

Integrated Nutrient Management: An Overview of Principles, Problems and Possibilities

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Abstract: The common concept of fertilization should be widened into the more comprehensive concept of nutrient management being integrated with other production factors. On the basis of nutrient flows and cycles, and in order to reach the yield potential under the prevailing growth conditions, this includes better use of the different nutrient sources, the adaptation of crop rotations to nutrient supply, the consideration of soil heterogeneity and optimum nutrition of crops for better product quality and resistance, finally also prevention of avoidable nutrient losses. Different farming systems require different nutrient management provisions. Exploiting cropping is still widely used, but should be replaced by sustainable agriculture at low, medium or high yield level (depending on general growth conditions). The regional nutrient transfer (natural or by trade, e.g., into cities) and the global nutrient export pose special nutrient management problems. Due to future shortages of some nutrients there will be conflicting objectives, and it will probably be necessary to adapt food demands (via population number) to the resources available, not only for some countries but on a global scale.

Key words: Nutrients, integrated nutrient management, precision farming, farming systems, shifting cultivation, sustainable agriculture, ecofarming.

Crops require mineral nutrients and the supply must be adequate for the targeted yield. Since the natural nutrient resources mostly provide only a part of the crop requirements, additional nutrients often are required. The concept of fertilization in its modern comprehensive form and on the basis of high soil fertility has proved to be a powerful tool for enormous yield increases in areas of intensive agriculture.

In many countries, however, e.g., in developing arid areas, the use of fertilizers is severely limited by water shortage, economical constraints, etc. Cropping under such low yielding conditions must, there-

fore, rely much more on the "capital" of farm nutrient resources. Therefore, it is necessary to manage more effectively the nutrient flows and cycles of a farm; the same applies to "organic" farming.

Under conditions of marginal profit cropping the goal must also be to minimize expensive inputs and to prevent avoidable losses. On the other hand, with intensive cropping, a somewhat careless use of some fertilizer nutrients, especially N, resulted in negative side-effects on the environment, provoking public demands for restrictions of fertilizer use, especially near drinking water resources.

Furthermore, in view of the increasing urbanization, the nutrients exported from the farms to the cities should be recycled, i.e., industrial food processing and communal waste products need to be used as cheap nutrient sources.

The necessity of adopting a wider concept of nutrient use (compared with usual fertilization) thus results from changing aspects (Finck, 1995):

- from individual crop nutrient requirements to optimum use of nutrient sources,
- from static nutrient balances to nutrient flows (fluxes), nutrient cycles,
- from first year (nutrient) effects to long-term effects (residual effects, losses),
- beyond yield effects on quality of the products and resistance of crops,
- from ideal growth conditions to awareness of stress and production risks,
- from exploitation of soil fertility to its improvement or maintenance.

In this framework of arguments the concept of fertilization (especially in its limited version of NPK-fertilization) appears to be a special case of the much wider concept of nutrient management (additionally integrated into the whole production process and environmental concern) and is applicable to and relevant for all agriculture.

Integrated nutrient management as defined by Harmsen (1995), here differs from the conventional nutrient management by more explicitly considering nutrients from different sources, notably organic materials, nutrients carried over from previous cropping seasons, the dynamics, transformations and interactions of nutrients in soils, in-

teraction between nutrients, their availability in the rooting zone and during growing season, in relation to the nutrient demand by the crop. In addition, it integrates the objectives of production, ecology, environment and is an important part of any sustainable agricultural system.

This concept is closely related to that of FAO's Integrated Plant Nutrition Systems (IPNS), where the basic goal is the maintenance or adjustment of soil fertility and of plant nutrient supply to an optimum level for sustaining the desired crop productivity by optimization of the benefits from all possible sources of plant nutrients in an integrated manner. The appropriate combination of mineral fertilizers, organic manures, crop residues, compost or N-fixing crops varies according to the system of land use and ecological, social and economical conditions (Roy, 1995).

Nutrient Supply, Flows and Cycles

Plants require 13 essential nutrient elements (6 major, 7 micronutrients) and can profit from some beneficial nutrients. The amount of nutrients required by crops depends largely on the target yield level, which largely determines the amount of fertilizer required, even if often a somewhat lower yield is actually obtained.

