought pre-shooting the efficiency of utilization of fertilizer N is much reduced (in 1982 less than half the N applied was taken up) but the efficiency of utilization of the N taken up is not changed. Thus residual N in the soil is much increased.

The need to take account of these two causes of reduced efficiency is in accord with the observations of *Hénin* and *Sebillotte [1981]* on the implications of using a parabola to represent the response to increasing rates of N. The authors show that the risk of pollution is not necessarily reduced by lowering N fertilizer rate.

- So far as concerns winter wheat, N fertilization should not be affected by the occurence of post-shooting drought since N s and α are the same whether or not there is water stress. The target yield should be the same in either case, that which it is hoped to achieve in the absence of water stress.

3. Conclusion

Post-shooting of winter wheat water deficit is likely to occur in France quite often, say once in two or three years. The results discussed above show that the recommended rate of fertilizer N should remain the same whether such drought occurs or not; the risk of pollution is not increased because the coefficient of utilization is the same in either case. The forecast should be based on the assumption that there will be no water stress (in our situation 210 kg/ha N for a target yield of 8 t/ha).

In 1983 in our experiment, the optimum rate (calculated for 8 t/ha yield) was 225 kg/ha N and this produced a yield of 8.25 t/ha under irrigation and of 4.98 t/ha with post-shooting drought, with, in the latter case a reduction in yield from the optimum of 0.2 t/ha by application of 60 kg/ha N more. N uptake was the same for both crops (290 kg/ha). If, on the other hand, the N rate had been calculated for the post-shooting drought, the rate recommended would have been 165 kg/ha N which would have given a yield of 5.18 t/ha. But, if rainfall had been sufficient, this rate would have produced a yield of only 6.16 t/ha, thus forfeiting almost 2 t/ha of the yield achieved with the higher rate of N.

Where there is a risk of early drought, on the contrary, the N recommendation should be based on a lower target yield which would be set by the likely magnitude of the pre-shooting water deficit using the yield equation for winter wheat. In this case the situation is analogous to that with the maize crop, as discussed in the introduction (uncertain profitability of irrigation). Further work on this aspect is now in progress.

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Fertilizer Needs in Fruit Production

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Summary

The paper sketches the background and history of fruit growing in the South Tyrol. Traditional mixed farming has been replaced by a system in which the grass cover is frequently cut and used as a mulch, a system which represents a virtually closed nutrient cycle. The bases for fertilizer recommendations under this system are discussed and long-term experimental work to determine nutrient requirements of orchards is described. Mulched orchards show a moderate N requirement and application of a quantity sufficient to balance removal in harvested fruit plus an allowance for leaching loss is all that is required – the average requirement is 50–70 kg/ha N. Sufficient K should be applied to maintain soil K status at a level sufficient to ensure the production of firm fruit of good keeping quality. There is no advantage in applying more than these indicated amounts and yields tend to decline with over generous fertilizer treatment. The importance of correct ratio between the nutrients in the fertilizer is emphasized.

1. Historical

Some 25 years ago fruit growing in the Southern Tyrol and in many other parts was combined with livestock husbandry. Clearly, with this dual land utilization, large dressings of fertilizers and manure were needed. At a yield of 7 t/ha dry matter, grass takes up about 110 kg N, 55 kg P, 210 kg K_2O, 30 kg MgO and 90 kg CaO. The soils were generally of low fertility so that, depending on the type of fruit, the following rates of fertilizers per year were recommended:
N: 80–200 kg/ha
P_2O_5: 100 kg/ha
K_2O: 150–250 kg/ha
MgO: 50–80 kg/ha
Borax: 20 kg/ha

Since that time, much has changed. Livestock husbandry has been abandoned, the grass is cut 5–7 times in the year and left to lie as a mulch.

Strips through the orchards are kept free of weeds with herbicides. Also, nowadays leaves and prunings remain on the ground to add to soil organic matter and to be mineralized. So, we now have an almost completely closed cycle, a fact which has not, perhaps, been fully recognized. In practice, generous fertilizer use mainly in the form of compound fertilizer is still the general rule. This policy has not been without result: physiological disturbances like bitter pit, internal browning and poor storage life become ever more frequent. Certainly other practices have contributed to this situation (plant protection, irrigation). Nutrients are leached so that there is a risk of pollution of the groundwater.

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2. Nutrient requirement

Fundamental in determining nutrient requirement are the quantities of nutrients taken up by the trees. *Batjer et al. [1]* have arrived at the figures in Table 1 for an orchard of Red Delicious, yielding 44.8 t/ha based on detailed sampling and analysis. *Gruppe [2]* arrived at a similar conclusion. This research shows that:

- the total requirement of pomaceous-fruit is not high;
- the amounts of nutrient removed in fruit are quite small; however, it must be admitted that a thorough search of the literature reveals great variation in respect of nutrient content of fruit;
- the requirement for individual nutrients is very uneven; P requirement is small (less than was once thought), in contrast the potassium requirement is high;
- the nitrogen requirement of fruit trees is much less than that of arable crops.

The modern system of fruit growing in which grass mulch, leaves and prunings are left *in situ* imposes a lesser nutrient demand than the former system, and one is faced with the question as to whether it may be sufficient only to use fertilizers to replace nutrients removed in the fruit. In this connection, several points must be emphasized.

Table 1. Nutrient requirements of Red Delicious (kg/ha/year) *(Batjer et al. [1952])*

	N	P_2O_5	K_2O	CaO	MgO
A. Fruit	20.8	6.3	56.6	4.4	2.2
B. Vegetative (roots, trunk, branches)	14.8	4.2	14.3	45.8	2.3
	35.6	10.5	70.9	50.2	4.5
C. Leaves	47.6	3.3	52.4	85.8	18.1
D. Flowers, young fruit	11.9	1.7	14.8	3.7	1.1
E. Prunings	11.8	2.3	3.6	28.0	1.7
	71.3	7.3	70.8	117.5	20.9

2.1 Nutrient losses

One of the great unknowns in arriving at an optimum fertilizer recommendation is the amount of nutrient lost by leaching and fixation. It is well known that nitrogen is very mobile and that, therefore, losses of this nutrient will be high. *Timmermann [3]* reports that, depending on site, rate and form of N fertilizer, losses may amount to between 10 and 85 kg/ha N per year. *Van der Boom [4]* applied a standard rate of N on various soils, following this with 100 mm irrigation and investigated the depth to which N was leached (Table 2). It is seen that the depth to which N is moved reduces as organic matter content and, particularly, clay content of the soil increase. Leaching of N and of other nutrients like potassium, calcium, magnesium and trace-elements (boron) is reduced by a grass cover.

Feger [5] tried to quantify this. He compared a repeatedly mown grass sward with uncropped cultivated soil receiving varying rates of fertilizer. Under grass, N losses varied between 7.2 and 18.3 kg/ha/year while under bare soil they ranged from

125.4 to 180.8 kg/ha. The highest losses were from the higher rates of fertilizer (up to 200 kg/ha/year N).

N losses also occur in gaseous form as N_2 and N_2O due to bacterial denitrification, especially in poorly aerated soils *[6]*.

Potassium can be leached and it is also fixed into non-available form in soils of high clay content. Liberation of this nutrient to plants depends on saturation of the clay complex.

Phosphorus is strongly held by soil and is not mobile so that there is virtually no risk of leaching. However there are losses through the formation of insoluble compounds – aluminium and iron phosphates in acid soils, insoluble Ca phosphates in alkaline soils but these effects can be ameliorated by such measures as liming, or application of organic materials. Phosphoric acid in soil is subject to an 'ageing' process with the result that 3 years after application only about 50% remains plant-available (7). Calcium and magnesium are freely soluble in the soil water and are easily leached as recent experiments at our Institute have shown.

Table 2. N transport in soil following application of 100 mm water *(Van der Boom [1967])*

Soil type	N transport
Coarse sand	90 cm soil depth
Fine sand	45 cm soil depth
Sandy loam (60% clay)	30 cm soil depth
Clay (40–60% clay)	20 cm soil depth
Peaty soil	12 cm soil depth

2.2 Optimum rates

In the light of the above, it is clearly insufficient to apply only enough fertilizer to replace nutrients removed in harvested fruit. Account must be taken of the losses if soil fertility is to be preserved. As the losses are difficult to quantify we advise growers in practice on medium textured soils of average productivity to apply 30 to 50% over and above the amounts of nutrients removed in fruit, trunk and root growth.

2.3 Soil analysis

Fertilizer recommendations must be varied according to nutrient supply in the soil. In our soils laboratory we use the *VDLUFA* (Fed. Rep. Germany) methods: CAL extraction for P_2O_5 and K_2O, $CaCl_2$ extract for MgO (after *Schachtschabel)*, hot water extract for boron *(Berger-Truog)*. Soils are classified in 5 groups, class C being considered the optimum, class A signifying deficiency and class E over-supply. The classes are described and the corresponding recommendations given in Table 3. The values are adjusted for organic matter content and soil pH. The latest critical values published by *VDLUFA [8]* are somewhat lower than those given in Table 3. The report on soil analysis also includes pH, organic matter content, sampling method and, on request, trace element content.

With a complete soil analysis every 3 or 4 years it should be possible to avoid risk of

Table 3. Nutrient content classification of soils and fertilizer recommendations (medium textured soil, pH 6.5)

Soil class	P_2O_5		K_2O		MgO		Boron	
	mg/100 g in soil	Fertilization kg/ha	mg/100 g in soil	Fertilization kg/ha	mg/100 g in soil	Fertilization kg/ha	ppm in soil	kg Borax/ha
A	0– 7	70–100	0– 8	160–200	0– 6	55–70	0.60–0.30	15–30
B	8–16	40– 70	9–17	120–160	7–14	40–55	0.31–0.70	10–15
C	17–25	30– 40	18–22	80–120	15–20	25–40	0.71–1.00	5–10
D	26–38	0–40*	23–33	40– 80	21–26	0–25*	1.01–1.25	5–10*
E	39–60	–	34–70	–	27–34	–	1.26–1.50	–

* Every other year

either deficiency or nutrient excess. The recommendations aim to maintain high yields of good quality and to minimize nutrient losses and pollution of the groundwater.

2.4 Nitrogen

Forecasting of N requirement is a special problem. It is possible to determine soil content of both mineral and organic N but these values are not a great help in making recommendations. The N values change constantly with soil temperature, aeration, water content and microbiological activity. So far as wheat is concerned the problem is claimed to have been solved by the N-min method *[9]* but in fruit growing it has not yet been fully investigated. Even so we already have some guide: if in spring the soil to 90 cm depth contains 70–100 kg soluble N the requirement for N fertilizer is generally nil *[10, 11]*. For the most part, however, it is usual to use the trees as an indicator and the N dressing is regulated according to:

- growth and leaf colour,
- yield per hectare,
- fruit quality and storage properties.

Such observation guides the grower as to the correctness of his N regime.
Certain other plants are useful indicators, *e.g.* daisy *(Bellis perennis)* oxe-eye daisy *(Chrysanthemum segetum* and *leucanthemum)* and legumes indicating N shortage and chervil *(Anthriscus sylvestris)*, hogweed *(Heracleum sphondylium)* and nettle *(Urtica* spp.) abundance of N.
We also have to bear in mind:

- soil organic matter content from the breakdown of which, according to situation, atmospheric conditions, cultivation system, 20–300 kg/ha N may be mineralized in the course of the year.
- management. Intensive mowing and mulching as generally practised today (except in dry areas!) supplies via mineralization significant quantities of N. Table 4, after *Weller [12]* summarizes data for N supply resulting from different management systems.

True much nitrogen is taken up in the short term by the grasses and weeds but the figures show that in modern systems of fruit growing some caution must be exercised with regard to nitrogen. A good fruit harvest removes annually only 30–40 kg/ha N and an average N dressing of 50–70 kg/ha per year should be sufficient for a grassed orchard with irrigation, good fruit yield, average growth and soil organic

Table 4. Approximate NO_3 supply in orchard soils in the open with different cultural treatments (kg/ha/year) *(Weller [1977])*

Soil depth	Bare soil	Straw mulch	Mown grass mulch	Grass cut and carried
0– 5 cm	70–100	50– 70	160–170	110–130
5–15 cm	90–110	50– 70	130–150	120–170
0–15 cm	160–210	100–140	290–320	230–300

matter content 3–4%. High rates (over 150 kg/ha) are needed only when building up a new grass cover. Of course such average recommendations may need upward or downward revision in the light of tree vigour, soil type, rainfall, variety, etc. In practice there are many examples where orchards have been maintained for years without applying any N fertilizer.

In the Southern Tyrol the rootstocks differ little in their N requirements. *Ohm* and *Lüdders [13]* found in their recent work that trees on M7 take up more water and minerals than trees on M9, but Ca uptake per m shoot was higher on M9.

There are greater differences in N requirement between varieties: Morgenduft and Winesap for example require little, Red Delicious (Standard), Granny Smith (at least when young), Gloster and Jonagold have a medium requirement while Golden Delicious, and especially pears, need more N.

2.5 Fertilizer timing

Phosphorus, potassium, magnesium and boron can be applied to medium and heavy soils in a single application in autumn or early spring. Because of its high solubility and mobility, nitrogen, especially when high rates are needed, should be applied in split dressings.

In a normal year it is sensible to give a first N dressing of 20–30 kg/ha immediately after fruit picking (protein synthesis). The roots continue to take up nutrients into late autumn, thus building up useful reserves in the tree which will favour early spring development and favour flowering and also promote frost hardiness. If the harvest is late or if it is very dry we advise urea sprays (3–5%) up to shortly before leaf-fall. N should be applied again in early spring. According to *Lüdders* and *Bünemann [14]* flower initiation is good if there is sufficient N in the soil from the end of July to September or if, in N shortage, shoot growth ceases early. For this reason in the South Tyrol a final small N dressing (nitrate) is given at the latest at the end of May. August growth should not be favoured by this.

3. Experimental

A fertilizer experiment was carried out at Laimburg in 1970 with Golden Delicious, Jonathan and Morgenduft on MM106 and Gravensteiner on M9. This was to investigate the effects of increasing N (60, 120, 180, 250 kg/ha N) and potassium (150 and 250 kg/ha K_2O) on tree growth, fruit yield, fruit quality and storability and also on nutrient status of the soil. The experiment included an unmanured control. Each plot consisted of 10 trees of each of the 4 varieties (16 for Gravensteiner) separated from neighbouring plots by a single guard-row. In the alleys the mown grass was mulched and strips in the rows were kept weed-free by herbicides. Fertilizer treatments commenced in spring 1972. After 12 years the following conclusions can be drawn.

