Fertilizers and their efficient use

Summary

1. Fertilizers are substances that supply plant nutrients or amend soil fertility. They are the most effective means of increasing crop production and of improving the quality of food and fodder. With them, food for more people can be produced than this planet would otherwise support.

2. Fertilizer use is most effective (for obtaining high crop yields) on soils with high natural or improved fertility, but even on low fertility soils crop growth can be substantially improved.

3. Fertilizers are used in order to supplement the natural nutrient supply in the soil, especially to correct the (yield-limiting) minimum factor.

4. Some mineral and organic substances can be used directly as fertilizers, but most must be chemically processed in order to adapt them to plant needs (manufactured fertilizers).

5. The most suitable type of macro- or micronutrient fertilizer for a particular purpose depends on the speed of nutrient uptake desired (leaf spray or quick soil supply in water-soluble form, or slow-acting for a continuous supply), on the combination of nutrients wanted and on growth-enhancing side-effects such as mobilization of other soil nutrients).

6. The amount of fertilizer applied should be based on diagnostic methods, e.g. graded according to the content of available nutrients in the soil; plant analysis can also reveal hidden minimum factors (which may be eliminated by additonal fertilizer application). The upper limit of fertilizer use from the production point of view is determined by the limit of economic return.

7. Fertilizers should be distributed in such a way that all the crop plants in the field obtain an adequate amount; this is generally achieved by broadcasting granular fertilizers, and to some extent by spraying fertilizers in solution. The granules are either worked into the top layer of the soil or left for slow penetration by rain water.

8. Food quality is definitely improved by adequate use of fertilizers in general, and of mineral fertilizers in particular, provided they are applied in accordance with the latest concepts and knowledge. Quality in this context is understood to include not only the presence of quality components but also the absence of unwanted surplus nutrients and of toxic substances in plant products. Food production using adequate mineral and organic fertilizers prevents, and increases resistance to, many diseases. Agriculture which is based on the most up-to-date fertilizer practices may rightly be described as "health-promoting".

9. There is a risk that fertilizer use may adversely affect the environment (soil, water or air) beyond the low and harmless level which is unavoidable in primary production ; but, in practice, any pollution which may occur beyond this level is mainly the result of faulty manurial practices, often of excessive use of organic manures.

10. Fertilizer use has been shown to be an effective means of enhancing crop production for more than a century. It has contributed largely to the major increases in yields which have been achieved worldwide and to a substantial improvement of human and animal health. The degree of pollution, which is to some extent unavoidable, can be kept to an insignificant level typical of primary production.

In brief, fertilizers applied with the latest 'know-how', are an important source of wealth for the farmer, and of food and health for the population.

Why use fertilizers ?

Use of fertilizers is needed for all types of long-term crop production in order to achieve yield levels which make the effort of cropping worthwhile.

Modern fertilizer practices, first introduced more than a century ago and based on the chemical concept of plant nutrition, have contributed very widely to the immense increase in agricultural production and have resulted in better quality food and fodder. As a beneficial side-effect, the fertility of soils has been improved resulting in more stable yield levels, as well as in a better (nutrition-induced) resistance to some diseases and climatic stress. Furthermore, the farmer's economic returns have increased due to more effective production.

The purpose of fertilizer use, especially for higher yields, is identical in temperate and tropical climates:
- to supplement the natural soil nutrient supply in order to satisfy the demand of crops with a high yield potential
- to compensate for the nutrients lost by the removal of plant products or by leaching, etc.
- to improve unfavourable or to maintain good soil conditions for cropping.

Nutrients required by plants

Plants contain practically all (92) natural elements but need only 16 for good growth. Thirteen of these are essential mineral nutrient elements, commonly abbreviated, though with less precision, to "nutrients" (Box 1). They must be provided either by the soil or by animal manure or mineral fertilizer. Some other mineral nutrient elements, e.g. Na, Si, Co, have a beneficial effect on some plants but are not essential.

Box 1: Essential and beneficial mineral nutrients for plants.

Essential mineral nutrients (13) required for growth (of equal importance physiologically):

Macronutrients (6) of which the critical contents in plants are 2-30 g/kg of dry matter:

Major nutrients (3), applied in fertilizers for almost all crops on most soils:
N = nitrogen (taken up as NO_3^- or NH_4^+)
P = phosphorus (taken up as $H_2PO_4^-$ etc.)
K = potassium (taken up as K^+)

Secondary nutrients (3), applied in fertilizers mainly for certain crops on some soils:
S = sulphur (taken up as SO_4^{2-})
Ca = calcium (taken up as Ca^{2+})
Mg = magnesium (taken up as Mg^{2+})

Micronutrients (7) of which the critical contents in plants are 0.3-50 mg/kg of dry matter:

Heavy metals (5):
Fe = Iron
Mn = manganese (Fe, Mn, Zn, Cu taken up as divalent cation or chelate)
Zn = zinc
Cu = copper
Mo = molybdenum (taken up as molybdate MoO_4^{2-})

Non-metals (2):
Cl = chlorine (taken up as Cl^-)
B = boron (taken up as $H_2BO_3^-$, etc.)

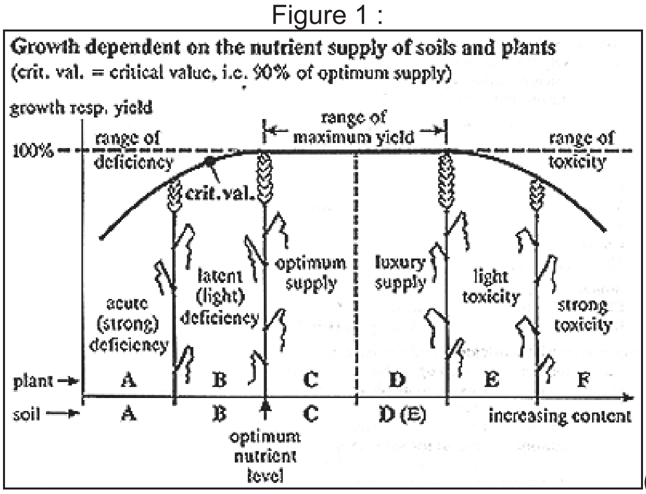
Some beneficial nutrients useful for some plants:
Na = sodium (taken up as Na+; can partly replace K for some crops)
Si = silicon (taken up as silicate, etc., e.g. for strengthening cereal stems to resist lodging)
Co = cobalt (mainly for N-fixation of legumes)
Cl = chlorine (useful for some crops in greater than essential amounts, for osmotic regulation and improved resistance to some fungi)
Al = aluminium (perhaps beneficial for some plants, e.g. tea ?).

Fertilizer use must also take into account the nutritional requirements of animals and human beings consuming the crops. It may, for example, be necessary or advisable to supply, for the benefit of grazing animals, increased amounts of elements which are not essential to the plants, e.g. of Na, or of essential elements like selenium and cobalt as a precaution against nutritional disorders caused by deficiencies.

Since hardly any soil can supply all the nutrients needed in sufficient amounts to meet the demands of high-yielding crops, the deficit must be made good by adding fertilizers and/or manures.

As a general rule, nutrient uptake should always be ahead of the production of plant dry matter during the vegetation period. The total amount needed at a given stage can be estimated from the critical nutrient level required in plant tissue for the optimum functioning of biochemical processes. In fact the nutrient contents of crops are usually somewhat higher than the critical levels, i.e. they are in the "normal" or optimum nutrient range (Fig. 1). On the other hand, a large surplus or luxury supply is unwanted, not only because of the money wasted on excess fertilizer but also because it may upset the nutrient balance.

Figure 1 :



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Plants, in general, contain maximum amounts of nutrients in the later stages of growth shortly before maturity (usually more than is actually needed), but nutrient balance calculations are for the most part based on the somewhat smaller amounts that are, or could be, removed from the field at the time of harvest. Relevant nutrient removal data (corrected, or not, for possible luxury uptake) should be established for all crops and farming systems.