Only under rare circumstances the nutrients required for high yields are "automatically" supplied from the soil nutrient reserves. Of all nutrients required, however, on many fields only less than half must be supplemented by fertilizers (mainly macronutrients).

The response of crop growth and yield to the nutrient supply can be expressed in growth or yield curves and described by "yield laws". In practical cropping, nutritive minimum factors are often responsible for unsatisfactory yields and thus present growth problems. Therefore, a proper nutrient management (of the nutrients added to the soil as well as in order to keep many nutrients, especially microelements, on a sufficient natural supply level) is of fundamental importance for effective, successful and sustainable agriculture.

The non-compensated use of soil nutrients is usually regarded as exploitation or "mining" of nutrients leading to degraded soil fertility. However, two different concepts should be distinguished: exploitation vs. utilization. Their difference can be compared with pumping water from wells. If a water level is slightly or considerably lowered, water is exploited and the system is not sustainable. If the water level is not noticeably lowered even after long period, water is "just" utilized, the system could be called sustainable.

Exploitation of soil nutrients is frequently applied which decreases the level of available nutrients quickly or slowly and is therefore non-sustainable.

Utilization of soil nutrients consists in partly removing nutrients without (significant) impoverishment of the nutrient supply or reduction of soil fertility. This can continue on fertile soils for a long time (centuries for some microelements) and creates the impression of permanence of natural nutrient supply.

Nutrient flows and cycles in fields and farm areas

Whereas the usual nutrient balances (a comparison of input vs. removal) represent a static concept, nutrient cycling involves a dynamic and much wider principle. Nutrient flows move in several directions and with different intensity; they could also be considered as a "fertility transfer", which can be intentional or self-acting by natural processes.

Classical examples are the phosphate accumulation in archaeological dwelling sites (used for detecting them) or the nutrient transfer from grassland to arable fields (proverb: grassland is "mother" of arable land, i.e., the "nutrient provider"). On field especially farm level, the following nutrient transfers take place.

The cycling quantities vary within a wide range and the nutrient export differs considerably among the crops, ranging from very little (e.g., with fibres like cotton lint) to medium (e.g., grain) to very high (forage crops).

Although the nutrient flows are common knowledge, in the standard fertilization practice some of them are only marginally considered or even neglected. A proper nutrient management is supposed to take care of them as far as possible.

From nutrient flows to cycles

A main objective is converting unwanted flows into useful cycles. Recycling of nutrients within the farm area tends to be not uniform. For example, slurry is preferably deposited on fields near a farm because of transport costs. On grassland with cows, the manure excreted is distributed

very unevenly. Another example is the spotty distribution of ashes after the burning of straw or of the natural vegetation.

None of the cycles is closed, most of them are leaking. Some losses are unavoidable (and may be considered as natural load, a minimum tribute for primary production), whereas, others are avoidable by adequate nutrient management. There is a widespread opinion that decreasing N-fertilization is the best preventive measure for reducing leaching losses of nitrate. This holds only true, however, for fertilization systems where N is over-emphasized (unfortunately not a rare practice in intensive fertilization cropping), whereas, even high application of N together with a sufficient supply of other nutrients (i.e., with no yield

limiting minimum factor) may result only in still tolerable losses.

Cycling is a very complex system. Although it is not so difficult to design a complex model of nutrient flows, their quantitative assessment will partly have to be based on some more or less uncertain estimates. Therefore, the result can only be approximate. For practical use, cycling models should be restricted to the important nutrient fluxes (Fig. 1).

In the case of big cities (especially megapopolis) the recycling of imported nutrients to the farm area is rather limited. Many waste products are rather deposited into landfills or led into rivers or the sea (after "biological" treatment, but mostly without extracting phosphate).