3.1 Yield

Nitrogen increased yield little in all varieties. Between unmanured and 60 kg/ha N the increase, according to variety was about 3.5 to 12.5%. Further N increased the

yield of Morgenduft and Golden Delicious only little, while, in the case of Gravensteiner and Jonathan yield was reduced (Figures 1–4).
This indicates that in the modern orchard, as discussed above, so much N is supplied by the breakdown of grass mulch and organic matter which is replenished annually by prunings and leaf-fall, that usually little extra N is needed.
Applying more than 150 kg/ha K_2O failed to increase the yield of any variety (Figures 1–4).

3.2 Soil organic matter content

Organic matter content of the soil was scarcely changed over the 12 years. There was even a slight decline in the subsoil (Figures 5 and 6). The higher N dressings did not increase organic matter content (where grass growth was increased, mineralization also increased).
It was found in a long-term cultivation experiment at Laimburg that if the grass were cut less frequently organic matter content of the soil was increased (older, more mature grass), but, against this there was a disadvantage in that the grass competed with the trees for water. It can be concluded that with good grass management there will be no decline in soil organic matter.
The grass should be mown frequently and kept short in spring and early summer and should be mown less often in late summer and autumn. In this way the build up of soil N late in the year with uncontrolled mineralization is avoided (poor keeping quality) while the grass makes a greater contribution to soil organic matter.

3.3 Effect on soil potassium

The higher rate (250 kg/ha) has, after 12 years, considerably increased soil K content up to a depth of 1 m (oversupply). The water table varied between 0.8 and 1.1 m and it can be assumed that appreciable amounts of potassium have been removed in the groundwater. For this reason it is important to avoid applying too much potash at least on the lighter soils (loamy sands, some with high silt content). 150 kg/ha K_2O is quite sufficient to maintain potassium status to 40 cm depth at optimum.

3.4 Fruit quality

Storage experiments with the test varieties Jonathan and Gravensteiner showed that the risk of physiological disorder (bitter pit and internal browning) increased as fertilizer rate increased. High nitrogen did not necessarily cause poor storability, especially when it did not cause excessive vegetative growth. This was confirmed for Jonathan in several years. However the data for Gravensteiner in Table 5 show that any tendency to over-fertilization is dangerous. Bitter pit increased from 10 to 30% as fertilizer rates were increased.

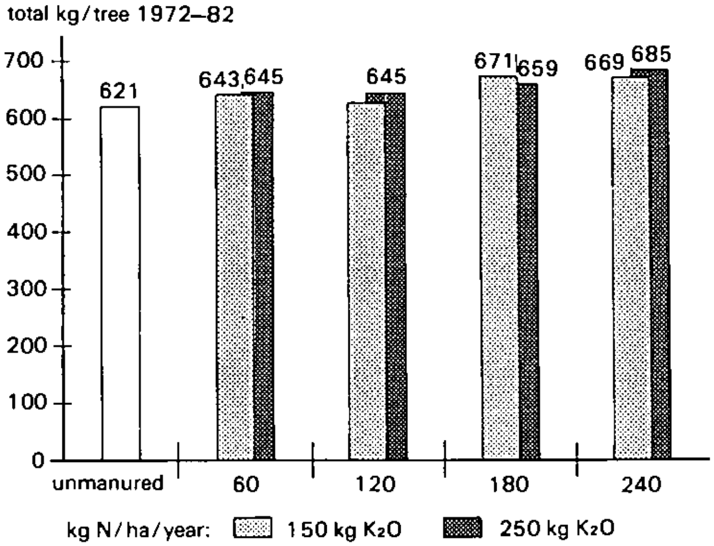

Fig. 1. Fertilizer experiment at Laimburg. Yield of Golden Delicious on MM106.

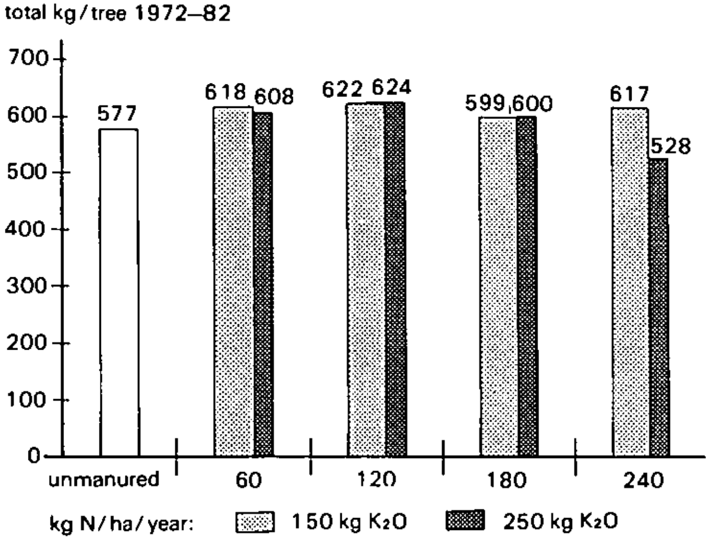

Fig. 2. Fertilizer experiment at Laimburg. Yield of Jonathan on MM106.

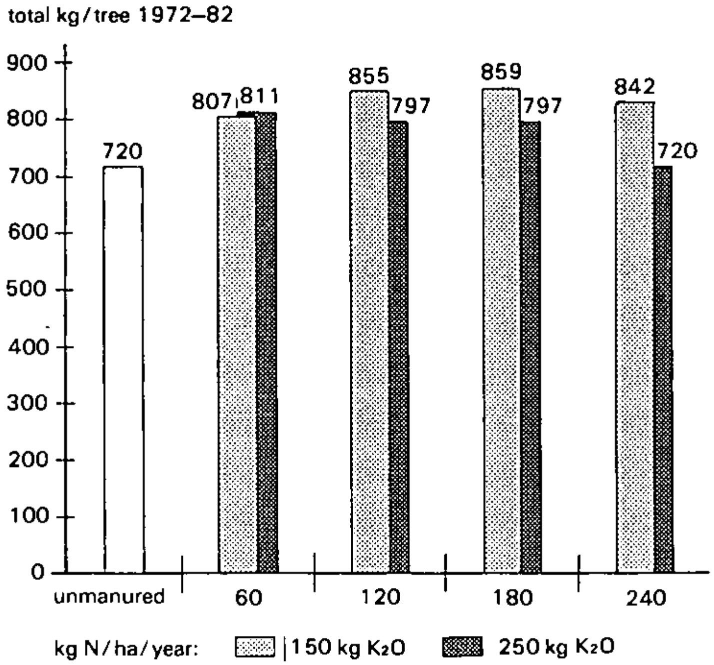

Fig. 3. Fertilizer experiment at Laimburg. Yield of Morgenduft on MM106.

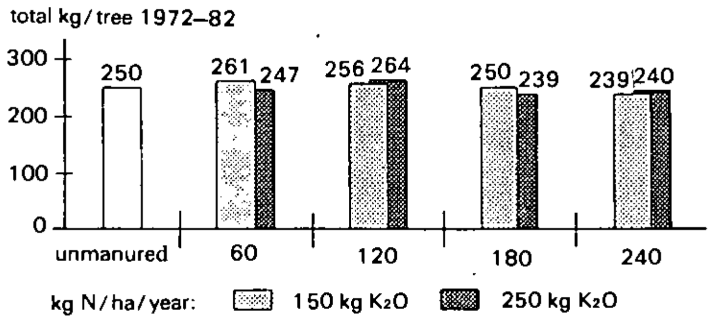

Fig. 4. Fertilizer experiment at Laimburg. Yield of Gravensteiner on M9.

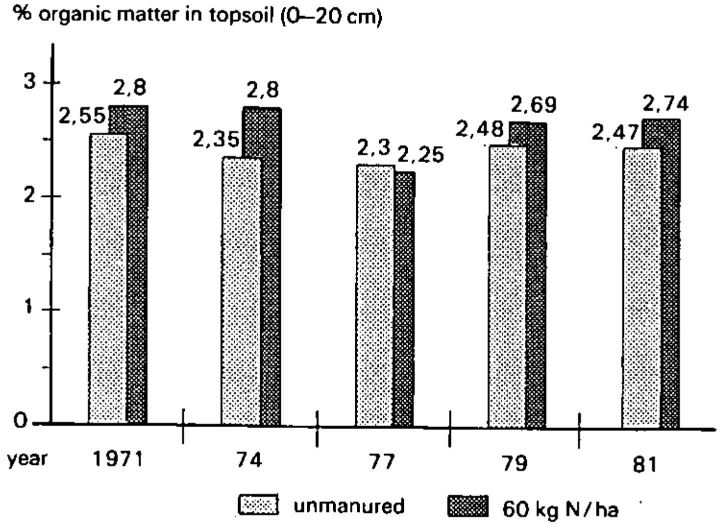

Fig. 5. Fertilizer experiment at Laimburg.

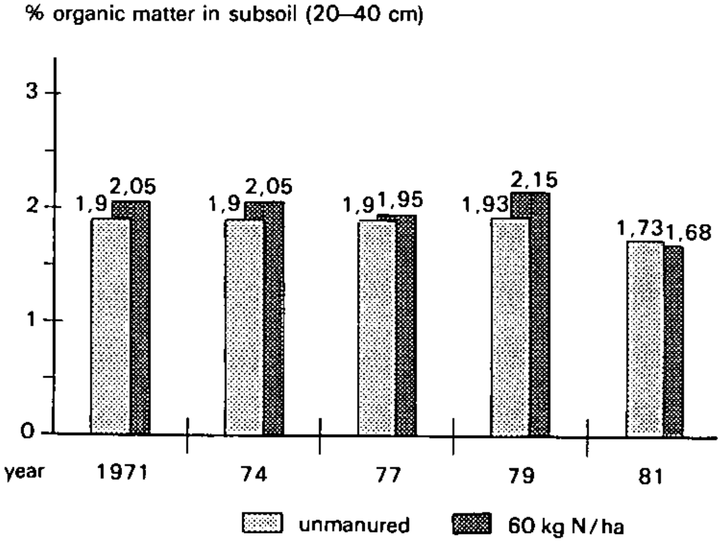

Fig. 6. Fertilizer experiment at Laimburg.

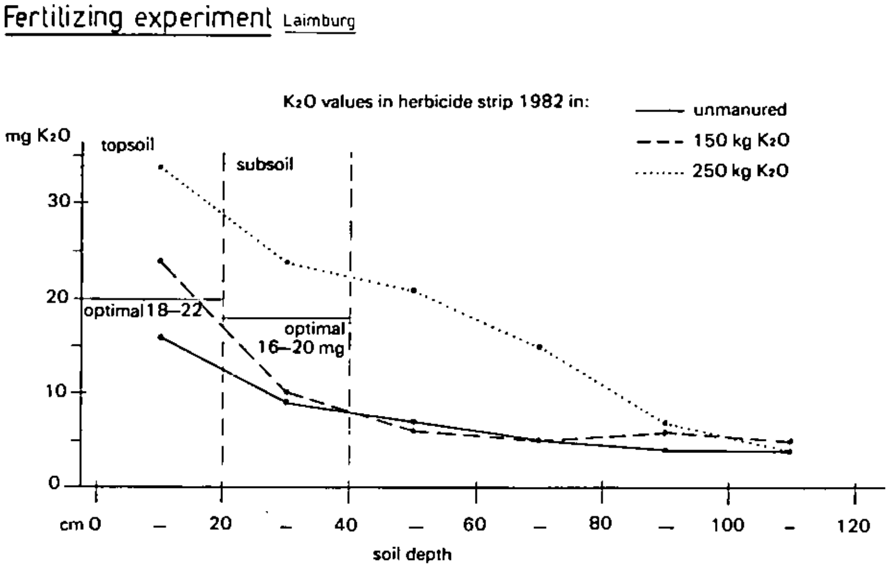

Fig. 7. Fertilizer experiment at Laimburg.

Table 5. Effect of high fertilizer rates on the incidence of bitter pit in Gravensteiner on M9. Laimburg 1982. Picked 2.8.1982.; measurements 9.11.82.

kg N/ha/year	% bitter pit		
	150 kg	K₂O	250 kg
60	10		14
120	15		20
180	21		23
240	29		30
unmanured		10	

4. Conclusion

This experiment confirms the findings of other investigations and practical experience. To summarize:

- In regularly mulched orchards it is only necessary to apply sufficient N to replace that removed in the fruit, but some allowance should be made for losses according to soil conditions, rainfall and soil management systems. Generally speaking the annual requirement is 50–70 kg/ha N.
- Concerning potassium, it is known that an adequate potassium supply is needed for firm fruit but applying larger quantities does not increase yield.
- In the long term, mulching with grass is a sure prevention of decline in soil organic matter content.

- For good yields of good quality, good keeping fruit the correct nutrient ratio of fertilizers is of greater importance than generous usage.

Recent advisory recommendations are to be taken only as guide-lines for apples and pears and may need to be adjusted to suit local conditions.

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Nutrient Needs in Wine Production

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Summary

Research by the author leads to the conclusion that determination of the nutrient requirements of the vine upon which to base fertilizer recommendations calls for the simultaneous use of several methods as concluded by the 5th International Colloquium on the Control of the Nutrition of Cultivated Plants held at Castelfranco Veneto in 1980. The nutrition maps represent a theoretical model which takes into consideration the many (soil-plant) factors involved.
A second conclusion is that there is a need for the greater use of data processing in this area. The massive accumulation of data should make possible refinements in analytical methods, better interpretation and a more rational approach to practical recommendations which can be realized by modern methods of data processing. The ultimate aim is to establish models for production functions to result in economical recommendations best suited to the physiological needs of the vine.

Introduction

While empirical fertilizer recommendations are fairly uniform, research in several countries shows the nutrient requirements of vines to be very variable. There are many factors which cause this variation and they have by no means been fully investigated. We shall review some of them briefly with reference to the vine growing ecosystem (cultivar-rootstock, climate, soil, cultivation technique).
The *genetic aspect* of the problem is not always given sufficient attention for it is known that different cultivar-rootstock combinations differ greatly in their nutrient requirements. Vine cultivars differ in vigour and productivity but it is only in some countries that there is any differentiation of fertilization in this respect; obviously, consumption of nutrients is correlated with grape production and with vegetative growth. This is well demonstrated by the difference between wine grapes and table grapes. It is possible, now, using foliar analysis to classify vines in accordance with their requirements for potassium, magnesium, iron, boron, zinc, etc. are more prone to exhibit deficiency symptoms than others.
The *rootstock* is another biological factor giving rise to wide variation in nutrient requirements; its selective capacity vis-a-vis the nutrient elements has been amply demonstrated. Some rootstocks are particularly sensitive to shortage of K, Mg, Fe, B, Zn, etc. *(Fregoni [1980]).* Nutrient uptake is often conditioned by resistance to drought or excessive humidity and to soil compaction. Rootstock vigour is a determinant factor in fruit production and vegetative growth. Rootstock-cultivar combinations may behave in an unpredictable manner and their behaviour is conditioned by soil-climate relationships.