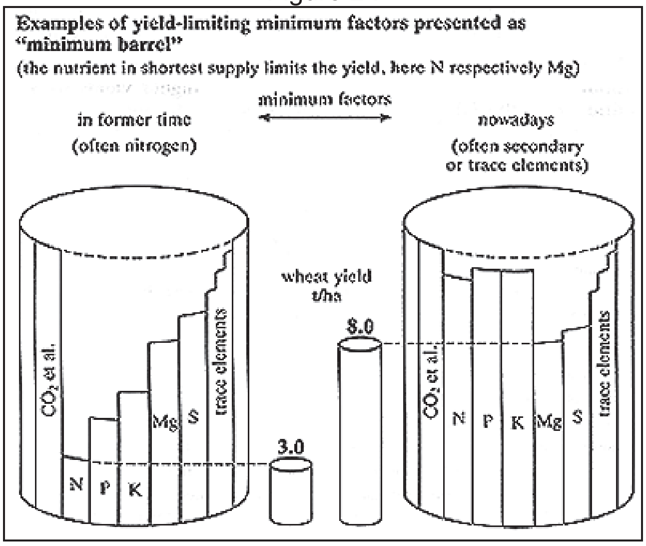
The amounts of nutrients which need to be added in fertilizers and manures depend on:

- the nutrient requirement of a crop for the desired yield level;
- the nutrient supply in the soil, which can be estimated by diagnostic methods.

No fertilizer or manure is needed if the uptake of a nutrient from the soil does not lead, even in the longer term, to any significant depletion of the soil reserves. This is often the case with micronutrients.

Fertilizer use should concentrate especially on the so-called "minimum factor" which, according to the Law of the Minimum, critically limits plant growth (Fig. 2).

Figure 2 :



Soil fertility and its improvement

The best results from fertilizer use are obtained on the basis of a high fertility level. Soils differ widely in their ability to meet plant requirements; most have only a moderate natural soil fertility but can be considerably improved by soil amendments. For successful farming the natural fertility of the soil is often less important than its potential productivity after the removal of its inherent limiting factors.
The term "soil fertility" comprises a complex of properties which should be optimized as far as possible (Box 2).

Box 2. Components of soil fertility.

Soil depth (determining the volume of soil accessible to the root system). Most arable crops prefer about one metre without any obstructing layer.

Soil structure (based on size distribution and aggregation of particles). This determines the distribution of pore sizes which is decisive for the supply of air and water to the roots.

Soil reaction (an indicator and regulator of chemical processes and equilibria).

Content of nutrients in different degrees of availability.

Storage capacity for soluble nutrients from the soil and fertilizers.

Humus content and quality (including proportion in mineralizable form).

Quantity and activity of soil organisms as agents of transformation processes.

Content of detrimental or toxic substances, either naturally occurring (e.g. salts in saline soils, aluminium in extremely acid soils) or man-made (e.g. from pollution).

A highly productive soil with high fertility, natural or improved,

- mobilizes soil nutrients from the reserves;
- transforms fertilizer nutrients into easily available forms;
- stores water-soluble nutrients in easily available forms, thus preventing leaching;
- offers the plants a balanced nutrient supply, due to its self-regulating system;
- stores and supplies sufficient water;
- maintains good soil aeration for the oxygen requirements of roots;
- does not 'fix' nutrients, i.e. convert them into unavailable form.

Soils with a high natural fertility can produce substantial crop yields even without added fertilizer, but can produce even higher yields with an additional supply of the critical nutrients. Good soil fertility provides the basis for all other measures for successful farming and should not be neglected.

There are alternative ways of making use of soil fertility in farming:

- exploitation i.e. farming without any added fertilizer (e.g. in shifting cultivation);
- utilization of as many components of soil fertility as possible without compensation and yet without negative yield effects (e.g. by applying only moderate amounts of fertilizer N and P);
- maintenance and improvement of soil fertility to assure consistent high yields (e.g. by compensating for losses due to removal and by soil amendments to improve fertility).

The large differences in fertility between different soil types and sub-types must be taken into account.
Some indications are given below for regional particularities.

Soils of the humid tropics
- are partly very acid (liming is required, generally to pH 5.5-6.5);
- are often low in available P or liable to P-fixation (use of phosphate fertilizer is therefore often essential, combined if necessary with liming);
- in very humid areas are often low in available K, Mg and S (therefore there are high fertilizer requirements for these nutrients);
- often have a low sorption or storage capacity for nutrients (so fertilizer application should be split between several dressings);
- are often low in available N, although the decomposable organic matter is rapidly mineralized.

Soils of the sub-tropics are characterized by:
- water shortage (so, without irrigation, fertilizer use must be suitably adapted to efficient water use);
- N being the main critical nutrient, on account of the low humus content;
- widespread P deficiency, especially in sandy soils;
- neutral soil reaction (therefore often a shortage of available Fe and Zn);
- a generally good supply of S, Mn and B;
- risk of salinity.

Soils of humid temperate zones are marked by:
- widespread soil acidity which requires liming;
- partly obstacles to root growth (e.g. hard layers in subsoil);
- often insufficient aeration (poor natural drainage of heavy soils);
- generally shortage of available N and often of P, K, Mg;
- low nutrient reserves in sandy soils, also only little storage and therefore considerable leaching with water surplus;
- partly fixation of P and Mo (due to natural soil acidity) and Cu (in organic soils);

- climatic cold stress retarding nutrient uptake, etc..

Soil reaction and liming

For soils to be highly productive, they must first be in the optimum pH range (the values mentioned below refer to measurements in water suspension).

Values under pH 4.5-5.0 can be very damaging to plants ("soil acidity syndrome") by causing nutrient deficiencies (of P, Mg, etc.) and toxicities (of Al, Fe, Mn). Liming should be employed to raise the pH to at least about 5.5. A pH range of 5.5-6.5 seems to be satisfactory for moderate yields of most crops. Optimum pH values, resp. ranges, for high yields have been established for different soils and rotations.

All kinds of liming materials may be used to increase the pH. In many acid soils, lime containing magnesium carbonate provides a double benefit by adjusting pH and by supplying Mg. However, liming experiments, especially in the tropics, often give disappointing results, not because liming is ineffective but because it is not complemented by appropriate fertilizer use to correct other critical factors.

In neutral to slightly alkaline soils under high yield conditions, use of acidifying N fertilizers can be advantageous through resulting in a better supply of micronutrients such as Mn or Zn (which tend to be somewhat immobilized).

Gypsum is a useful soil amendment on saline/sodic soils (for removal of Na and supply of structure improving Ca).

Organic fertilizers inclusive manures

A number of organic materials can be useful soil amendments and suppliers of nutrients (Box 3). Since many are waste products, they can sometimes be cheaply available, especially if used near to where they are produced. Some farm wastes are used because recycling is the only, and moreover beneficial, means of disposing of them. If waste material of any kind has to be bought in by the farmer, it must be comparatively cheap and have no detrimental or toxic effect, and it must be profitable.

Box 3. Types of organic fertilizers inclusive manures.

Naturally occurring material, e.g. peat.

Farm wastes:
- crop residues (straw, leaves, etc.)
- animal manures (farmyard manure, liquid manure, slurry)
- compost (mixture of decomposed plant residues etc.)
- green manures (leguminous or other crops incorporated into the soil).

Residues from processing of plant products, e.g.:
- fibres (from paper industry) and pressed cakes (from oilseeds)
- wood materials (bark, sawdust; lignin from paper industry)
- molasses (from sugar industry).

Residues from processing of animal products, e.g.:
- blood-, horn- and bone-meal
- leather dust, etc.

Town wastes:
- composted household refuse
- sewage sludge.

Soil inoculants (e.g. living micro-organisms.).

Processed organic wastes, especially if they are to be sold, generally require mechanical and chemical preparation, i.e. they must be dried, ground, mixed, granulated, neutralized, complemented by the addition of particular nutrients, and free of pathogenic germs.

Important criteria for organic fertilizers are:
- dry matter content;
- total and easily mineralizable humus;
- total and quick-acting N:
- C/N ratio;
- contents of substances detrimental to plant growth or product quality (heavy metals in particular should be below established critical limits).

The rates at which they are applied should take into account both the expected nutrient supply available to the crop (for N in farmyard manure, about 20-30 % of the amount applied is available to the crop during the first year) and the need to minimize nutrient losses or detrimental effects.

Organic matter, applied as a fertilizer, has a complex influence on plant growth (Box 4). The minimum amount required for sustaining optimum activity of soil life is in the range of 3-5 t/ha. In high yielding cereal fields the decomposition of very high amounts of straw must be aided by adding about 1 kg of N per 100 kg of straw.