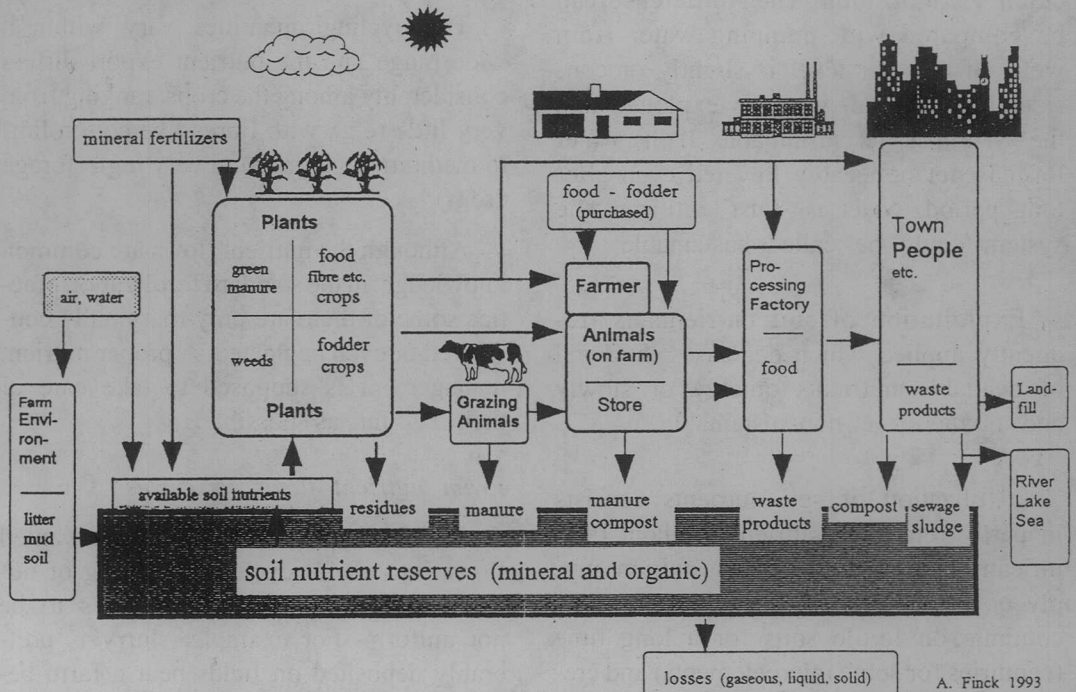


Fig. 1. Nutrient cycling on different scales.

Better Use of Nutrient Sources

Soil nutrients and soil fertility aspects

Soil nutrients are the basic source of the farm nutrient supply. Part of them is utilized by crops, i.e., the easily available portion (water-soluble, exchangeable) as well as the easily mobilizable fraction. The mobilization of nutrients from (mineral and organic) slowly available sources can be enhanced to a certain extent by activating soil life (in general by organic matter or by special biofertilizers), by crop varieties with strongly mobilizing capacity, by better accessibility of nutrients after structure improvement, by deepening of the plow layer or by fallow periods.

The best use of nutrients for crop growth can be obtained on the basis of a high soil fertility level. Soil fertility is a complex term (not very precise, but very useful even in its vague form) which includes many components: soil depth, texture and structure (pore space for supply of oxygen and water), soil reaction, organic matter content and composition, activity of soil organisms, nutrient content, storage capacity for nutrients, content, respectively, absence of detrimental or toxic substances. The result of an optimum combination of these factors is a high soil fertility that means a high crop production potential.

For the practical use of soil nutrients, the basic problem is the estimation of the amount that will be available during the growing season (in order to fill the remaining gap with additional nutrients). The main diagnostic method is soil testing for available nutrients, and most countries have their soil testing system calibrated for special areas. Whereas, the analytical methods are

rather precise, due to the heterogeneity of most soils, the diagnosis can only provide an approximate estimate. Nevertheless, it is possible to draw useful conclusions on the necessity of additional nutrients. For more precise information, systems of plant analysis have been developed.

Very fertile (and thus productive) soils are rarely found in nature. Unfortunately, most soils are far from being ideally fertile and should therefore be improved, not only by adding nutrients, but also by other soil amendments, e.g., lime for correcting strong soil acidity, organic matter for maintaining the activity of "soil life", etc.

Soil fertility may be rather uniform in a field, but it sometimes varies within a short range (in some fields visible by considerable differences in plant height). In such cases, soil productivity studies (by soil and plant analysis) are suitable to determine the cause of such differentiated growth and offer the possibility of eliminating the limiting factor.

Optimum soil reaction: Many soils, due to a continuous acidification caused by several factors, are a little or much too acidic for high productivity. Therefore, liming is required and the soil should have its optimum soil reaction which varies with soil texture, cropping intensity, etc. The usual (local) recommendations for optimum pH are generally higher with a higher clay content and yield level.