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Climate, with variation in available light, temperature and precipitation largely determines nutrient need as the basic physiological processes (photosynthesis, transpiration, respiration) determine growth and productivity and are controlled by the climate. High illumination may, in part, make up for low nutrient supply while temperature, including that of the soil, and precipitation are more important than the actual level of nutrients in the soil.

The influence of the *soil* has been much investigated. Geological origin, structure, physico-chemical composition and microbiological activity affect growth and production and, in turn, nutrient requirements. Wine quality is higher in soils with certain geological origins, with a loose, pebbly structure easily penetrated by roots low in nitrogen and without abundant water supply. Soils which analysis shows to be high in nutrients are, provided there is sufficient root room, preferable to clayey, compact, fertile soils. It is better to supply nutrients via fertilizer at the appropriate rate and correctly timed on a poor soil than to grow on soil which supplies abundant nutrients and water throughout the year. On poor, loose soils the vine ceases active growth shortly before the colour turns while on deep, fertile soils vegetative growth tends to continue even while the fruit is maturing.

Many *cultural practices* modify nutrient needs: cultivation, weeding, cover-crop weed control, etc. Among the most important are planting density, plant buds number, and training method which affect vegetative growth and fruiting *(Fregoni [1980])*. In closely planted vines with few buds per plant and trained low, nutrient consumption per hectare may be only a quarter to a third of that of widely spaced plants with many buds per plant and high extended training. In the former case nutrients are used predominantly in grape production while, in the latter, vegetative (leaf) growth is favoured.

Irrigation has a large effect, increasing the uptake of nitrogen and potassium while reducing that of calcium and, especially, magnesium *(Fregoni [Ibid])*. This may create nutrient imbalance and related physiological disorders (*e.g.* desiccation of the rachis). On the whole, irrigation tends to increase both vegetative growth and grape production and to increase nutrient requirements.

Methods for determining the nutrient requirements of grapes

Much fundamental work has been done and there is continuous development in this field. The aim of such work is to define the physiological roles of the various nutrients with a view to using the results in practical advice. There are, of course, difficulties in applying fundamental research findings to practical field conditions associated with interference of numerous and uncontrollable soil and climatic factors. The various methods which are used include: analysis of representative and physiologically important organs or tissues, the use of radio-isotopes, hydroponic or pot culture in the greenhouse, the culture of buds and tissues on artificial media, enzyme and bioelectric diagnosis, growth under controlled conditions (photosynthesis, respiration, transpiration) in the greenhouse with varying fertilizer treatment, etc. Such fundamental work is important but, when it comes to defining fertilizer treatment, it is still necessary to resort to the classical methods (soil and leaf analysis, etc.).

Twenty year's experience by the author has made it clear that these traditional methods have both advantages and disadvantages and suggested that a more general approach might be preferable. Thus, and for other more strictly scientific reasons, arose the concept of 'nutrition maps' which involve thorough survey of a vine growing area, divided into subzones with homogenous soil (calcareous, clay, etc.) and growing conditions (cultivars, rootstocks, training method, dry or well watered). Random sampling of vineyards is carried out, the number sampled being proportional to the extent of the zone or sub-zone and the samples taken being: one soil sample for chemical and mechanical analysis and two leaf samples. The results of analysis of these samples is sufficient to characterize the soil and to indicate the availability of nutrients.

Though soil and leaf analysis enable us to characterize in a qualitative manner the nutritional status of the relevant area they are not by themselves sufficient to give quantitative guidance as to the rates of fertilizers to be applied. For this it is necessary to draw up a nutrient balance sheet for the vineyard by quantitative measurement of:

- Nutrient uptake for growth of trunk and branches, roots, cluster formation, shoots and prunings,
- Estimation of nutrient losses (both from fertilizer and of soil origin) by leaching, erosion, denitrification and fixation.

The sum of these two indicates the maintenance dressing of a nutrient which should be applied.

However, such a balance is not by itself sufficient and it is necessary to link the quantitative and qualitative indications:

Qualitative	*Quantitative*
Soil analysis	Uptake of nutrients
Leaf analysis	Nutrient losses

In a general way there are three possible situations for each nutrient.

1) Subzones with normal values for soil nutrient content and normal leaf content. Here the recommendation is to apply the rate (D) of nutrient calculated from the balance to replace nutrients removed by plant uptake and losses, thus maintaining the nutrient status of the soil.

2) Subzones where soil or leaf contents indicate deficiency. The recommendation here is to apply extra nutrient in addition to the restitution application D, the size of the addition being dependent upon the seriousness of the deficiency and growing conditions in order to build up the nutrient status to a satisfactory level.

3) Subzone where leaf and/or soil values indicate excess nutrient. Here the recommendation is to deduct an amount from the normal maintenance dressing (D) depending on the degree of excess and growing conditions. It may be necessary to suspend for a time application of certain nutrients (*e.g.* Ca on calcareous soils) or to apply antagonistic elements (*e.g.* Mg *versus* K or *vice versa*) or to apply amendments and correctives (*e.g.* liming of acid soils to reduce the uptake of oligo-elements below a toxic level).

Recommendations made on such a basis should apply throughout a homogeneous subzone especially when adjusted in accordance with yield level.

It is possible to draw up 'nutrition maps' taking the form of topographical maps on which the zones and subzones are marked with indications of soil characteristics, leaf nutrient status, consumption and losses of nutrients and finally the recommendations.

Methods used in nutrition map making and results obtained during 15 years

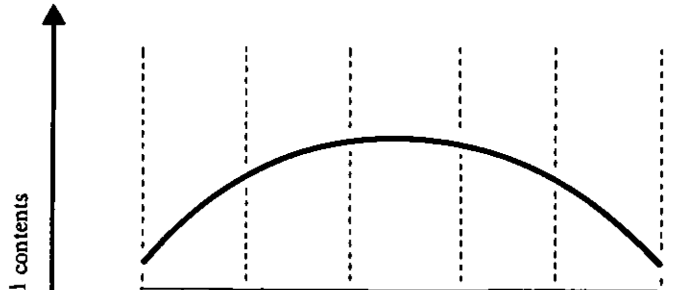
Soil analysis

The search for methods to give a true picture of nutrient availability goes on, but in spite of progress there are still several methods in use which give different results so that comparison of data from one method with another is difficult. Factors which affect nutrient dynamics in the soil such as pH, organic matter content, moisture characteristics, temperature and structure are more important than actual nutrient contents. So it happens that a soil judged to be poor may give better results than a rich soil, especially if the former allows better root penetration. Results for oligo-element content are not easy to interpret and here the effect of pH is important (increased availability and the possibility of toxicity in acid soils and reduced availability in alkaline soils). The *Commission Romande des Fumures [1983]* in Switzerland uses 'weighting indices' to improve the interpretation of soil analysis which depend on situation and nutrient status of the vine. For P_2O_5, K_2O and MgO these indices vary from − 5 to + 5 and for nitrogen from − 13 to + 13. This is a step forward but its usefulness is limited because it takes no account of genetic potential (rootstock cultivars) or of growing methods (training, yield level, etc.).

Foliar analysis

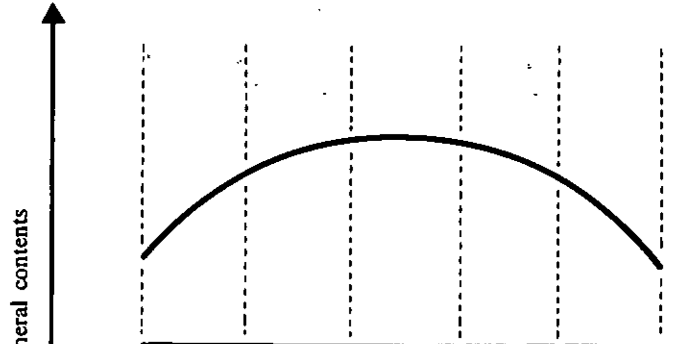
This method was developed for the vine and has been extended to other crops with variation as appropriate (petiole, leaf blade, etc.). Work has been done on correlation with soil analysis and relationships with growth and productivity have been established. It is usually possible to define states of deficiency, optimum and excess according to the general curve linking leaf contents with productivity (Tables 1, 2). It is possible to take immediate action to correct defects or imbalances within the growing season. However, depending on climate, soil and other conditions, vines in which leaf analysis indicates a non-ideal situation often perform well and effects on quality, as distinct from effects on yield, should be taken into consideration. Ratios between elements are better correlated with yield than absolute contents (Table 3).
The *DRIS (Diagnosis and Recommendation Integrated System)* has been developed as an improvement. It takes into account ratios between individual nutrients in the leaf and these are statistically related to productivity. Indices are established for the whole series of macro- and micro-elements which, for example could range from − 9 to 0 to + 17 where 0 represents the optimum, negative figures deficiency and positive excess. For the N index the ratios N/P, N/K, S/N are included in the equation; for P, the ratios P/K, N/P, S/P; for K, N/K, P/K, S/K *(Beaufils [1973], Sumner [1977], Lee [1980], Kelling et al. [1981])*. It is possible to allow for antagonism or synergism between elements and to eliminate the effects of environmental variables.

Table 1. Relation of macroelement contents of leaves to quality-quantity.



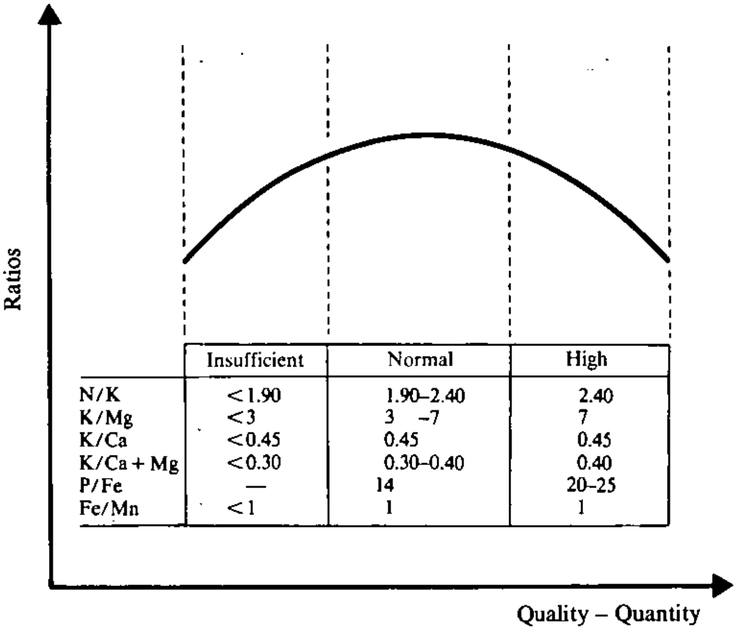
	Deficiency	Light deficiency	Optimum	Light excess	Excess
N	<2	2 –2.40	2.40 –2.60	2.60–2.80	>2.80
P	<0.15	0.15–0.20	0.20 –0.24	0.24–0.26	>0.26
K	<1	1 –1.20	1.20 –1.40	1.40–1.60	>1.60
Ca	<2	2 –2.50	2.50 –3.50	3.50–3.70	>3.70
Mg	<0.20	0.20–0.23	0.23 –0.27	0.27–0.30	>0.30
Σ	<6	6 –6.53	6.53 –8.01	8.01–8.20	>8.20
S	<0.18	—	0.40 –0.50	—	—
Cl	<0.04	—	0.05 –0.3	—	>0.5–1.5
Na	<0.018	—	0.024–0.026	—	>0.033

Table 2. Relation of microelement contents of leaves to quality-quantity.



	Deficiency	Light deficiency	Optimum	Light excess	Excess
Fe	<50	50–100	100–250	250–300	>300
B	<15	15– 25	25– 40	40– 60	> 60
Mn	<20	20– 30	30–200	200–500	>500
Zn	<20	20– 30	30–150	150–400	>450
Cu	< 4	4– 5	5– 20	20– 40	> 40
Mo	<0.1	0.1–0.5	0.5– 10	?	?
Co	<0.1	0.1–0.5	0.5– 10	?	?

Table 3. Nutrient ratios in leaves are as important as absolute contents indicating sufficiency, deficiency or excess.



	Insufficient	Normal	High
N/K	<1.90	1.90–2.40	2.40
K/Mg	<3	3 –7	7
K/Ca	<0.45	0.45	0.45
K/Ca + Mg	<0.30	0.30–0.40	0.40
P/Fe	—	14	20–25
Fe/Mn	<1	1	1

Table 4. Examples of TEAM for vines (*Perosino* and *Hsu*)

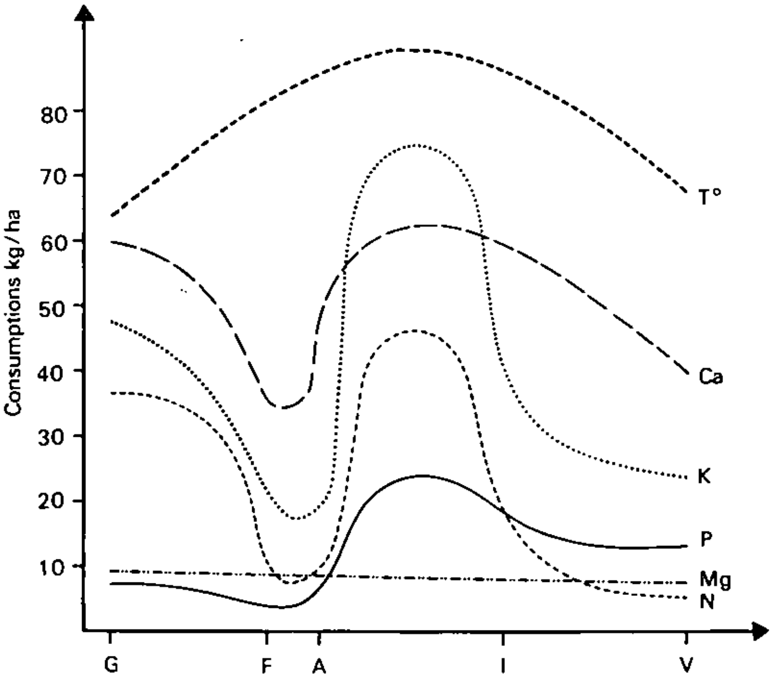
Pinot grigio (Friuli) 140 q/ha	Refosco (Friuli) 50 q/ha	Pinot grigio (Friuli) 130 q/ha	Merlot (Friuli) 170 q/ha	Dolcetto (Piemonte) 90 q/ha	Moscato (Piemonte) Nursery	Vite (Piemonte) Nursery
Cu −60	B −42	Mg −58	Mg −85	Mn −78	B −205	P −211
B −39	Mg −28	S −32	B −57	B −60	Cu −132	K −159
Mg −27	Cu −18	K −27	K −57	Mg −43	P −27	B −119
K −14	Ca −8	B −21	S −28	K −39	S −23	S −61
Ca 0	Fe −1	Ca −21	Ca −27	Cu −4	Mg −20	Mg −51
Fe 4	K 0	Cu −15	Mn −26	Ca 3	K −19	Ca −47
N 8	S 0	Mn −15	P −9	P 5	Ca −14	N −14
S 16	N 3	P 4	N −6	S 5	Mn 0	Cu 0
Zn 17	Zn 16	N 13	Cu 56	N 11	N 7	Fe 64
P 34	P 33	Fe 40	Zn 195	Fe 38	Zn 35	Zn 161
Mn 48	Mn 34	Zn 89		Zn 153	Fe 80	Mn 328

Using ratios it is possible to carry out leaf sampling at any time, though as the ratios change with age, the phenological stage at sampling must be taken into account. DRIS can also classify soil, climatic and crop factors.