Box 4. Effects of organic materials on plant growth (via the soil).
Improvement of physical soil properties, either directly or by activating living organisms in the soil;
- better soil structure as a result of soil loosening and crumb stabilization;
- better water-holding capacity and soil aeration;
- surface protection by mulch layer.

Influence on chemical properties:
- sorption of nutrients by humic acids;
- supply of nutrients from decomposition of humus and from dissolving action on soil minerals:
- fixation of nutrients in organic complexes (mainly a negative influence for a shorter or longer period);
- effects of growth regulators produced in soil (e.g. growth inhibitors accumulating in monocultures, and antibiotics protecting against some bacterial diseases).

Soil inoculants may, for example, contain Rhizobium spp. for inoculating seeds of leguminous crops where suitable strains are not present in sufficient quantity. The amount of nitrogen gained by legumes through an effective Rhizobium symbiosis is usually in the range 50-200 kg/ha N, whereas in paddy fields the Azolla/Anabaena symbiosis amounts up to 400 kg/ha N. Application of other bacteria to promote N fixation from the atmosphere, e.g. Azotobacter spp., or to enhance the release of P and K from soil minerals, has not yet proved successful.

Special problems concerning organic fertilizers, esp. manures, result from high rates of application of slurry (from cattle or from pigs) in certain areas, and from town compost and sewage sludge which may contain an excess of certain nutrients or be contaminated with heavy metals or toxic organic substances.

Mineral fertilizers

Numerous mineral fertilizers have been developed to supplement soil nutrients and to meet the high requirements of crops (Box 5). They are generally mineral salts, except for some organic chemicals such as urea which are easily converted into salts.

Box 5. Types of mineral fertilizers. (according to different criteria)

Method of production:

- "natural" (as found in nature or only slightly processed);
- synthetic (manufactured by industrial processes).

Number of nutrients:
- single-nutrient or straight fertilizers (whether for major, secondary or micro nutrients);
- multinutrient (multiple nutrient) or compound fertilizers, with 2, 3 or more nutrients:

Type of combination:
mixed fertilizers, i.e. either a physical mixture of two or more single-nutrient or multinutrient fertilizers (for granular products this may comprise a mixture of separate granules of the individual ingredients, or granules each containing these ingredients);
complex fertilizers, in which two or more of the nutrients are chemically combined (e.g. nitrophosphates, ammonium phosphates).

Physical condition:
- solid (crystalline, powdered, prilled or granular) of various size ranges;
- liquid (solutions and suspensions);
- gaseous (liquid under pressure, e.g. ammonia).

Mode of action:
- quick-acting (water-soluble and immediately available);
- slow-acting (transformation into soluble form required).

The customary classification into single- or multi-nutrient fertilizers usually refers only to the three major nutrients. Many so-called single-nutrient fertilizers actually supply more than one nutrient, e.g. ammonium sulphate which contains both N and S.

The nutrient content, or grade, may refer either to the total or to the available nutrient content, and may be expressed traditionally for some nutrients in oxide form (P2O5, K2O) or in elemental form (N, P, K).

In order to guarantee the farmer good quality and to exclude hazards, the composition of mineral fertilizers, and the trade in mineral fertilizers, are officially controlled in many countries (in Germany since 1918). Recently, with the object of obtaining better control of pollution, special regulations have been introduced for the application of certain organic fertilizers and manures (e.g. slurry). In the near future governmental regulations will be introduced for fertilizer application in general, in order to minimize any avoidable fertilizer-induced pollution or food contamination. Many fertilizer products, however, are not yet subjected to legal control, though there is an increasing voluntary standardization by producers in order to ensure uniformity of quality, especially for organic and organic-mineral fertilizers. Even so, there still remain a number of "unorthodox" fertilizers (mainly organic) on the market which, in spite of "expert" recommendations, have little real value.

Nitrogen fertilizers

They are valued according to their total N-content, the different N-forms (which determine the rate of action) and side-effects if any (Box 6).

Box 6. Types of N fertilizers (N content refers to total N)

Ammonium fertilizers:
- ammonia (80 % N), ammonium sulphate (21 % N), ammonium bicarbonate (17 % N), all moderately quick-acting. Uptake by plants can be retarded by addition of nitrification inhibitors, e.g. dicyandiamide (DCD).

Nitrate fertilizers:
- calcium nitrate (16 % N), sodium nitrate (16 % N), Chilean nitrate, all quick-acting and increasing soil pH.

Ammonium nitrate fertilizers:
- ammonium nitrate (about 34 % N), calcium ammonium nitrate which is a combination of ammonium nitrate and calcium carbonate (21-27 % N), ammonium sulphate nitrate (26-30 % N).

Amide fertilizers:
- urea (45-46 % N), calcium cyanamide (20 % N).

Solutions containing more than one form of N:
- urea ammonium nitrate solution (28-32 % N).

Slow release fertilizers:
- either derivatives of urea with N in large molecules, or granular water-soluble N fertilizers encased in thin plastic film, but slow or very slow-acting according to type of coating; partly including a quick-acting component.
- or other means of slow release, e.g. sulphur coated urea (SCU)

Multinutrient fertilizers containing N
- NP: nitrophosphate NP (20-23 % N, 20-23 % P2O5)
  monoammonium phosphate = MAP (11 % N, 52 % P2O5)
  diammonium phosphate = DAP (18 % N, 46 % P2O5)
  liquid ammonium polyphosphates (e.g. 12 % N, 40 % P2O5);
- NK;
- NPK.

Nitrate N in the soil solution is immediately available and thus acts quickly but is most liable to leaching. Plants take up N mainly in nitrate form. Ammonium N, although fully available, has a somewhat slower effect, because it is first adsorbed and then only gradually released and nitrified.

Amide N, e.g. as urea, must first be transformed to ammonium as a result of microbial action which is dependent upon temperature. However, urea applied as a foliar spray provides the quickest possible N supply, but for this purpose the biuret content must be below 0.3 %. Calcium cyanamide, in addition to its fertilizer value, has herbicidal and fungicidal properties due to intermediate decomposition products.

For most purposes the different forms of N give about the same yield responses (apart from any possible side-effects or gaseous losses which occur more with urea than with salts) because quick action, via the soil, is only needed in special cases, e.g. for application in spring at rather low temperatures. Considering the S-shaped curve of plants' nitrogen requirements during the vegetation period, most N fertilizers tend to act rather too quickly. This means that high rates given wholly at sowing time often provide too much for the young plant but not enough during the later stages. This can be compensated by dividing the total N application between a basal application at sowing and one or more topdressings. The N supply from slow release fertilizers is theoretically better adapted to the curve of N uptake but depends on temperature. Being more expensive, they are mostly confined to domestic garden use.

The most important side-effect of nitrogenous fertilizers to be considered is the acidifying effect of ammonium and amide fertilizers. Since this has to be counteracted by liming, it is convenient to express it in terms of the equivalent loss of CaO (Table 1).

Table 1. Soil acidification by nitrogen fertilizers.

Fertilizer	**Amount of CaO to compensate the soil acidification induced by 1 kg N***
Calcium ammonium nitrate (27 % N)	0.6

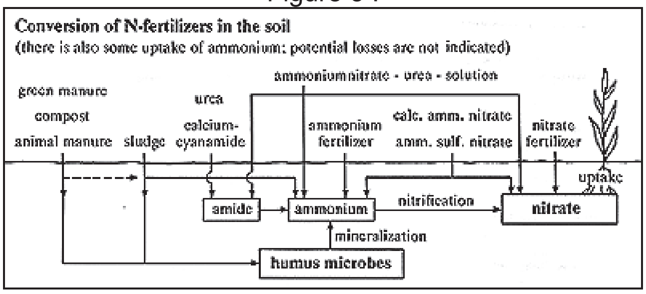
Ammonia, urea, ammonium nitrate	1
Diammonium phosphate, ammonium sulphate nitrate	2
Ammonium sulphate	3
* On the basis of 50 % utilization rate.	

N dynamics in soils are very complex (Fig. 3). The important process of nitrification (transformation of ammonium to nitrate by bacteria) proceeds rather quickly when temperatures are warm. At temperatures of 20-25 °C an application supplying 50-100 kg/ha N would nitrify in about one to two weeks.