Optimum pH values or ranges are often a compromise between two different goals: first a good soil (crumb) structure which requires rather neutral pH range on heavy soils and second a better rate of mobilization of most nutrients, especially micronutrients

like Fe, Mn and Zn, which requires a somewhat lower pH range.

In rare cases of over-limed soil in intensive cropping areas, the pH can be temporarily lowered by application of acidifying N-fertilizers (mobilizing nutrients like Mn or Zn on tiny spots).

Soil organic matter: The qualitative importance of organic matter for soil fertility is rather well known, but many quantitative aspects are still to be solved. The main functions of soil organic matter are physical soil improvement (increase in water and air capacity, protection against erosion, etc.) and several chemical functions (increase of sorption capacity, mobilization of nutrients by mineralization of organic matter and from minerals, short term immobilization into soil organisms (which thus compete with crop for N) and long term fixation into stable humic substances (e.g., improvement of quality via C/N ratio), supply of beneficial organic substances (growth promoters, antibiotics, etc.).

The importance of soil organic matter differs in climatic regions, the role of nutrient source often being a dominant one. It should not be decreased, but maintained at an acceptable level, above critical values corresponding to structural stability and biological activity. In rainfed tropical agriculture, soil organic matter is the cornerstone for the building of any sustainable annual cropping system, but there is not yet a definite answer to the critical level that should be maintained (Pieri, 1995).

In areas of intensive cropping, an increased level and better quality of soil organic matter has significantly contributed to the high productivity level.

Mineral fertilizers and fertilization

Mineral fertilization of crops has proved to be a powerful tool for yield increase. It developed within about 100 years from simple NPK-concept to a modern comprehensive fertilization (including all nutrients) for yield levels of over 10 t ha⁻¹ wheat or rice.

In intensive cropping, a good supply of nutrients is required, especially during the period of rapid growth. For most major nutrients and some micronutrients this cannot be supplied from the slowly decomposing soil reserves (mineral or organic), but must come from quickly acting mineral fertilizers.

Farmers have many effective fertilizers at their disposal and the "know-how" of efficient fertilization is widespread. Nevertheless, there is also some misuse of fertilizers (especially nitrogen) for ineffective compensation of poor growth caused by lack of other nutrients or even for excessive losses on unsuitable soils. These problems should be taken care of by corresponding nutrient management.

Despite some shortcomings of practical fertilizer use, the modern comprehensive concept of fertilization can be applied with high efficiency in order to supplement an insufficient natural supply (FAO, 1984; Tisdale *et al.*, 1985; Wild, 1988).

Organic materials

There is a large variety of materials produced on the farm as well as "imported" from outside, especially communal and food processing waste materials.

Crop residues and farm manures: Crop residues vary considerably in their nutrient

contents (e.g., grain straw vs. green leaves). Residues and manures should be returned to the fields with only little nutrient losses. As for animal manures, the change from the old-type animal manure/straw mixture to slurry (induced by the labour-saving but otherwise somewhat doubtful progress due to straw-less stubbles) has substantially contributed to N-losses. Main losses of animal sludge distribution occur from ammonia volatilization (sometimes more than half), but losses can be reduced substantially by application of the sludge into the soil instead of spreading it on the surface, the latter procedure being unfortunately still widely used in practice.

A general question of nutrient management is the alternative of using waste materials directly or improving them by special treatments, especially by effective composting.

In many regions, there is a competitive use of organic matter that could be used as feedstuff, fertilizer, fuel for direct burning or for biogas. As a rule, organic matter fit for soil application should not be burned, although in some situations, there may be little choice for a farmer.

Organic materials should be applied to crops which make the best use of them, e.g., the immediately available ammonia of slurry given to crops before the period of rapid growth, or slowly acting N-sources to crops with a long growing season and with extra profit from the structural improvement for root growth.

Under humid conditions, crop residues are generally mixed into the topsoil as a nutrient source and also for soil improvement. Input of organic material should not

only increase, but also improve (higher C/N ratio, etc.) soil organic matter (Burgos, 1995). In arid regions (although an increase in soil humus would even be more important), crop residues are often left on or near the surface for soil erosion control and for water conservation (Prasad and Power, 1991).

Under high yield conditions it may be difficult to get the straw of the previous crop decomposed in a short time and there can be negative effects like temporary fixing of available N (due to the large requirements of the decomposing bacteria). The practice of burning a surplus of straw and just using the ash as a mineral fertilizer is now forbidden in some countries for environmental reasons (smog).