TEAM (Perosino, Hsu [1983]) is an improvement on DRIS which takes into account both ratios and absolute leaf nutrient levels, thus taking account of 'critical levels'

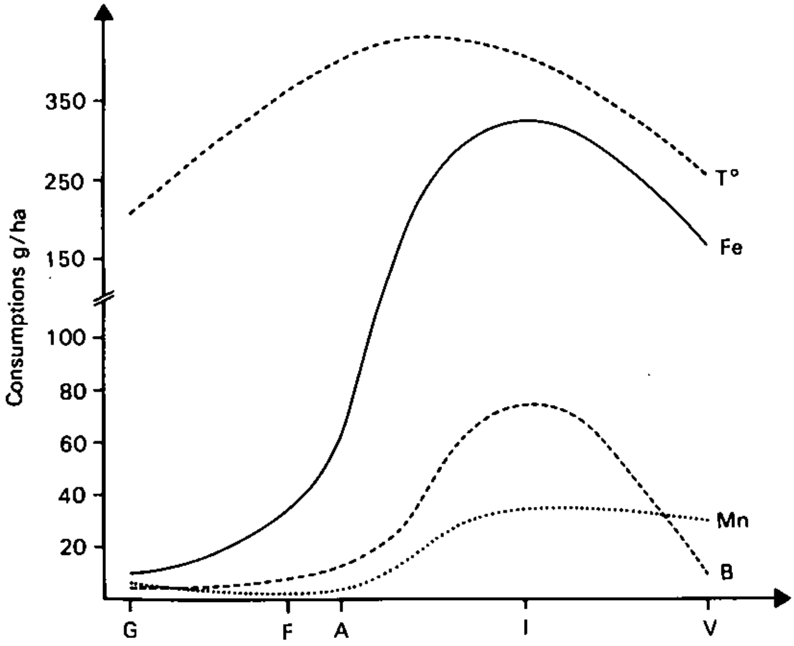
Table 5. Uptakes of macro- and microelements by grapes, shoots, and leaves (45 cultivars, 15 forms of training, mean production 7 to 25 t/ha, vineyards in North, Central and South Italy) *(Fregoni et al.)*

Macro- and microelements		Minimum per ha	Maximum per ha	Minimum per 100 kg/ha	Maximum per 100 kg/ha
N	kg	21.79	83.69	0.12	0.71
P	kg	2.32	15.34	0.01	0.13
K	kg	34.17	122.97	0.24	0.80
Ca	kg	19.78	145.81	0.08	0.91
Mg	kg	3.55	15.41	0.02	0.17
Fe	gr	292	1121	1.63	9.24
B	gr	37	228	0.26	3.22
Mn	gr	49	787	0.29	8.80
Zn	gr	110	585	0.66	3.20
Cu	gr	64	910	0.35	13.92



G = budding
F = bloom
A = fruit-set
I = veraison
V = harvest

Fig. 1. Macroelement uptake patterns. The maxima are found at budding during growth of berries and shoots (fruit set-veraison). The climate (temperature) has a determining influence on consumption, apart from the phenological phases.



G = budding
F = bloom
A = fruit-set
I = veraison
V = harvest

Fig. 2. Microelement uptake patterns. Maxima occur at veraison and the influence of the climate is slight.

(Table 4). Considering ten elements of fundamental importance (N, P, K, Ca, Mg, Fe, B, Mn, Zn, and Cu) the N index, for example can be calculated from the following:

$$\text{N index} = \frac{f(N/P) + f(N/K) - f(Ca/N) - f(Mg/N) + f(N) + \ldots - f(Cu/N)}{10}$$

Nutrient uptakes

Essential for establishing the balance, these, being related to dry matter production, are very variable. Our research in Italy shows that dry matter production varies between 3 and 10 t/ha. The ranges for total uptake of nutrient in Italy are given in Table 5.

Macroelement uptake is at a maximum from budding to veraison, that of microelements later as the fruit veraison (Figures 1 and 2).

Table 6. Mean rates of macroelements taken from nutrition maps compiled for all Italy (checks on over 260 sample vineyards)

Grape yield t/ha	N kg/ha	P_2O_5 kg/ha	K_2O kg/ha	CaO kg/ha	MgO kg/ha	$N + P_2O_5 + K_2O$ kg/ha	$N + P_2O_5 + K_2O + CaO + MgO$ kg/ha
5	65	14	96	300	28	202	530
10	76	44	112	358	31	232	621
15	87	46	128	417	34	261	712
20	98	49	144	476	37	291	804
25	109	51	160	534	40	320	894
30	120	54	176	593	43	350	986
35	131	56	192	651	46	379	1076
40	142	59	208	710	49	409	1168

Table 7. Ratios between elements according to rates listed in preceding Table

Grape yield t/ha	N	P_2O_5	K_2O	MgO
5	1.6	1	2.4	0.69
10	1.7	1	2.6	0.71
15	1.9	1	2.8	0.74
20	2.0	1	2.9	0.76
25	2.1	1	3.1	0.79
30	2.2	1	3.3	0.80
35	2.3	1	3.4	0.83
40	2.4	1	3.5	0.83

Nutrient losses

These are estimated in relation to soil type, rainfall pattern, etc. Research by the author and others indicates the range of losses to be expected as follows:

N	15– 90 kg/ha	B	20–50 g/ha
P	0– 10 kg/ha	Mn	20–40 g/ha
K	20– 70 kg/ha	Cu	30–60 g/ha
Ca	200–600 kg/ha	Zn	40–65 g/ha
Mg	15–100 kg/ha	Mo	10–20 g/ha
S	50–100 kg/ha		

Fifteen years' experience with nutrition maps

Nutrition maps have been compiled for about 80 vine growing areas in Italy from the North to Sicily. They cover several thousands of vineyards, 20 types of training, 60 cultivars with yields from 5 to 40 t/ha grapes.

The results reported in Tables 6 and 7 and Figures 3–8 were obtained from investigation of 260 fertilizer recommendations noted in the maps and the following conclusions can be drawn:

- The fertilizer recommendations are positively correlated (P = 0.01) with grape yield per ha. This is because nutrient uptake is related to yield and is of much greater importance than nutrient losses or amendments to the recommendation designed to correct deficiency or excess.
- The nutrient ratio, contrary to what is generally supposed, varies greatly with yield (N:P_2O_5: K_2O:MgO):1.6:1:2.4:0.69 to 2.4:1:3.5:0.83.

As the yield varies the relative uptake of the various nutrients does not remain constant. In fact, as grape yield increases from 5 to 40 t/ha, N increases by 0.8 (from 1.6 to 2.4), K by 0.9 and Mg by 0.14. This is a very important point in the rational choice of fertilizers and it is rarely possible to find such variation in nutrient ratio of fertilizers on the market.

It is not easy to make practical use of these results since there are so many variables related to site, etc., which must be taken into account. This is clear from the above statistical evaluation which is restricted to the major nutrients and applies to single vineyards. The survey of 260 vineyards covers a wide range of conditions but there is still far to go and for the present the use of nutrition maps is restricted to zones and sub-zones.

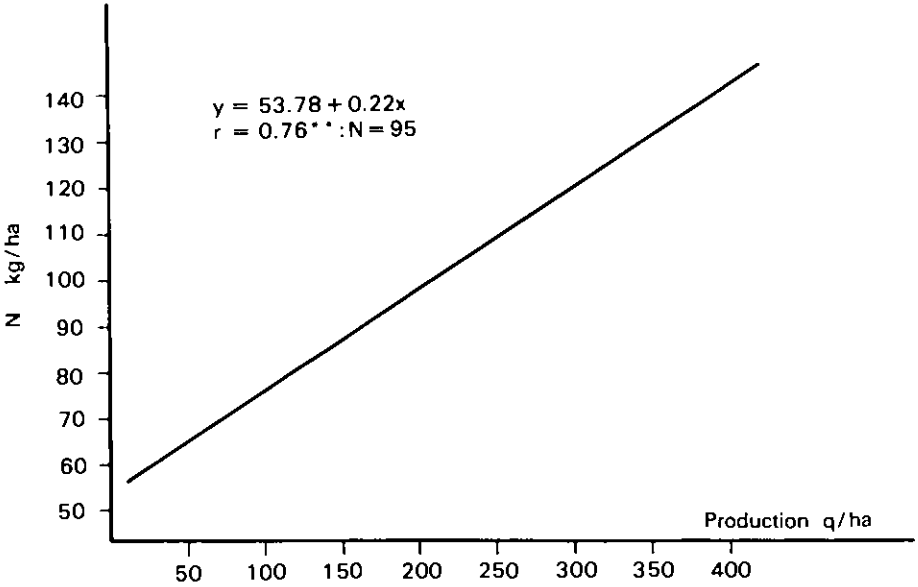


Fig. 3. Linear regression of grape yield on rate of N.

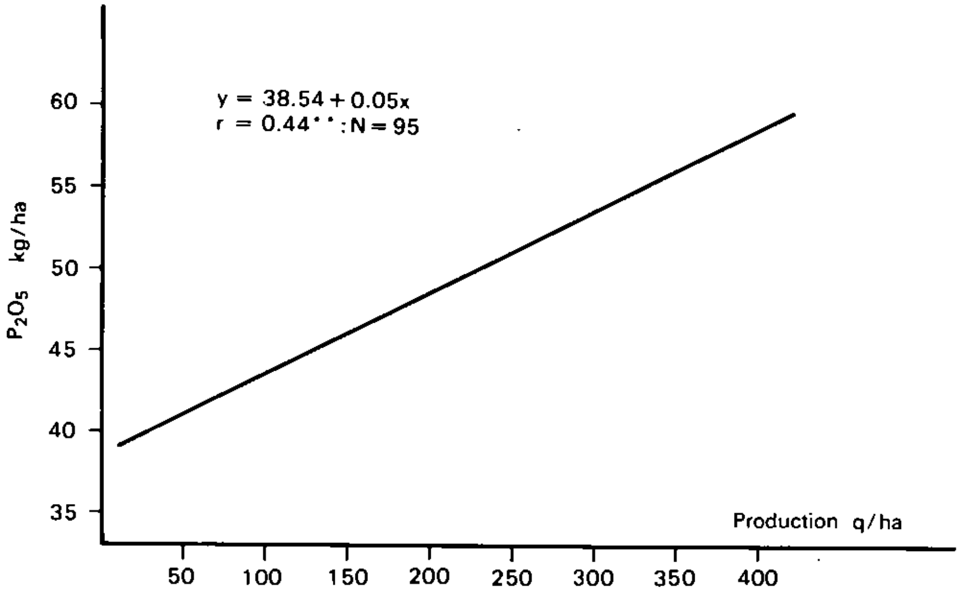


Fig. 4. Linear regression of grape yield on rate of P_2O_5.

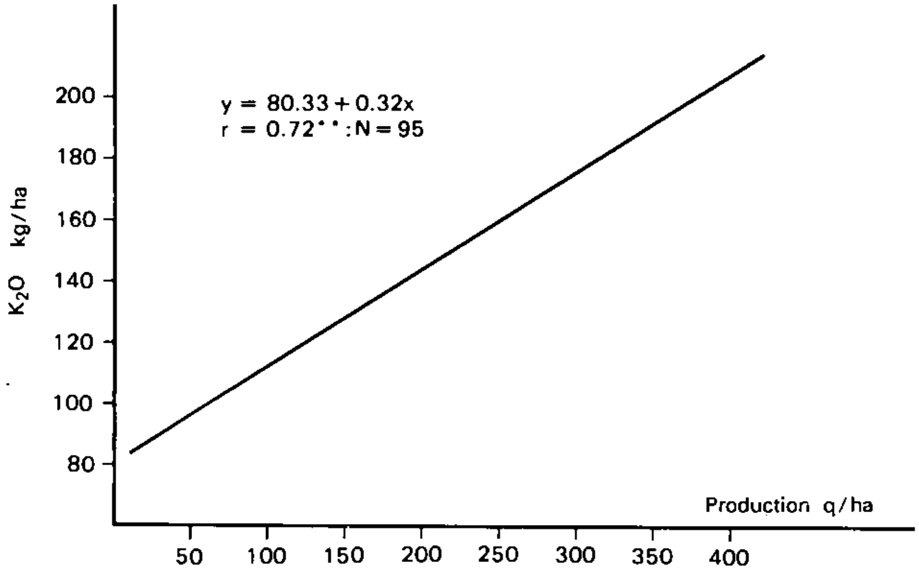


Fig. 5. Linear regression of grape yield on rate of K_2O.

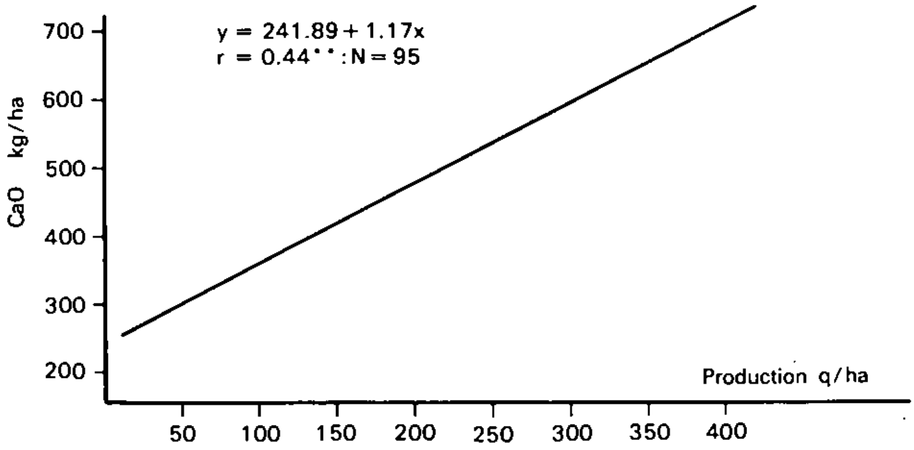


Fig. 6. Linear regression of grape yield on rate of CaO.