Nitrification can be delayed for several weeks by adding special nitrification inhibitors to the fertilizer. This can be useful for preventing an undesirable accumulation of nitrate in vegetable crops or reducing loss by leaching.

The utilization rate of N in fertilizers is mostly about 50-70 % during the first year.

Figure 3 :



In terms of energy the production of 1 kg N in fertilizer requires the equivalent of about 1 litre of oil. The energy required for fertilizers is per area-wise about one-third of total energy requirement. However, the energy output of the principal crops is about two to three times the energy input. More effective fertilizer use, particularly of N fertilizers, therefore means a saving in energy.

Phosphate fertilizers

Box 7. Types of P fertilizers
(P2O5 content refers to 'available' portion, except for rock phosphate where it means total cotent)

Water-soluble types (quick-acting):

- single superphosphate (18-20 % P2O5);
- triple superphosphate (45 % P2O5).

Partly water-soluble types (quick- and slow-acting):
- partly acidulated phosphate (23-26 % P2O5, at least one-third water-soluble).

Slow-acting types:
- dicalcium phosphate (citrate-soluble);
- basic slag (citric acid-soluble).

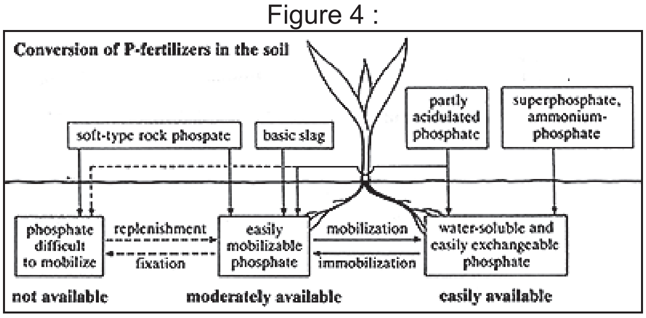
Very slow-acting types:
- rock phosphate (finely-powdered soft type, e.g. 30 % P2O5), with reactivity indicated by formic acid-solubility; permitted minimum is about one-half of total P2O5 content).

Multinutrient fertilizers containing P:
- NP (see N fertilizers, Box 6);
- PK (mixtures very commonly used);
- NPK (may contain about one-third or more water-soluble P for quick supply and two-thirds slow acting P for

'Availability' is measured by solubility in specified extractants as an indication of the rate of transformation under various soil conditions. Water-soluble P (e.g. mono-calcium phosphate) is easily available to plants and remains available, though to a somewhat less extent after immobilization into other forms, this transformation being retarded by granulation and placement of the fertilizer. Citrate-/citric acid-soluble P is moderately available to plants and is suitable for many purposes over a wide range of acidic to neutral soil conditions except where quick action is required. Formic acid-soluble P in soft powdery rock phosphate is only very slowly available to plants; its reactivity (release of soluble P) is somewhat better where soils are warmer, moister and more acidic, but still above the acidity damage range.

Under conditions of intensive farming on well, or quite well supplied soils, for most purposes, the common phosphate fertilizers give about an equal yield response per unit of 'available' P2O5. Water-soluble P, however, is superior for crops with a short growing season and limited root system in deficient soils. The dynamics of phosphate fertilizers in soil is illustrated in Fig. 4.

Figure 4 :



NP fertilizers are generally superior in placement application; gaseous losses may occur from surface-applied diammonium phosphate on neutral soils. Phosphate fixation, i.e. the transformation of soluble fertilizer P into unavailable forms, is fortunately restricted to special soil conditions, e.g. high content of active Al and Fe, and is rather insignificant from a practical point of view in most soils. The utilization rate of P in fertilizers is usually about 15 % in the first year but only 1-2 % per year thereafter, with the result that only about two-thirds is taken up by the end of thirty years.

Potash fertilizers

These are mainly derived from geological saline deposits. Although low-grade, unrefined materials can be used directly, most fertilizer use is now in the form of higher-concentration products, all of which are water-soluble and quick-acting:

- potassium chloride, or muriate of potash (40-60 % K2O), the lower grades providing Na in addition to K2O, with or without Mg;
- potassium sulphate (50 % K2O), for Cl-sensitive crops (e.g.potatoes, tobacco);
- potassium magnesium sulphate, also known as sulphate of potash magnesia or Patentkali (e.g. 40 % K2O, 6 % Mg).

Recently, several industrial residues containing K, e.g. filter dust, have been developed for use as slower-acting forms, especially where it is desired to avoid loss by leaching.

Potash fertilizers should generally be applied at sowing time. The K+ ions are adsorbed in the soil and thus remain available, yet largely protected against leaching. However, split application is advisable (e.g. part autumn, part spring) in sandy soils where higher leaching losses may be expected. Some immobilization into clay lattice layers reduces availability but strong fixation into completely unavailable forms is fortunately restricted to a few special soil types. The utilization rate of K in fertilizers is about 50-60 % during the first year.

Secondary nutrient fertilizers

Magnesium fertilizers are either quick-acting soluble salts (mainly sulphates) or in slow-acting form (their nutrient content may be expressed in terms of either Mg or MgO).

Quick-acting types:
- magnesium sulphate, in the forms of Epsom salts (10 % Mg) or kieserite (16 % Mg);
- potassium magnesium sulphate (see under potash fertilizers) or NMg fertilizers.

Slow-acting:
- magnesium carbonate (dolomitic lime).

The utilization rate and potential leaching loss of water-soluble Mg are similar to K.

For soils needing liming, the cheapest source of Mg is a lime containing Mg, of which a high rate of application can ensure a good supply of Mg for several years without detrimental effect.

Sulphur: The increasing incidence of sulphur deficiency, especially in crops with high requirements such as oilseed rape and legumes, has considerably increased the use of sulphur fertilizers. Water-soluble sulphates, e.g. potassium sulphate or magnesium sulphate (18 % S), are most effective for the treatment of growing crops, as also is ammonium sulphate (24 % S) where its acidifying effect can provide an added benefit. Slower-acting types such as pure gypsum (18 % S) or the by-product calcium sulphate of superphosphate (14 % S) should be used if leaching poses a problem. (Yellow) elemental sulphur (100 % S) may be applied either in powdered form or as the coating in sulphur-coated urea (10-20 % S). Both the water-soluble and slower-acting forms are suitable for application at sowing time.

Calcium is only applied other than for liming in cases of definite deficiency. Sources which do not raise the pH are:

Quick-acting:
- calcium chloride, solid or in solution;
- Ca components of foliar sprays.

Slow-acting: gypsum.

Soil application, though simple, is often disappointing because of restricted translocation within the plant; in such cases a foliar spray is preferable.

Micronutrient fertilizers

Apart from the widespread recognized areas of natural deficiencies of micronutrients, attention should be given to the possibility that they may become critical "minimum factors" as other critical factors are amended and yield levels rise. They may be applied either as single-nutrient fertilizers or as supplements in macronutrient fertilizers. The quickest and commonest method of correcting deficiencies is by foliar application.

Iron is usually applied as a foliar spray in the form of chelates such as Fe-EDTA (9 % Fe) or Fe-EDDHA (6 % Fe). For soil application the latter has the advantage that it is more stable in neutral soils.

Manganese deficiency occurs mainly in slightly acidic to neutral soils. Both Mn sulphate (24-32 % Mn) and Mn-EDTA (13 % Mn) are water-soluble and quick-acting, and are suitable for foliar or soil application; Mn oxides may be used as a means of increasing the soil's reserves. Indirect improvement of the soil supply may be achieved by using acidifying N fertilizers.

Zinc is usually applied to deficient crops as a foliar spray of Zn sulphate (e.g. 23 % Zn) or Zn chelate (e.g. Zn-EDTA), for soil application a rate of 5-10 kg/ha Zn is recommended.

Copper deficiency may most easily be corrected for a longer period by soil application of 5 kg/ha Cu as Cu sulphate or oxides, etc. Chelates or neutralized Cu sulphate (25 % Cu) are suitable for foliar spraying of deficient crops.

Boron needs vary widely. As a prophylactic treatment for crops with high demands, soil application of borax (11 % or 22 % B) is advisable, the rate depending on the crop (0.5-2.0 kg/ha B), but no more should be given than needed for that crop in order to avoid the risk of a damaging surplus affecting a succeeding crop with a low requirement. A better distribution can be obtained by incorporating the boron in e.g. phosphate or multinutrient fertilizers. Polyborates seem to be superior to borax for foliar application (at about 1 kg/ha).