Communal and industrial waste products: The waste products that can be used as nutrient sources are materials produced by composting from sewage sludge or (organic) garbage.

It is in the interest of towns and food processing industries to return their waste products to farmers' fields. These waste materials may even be offered as cheap nutrient sources which can save mineral fertilizer input. The advantage for a farmer can be estimated by taking into account the nutrient content and some additional organic matter effect.

There is a growing concern, however, about some toxic elements and even toxic organic substances that might decrease soil fertility and quality of food and fodder products. Especially in the case of some heavy metals farmers should be very conscious of not enriching their soils above the toxic limit in an irreversible way since

amelioration will prove to be very difficult. Some protection against this danger is given by keeping the contents of toxic substances below tolerable limits and by using these materials only on soils which still are rather uncontaminated.

Other organic fertilizers: It is well known, that with some biofertilizers the fixing of atmospheric N can be increased by organisms such as *Rhizobium*, *Azotobacter*, blue green algae, *Azolla/Anabaena* (Gaur and Singh, 1995).

Soil conditioners for structural soil improvement still have only a restricted use in agriculture.

Better Nutrient Management for Crops and Crop Rotations

Adaptation of crops and crop rotations to nutrient supply

For cropping conditions of low natural nutrient supply and restricted input special emphasis must be placed on the nutrient efficiency of crops, mainly uptake efficiency, but possibly also internal use efficiency.

Crop species and even varieties differ to a certain extent in their ability for mobilization and uptake of soil nutrients, especially under conditions of low natural supply. Since under low input conditions the contribution of soil nutrient reserves (especially P and K) is of eminent importance (Syers, 1995), varieties should be chosen that provide special mechanisms like root excretions for their mobilization and for improved uptake. The same holds true for cases of rather immobile single micronutrients (e.g., Fe, Mn, Zn, Cu deficiency).

In intensive agriculture more emphasis is placed on high yield performance and disease resistance than on nutrient efficiency since it is more economical to supply extra nutrients (for micronutrients even by leaf spray).

The uptake from only slowly available soil reserves can be further improved by choice of crops with an extra potential of nutrient mobilization via mycorrhiza or rhizosphere associated organisms. Symbiotic mycorrhiza fungi (VAM = vesicular-arbuscular mycorrhiza) are widely present in fertile soils (or may be inoculated for special crops). The effect of this symbiosis is an improved nutrient uptake in general, mainly a better P-uptake of the roots due to better mobilization of soil P reserves and also to more efficient use of added P fertilizers, furthermore an improved uptake of other nutrients with low mobility like some micronutrient metals. VAM improves the productivity by reducing the input, whereas relying more on soil nutrient reserves, but also by enhancing plant survival under nutritional stress conditions (Barea, 1991).

The most striking example of crop adaptation to nutrient deficiency is the cropping of legumes with rhizobia for fixing nitrogen. An example typical for paddy rice is the *Azolla-Anabaena* symbiosis.

Not only a crop has to be adapted to nutrient supply, but also general agronomic measures like proper weed control (saving nutrients for crops) and efficient crop protection (for obtaining and protecting high yields) are required to make the best use of nutrient sources.

Adaptation of crop rotations to nutrient supply: Although monocultures (like tree plantations or sugar cane) offer the easiest way of production on arable land, many crops are not self-compatible and a farmer usually has to consider the nutrient supply of crop rotations (cropping systems).

Rotations are planned for several (and partly competing) reasons: for special products wanted due to economical reasons, for maintenance of soil fertility, for plant disease and pest control, for nutrient supply, etc.

From the crop nutrition point of view, different aspects have to be considered. Rotations can consist of crops with high or low nutrient requirements or of crops known either to improve or decrease soil structure and activity of soil life.

The well-known example of legumes alternating with non N-fixing crops should also be mentioned. Rotations may be chosen which do not leave the soil without green cover (intermediate crops, green manure or even weeds) in order to prevent nutrient losses from bare fallow in the period with pronounced leaching.

The soil nutrient supply may also be improved by not using one crop, but crop combinations like intercropping or mixed cropping (Francis, 1989). A widely applied practice is the simultaneous growth of grasses with legumes in fodder production.