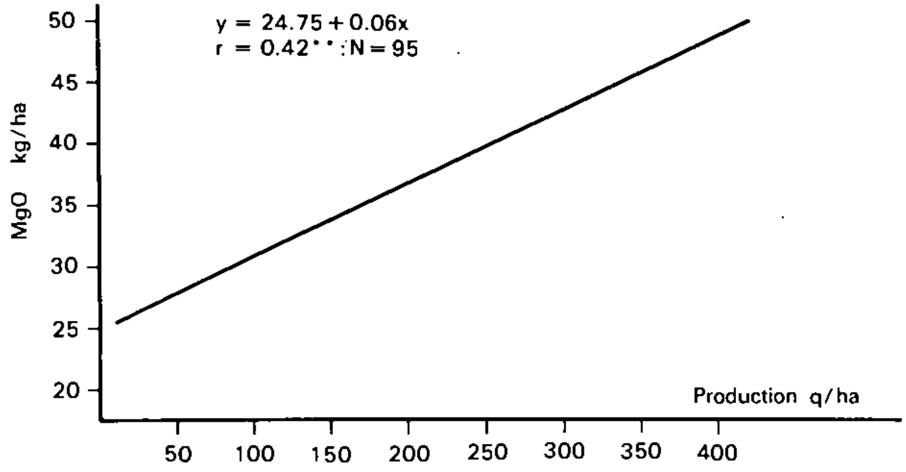


Fig. 7. Linear regression of grape yield on rate of MgO.

Testing of nutrition maps

Checks have been made on yield and quality aided by leaf analysis. Comparison of recommendations from the maps with traditional practice of the growers has shown that the recommendations did not generally modify yield but almost always improved inversion and thus quality. The work has been done by the author assisted by many technicians and growers throughout Italy. With 15 years' experience it can be said that the nutrition maps have achieved two important aims: quality improvement and economy. Both are concerned with nutrient balance.

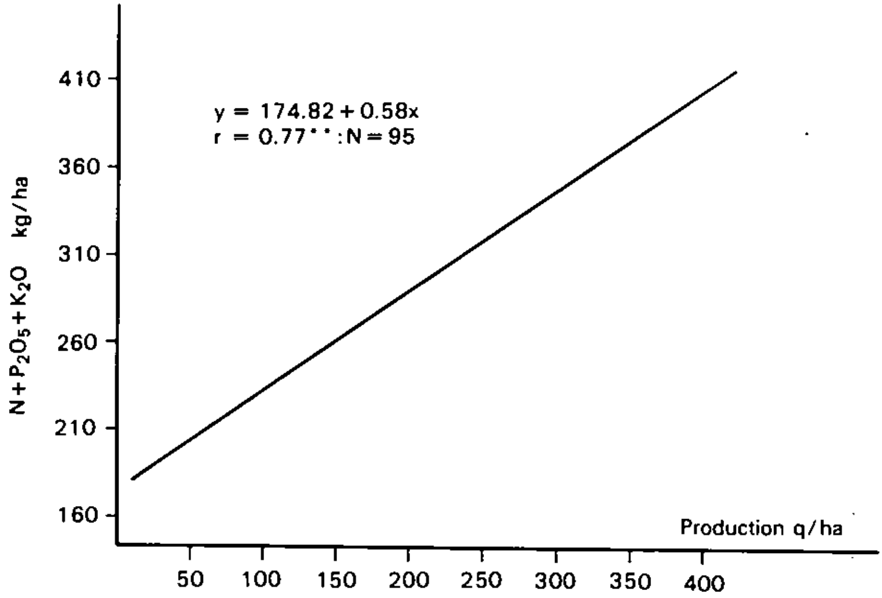


Fig. 8. Linear regression of grape yield on combined rate of nitrogen + phosphorus + potassium.

Conclusion

Research by the author leads to the conclusion that determination of the nutrient requirements of the vine upon which to base fertilizer recommendations calls for the simultaneous use of several methods as concluded by the *5th International Colloquium on the Control of the Nutrition of Cultivated Plants* held at Castelfranco Veneto in 1980. The nutrition maps represent a theoretical model which takes into consideration the many (soil-plant) factors involved.

A second conclusion is that there is a need for the greater use of data processing in this area. The massive accumulation of data should make possible refinements in analytical methods, better interpretation and a more rational approach to practical recommendations which can be realized by modern methods of data processing. The ultimate aim is to establish models for production functions to result in economical recommendations best suited to the physiological needs of the vine.

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Co-ordinator's Report on the 4th Session

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Fertilizer Needs in Temperate Ecosystems

The aim of this session was to consider the principles governing the adjustment of fertilizer inputs under the ecological conditions of temperate area. This involves consideration of all the endogenous and exogenous factors governing the nutrient requirements of crops as well as economic aspects.

Rational fertilizer use aims to achieve optimum economic returns with high quality. This means that fertilizers should supply the requirements of the crop at all stages of nutrient needs and a knowledge of the ecological impact of fertilizer application.

In his main paper introducing the session *J. Hébert* surveyed patterns of fertilizer usage in *European Economic Community* countries and in general terms the nutrient status of soils. There are large differences in practice between the various countries and between areas within them. Throughout Europe the tendency up to 1980 has been for N usage to increase substantially while the increase in P and K usage has been only modest. The average nutrient ratio has shifted in favour of N. This trend reflects the fact that over the past 20 or 30 years soil P and K levels have been built up. Also crop varieties of higher yield potential have become available, average cereal yields having increased at the rate of about 100 kg/ha grain per annum. Higher yields require higher inputs of N, a principal determinant of yield. In comparison with P and K, N is very mobile in the soil and its effects comparatively short-lived.

Between 1969/70 and 1980/81 N usage has increased by 59%, P usage by 15% and K by 20%. Mr. *Hérbert* considered nutrient balance sheets for different types of farm with and without livestock. He found that, as concerns the three main nutrients, the balance (nutrient applications – crop removals) was in equilibrium or positive. He stressed the increasing importance of such balance sheets as a basis for fertilizer advice. Following his consideration of balance sheets the author dealt with the indications of soil analysis. A general conclusion was that input of nutrients via fertilizer frequently exceeded nutrient offtakes in crop and animal produce sold off the farm and that, if the input of plant nutrients in purchased feeds was taken into consideration the surplus was even greater.

There are clear indications that the P status of soils has improved but the situation as regards K is not so clear. So far as N is concerned there are significant losses by way of leaching and denitrification, while for P and K fixation is important.

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The author's opinion was that soil analysis was useful in predicting fertilizer response at high and low soil P or K values but that it was of less use at intermediate levels. We require more knowledge of mechanisms involved in fixation. Despite the fact that nutrient balances are generally positive we still encounter soils which are under-supplied. There is still a need for more meaningful soil analysis and more attention should be paid to the role of the subsoil in contributing to the nutrient supply to crops, and to sources of nutrient loss in farming systems.

In the second paper, *Droeven* dealt with long-term experiments which were concerned with the effects of fertilizers, crop rotation and cultivation methods on crop yield and soil fertility. He mentioned changes in farming practice in arable areas: a swing towards stockless farming and the adoption of minimum cultivation techniques which are most relevant in this connexion.

Nitrogen supply largely determines yield and the forecasting of the requirements is of the highest importance. Soil supply of N is usually insufficient to support full crop yields. The availability of soil N depends on the rate of mineralization of soil organic matter.

There are considerable difficulties in the evaluation of soil N which is much affected by crop rotation (inclusion of legumes) and additions of organic farm manures, in which the availability of N depends on a number of factors. It is interesting that one result of direct drilling is a 20% reduction in N mineralization. A further effect of minimum cultivation is to enrich the surface soil in P and K.

G. Thevenet dealt with the interaction between irrigation and N fertilizer. Soil water supply can be a limiting factor in the temperate region either through insufficient total rainfall or through unfavorable distribution. While there is no question as to the profitability of irrigation for bulky crops such as sugar beet, potatoes, maize and vegetables, the situation with small grain cereals is otherwise.

It can be demonstrated experimentally that there is a linear relationship between water supply and crop yield but, in France, the problem is that, while it is simple to determine the N requirement of irrigated wheat, the occurrence of drought is unpredictable and the forecasting of N requirement for the unirrigated crop is difficult.

In this connection the response needed to cover the cost of installing and running irrigation equipment is of the order of 2 to 2½ t/ha grain. Availability of irrigation is primarily an insurance against yield loss. Experiments show that the combination of irrigation and high N greatly increases ear number/m^2 but has little effect on 1000 grains weight. The author concludes that the rate of N fertilizer should be decided on the assumption that yield will not be limited by water supply; if drought occurs after shooting the risk of pollution will not be increased, while the occurrence of drought at the earlier stage of growth is rare.

Mantinger considered the fertilization of fruit in the South Tyrol. Formerly, fruit growing was combined with livestock farming but this practice has been abandoned and grass covers which are frequently cut are the general rule. Grass mulch as well as prunings are left in the orchard so that there is a closed nutrient cycle. This change in practice has a great impact on fertilizer requirement which is less than under the traditional system and this has not been widely understood by farmers.

An experiment with various apple cultivars over twelve years shows that the N requirement for top yield is around 50 to 70 kg/ha N. Higher rates (120 to 250 kg/ha) did not increase yield. K is important for firm fruit but application of more than

150 kg/ha K_2O cannot be justified. Correct nutrient ratio is of more importance than generous usage.

Fregoni dealt with the problem of fertilizer recommendations for vineyards. His approach to the problem is based on the drawing up of nutritional maps from surveys of the wine-growing areas divided into zones and sub-zones, embracing data for leaf and soil analysis, nutrient uptake and nutrient losses.

An emerging result of this work was a close correlation between fertilizer treatment and grape yield over eighty wine-growing districts. There is much variation in N:P:K:Mg ratio and it is hardly possible to select fertilizer of the correct nutrient ratio for a particular area from the range of mixed fertilizers available in the market.

Comparison of recommendations made on the basis of the nutrient maps with farmers' practice shows that the former, while not always producing the highest yield, always have favorable effects upon quality.

The twofold aim of recommendations emerging from the nutrient maps is to improve the economic return and to improve quality.

Future development of the method demands the collection of more detailed data to be computer processed.

Chairman of the 5th Session

Prof. *A. Malquori,* Istituto di Chimica Agraria e Forestale, Florence/Italy; member of the Scientific Board of the International Potash Institute; chairman of the 18th IPI-Colloquium

5th Session

Agricultural Productivity in Ecosystems

Biogeochemistry of Forest Ecosystems in Relation to Maintaining or Increasing their Productivity

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Summary

The forest is the most complicated ecosystem known to us. Innumerable organisms of all levels of organization live close together and interact. As long as external conditions remain more or less stable the forest itself, once it has reached the climax vegetation for its particular site, will remain in a state of dynamic equilibrium, in which fluctuations of greater or smaller amplitude occur on either side of a condition of equilibrium. The scale of the fluctuations depends upon the stability of the biotope and site.

Ability to resist environmental damage also varies and here the forest has a new and important function as an environmental indicator. Over the last 20 years growing concern has been apparent for the effect of air pollution on the European as well as the world's forests. Today, all over Central Europe scattered but immense forest damage is confirmed. In the last years a reduction in the vitality of forests has been observed and irreversible changes may be occurring in the soils and forests of widespread areas of Europe and, perhaps, North America as well. Since the effects of air pollution on ecosystems are mostly indirect and cumulative – for example, reduction in the reproduction capacity of a key species or the progressive loss of soil fertility in forest – there is a legitimate concern that in a few decades the vulnerable forest ecosystems may simply deteriorate and collapse.

If natural functions are damaged or destroyed, they must be replaced by human intervention if the quality of life is to be maintained. There are several examples showing productivity and stress tolerance improved by fertilizer application and balanced nutrition, respectively. No aspect of ongoing research on this topic is more challenging or more urgent to soil scientists and the fertilizer industry than the effort to assess the impact of acid deposition on biogeochemical pathways and processes linked with soil productivity and plant growth.

The forest ecosystem, an integral part of our environment

The forest is the most complicated ecosystem known to us. Innumerable organisms of all levels of organization live close together and interact. Though in terms of numbers trees account for only a very small proportion of these organisms, they nevertheless have the greatest effect on the ecosystem. Forest ecosystems are characterized by a considerable accumulation of biomass, approximately 500 ton-

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nes per hectare dry weight of living and dead organic matter in Central European forest under management. Forest ecosystems have been functioning for thousands of years with virtually no external input apart from solar energy and water. To some degree, ecosystems have adapted to the materials or inputs they receive from the atmosphere, such as the amount and distribution of rainfall. Changes in inputs resulting from shifts in climate, volcanic activity, and similar modifications may cause major and long-lasting changes in the structure and function of local or regional ecosystems.

Forest ecosystems, however, are thought to be adapted to a range of naturally occuring fluctuations in atmospheric inputs resulting from the vagaries of year to year changes in local climate. Indeed, the first factor determining which forest communities will occur on a given site is regional climate, followed by soil or the parent rock from which it is formed. It is well known that in very broad terms Europe divides into the Mediterranean sclerophyllous regions adapted to dry summers, the temperate zone of deciduous broad-leaved woodland and the coniferous forests of the mountains and the north, where the climate is continental and winters are cold. A mixed forest region forms the transition in upland areas.

As long as external conditions remain more or less stable the forest itself, once it has reached the climax vegetation of its particular site, will remain in a state of dynamic equilibrium, in which fluctuations of greater or smaller amplitude occur either side of a condition of equilibrium. The scale of the fluctuations depends upon the stability of the biotope and site. As a general rule diversity of life forms and species enhances stability, but is not a precondition of this. In extreme sites where relatively few species can flourish, as in the sub-alpine fir forest, it is perfectly possible for forests with a very limited number of species to be stable.

The reactions of various woodland types to management measures are as varied as their structure. It follows that experience with one type of woodland should not be transferred uncritically to other forest ecosystems.

Ability to resist environmental damage also varies and here the forest has a new and important function as an environmental indicator. Today, not only in Europe but in most parts of the world, forest are increasingly threatened and their protection is becoming ever more urgent. Over the last 20 years growing concern has been apparent for the effects of air pollution on the European as well as the world's forests. During the last few years new and alarming reports have come from Central Europe in connection with the occurrence of dying forests.