Molybdenum is required in only very small amounts: 0.5-1.0 kg/ha Mo for soil application of water-soluble Na molybdate or ammonium molybdate (40-50 % Mo); less than 100 g/ha Mo for foliar application.

Multinutrient fertilizers

Since crops often require an additional supply of several nutrients, special combinations with different nutrient ratios offer a considerable simplification and facilitation of fertilizer application. Most combinations are of the complex NPK-type, which contains N in part as ammonium and part as nitrate, one-third of the phosphate in water-soluble form and K mostly as chloride.

Diagnosis of fertilizer requirements

The still widely used practice of deciding rates of fertilizer use on the basis of local experience or general data for crop requirements is certainly useful for obtaining at least medium yield levels, but neither very effective nor economic.

Soils differ widely in their capacity for providing nutrients, depending on the amount of total reserves, on mobilization or fixation dynamics, accessability of the chemically available nutrients to the roots, etc.

Therefore it remains necessary to assess empirically the nutrient status of soils and plants in order to provide guidelines for effective fertilizer use.

Box 8. Methods of diagnosis.

Optical (plant observation):
- extent of deviation from full green colour;
- identifiable deficiency symptoms;
- growth difference compared with plots without fertilizer.

Chemical:
- soil testing:
  - content of available nutrients as a basis for fertilizer requirements;
  - pH, salinity, etc.

- plant testing:
  - spot tests, e.g. on the leaf, or with extracts;
  - plant analysis, using nutrient contents as a basis for estimating additional requirements

Box 9. Checklist before applying fertilizers.

1. Are other agronomic factors (variety, plant protection, water, etc.) satisfactory?
2. Are basic requirements of soil fertility fulfilled? (pH, organic matter, stable porous soil structure, absence of compacted layer, good drainage, no salinity).
3. Which nutrients need not be considered in this particular soil? (Many soils have adequate Ca, Fe, Mo, etc.)
4. Which nutrients need not be considered every year? (e.g. Mg may be supplied in liming material, Zn and Cu in long-lasting, slow-acting fertilizers, and S may not be needed for crops with low requirements)
5. What amounts of fertilizer P and K are needed at sowing time? (To be determined by soil testing or, in well supplied soils, estimated from nutrient removal by crop)
6. What kind and amount of N fertilizer is needed, and when ? (Either based on expected yield or soil testing)
7. Which nutrients may have special problems in this soil (e.g. fixation of Mn) or are needed in large amounts by particular plant species (e.g. S for oilseed rape, B for beet and legumes)?

Diagnosis by plant observation

A normal dark green colour characterizes a good nutrient supply, but any change to light green or yellowish tinges, suggests a deficiency, provided other factors such as extreme temperatures, diseases, spray damage, air pollution etc. are not responsible. The easiest means of diagnosis is by identification from colour photographs showing deficiency symptoms in the particular crop concerned (see also Box 10 below). The precise cause may, however, not be easy to establish from observation alone, particularly in cases of latent deficiency ("hidden hunger") for which chemical methods will usually be needed.

Box 10. Brief key to deficiency symptoms.

Symptoms	**Deficiency**
Symptoms appearing first on older leaves:	
Chlorosis starting from leaf tips	N
Necrosis on leaf margins	K
Chlorosis mainly between veins (which remain green)	Mg
Brownish, greyish, whitish spots (e.g. on cereals)	Mn
Reddish colour on green leaves or stem	P
Symptoms appearing first on younger leaves:	
Mottled yellow-green leaves with yellowish veins	S
Mottled yellow-green leaves with green veins	Fe
Brownish black spots (e.g. on legumes, potatoes)	Mn
Youngest leaf has white tip	Cu
Youngest leaf is brownish or dead (e.g. on beet)	B

A direct comparison in the field, sometimes called the "window" technique, may be obtained by using a small control plot without fertilizer (by stopping the distributor for some metres), which will often reveal an obvious colour difference. If it does not, then chemical methods are necessary.

Diagnosis by soil testing

Testing, which is based on the concept of "available" nutrients, in its usual form is rather simple and inexpensive, but the main problem lies in selecting and calibrating suitable extraction methods for particular soil types, sub-types or units. The value of these methods must be established empirically in the soil area concerned.

Box 11. Soil testing procedure and interpretation.

1. Representative soil sampling
About 20 auger cores are taken and mixed per hectare, or from test plot, from a depth, for most purposes, of 0-20 cm in arable land or 0-10 cm in grassland (sometimes also from the subsoil).

2. Preparation of sample.
Air-dried and sieved (<2 mm).

3. Extraction of available nutrients by appropriate method, e.g.:
for N: water (for nitrate) or calcium chloride (for ammonium);
for P: NaHCO3 (Olsen) or diluted HCl (Bray); or organic acids like lactic acid;
for K, Mg: ammonium acetate (for exchangeable K) or diluted and buffered mineral or organic acids (e.g. citric or lactic);
for Fe, Mn, Zn, Cu: chelating agents (e.g. EDTA, DTPA);
for B: hot water (Berger and Truog).

4. Chemical determination of extracted nutrients (expressed as %, mg/1oo g or mg/kg[ppm] of air-dried soil or per litre of soil).

5. Interpretation:
for P, K, Mg: in relation to expected relative yield without fertilizer
(see Table 2)

for Mn, Zn, Cu, B (see Table 3)

Table 2

Interpretation of soil test data for macro nurients				
Supply class	**Expected relative yield without fertilizer**	**Available (extractable) nutrients (mg/kg soil)**		
	%	**P**	**K**	**Mg**
very low	50	< 5	< 50	< 20
low	50-80	5- 9	50-100	20- 40
medium	80-100	10-17	100-175	40- 80
high	100	18-25	175-300	80-180
very high	100	>25	> 300	> 180

Methods:
P: OLSEN (0.5 N NaHCO3; pH 8.5)
K, Mg: MEHLICH (0.2 N NH4Cl + acetic acid, 0.015 N NH4F, 0.012 N HCl; pH 2.5); data for soils with medium CEC (10 - 20 mg/100 g)

Table 3

Interpretation of soil data for micronutrients				
Element	Extraction method	**Available nutrients (mg/litre of soil = 1.5 kg min. soil) Ranges of supply**		
		Deficient	**Medium**	**Excess**
Mn	AAAc + pH correction	< 10 - 25	(100 - 500)	> 1 300
Zn	DTPA	< 0.4-0.6	(1 - 5)	> 10 - 20
Cu	AAAc-EDTA	< 0.8-1.0	(2 - 10)	> 17 - 25
B	hot water	< 0.3-0.5	(0.5- 2)	> 3 - 5

Methods: AAAc: Acid amm.-acetat. (0.5 M amm.-acetate + acetic acid; pH 4.7; with 0.02 M Na-EDTA respectively (LAKANEN and ERVIOE) (pH-correction for Mn: at pH 6.5 - factor 0.5; at pH 6 - factor 1; at pH 5.5 - factor 1.5) DTPA: 0.005 M; pH 7.3 (LINDSAY and NORWELL) Hot water: BERGER and TRUOG

The choice of a suitable method requires calibration either:

by field experiments, in which the relative crop yield with and without fertilizer is correlated with the relative extraction data from soil with and without fertilizer (r2 should be at least 60 % and preferably > 70 %);

or by plant nutrient content, i.e. by correlating the nutrient content in the plant at a particular stage with the nutrient extraction data from the soil (less expensive but still rather useful);

or by the appearance of deficiency symptoms, comparing the nutrient extraction data from the soil with the appearance or non-appearance of symptoms (useful for approximate classification in the case of micronutrients).

Diagnosis by plant analysis

The nutrient content of plants provides reliable information on their nutritional status at the date of sampling, thus giving a guide not only to any supplementary fertilizer needs of the current crop but also to the probable requirements of future crops. Although it is more costly than soil testing and needs more care in the handling of samples, this method is growing in importance(Box 12). Interpretation is usually based on the total contents of nutrients in leaves, or other suitable plant parts, in comparison with critical nutrient concentrations or "critical values"; but there are more sophisticated methods which either consider the "active" mobile contents (this can be somewhat better for e.g. Ca and Fe), or simple or complex nutrient ratios (e.g. Beaufil's Diagnostic and Recommendation Integrated System = D.R.I.S., which seems to have advantages for more detailed studies). It is essential to ensure that the "critical values" used relate to the expected level of yield (e.g. 80, 90 or 100 %); once properly established, they are applicable to the same crop worldwide.