Adaptation of fertilizer amounts to heterogeneous soil nutrient supply: With the common fertilization practice a more or less uniform content of available nutrients is assumed. The fertilizer amount is based on one (composite, average) soil sample per ha or small field (obtained from several

individual samples) and evenly distributed on the field. This standard method is modified for fields with parts of different nutrient supply by dividing it into few (in itself more uniform) sections which are then differently analyzed and fertilized. This traditional method, however, has its drawbacks on large fields with many areas of different soil fertility.

Therefore precision farming is developed in order to adapt a soil or crop treatment to heterogeneous conditions. In the case of fertilization the amount of fertilizer will be continuously adapted to the nutrient supply of so-called pedocells. This procedure requires special diagnostic and soil mapping techniques as well as machinery.

Although the principle of precision fertilization is very convincing, the costs are rather high if this procedure cannot be based on cheap diagnosis by sensors. Since for N-fertilization at sowing time the nitrate content of a soil is the decisive factor, precision fertilization actually would require (above ground) sensors for continuously monitoring the nitrate distribution in the root zone. With such methods not yet available, extended soil sampling is still required, but the costs can be prohibitive. If the procedure is based on few samples only, the results will be rather vague and might hardly be called "precise" any more.

The second N-dose is based on the green colour of the crop (actually the degree of chlorosis obtained by sensors). It should be established, however, that the chlorosis is really caused by N and not by any other deficiency (but there is no simple "sensor" method for his distinction yet).

The advantages of precision fertilization are most likely obtained with N-fertilization because of the necessity for exact dosage, but less likely to be profitable with P and K because of high diagnostic costs compared with agronomic and economic results. Especially in the case of P, the soil supply should anyhow be on the safe side, the differences of easily extractable soil P are less reflected in plant P, there are no surplus problems for crops and there is hardly any leaching of P.

Summing up, precision fertilization offers a reliable distribution technique, the main problem, however, remains a cheap and reliable diagnosis.

Nutrient management for product quality and stress resistance

Higher quality of food and fodder products: Nutrient management, beyond the yield aspect, includes also aspects of quality since food or fodder should contain sufficient mineral elements for healthy growth of men and animals, especially since some critical values for quality are higher than those for high yields. As a general rule, better nutrient supply of crops improves food quality, i.e., increases the mineral and organic components required by men. On the other hand, an unwanted surplus of some nutrients (especially N) may decrease quality parameters. Food quality also includes aspects of undesirable toxic elements like cadmium, the uptake of which should be kept as low as possible.

Nutrient management of grassland for fodder quality: The nutrient cycling in

grazed pasture ecosystems has been reviewed by Haynes and Williams (1993). A prominent feature is the recycling with a very uneven distribution because of the spotted deposition of excretions by grazing animals.

As for the quality aspect, an adequate nutrient supply of grassland must take into account not only the yield (of milk, meat, etc.), but also the health and fertility, e.g., of cows. The nutrient requirements of grassland plants and animals are more or less similar, but they can also differ in part. For example, for highly productive milking cows a higher content of P, Mg, Mn, Zn, Cu in the fodder is required than for a high grass yield. In addition, the special requirement of cobalt, selenium or even chromium for animals should be considered, especially in deficient areas (unless mineral supplements are given).

If grassland is included in crop rotations, there should not be too much carry-over of such nutrients which may disturb the nutrient balance of fodder, e.g., surplus of K may induce Mg deficiency.

Higher stress resistance of crops due to better nutrition: The usual concept of nutrient supply is based on "normal" growth conditions. In fact, however, there are frequently constraints for crop growth under stress conditions which require special nutrient management.

The stress situation is often aggravated by combination of several factors, e.g., low temperature at the time of crop protection spraying.

Resistance of crops against cold stress can be increased by optimizing the supply of some of the nutrients (K, P, Mn, Cu).

For arid conditions, it is important to realize that with better crop nutrition less water is required and that especially with good K supply the transpiration of crops is reduced. Saline soils need a special nutrient management for reducing the uptake of unwanted Na, etc. The water-use efficiency depending on plant nutrient supply is reviewed by Davis (1994).

Soil acidity problems are wide-spread in humid areas, the most striking example being the acid sulfate soils. Soils below about pH 4.5 mostly produce low yields (if at all) and the plants are more susceptible to diseases due to the soil acidity syndrome (lack of some nutrients, especially P, and surplus of toxic substances like Al).