Acidic deposition is falling on both the managed and umanaged ecosystems throughout much of the Northern Hemisphere. Most of the terrestrial landscape within this region of the world is covered by vegetation. Since vegetation collectively includes the primary producers in our food web, its importance to man is without question. Thus, any changes in plant productivity, whether it be an increase or decrease in production, can have significant implications for man's food and fibre systems.

The aims of this paper is to briefly discuss on the basis of present knowledge, a few selected connections and geobiochemical processes which should be integral parts of a hypothesis describing the present situation of some European forest ecosystems under pollution stress. It is important to recognize that there is a large variation in the potential effects of air pollution on forest. This is due to geographical variation in soil and vegetation properties and in the amount of pollutants deposited. The objective of the mentioned hypothesis cannot be the present ongoing forest damage, it must be the understanding and quantification of forest ecosystem stability and resilience in relation to maintaining or increasing their productivity.

Air pollution as a threat to forest ecosystems

Throughout human history, pollution has caused substantial damage to local ecosystems, but now industrialized man is heavily influencing the geobiochemical pathways through air, water and soil pollution on a regional scale. There is some evidence that, for the first time, man-made pollution may be causing fundamental changes in regional landscapes in the order of millions of square kilometres particularly in the Northern Hemisphere.

Air pollution as a region-wide problem began four or five decades ago and since then has grown fairly steadily both in intensity and in extent. In the neighbourhood of industries with high gas and dust emissions damage has been shown to occur for a long time. These deleterious effects have influenced the growth of trees and in extreme cases have now caused their early death. All over Central Europe a scattered but immense forest damage is confirmed. In the last years a reduction in the vitality of forests has been observed even in areas remote from industrialized regions.

Pollutants in this context are not simply acid rain or photooxidants but an array of substances often acting simultaneously whose interactive effects largely remain to be discovered. Today, pollutants in the air of large parts of the world are intense enough to gradually damage our landscape. This is occurring at a time when other stresses on the landscapes – such as more intensive forest harvesting, a rapidly increasing demand for fire wood, and rising recreational use – are rapidly escalating.

The measurement of damage to the landscape is difficult, not only because of the complexity of natural systems, but also because of lack of long-term baseline studies in prepollution times which could serve to evaluate modern changes. Nevertheless, a variety of evidence and inference indicates that large areas of the European landscape are endangered. Large-scale genetic, biological, and ecosystem changes are probably occurring under current Central European levels of air pollution stress. Since the effects of air pollution on ecosystems are mostly indirect and cumulative – for example, reduction in the reproduction capacity of a key species or the progressive loss of soil fertility in forests or alkalinity in lakes – there is legitimate concern that in a few decades vulnerable forest, lake and stream systems may simply fall apart. Already many lakes over an enormous area of the Northern Hemisphere have undergone severe deterioration and tens of thousands more are progressively nearing that state.

Vegetation damage

The effects of acidic deposition on vegetation has been a research area dominated by logic, speculation and few conclusive data points. The multivariable nature of natural system responses and an inadequate historical perspective make it less than surprising that scientists do not have a complete understanding of real, and even potential, acidic deposition effects on terrestrial ecosystems.

Acidic deposition may influence the growth, reproduction, quality, and/or yield of vegetation. These effects may result from the direct influence of acidic or acidifying substances on vegetation, including modification of the morphology of leaf surfaces, nutrient status of aerial plants due to leaching and absorption of essential nutrients, metabolic function rates, genetic structuring of population, and/or reproductive success and processes. The effects, although important considerations in quantifying the impact of acidic deposition on all vegetation, are particularly important to perennial plants where the effects might be cumulative over long-term exposures.

Indirect effects on vegetation are also of importance in the development of an improved understanding of plant response to acidic inputs. Of primary importance is the effect of acidic deposition on the physicochemical characteristics of soil and soil nature; the medium in which terrestrial plants are constantly exposed. Of particular concern with respect to the overall productivity is the potential for increased or decreased plant nutrient availability in soils, and the increased availability of metals and subsequent toxicity that may result from acidic deposition. Other potentially important plant/environment interactions that might be altered by acidic deposition include modifications of the susceptibility of plants to insects, disease, drought and other pollutants, and the relationship between plants and soil-borne organisms.

Our understanding of acidic deposition effects on plants is inadequate. Methodological inconsistencies are primarily responsible for our inability to quantify the effect of acidic deposition on annual plant species. The lack of historical deposition data makes it difficult to assess perennial plant responses to acidic deposition. However, changes in the plant systems are being observed. Evidence exists that suggests forest and select crop productivity may be altered by either direct.or indirect effects of acidic deposition. Conclusive evidence which draws a link between ambient level of acidic deposition and crop effects is still lacking. Time, careful experimentation, and creative research are needed to better understand plant response to acidic inputs.

Interaction with soils

The effects of acidic and acidifying substances on soils may be the most significant factor which ultimately affects the growth of vegetation, either positively or negatively. Changes in soil systems will be particularly important in considerations of long-terms effects on forest tree species. Acidification, nutrient losses, sulphate adsorption, mineral weathering, metal availability, and nitrate additions are among the primary issues facing the soil scientists' understanding of acidic deposition impacts on soils. Each of these variables can be significant in regulating plant growth and development. Therefore, it is likely that our discussion of acidic deposition as an important factor affecting vegetation will rest on our understanding of the soil response to these inputs.

Many forest soils are acid. Sandy, well drained soils of intermediate pH (5–6) are particularly susceptible to acidification. Soil acidification is a slow process. Hydrogen ion in acid percolating waters will exchange with other cations in the soil. This increases the leaching of Ca, Mg and K, and in soils with pH below 5.0, increases the mobility of potentially toxic metals such as Al, Mn, Cu, Cd and Zn. These exchange processes neutralize the water, but acidify the soil, unless hydrogen ions are consumed in weathering processes so that cations are replenished in the soil by cycling through vegetation. The rates of these processes present one of the major challenges to future research. Several other processes are known to affect the acidity of soils, i.e. root uptake of cations; CO_2 derived from respiration; oxidation and reduction of N and S compounds and organic acids from deposition.

Hydrological conditions and water flow pathways through soil and rock determine the contact time of acidic deposition with neutralizing substances and thus the degree of water and soil acidification. In most north temperate conditions, sulphur inputs to terrestrial ecosystems generally balance the outputs, although some soils may retain sulphur for decades.

Sulphate ions are important as vehicles for cation transport. They are leached into surface waters accompained by charge-balancing cations, mainly Ca, but also H and Al when these cations dominate the soil system. Sulphate ions therefore play a decisive role in the acidification of freshwater as a mobile carrier of the hydrogen and aluminium ions, whether the H^+ and Al stem from atmospheric deposition or from catchment processes. For an increase in acidic sulphur deposition there will be either an increase in soil acidity or in water acidity, or a mixture of the two. In terrestrial ecosystems that retain sulphur the anion mobility is reduced. However, if the terrestrial ecosystem is saturated with sulphur, rates of acidification will increase.

Soil/plant interactions

Potentially, acid deposition can have a number of different effects in soil that are of significance for plant growth. Apparently, the most important effects can be classified into two; 1) the fertilizer effects of N and S, and 2) the acidification effects of increased leaching of SO_4^{2-} and sometimes NO_3^- together with base cations such as Mg^{2+}, Ca^{2+} and possibly K^+.

NO_x emissions lead to the formation and deposition of NO_3^- which, with NH_4^+, may in most conditions increase tree growth. There is evidence that the amounts may exceed immediate requirements, possibly leading to N saturation in tree stands, depending upon site quality and rates of annual deposition. If the forest ecosystem becomes saturated, increased leaching losses of NO_3^- and equivalent amounts of cations occur. This will increase the acidification pressure on soils.

While SO_2 might correct sulphur deficiencies in some areas (*e.g.* Australia and the tropics) this is not thought to be significant for trees in temperate and boreal forests.

Compared with those of incident (open) rain, concentrations of S, K, Mg and Ca in foliar leachates are usually increased and those of NO_3^- and NH_4^+ decreased. Amounts leached increase with increasing acidity. The effects of these exchanges on nutrient status and resistance to insects and pathogens are mostly unknown.

Increased soil acidification will increase net losses of plant-available Ca, Mg and K, and possibly decrease forest productivity. In areas of intense acidic deposition these losses added to those associated with logging, particularly whole-tree harvesting may jeopardize the ability to sustain yield. In many parts of Central Europe there is already evidence that Mg deficencies have been aggravated. It is well-known that aluminium can be toxic to plants. In many soils, such as acidic soils in the north temperate and boreal forest zones, the soil forming process leads to relatively large concentrations of exchangeable aluminium compared to those of 'basic' cations. Although many tree species are well able to tolerate these conditions, there is concern that large amounts of acidic deposition, occurring in some areas, may be decreasing the ratio of calcium: aluminium in soil solutions to an extent that impairs root growth and endangers tree survival.

These changes in soil properties have, or might be expected to alter; 1) the species composition and activities of soil organisms in particular decreases in rates of (a) decomposition and mineralization, with consequent accumulation of soil organic matter, (b) N-fixation and (c) internal acidification. 2) The uptake by plants of reserve and deposited potentially toxic elements (including Al, Cd, Cu, Mn, Pb and Zn) which may accumulate in the foliage, and 3) the composition of forest assemblages.

The present consideration of soil/plant interactions suggest that forest ecosystems subjected to acidic deposition are likely to be at greatest risk when on silty and thin sandy acidic soils overlying non-calcareous bedrock.

Recent observations in Central European forests

Symptoms

Scientifically unprecedented changes in the appearance and behaviour of forests are taking place in large parts of Central Europe. The most remarkable of these disease symptoms include the following:

- simultaneous and rapid decline of forests involving 4 coniferous and 6 angiospermous species of trees growing under many different soil and site conditions;
- abnormal shape, size, geometrical form, and distribution of leaves and shoots;
- active casting of green leaves and shoots;
- decreased growth and abnormal allocation of photosynthate among the foliage, annual increments along the tree stem, adventitious shoots, distress crops of seeds and cones, and fine roots and mycorrhizae;
- death of herbaceous vegetation under the canopy of some affected trees;
- development of microscopic crystals of calcium sulphate in the stomata of some affected spruce.

It is widely assumed that air pollutants and/or acid deposition are among the stress factors that have contributed to the symptoms described above. But this idea is still only an hypothesis; it has not been proven unequivocally. Most of the remarkable symptoms listed above have been reported in the German-language literature of forestry, soil science, or environmental protection in Central Europe.

The symptoms of decline are not indentical in rate or sequence of development in various species of trees or parts of Central Europe. Nevertheless, they include the following features some of which have never or only very rarely been reported before in the literature:

A. The changes have developed very rapidly and unevenly, but roughly simultaneously in many different species and types of forests.

B. The wide array of symptoms described has developed;

1) Very rapidly (during the years since 1979 or 1980)
2) On many different species of forest trees
3) In planted forests and naturally regenerated forests
4) On trees growing on both fertile and infertile soils and both basic and acid soils
5) In stands of all ages. Although the mentioned symptoms have often been reported in high elevation forests (800–1400 metres), essentially similar symptoms also have been observed in forests at moderate and at low elevation.

Although the first survey of the geographical extent of these forest-decline symptoms indicated that about 8 percent of the total forest area of West Germany was affected in 1981, preliminary results of a more recent (1983) survey indicate that as much as 25 percent of the forest area may be affected.

Major hypothesis

Four major hypotheses or schools of thought have been developed by various scientists in attempts to explain the current decline of forests in West Germany.

1. The gaseous-pollutant hypothesis of the *Air Pollution Research Institute* at Essen. This hypothesis is based mainly on field observations of ozone and sulphur dioxide concentration in various parts of Germany and controlled exposures of various tree species to these pollutants both alone and in various combinations.

2. The magnesium-deficiency hypothesis of the *Department of Soil Science* at the *University of Munich.* It is based primarily on field observations and both soil and foliar chemical analysis in stands of spruce at high elevation. According to this hypothesis the decline symptoms are a product of extreme magnesium deficiency in trees with plentiful supplies of nitrogen and calcium.

According to this hypothesis there is evidence that acid deposition from the atmosphere may contribute to these growth disturbances; it adds nitrogen to the ecosystem but may leach out magnesium and calcium from needles and soils. The leaching from the foliage is presumably accelerated by episodic ozone or frost damage to cuticles and cell membranes. The magnesium deficiency seems to lead to decreased frost hardiness of the spruce needles. There is no indication that toxic effects of heavy metals may be causing the disease.

3. The general stress hypothesis of the *Department of Forest Botany* at the *University of Munich.* This hypothesis is based on field and laboratory observations of symptoms in various tree species. These observations include changes in gas-exchange rates and formation of plant growth hormones and secondary metabolites during symptom development. According to this hypothesis, air pollution has led in recent years to a decrease in net photosynthesis and associated diversion of photosynthesis from mobile carbohydrates to relatively less mobile and toxic secondary metabolities. This in turn, leads to a poorer energy status in roots and accumulation of toxic substances in shoots which leads to poor development of fine root and mycorrhizae and to foliar decline symptoms. Reduced energy status increases the susceptibility of the trees to other stress factors such as drought, nutrient deficiency, and the usual secondary biotic pathogens.

The acidification-aluminium toxicity hypothesis of the *Department of Soil Science* at the *University of Göttingen.* This hypothesis is based mainly on observations below ground. In short, this hypothesis holds that the natural acidification of forest soils is accelerated as a direct and/or indirect result of deposition of acidic and acidifying substances from the atmosphere. Increased acidity (or loss of alkalinity) in the soil leads to increased concentrations of soluble aluminium ions in the soil solution which in turn results in accelerated morbidity and/or decreased synthesis of fine feeder roots. Lack of (or poor functioning of) feeder roots leads to increased moisture and nutrient stress and eventually to 'drying out' and death of the trees, particularly during periods of drought.

As in all countries around the world, the described hypotheses proposed by some German scientists to explain complex natural phenomena are reflections in part of the scientific background and experience of the scientists involved. Indeed, it is a matter of fact that there is no scientific consensus about the causes of the forest damage, even if there is general agreement about the importance of air pollutants.

Concluding remarks

As natural systems are destroyed or degraded, they lose some of their capacity to carry out natural functions; to maintain stable landscapes and biological diversity; to moderate temperature; to filter air and water; to recharge groundwater, to control erosion and yield sediment-free water to streams; to provide aesthetic and recreational enjoyment; and to produce forest and forage products. It is through inputs and outputs of materials and energy that the individual ecosystem is connected with the larger biogeochemical cycles of the earth. The behaviour of the ecosystem is in large measure determined by the inputs and, in turn, the ecosystem affects the behaviour of other interconnected ecosystems by its output.