Box 12. Plant analysis procedure and interpretation.

1. Representative sampling of specified plant part at stage corresponding with table of critical values.
2. Preparation of sample: same-day washing in distilled water, followed by oven-drying and careful grinding;
3. Chemical analysis: standard methods after dry or wet ashing (results expressed as %, %o or ppm = mg/kg).
4. Interpretation, e.g. by comparison with critical values or categories, which will determine whether immediate action is needed to correct a deficiency or to adjust a nutrient ratio; furthermore conclusions can be drawn whether the amount of fertilizer applied at sowing time was sufficient or should be increased for the next crop.

Diagnosis by fertilizer experiments

On account of the cost and labour involved, this method is much less suitable for individual farmers than for Advisory Services and Research Institutes. The experiments may be conducted either in the field or in pots (costing less but giving restricted information). Advice on field experimental design is given in Box 13 below. Although the statistical analysis of the yield results follows standard procedures, great care is needed to ensure that the correct conclusions are drawn concerning cause and effect. A statistically significant yield response to a particular fertilizer treatment might, for example, be due either to an increased supply of a subsidiary nutrient contained in that fertilizer or to an indirect effect on the availability of micronutrients in the soil rather than to the nutrient(s) which the fertilizer was intended to supply. Great care must also be taken in extrapolating the results, which strictly apply only to the soil area of the experimental plots under the conditions then prevailing, not to other areas and other crops in different seasons.

Box 13. Advice on design of fertilizer field experiments.

1. Provided the field has a reasonably uniform soil, a suitable choice of layout will probably compensate for small irregularities.

2. Good growth conditions must be ensured by careful management, including effective measures for weed control and crop protection.

3. The number of replications required (normally 4) depends on the purpose of the experiment.

4. Rates of fertilizer nutrient application should preferably be graded in equal steps from zero to that which possibly will give the maximum yield; a larger number of smaller steps gives more information but costs more.

5. The number of plots is determined by the number of different treatments and the number of replications, e.g. 5 rates of application (say O, 40, 80, 120, 160 kg/ha) with 4 replications requires 20 plots, or for example 3 rates of application of each of 3 nutrients (say N, P, K) with 4 replications would require 108 plots but this number may be reduced by including only the most important combinations (for example 4 replications of the 8 treatments NOPOKO, N0P1K1, N1POK1, N1P1KO, N1P1K1, N2P1K1, N1P2K1, N1P1K2 or N2P2K2 needs only 32 plots). The way in which the plots are laid out can range from simple blocks in a single row to more complicated multivariate designs such as the Latin square.

6. The total area of an experiment is usually limited by practical management considerations.

7. The results should be calculated by appropriate statistical methods, e.g. analysis of variance, and expressed in a manner indicating the statistical significance of differences in yield.

Significance, however, does not automatically mean "truth" of the results obtained.

Practical recommendations for fertilizer use

Recommendations based on any of the above methods of diagnosis must take into account the farmers' objectives and the economics of fertilizer use. Most farmers are interested in a system of fertilizer practice which will raise their level of crop yields and maintain that higher level, possibly over a long period. Those who are already achieving a medium yield level may wish to move into high-yield farming in which adequate supplies of all nutrients will need to be taken into account, while those who are now at a low yield level will need to concentrate first on the major "limiting factors".

The total amount of fertilizer N required is mainly established from response curves based on field experiments which are then transformed into local guidelines and modified in the light of farmers' long experience. However, correct timing, and the split between early application and later topdressings, are even more important than the total amount of N applied. In the example of a first (major) application of N in spring at the beginning of growth of autumn-sown crops or at the sowing of spring-sown crops, diagnosis may be based on the amount of mineral N (Nmin), mainly nitrate with some ammonium, in the 0-1 m soil layer; this amount expressed as kg/ha Nmin is then considered as if it were fertilizer which had already been applied. The desirable amount of Nmin for a particular crop is derived from field experiments. Taking the example of winter wheat for which the desired Nmin for high yield (8-10 t/ha) is about 120 kg/ha and the actual Nmin from a soil test in spring is 50 kg/ha, the difference to be applied in fertilizer would be 70 kg/ha N. Theoretically the amount to be applied at a later stage could be based on the "easily mineralizable organic N" in the soil at that later stage but the increase in accuracy compared with using the local guidelines is seldom enough to justify the extra cost. Even the Nmin, which is known to work well but is rather expensive, is more used by Advisory Services than by individual farmers.

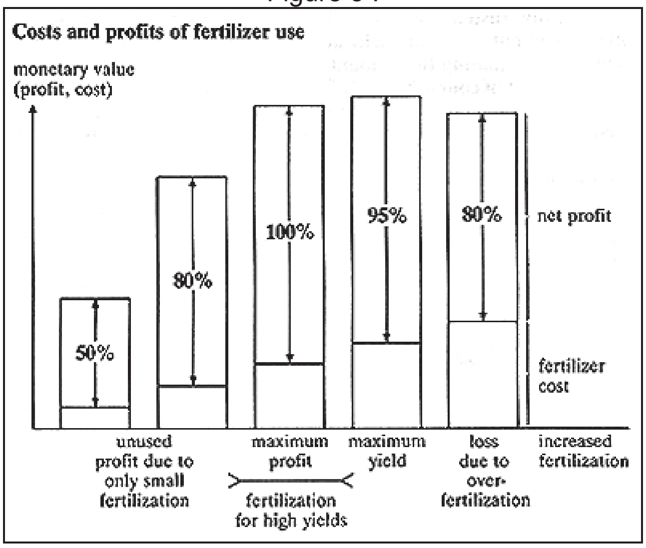
The amounts of other macronutrients to be applied should be based on the concept of supplying and maintaining permanently an adequate nutrition level for the (high-yielding) varieties of crops to be grown. This implies the replacement of nutrients removed from the field at harvest or lost by leaching, erosion etc. Theoretically all additions and removals should be taken into account but this would complicate the calculation unnecessarily. Instead, it is usually sufficient to multiply the average nutrient content per unit yield at harvest by the expected yield per hectare. In estimating the amounts to be applied in mineral fertilizers, allowance must of course be made for any nutrients to be applied in other forms (organic manures, etc.). Preferably the calculations should be based on crop rotations as a whole, with due allowance for any expected "carry-over" from one crop to the next (and not lost by leaching), rather than on individual crops.

Foliar application provides a quick means of remedying nutrient deficiencies, particularly of micronutrients, but can seldom provide large enough quantities to meet the whole of the requirements for macronutrients except where repeated spraying, e.g. with N, is practicable.

Economics of fertilizer use

While in periods of food shortage the main aim may be a high level of food production, in market economies any input must produce a reasonable financial return. Because of the Law of Diminishing Returns the amount of fertilizer applied will be limited by the maximum profit obtainable, which will be at a slightly lower level of fertilizer use than that required for maximum yield.

Figure 5 :



Theoretically, from a comprehensive series of field experiments, it should be a simple matter to obtain yield response curves from which the economic optimum levels of fertilizer use can be calculated. The main problem is that such ideal response curves for a single nutrient often assume that there is no deficiency in any other nutrient, which is rarely the case in farmers' fields. Economic interpretation of response curves therefore needs to be undertaken with considerable caution. A further difficulty is that, in soils well supplied with nutrients such as P and K, unless the results of long-term field experiments extending over several years are available, it may not be possible to produce any yield response curve at all to these nutrients. In this case the practical solution is simply to apply fertilizer on the basis of nutrient removal, which is generally economic in the high yield range.

In those developing countries, where yields are lower, a simple rule of thumb is provided by the Value:Cost Ratio ("VCR"), i.e. the ratio between the value of the extra yield obtained by using fertilizer and the cost of the fertilizer applied. This ratio has been found to range from 1 to 10, but it is recommended that it should be at least 2, i.e. the value of the extra output obtained should be at least double the cost of the input. Here too, a measure of caution is needed. Unless the field experiments from which the ratio is derived were carried out on typically managed farmers' fields, there is always a danger that the economic value of the response may be slightly exaggerated, so that a purported ratio of 2 may perhaps in reality be only 1.5. This, of course, is one of the reasons why it is recommended that the VCR should be at least 2.