Soil-borne stress can be eliminated or at least decreased by soil amelioration. On soils polluted with toxic heavy metals their negative effect on crops can be decreased by special amendments (stronger fixation of the mobile portion by liming and metal fixing agents).

A balanced nutrient supply (instead of a relative N-surplus) generally increases the resistance against certain bacteria and fungi (resulting in a lower requirement of pesticides).

Preventive measures against avoidable nutrient losses

In humid climates there can be no cropping without nutrient losses to the environment and a certain amount is tolerable, like it occurs with nitrate into the ground water or ammonia and other gases into

the air. Good nutrient management in sustainable agriculture, however, must prevent the avoidable losses (due to excessive leaching, runoff and soil erosion as well as evaporation) and keep the losses below an acceptable level. As for leaching, in humid areas of Europe less than 40 to 50 kg ha⁻¹ N and about less than 0.3 kg ha⁻¹ P seems to be acceptable for avoiding eutrophication of surface water.

The nutrients mainly affected by leaching are nitrogen (nitrate), sulfate, K and Mg. If they are only transferred below the root zone of annual crops, they may be recovered by deeper rooting crops (Fig. 2).

A reduction of N-losses means an increase of N-use efficiency. Few sections of nutrient management have got so much attention as the different N-losses and their prohibition. Although to a certain extent N-losses are unavoidable, they are often the result of management failures.

The main prevention measure against leaching of nitrate is to keep a permanent vegetation cover on the soil (either winter crop or at least green manure crop), the second to minimize the N-surplus left for potential leaching in the soil at harvest time (mainly unused nitrate, but also nitrate mineralized from organic matter after harvest). This can be done by restricting N-fertilization to the amount required for a realistic yield level.

Losses from runoff and erosion can be reduced by contour tillage and cropping, strip cropping, terraces, grassed waterways, minimum tillage (Magdoff *et al.*, 1997).

In intensive agriculture, the potentially leachable N-amount is mostly the result of the discrepancy between the N-amount

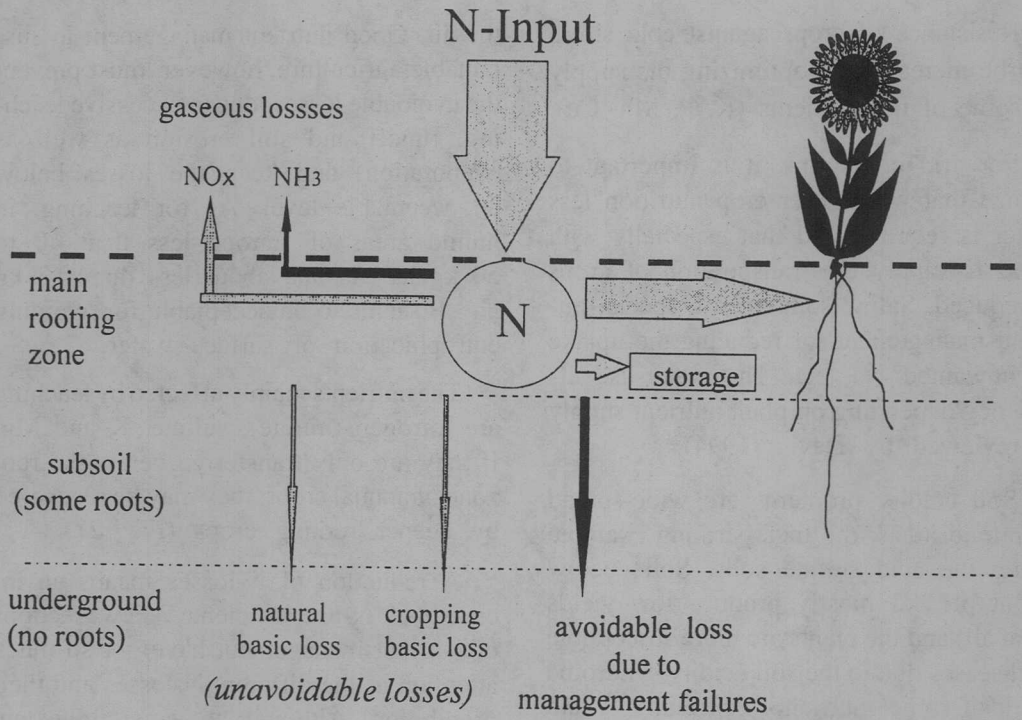


Fig. 2. Leaching losses consisting of unavoidable and avoidable losses.