Large-scale genetic, biological, and ecosystem changes are probably occurring under current European levels of air pollution stress. Since the effects of air pollution on ecosystems are mostly indirect and cumulative, there is a legitimate concern that in a few decades vulnerable forest, lake and stream systems, may simply collapse structurally and functionally.

If natural functions are damaged or destroyed, they must be replaced by human intervention if the quality of life is to be maintained. Such intervention requires substitutes for wood products, breeding and establishment of pollution-resistant crops and vegetation, addition of lime to lakes and fertilizers to forests, etc. These man-made substitutes require a considerable capital and energy expenditure part of which is needed to maintain functions formerly provided on a continuing basis by natural ecosystems using free solar power. In an age of increasing awareness of the limitations of the world's natural resource base, this is a hazardous path indeed. Forest ecosystems may show a high resilience in certain respects, i.e. they can 'buffer' a change in soil chemical and biological properties, as long as the tree stand is intact. When the stand is cut, which in most European forests is done at an age between 40 and 100 years, the soil biological system changes completely, and effects accumulated over the rotation time may appear. When the nutrient cycling is interrupted by clear-felling, excessive nitrification may occur, followed by leaching of nitrate and cations, denitrification and acidification, all processes which imply potential environmental hazards. Acid deposition may also have delayed effects in a similar way.

There are several examples showing productivity and stress tolerance improved by fertilizer application and balanced nutrition, respectively. In other words it has been shown that canopies with better nutrient and water status are less susceptible. Fertilizer experiments in the Nordic countries have shown that N generally is the only nutrient element in short supply in mineral forest soil. However, at more southerly latitudes both in Europe and North America, shortage of P, K, and Mg together with N-deficiency is commonly reported. The reduced response to N-fertilization in forests in various parts of Europe recently reported, might be a sign of N-saturation with increased NO_3-leaching as a likely consequence.

The problem of forecasting biogeochemical effects of slow environmental changes is extremely difficult. Indeed, the time factor is the greatest obstacle in experimental research in forest ecosystems. This applies in particular to research on the effects of the changes in chemical climate due to anthropogenic emissions within industrialized regions. While comparative field studies, process studies in the laboratory, and mathematical modelling may all deal with a wide range of conditions, large-scale field experiments can only comprise a limited number of treatments and site conditions for obvious cost reasons. It is uncertain whether acid afflicted forests can be saved or acid-induced impacts on forests or forest soils reversed. No natural process is known which would, in the near future, replenish nutrients leached from forest soils. Therefore, no aspect of ongoing research on this topic is more challenging or more urgent to soil scientists and the fertilizer industry than the effort to assess the impact of acid deposition on biogeochemical pathways and processes linked with overall soil productivity and plant growth. At any rate, liming and fertilization of forest land would probably present massive logistic problems given the expanse of area which could require such treatment.

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Nutrient Availability, Fertilizer Input, and Agricultural Yields

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Summary

Optimum nutrient levels in the soil provide maximum economic yields. The level of available nutrients (nitrogen, phosphorus, potassium) in the soil is influenced by nutrient removal and nutrient gains. Nutrient availability is controlled by physico-chemical factors such as nutrient concentration in the soil solution, nutrient buffer power, and diffusion coefficients and by biological factors such as root growth rate and root morphology. Biological factors are particularly important for the availability of phosphorus and potassium.

The yield plateau (maximum yield obtained by an increase in nutrient availability) is dependent on climatic and site factors such as temperature, solar radiation and water supply. Among these, available soil water frequently limits crop production.

Nutrient recovery is mainly influenced by losses in available nutrients. For potassium these losses may originate from K^+ fixation, which can easily be overcome by heavy fertilizer dressings, and on light soils by leaching. Leaching losses may be substantially reduced by appropriate timing and rating of K fertilizer application. Phosphate losses are mainly due to aging of phosphate. Aging can be reduced by correcting soil pH. Nitrogen losses occur by nitrate leaching, denitrification, and volatilization of NH_3. The latter process occurs particularly on soils with $pH > 7$. Denitrification losses may be considerable and thus merit further attention.

Fertilizer application is one of the most efficient means of increasing agricultural profitability. The level of agricultural yields (yield per ha) may be increased considerably by appropriate application of fertilizers. This may be of crucial importance for the productivity of farming and has in addition a beneficial impact on the whole economic system of a country.

1. Profitability and maximum yield potential

The causal relationship between nutrient availability, fertilizer application, and yield is shown in Figure 1. A linear increase in 'nutrient availability' results in a yield increase characterized by a saturation type of curve. Assuming that the increase in nutrient availability indicated in Figure 1 corresponds to a fertilizer input of 25 kg N ha^{-1} and the resulting yield increase amounts to 0.1 t ha^{-1} grain, the resulting profit for the farmer is satisfactory, since the output in terms of money is almost twice as

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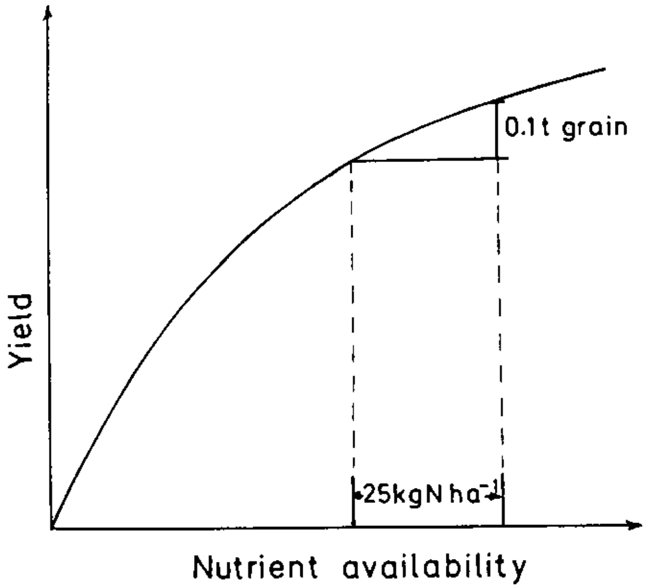

Fig. 1. Relationship between nutrient availability and yield increase. Marginal yield increment 0.1 t ha^{-1} grain obtained by 25 kg fertilizer N ha^{-1}.

high as the EEC input prices. 0.1 t grain, however, contains only 2.5 kg N which is just about ⅒ of the N fertilizer added in the above example. It may show that at the marginal range of profitability the fertilizer recovery rate is low, in the example shown here about 10%. This agrees with *Thevenet*'s experimental results (see p. 291 of this issue). The rest of the fertilizer not absorbed by the crop may be incorporated into soil organic matter or clay minerals; some of it, however, may be lost by leaching or denitrification.

Fertilizer response curves are not always of the saturation type but rather may consist of two linear components, one steep the other flat. Thus *Tinker* (see p. 193 this issue) showed that the yield increase *versus* phosphate availability was reflected by such a two component curve. Similar fertilizer response curves were reported by *Boyd [5]*. Optimum nutrient availability level is assumed to correspond to the intersection of the linears as an increase above the intersection point generally does not give a profitable yield increment on the basis of a single year's yield. If, as shown in Figure 2, applying 600 kg K ha^{-1} yields an increase of 0.2 t ha^{-1} grain per year the input in terms of money is about 3 to 4 times higher than the output. Such a calculation, however, is not completely correct, since it takes only one year into consideration. The beneficial effect of K^+ may last over several years. On soils with practically no K^+ leaching this beneficial effect may last 10 years and thus may be profitable. On soils with no K^+ leaching and with a high yield level it seems more profitable to produce at a higher level of available K^+ (see also *Beringer* in this issue, p. 91). This does not apply to nitrogen or phosphorus, since at a higher level of available nitrogen more nitrogen may be leached and/or denitrified and at a higher level of phosphate more available phosphate may be lost by aging.

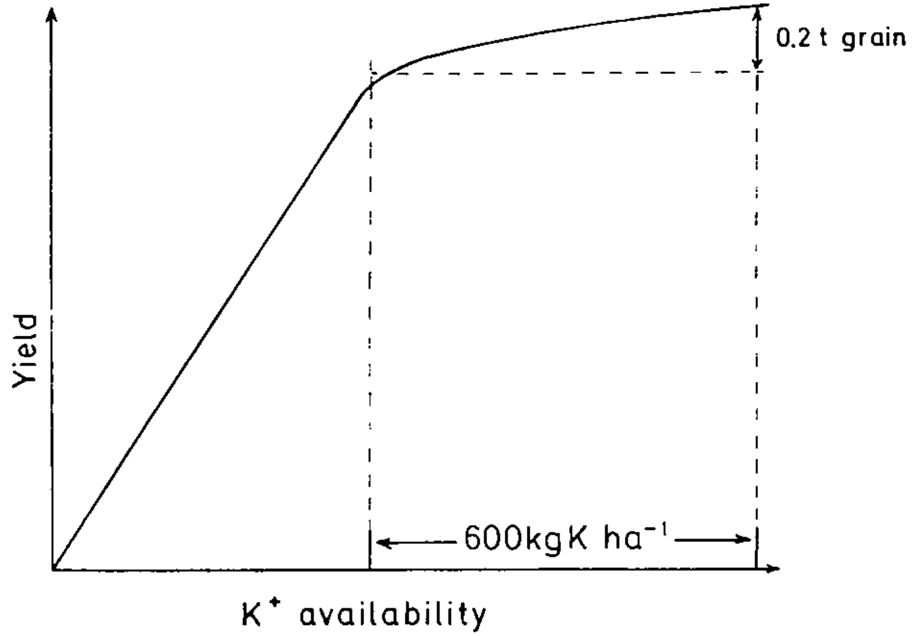

Fig. 2. Relationship between K^+ availability and yield increase. Yield increment of 0.2 t ha^{-1} grain obtained by 600 kg K ha^{-1}.

The maximum yield potential of a site is limited by noncontrollable factors such as water, temperature, solar radiation, soil texture, and rooting depth. These factors control the plateau of the yield curve as has been shown by *Shimshi [32]* and by *Eck [8]* for soil water. On many locations the water holding capacity of the soil can be a factor limiting the yield level. In a recent investigation *Rex [25]* was able to show that the available soil water in that part of the soil profile which is accessible to plant roots, has an essential impact on the yield level of cereals and also on the fertilizer requirement. It was demonstrated that even under the relatively humid conditions of Central Europe with fairly good rainfall distribution throughout the year periods of water stress affect plant growth on shallow soils, while on soils with a deep rooting profile (luvisol) under the same climatic and weather conditions no water stress was observed. In the first case (shallow soils, brown earths) higher rates of potassium fertilizer did not increase grain yield, although the level of available soil potassium was only medium. In the second case the higher potassium rate increased grain yield significantly at an already high level of available soil K (445 mg lactate soluble K kg^{-1} soil). *Tinker* (see this issue, p. 193) in evaluating numerous field experiments carried out in England, found that the strongest impact on the yield level was related to soil series which may mean water holding capacity, root growth and nutrient buffer power of the soils. In more continental and arid climate zones available soil water is by far the most important factor controlling the yield potential.

2. Problems of nutrient availability

A main difference between the availability of nitrate on one hand and the availability of phosphate and K^+ on the other hand is related to the fact that NO_3^- is very mobile in the soil medium while K^+ and phosphate are not. In most soils only the soil volume around the root is exploited for available K^+ and phosphate, since neither ion species is translocated over longer distances. Assuming a root length of about 8 km per m^2 in the upper soil layer (0–20 cm), a length which is representative for cereals, and a depletion of soil phosphate to about 1 mm distance from the root surface *(Hendriks et al. [12])* about 12.5% of the soil volume (upper layer) may provide phosphate to the roots. Phosphate more distant than 1 mm from the root surface is hardly available. For K^+ the extension of depletion is deeper *[7]* and the soil volume exploited may amount to about 25% of the upper soil layer. For this reason only a minor portion of the total amount of exchangeable K^+ or desorbable phosphate is reached by the roots. Thus on arable soils the quantity of available phosphate has to be about 10 times higher than the phosphate requirement of the crop. For potassium the ratio is about 1 (uptake of the crop) to 4 (available amount in the soil). Due to its high mobility, nitrate can be depleted by the crop to a very low level of about 10 to 20 kg NO_3-N ha^{-1} (see *Droeven* and *Rixhon,* p. 273 this issue). From this it follows that root length and root density is of much higher importance for the acquisition of phosphate and K^+ than for the acquisition of NO_3^-. Only in cases where NH_4^+ is the major nutrient form as in paddy soils, may root length have a stronger impact on the acquisition of soil N also. It is well known that root morphology and root length differ considerably between species. Thus *Steffens [36]* reported that the root length of *Lolium perenne* is about 5 times longer than the root length of *Trifolium pratense.* Even the same crop species may differ considerably in root length because of soil structure and profile. This has been shown by *Rex [25]* for winter wheat grown in the same area on different soil types. As can be seen from Table 1 the root length of wheat grown was much shorter on a shallow entisol than the root length of wheat grown on an alfisol.

Table 1. Root parameters of winter wheat grown in the field on different sites (after *Rex [25]*)

	Root length km m^{-2}	Root length m/culm	Rooting depth cm
Entisol	8.7	29.7	45
Entisol	12.9	50.2	45
Alfisol	14.4	37.6	100
Alfisol	21.3	45.0	100

The longer the root length the more soil volume can be exploited by the plant. It thus appears that at least for K^+ and phosphate nutrient, availability cannot be defined solely in physico-chemical terms but is also related to biological factors. This has been shown clearly by *Silberbush* and *Barber [33, 34]* in establishing a model for the uptake of K^+ and phosphate and by calculating the effect of variance in some availability factors on the nutrient uptake. The importance of the factors studied decreased in the following sequence: root growth rate>root radius>nutrient concentration in the soil solution>nutrient buffer power> diffusion coefficient. This finding demonstrates that the 'biological' factors (root growth rate, root radius) had a stronger impact on K^+ or phosphate uptake respectively than the physico-chemical factors (nutrient concentration, buffer power, diffusion coefficient). *Steffens [36]* also found that root length of grass and clover was closely correlated with phosphate uptake.

Since the biological factors of nutrient availability are not easy to measure or to predict, the estimation of the virtual availability of phosphate and K^+ meets with difficulty, even in cases where soil test data are available. In practical farming the nutrient buffer power has not, up to now, been considered an important factor of K or phosphate availability. Its importance has been recently shown by *Nair* and *Mengel [20]* in studying phosphate uptake by rye from eight soils differing by a factor of four in the P buffer power. The correlation between soil test data (CAL-P, EUF-P) and P uptake or P concentration in the crop was much improved by taking the P buffer power of the soil into consideration. This is shown in Table 2.