Fertilizer application

Fertilizers may be applied on or into the soil or directly to the plants. The aim is to apply them cheaply, uniformly and effectively. The method will depend on the type of material.

Box 14. Application methods according to type of material used.

Mineral fertilizers applied as nutrient sources:

- Solid water-soluble fertilizers are evenly distributed on to the soil surface (penetration into the root zone then takes place during leaching after dissolution by water) or are placed directly into the root zone, e.g. beneath the seed at sowing time.

- Solid water-insoluble fertilizers are distributed on to the soil surface and mechanically mixed into the arable layer (where this is impracticable, e.g. on grassland, there is a natural but slow penetration by soil organisms).

- Liquid fertilizers are:

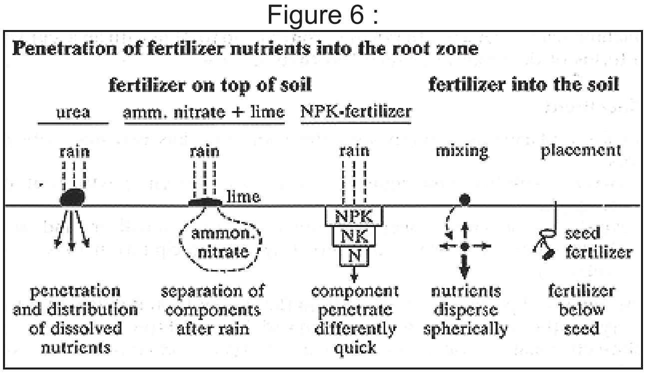
either sprayed on to the soil surface in their original concentration and left to penetrate (only suitable if no gaseous losses occur);
or mixed into the soil immediately after application (to prevent gaseous losses);
or injected directly into the soil;
or sprayed in diluted form directly on to the plants.

- Gaseous fertilizers are injected into the top layer of the soil (e.g. gaseous ammonia at a depth of at least 10 cm).

Bulky organic manures and amendments:

They should be evenly distributed on the soil surface to the extent possible and mixed into the arable layer, e.g. by harrow, disc harrow or plough, but some amendments need to be applied directly into the subsoil. Organic manures with a low nutrient content may be used as a mulch (surface protection layer).

Figure 6 :



Theoretically, finely powdered material mixed thoroughly into the arable layer would give the most uniform distribution within the root zone but this is often not necessary and too costly. The use of granular fertilizer represents a compromise between uniformity of distribution and ease of application. The granule size of water-soluble fertilizers is standardized , for example 90 % of the granules at 2-5 mm. Since water-insoluble fertilizer in similar granules of this size would generally act too slowly, they are usually granulated in such a way that powdery material is only loosely connected and the granules therefore disintegrate rapidly, though in all cases granules must be sufficiently stable to withstand the mechanical pressures encountered during transport and spreading.

Large super-granules are useful for some types of manual application.

In very large fields with exceptional heterogeneity in soil nutrient supply there may be an advantage in varying fertilizer use in conformity with the results of a close network of soil tests; in this case the process can be facilitated by a computer-assisted fertilizer application programme on the distributing machine.

The cost of distribution depends on the accuracy desired. Since medium accuracy suffices for most purposes, broadcasting by simple types of spinning disc distributors (with a spread of around 10-24 m) is very common. The amount of fertilizer to be distributed ranges from about 100 kg to more than 1 500 kg per hectare and the accuracy of distribution, in terms of deviaton from the desired rate, is usually about ± 10 %, up to a maximum of ± 20 %.

For more precise distribution, and especially for the application of fertilizers with varying physical characteristics, pneumatic or similar types of distributors are preferred, which either blow or throw the fertilizer through a number of distribution tubes on to the soil. Such machines can cover a width ranging from 5 m up to 24 m with an accuracy, in terms of deviation, of much less than ± 10 %.

Placement

Fertilizer placement directly into the root zone has two main objectives:

- early accessibility of nutrients (e.g. N, P, micronutrients) to the roots of young plants;
- avoidance of close, overall contact between fertilizer and soil which would decrease availability (e.g. by precipitation of water-soluble P).

The benefit of placement is greatest, in the case of P, on P-deficient soils, in dry weather conditions, with crops in widely spaced rows and receiving relatively small amounts of fertilizer. A typical example would be maize.

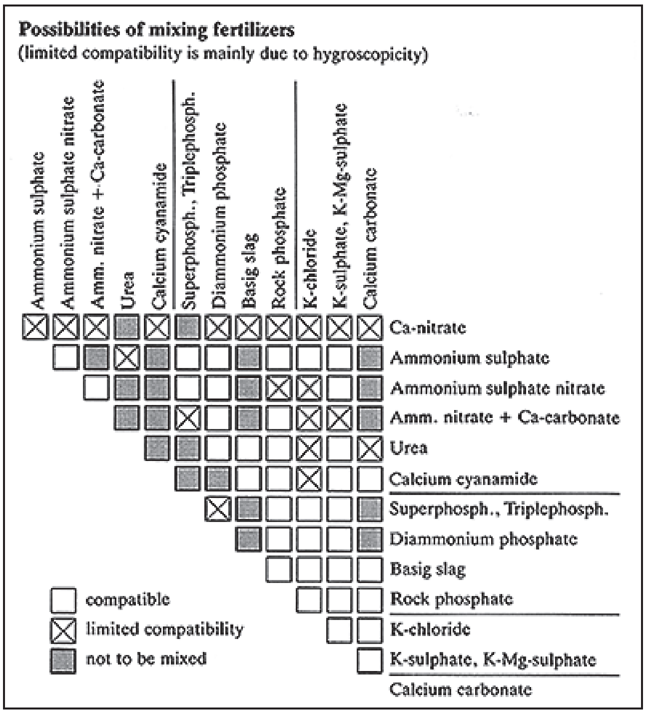
In contrast, wheat in humid areas with its narrower row-spacing would hardly justify the extra cost. For micronutrients, placement can take the form of actual attachment to the seed.

Bulk blending

Instead of distributing single-nutrient fertilizers separately or making use of factory-manufactured multinutrient fertilizers (complex fertilizers), the farmer may wish either to mix the fertilizers himself or to avail himself of the services of one of the retailers with mixing units who, in many countries, offer cheap mixing facilities. This provides the opportunity to prepare special blends with nutrient ratios to suit the particular farmer's needs appropriate to his own soils and crops. However, fertilizers which are to be mixed must be compatible both chemically and physically:

- chemically, so that no gaseous loss will occur nor any decrease in nutrient availability or caking due to chemical reactions
- physically, i.e. of similar granule size (e.g. in Europe 2-4 mm, or in USA 1-3.5 mm), to prevent segregation during transport and spreading and possibly also of similar density (urea, for example, can create problems through its lightness compared with other fertilizers), and to avoid probable yield reduction.

Figure 7 :



Liquid fertilizer application

Special spraying machinery is needed, especially for suspensions.

Advantages are the easy transfer from one container to another by pumping, the accuracy of distribution, the speed of application (covering 5-10 ha/hr), the possibility of incorporating fungicides , etc., and, in irrigated agriculture, the ease of inclusion of fertilizer in irrigation water.

Foliar application

Although possessing the advantage of quick action, the amount of fertilizer that can be distributed in a foliar dressing is limited by the sensitivity of the leaves to osmotic agents such as dissolved salts or (somewhat less) to organic chemicals such as urea. With the exception of some N fertilizers (due to the rather high tolerance of urea), foliar application can supply only very limited amounts of the primary nutrients compared with requirements. The situation is somewhat better for the secondary nutrients, but the best result are obtained with micronutrients because a relatively large proportion of the total requirement can be supplied in a single spraying. In cases of marked deficiency, repeated spraying is essential.

Spraying is most effective, and the risk of scorch is minimized, if the spray droplets do not dry too rapidly, i.e. on cloudy days and in the early morning or late afternoon. The amount of water used is often around 400 l/ha but progress is being made with lower volumes. Amounts of up to 30 kg N, 1 kg Mg and 0.2-0.5 kg micronutrients can be applied per hectare in a single foliar spray.