Table 2. Correlation coefficients for phosphate uptake and phosphate concentration in plant tops vs. EUF-P and vs. CAL-P. A = without integration of the phosphate buffer power; B = with integration of the phosphate buffer power (after *Nair* and *Mengel [20]*)

	A	B
P uptake vs. EUF-P	0.393^{+}	0.8870^{++}
P uptake vs. CAL-P	0.714^{++}	0.9415^{++}
P concentration vs. EUF-P	0.696^{++}	0.8982^{++}
P concentration vs. CAL-P	0.864^{++}	0.9231^{++}

$^{+}$ significant at 5% level $^{++}$ significant at 0.1% level

Following from what has been outlined above a better interpretation of soil test data may be obtained by considering the crop species, especially its rooting pattern, the soil type, especially the rooting depth, and the soil buffer power for phosphate or K^+ respectively (see also *Beringer,* this issue, p. 91).

3. Potassium availability

Exchangeable soil K^+ is considered to be the fraction which best reflects K^+ availability. However, in soils with 2:1 clay minerals containing interlayer K^+ the nonexchangeable soil K^+ may also contribute considerably to crop nutrition *[16, 19]*. It is for this reason that changes in exchangeable K^+ do not completely reflect the K uptake of crops (see *Hébert* and also *Köchl,* this issue, p. 249 and p. 177). Potassium uptake from the nonexchangeable pool is the higher, the lower the content of exchangeable K^+. From the total interlayer K^+ only a small proportion will be released and can be used by the crop. The quantitative determination of this available portion of nonexchangeable soil K^+ meets with difficulties. The K^+ release can be affected by dry soil conditions *[19]*. Plant species differ in their capability to feed from interlayer K^+ *[37]*. *Ryser* (see this issue, p. 129) showed that potatoes required a higher level of easily available K^+ than maize and maize a higher level than barley.

This sequence of crops may also show their capability to feed from interlayer K^+. In many cases interlayer K^+ alone does not provide enough K to attain maximum yield *[4]*. Table 3 shows some research data from field experiments with sugar beet on loess in Lower Saxony carried out by *Recke [24]*. It can be seen that in the absence of K^+ fertilizer much K^+ was provided by the nonexchangeable fraction. This is typical of soils derived from loess which contain much illitic clay mineral rich in interlayer K^+. On this soil, fertilizer K^+ still resulted in a significant yield increase. The highest beet yields were obtained on those treatments in which the nonexchangeable K^+ contributed only about 10% of total K^+ uptake.

Table 3. Potassium uptake of sugar beet from the exchangeable and the nonexchangeable soil K fraction related to sugar yield of sugar beet grown in the field on a luvisol derived from loess (after *Recke [24]*)

K fertilizer rate kg K ha^{-1}	K uptake, kg K ha^{-1}		Sugar yield dt ha^{-1}
	exchangeable	nonexchangeable	
0	185	290	115
250	320	200	118
500	530	95	128
750	610	20	125

LSD for sugar yield at 5% level = 8.7 dt ha^{-1}

4. Available nitrogen

Soil nitrogen is subjected to various chemical, physical, and biological processes (see *van Diest,* this issue, p. 13). The quantity of directly available nitrogen, NO_3^- and NH_4^+ in the soil profile is low in comparison with total soil N. Generally the organic soil fraction is considered to be the most important nitrogen pool providing available nitrogen by mineralization. However, soils rich in 2:1 clay minerals, may contain substantial quantities of interlayer NH_4^+, which in an analogous way to K^+ is not exchangeable, but can be released especially under the conditions of crop growth *[14]* while it is subjected to microbiological attack to a lesser degree *[9]*. Table 4 shows the change in nonexchangeable NH_4^+ in a soil profile derived from loess cropped under field conditions with wheat followed by oats *[23]*. The total quantity of NH_4^+ released during one year amounted to about 260 kg N ha^{-1}. From the data in Table 4 it is obvious that the deeper soil layers, 20 to 70 cm particularly, contributed much to the total release of nonexchangeable NH_4^+. This observation is in good agreement with results of *Mengel* and *Scherer [18]* who also found a release of nonexchangeable NH_4^+ in a loess soil profile amounting to about 300 kg N ha^{-1} $year^{-1}$. Until now this fraction of nonexchangeable NH_4^+ has been largely neglected in estimating soil nitrogen availability and in establishing nitrogen balances.

The estimation of available soil nitrogen has been much promoted by the introduction of the N_{min}-method *[43]*. A drawback of the method is the need to sample different soil layers over a rather short period. The EUF-method on the other hand

Table 4. Change of nonexchangeable NH_4^+ in the soil profile during a cropping period (after *van Praag et al. [23]*)

Profile depth cm	Under wheat 1972	Under oats 1973	Net release of NH_4^+ kg N ha^{-1}
	mg N kg^{-1} soil		
0–10	80.5	81.4	–
10–20	89.3	81.4	11.9
20–30	92.8	69.1	34.0
30–40	104	62.5	62.3
40–50	110	63.9	69.1
50–60	115	88.1	40.3
60–70	128	98.0	45.0
Total			262.6

requires a much simpler technique for collecting soil samples. As shown by *Németh et al. [21]* EUF at 80 °C extracts also organic N. The quantity of organic N thus recovered is considered as an indicator of the nitrogen mineralization potential of a soil (see *Németh*, this issue, p. 217).

The results obtained so far with the EUF-method are encouraging. Thus *Wiklicky et al. [44]* found a significant relationship ($r = 0.86^{+++}$) between available N obtained by EUF and the increase in sugar yield due to nitrogen fertilizer application. *Rex [25]* found in field experiments carried out on three different locations near Giessen a highly significant correlation ($r = 0.968^{+++}$) between N uptake by wheat and the EUF extractable nitrogen obtained from soil samples collected in the summer before the winter wheat was grown.

5. Fertilizer efficiency and recovery

The main components affecting plant nutrient balance in soils are fertilizer input, nutrient gain by weathering and biological processes (N_2 fixation), nutrient removal in the harvested crop, nutrient loss by leaching, denitrification, volatilization, and fixation. Nutrient input by fertilizer application and also nutrient removal by the crop are easily estimated. Good valuable data on nutrient removal are available even for fruits such as vine and apples (see *Mantinger*, p. 307 and *Fregoni*, p. 319 this issue). On most intensively cropped soils nutrient gains by weathering are negligible. But on young soils rich in 2:1 clay minerals K^+ release may be high so that they do not need K fertilizer for a considerable time *[16, 35]*. Gains of available nitrogen may be high where leguminous crops are grown. *McEwen* and *Johnston* (this issue, p. 47) reported that clover may fix 200 to 300 kg N ha^{-1} per year.

Fertilizer recovery is much affected by losses in available nutrients. For potassium, losses may occur by fixation and leaching. Potassium fixation is only a problem in particular soils *[2]* and may be overcome by heavy fertilizer doses *[6, 13, 28]*. Potassium losses by leaching may occur on many locations in soils low in 2:1 clay minerals. When much K (as fertilizer and farmyard manure) has been applied regularly over a long period substantial amounts of K^+ can be moved into the subsoil (see *Johnston* and *McEwen*, p. 157 this issue). The great differences in potassium fertilizer recovery, which for live stock farming may range from 20 to 100% (see this issue *van Diest*, p. 13 and *Walther*, p. 71), may be partially explained by leaching losses. Particularly on lighter soils and organic soils the potassium in urine released by grazing animals or applied as slurry may be largely leached by winter rainfall.

Phosphate loss by leaching is negligible on most soils. Only on organic soils may major phosphate leaching losses occur. Recovery of phosphate fertilizer is mainly affected by aging which means by rendering the available form unavailable (see also *Hébert*, this issue, p. 249). Recent work by *Barekzai [3]* has provided evidence that specific phosphate adsorption, probably in the binuclear form, can render fertilizer phosphate unavailable over short periods (3 to 6 months). Adsorption strength for phosphate increases with a decrease in pH. Hence phosphate aging may be particularly serious in acid soils. *Barekzai [3]* in studying different soils found the strongest aging effect in an acid brown earth soil (pH 4.6, KCl) while in a calcareous soil (pH 7.6; 67% $CaCO_3$) no major phosphate aging was found during the experimental period of six months. The most important results of Barekzai's investigation are shown in Figure 3. Phosphate availability in the brown earth as measured by phos-

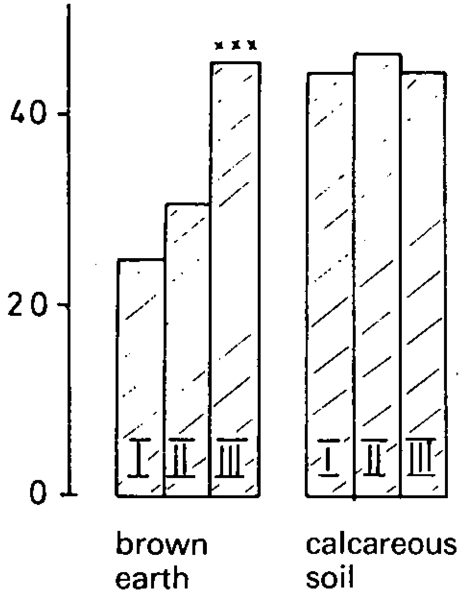

Fig. 3. Effect of time of phosphate fertilizer application on phosphate uptake of rye-grass. Pot experiment with an acid brown earth and a calcareous soil.

I Phosphate application 6 months before sowing

II Phosphate application 3 months before sowing

III Phosphate application directly before sowing (after *Barekzai [3]*)

*** significant difference ($p<0.1\%$) to treatment I and II.

phate uptake by *Lolium perenne* was significantly reduced when the phosphate fertilizer (superphosphate) was applied three or six months before sowing. In the calcareous soil, however, phosphate uptake of the crop was not significantly affected by the time of fertilizer application. The finding that phosphate aging occurs especially in acid soils is in good agreement with a study of *Sturm* and *Isermann [38]* who reported phosphate recovery rates between 50 to 80%. Highest rates were found on neutral soils with an optimum water regime, lowest rates on acid soils. Phosphate availability may be increased by liming *[29]*. However, in some soils, especially acid tropical soils, pH increase may have a negative effect on phosphate availability *[10, 11]*.

Phosphate efficiency and recovery is also a question of phosphate fertilizer type. Fertilizers containing apatite such as soft rock phosphates or partially acidulated phosphate fertilizers have a low solubility and are thus characterized by a poor recovery in soils with $pH > 5.5$ *[17, 45]*.

High nitrogen losses as volatile NH_3 occur on soils with $pH > 7$ in the soil solution *[39]* because of the equilibrium $NH_4^+ \rightleftarrows NH_3 + H^+$ which is shifted the more to the NH_3 the higher the pH. Thus on alkaline soils even NH_3 resulting from the ammonification of organic N can be lost from the system. In neutral and acid soils leaching and denitrification are the main processes affecting efficiency and recovery of fertilizer nitrogen. *Riga et al. [26]* carrying out field experiments on a luvisol derived from loess with ^{15}N labelled fertilizer found losses in the range of 20 to 40% of the application rate. Some important data by *Riga et al. [26]* are shown in Table 5. It appears that the crop (winter wheat), to which the labelled fertilizer was applied, took up about 50% of the N fertilizer dose while the uptake of fertilizer nitrogen by the following crops (oats, 2nd year, and two times forage maize, 3rd year) was rather low. Losses were higher with nitrate than with NH_4^+ fertilizer. Applying in two splits resulted in higher losses than applying in three; NH_4^+ fertilizer led to a higher nitrogen incorporation into the soil than nitrate fertilizer. The authors assume that nitrogen losses occurred mainly by denitrification. These experiments carried out in Belgium are considered as representative for West- and Central Europe with similar soils. Analogous results were reported by *Teske* and *Matzel [40]* carrying out lysimeter experiments with labelled urea. Even under the more humid conditions of Denmark *Kjellerup* and *Dam Kofoed [15]* found in lysimeter experiments with labelled nitrogen fertilizer that only abut 5% of the applied nitrogen was lost by leaching while the volatile losses amounted to 16%; crop recovery was 58%. Similar

Table 5. Balance of 100 kg N ha^{-1} fertilizer labelled with ^{15}N on a luvisol from loess cropped with winter wheat followed by oats and forage maize. Maize two times per year. Nitrogen fertilizer added as NO_3^- or NH_4^+ in two or three split applications (after *Riga et al. [26]*)

N fertilization	N uptake of the crop, kg N ha^{-1}			Soil	Loss
	Wheat	Oats	$2 \times$ maize		
$3 \times NO_3^-$	57.4	1.31	2.02	8.1	31.2
$2 \times NO_3^-$	46.7	1.27	1.54	8.2	42.3
$3 \times NH_4^+$	64.1	1.48	2.52	13.4	18.3
$2 \times NH_4^+$	45.6	1.70	2.74	14.1	35.9

fertilizer nitrogen losses (15–20%) were reported by *Olson* and *Swallow [22]*. These authors carried out field experiments with labelled NH_4^+ fertilizer under the continental climate conditions of Kansas USA. About 30% of the fertilizer nitrogen was recovered in the wheat grain. Most of the fertilizer nitrogen was fixed in organic form in the surface soil layer in a rather unavailable form.

It appears that if nitrogen fertilizers are applied correctly, the hazard of denitrification losses seems to be greater than that of leaching. Denitrification may lead to considerable losses during a short time provided that conditions are favourable for denitrification *[27, 42]*. In this respect straw application merits particular attention. It is well known that straw reduces the nitrogen availability in the soil considerably *[30, 41]*. To what extent the nitrogen fixed during the decomposition of straw will be recovered later, is an open question. *Schmeer [31]* found in model experiments that in fallow soil, straw application did not promote denitrification. In soils cropped with rye-grass (pot experiments), however, nitrogen incorporated into the organic N fraction due to straw application was particularly subjected to denitrification. *Araragi* and *Tangcham [1]* found high denitrification losses after the incorporation of straw into paddy soils. The losses originated less from the fertilizer nitrogen than from the organic soil nitrogen.

6. Targets and challenges

It is most important to achieve efficient utilization of energy and raw materials. Fertilizer application resulting in higher yields may contribute to this target. Excessive fertilizer application on the other hand may have an opposite effect and may even be hazardous to the environment. Hence appropriate fertilizer application is a challenge for modern farming. Fertilizer recovery can be improved by reducing plant nutrient losses from the soil profile. For potassium these losses occur mainly by leaching. Potassium fertilizer application thus should be adjusted to soil and climate conditions. Phosphate losses may occur by aging. Phosphate aging may be reduced by the application of appropriate phosphate fertilizers, by the timing of phosphate application and by providing optimum soil pH. Leaching and denitrification of nitrate as well as volatile losses of NH_3 are the main processes affecting the recovery rate of nitrogen fertilizers. Among these, denitrification is the process least understood. Its control is a challenge to researchers working on soil fertility.

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