Fertilization, food quality and environmental pollution

Under conditions of food shortage, the major goal of fertilizer use is a high crop yield giving a lower priority to food quality and possible negative influences on the environment. However, when production efforts have resulted in meeting the food demand or even in a surplus, the quality aspect and the potential pollution effects on soil, water and air receive the same importance than the crop yield itself or even more.

Fertilizers and food quality

This topic should be considered in a broad sense. Fertilizers can influence quality:

- either indirectly, by improving plant health, especially resistance to adverse climatic factors, diseases and pests;

- or directly, by increasing the content of essential and beneficial organic and mineral nutrients in human food and animal feed;

- or negatively, through their incorrect or imbalanced use or by the involontary addition of toxic substances.

Examples of the improved resistance of well nourished plants to adverse climatic factors:

- resistance to drought: a better supply of K improves their waterholding capacity, and P encourages early root growth and so ensures better survival in dry spells;

- resistance to frost and cold: increased by a better supply of K, P and some micronutrients (e.g. Mn, Cu);

- resistance to ultra-violet radiation: a good supply of Zn counteracts radiation-induced destruction of growth regulators.

Clearly, the damaging effects of plant diseases and pests cannot be completely eliminated simply by supplying abundant and balanced plant nutrition, but in many cases they can be contained and reduced to a lower and sometimes negligible level. Examples include:

- better resistance to some insect pests resulting from a good supply of K, as a result of better mechanical protection and a decrease in cell constituents attractive to insects;

- better resistance to fungal attack resulting from a good supply of boron.

- improved soil fertility also seems to result in soil fungi producing a better supply of antibiotics which protect plants therapeutically against some bacterial diseases. Further research is certainly needed in this border area between plant nutrition and plant protection with the aim of minimizing the need for protective sprays.

There are two separate aspects of food and fodder quality:

- market value, depending on easily recognizable external characteristics such as cleanness and absence of decay; furthermore, on the content of protein, suugar, etc. for the processing industry.

- nutritional value, comprising palatability (taste and smell, difficult to categorize), content of the many important organic and mineral nutritional constituents, and absence of undesirable or even dangerous toxic substances.

Box 15. Influence of nutrient supply on food quality.

N: better supply increases amounts of total and pure protein, protein quality (more of essential amino-acids), and some vitamins, especially B1; excessive supply tends to increase amide content, resulting in bad flavour after cooking, or to raise nitrate content unacceptably.

P: better supply improves protein quality and increases the content of some vitamins and of mineral phosphate, which is an important mineral nutrient; slightly increased radioactivity due to uranium present as natural impurity in P fertilizer seems to be of no importance whatsoever.

K: better supply increases carbohydrates, and especially vitamin C; as with P, slightly increased radioactivity coming from the naturally occurring K40 isotope is of no importance.

Other nutrients: the obvious advantage of having an optimum supply of all nutrients hardly needs mention. Individual nutrients which may adversely affect quality when supplied in excess include the heavy metals such as Zn and Cu. Unwanted contamination with the toxic heavy metal Cd may arise from the use of town wastes or, less importantly, from P fertilizers.

Fertilizers and health

Although the fertilizer-induced increase in the content of essential food constituents does not necessarily signify that fertilizers improve "health", it seems nevertheless to be so. Before the advent of fertilizer use, deficiency diseases in farm animals and humans were widespread : bone weaknesses due to lack of P, vitamin deficiencies due to inadequate plant nutrition, diseases in grazing livestock due to deficiencies of Cu and Co, for example. Furthermore, some virus and bacterial diseases seem to have diminished in their infective capacity as a result of improved nutrition. The considerable increase in human life expectancy must also be attributed in part at least to having more and better food, stemming in turn from fertilizer etc.

Even so, it has to be admitted that a significant proportion of the benefits to food quality are lost in processing, e.g. in the production of white bread, and may even be lost during cooking, as with some heat-sensitive vitamins.

In view of the established generally positive effect of fertilizer use on food quality, it is surprising that certain groups of consumers in the developed countries are requesting so-called "natural" food in the sense of food produced not only without chemical plant protection but also without the use of synthetic mineral fertilizers (quite apart from the entirely separate question of food additives such as preservatives and colourants).

A special market has been developed for such products of "organic farming" using either organic manure alone or together with "natural" mineral fertilizer such as rock phosphate. This is fully acceptable so long as scientific principles are observed and no unfounded claims are made for superior quality.

Mineral fertilizers, manures and environmental pollution

Whereas positive effects of fertilizer use on the environment are often overlooked, attention nowadays is focussed on negative aspects. Mineral and organic fertilizers are accused of:

- accumulation of dangerous or even toxic substances in soil from fertilizer constituents, e.g. Cd from mineral phosphate fertilizers or from town or industrial waste products;

- eutrophication of surface water, with its negative effect on oxygen supply (damaging to fish and other forms of animal life);

- nitrate accumulation in ground water, thus diminishing the quality of drinking water;

- unwanted enrichment of the atmosphere with ammonia from organic manures and mineral fertilizers, and with N2O from denitrification of excessive or wrongly placed N fertilizer.

As to contamination of soils with toxic heavy metals, it can easily be shown that mineral fertilizers make only a rather small contribution in comparison with, for example, town wastes. However, as soil fertility must be considered in the very long term and not only in decades or centuries, the annual addition should be kept at such a low level that the enrichment is negligible. Industrial waste products should always be carefully checked to determine whether they contain potentially toxic substances, and appropriate critical limits should be established.

Nutrient losses from the soil into surface and ground water (mainly nitrate by leaching and phosphate by erosion) occur even when fertilizers are not used, but they are increased slightly but unavoidably even by correct fertilizer use and are increased substantially by excessive or unbalanced use, which can be avoided.

Considerable leaching of nitrate is caused, for example, by:

- excessive application of organic liquid manure;
- intensively fertilized speciality crops;
- ploughing of grassland
- fertilizer application for over-optimistic yield expectations which fail to materialize (thus resulting in a surplus at the end of the vegetation period);
- part of the correctly estimated N requirement remaining unused because of other limiting factors not being taken into account, e.g. deficiencies of secondary or micronutrients;

In other words, N losses are mainly due to mistakes in fertilizer use or crop management, not to fertilizer use itself. Moreover, counter-measures can be taken to prevent loss of nitrate residues after harvesting (soil must not be left bare over winter) and to prevent soil erosion.

N loss by leaching seems to range from 10 to more than 100, in extreme cases more than 150 kg/ha N depending on the accuracy of fertilizer use and the extent of the preventive methods used. In Germany, at present the average appears to be far below the officially (but wrongly) discussed figure of 100 kg/ha N, but for most soils rather in the range of 30-60 kg/ha N. In any case, exaggerated overall averages do great injustice to farmers who apply fertilizers accurately and spend much effort in preventing excess leaching. From a scientific point of view, much more attention needs to be given to the enigma of N balance sheets before drawing premature conclusions on N losses.

Loss of phosphate by leaching (< 1 kg/ha P) is negligible, while loss by erosion is due to bad soil management rather than fertilizer use.

Atmospheric pollution by ammonia is mainly due to primitive methods of storing and spreading organic manure. N immission (involuntary intake from the air) ranges, in Central Europe, from 10 to 15 kg/ha N, with over 40 kg/ha N recorded in the vicinity of intensive animal husbandry.

Of the mineral fertilizers, only urea and ammonium sulphate might cause significant NH3-volatilization losses, especially if not incorporated (e.g. grassland, topdressing of cereals). To minimize these losses, incorporation into the soil or application before rain or irrigation is recommended.

The contention that agriculture contributes considerably to N2O production via denitrification, as a result of excessive or wrongly applied fertilizer N, is a serious problem, because this gas contributes to the destruction of the ozone layer in the stratosphere which protects against ultra-violet radiation. Official estimates, derived mainly under artificial conditions or by the difference method, showing losses of approximately 15 % or more of the applied N, are not really substantiated; total denitrification losses in the range of 5-10 % of the applied N, of which only about 10 % is as N_2O, seem to be more realistic, especially for soils under normal moisture conditions.

Since pollution of the environment should be minimized, governments are trying to control the avoidable negative influences by special laws.

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