for the yield expected compared with the final yield actually obtained. Example; for a yield expectation of 10 t ha^{-1} grain about 250 kg ha^{-1} N is required (about the amount removed with the grains). If due to some yield limiting factors (nutrients or disease) only 8 t ha^{-1} are obtained, a surplus of $20 \times 2.5 = 50 \text{ kg ha}^{-1}$ N remains unused in the soil. This extra amount added to the average loss of 40 kg ha^{-1} N results in a total of 90 kg ha^{-1} N and is thus substantially increased due to inadequate nutrient management.

The term inadequate, however, needs specification. This example demonstrates a principal problem of nutrient management. It is easy for scientists to advise the exact amount of N theoretically required for a certain targeted yield, but this advice is

only valid under several preconditions which may or may not be fulfilled during the cropping period. Yield estimations in spring are necessarily vague, and farmers understandably expect always a little more yield than last year.

Methods for reduction of leaching losses are reviewed by Smith *et al.* (1990) who emphasize the need of integrated nutrient management by special fertilization and cropping practices, i.e., a multi-factorial approach, furthermore, the concepts which are effective under experimental conditions may not give similar results under the reality of farmers' daily practice.

Gaseous losses have already been discussed (for slurry) and will be mentioned later on for paddy rice.

Nutrient Management in Farming Systems

Farming systems and their special nutrient management problems

All farming systems have their qualifications under special natural or economical conditions. Of the determining factors nutrient management may not have priority, but it nevertheless plays an important (an increasing) role, namely to make the best use of soil and fertilizer nutrients within the framework of the dominating factors for a special farming system.

For the present purpose, various types of farming systems and agricultural land utilization are shortly listed in alternative groups with some corresponding problems of nutrient management added.

Exploitation cropping vs. sustainable agriculture at different yield levels

In this section some examples will be given of farming systems with nutrient exploitation and of sustainable systems at low, medium or high yield levels.

Exploitation cropping: Exploitation of soil nutrient basically means cultivating crops until available soil nutrients are exhausted and the yields are so strongly declining after some years that the field must be abandoned and left again to natural vegetation.

A typical example of exploitation and thus non-sustainable cropping is the (standard-type) shifting cultivation used by subsistence farming in tropical forest areas (e.g., described in Africa by Nye and Greenland, 1960, in South America by Sanchez, 1976). After clearing of the land (usually

by burning the forest trees) a short rotation of annual crops is grown which uses the available nutrients of the tree ashes and those mobilized from soil organic matter. The cropping period is generally short due to nutrient removal and especially to losses by leaching below the root zone of annual crops. This nutrient depletion (together with other causes) results in substantial successive yield decrease. If after 3 to 5 years cropping yield levels of only half or one-third of the first year are obtained, the field is left to natural vegetation again. The "forest fallow" usually restores the soil nutrient status (also by recovering nutrients from the subsoil) and the humus content within a period of 15 to 20 years.

This system of alternating short cropping and long (forest) fallow period is not very efficient, produces only low yields (except for the first few years) and is exploiting because losses are not compensated. Nevertheless, to a certain extent, it is stable as long as there is sufficient land available for long regenerative phases under natural vegetation provided that no serious soil deterioration takes place during the cropping period (the population needs at least seven times more land than actually used).

The poor reputation of shifting cultivation as a misuse of soil resources is mainly due to deviation from the original concept by shortening the forest fallow period and thus soil regeneration, mostly as a result of an increased population pressure.

Exploitation cropping is still widely used due to economical and other constraints, but at least the systems with insufficient regeneration should be replaced as far as possible by a sustainable type of agriculture.

Sustainable agriculture at low to medium yield level: The concept of sustainable agriculture is getting a high priority. It involves the successful management of resources for agriculture to satisfy human needs while maintaining or enhancing the quality of the environment and conserving natural resources (Plucknett, 1990). Obviously, systems of this kind involve complex interactions and require integration (Edwards, 1990).

A prominent concept is called by the acronym LISA, i.e., Low-Input Sustainable Agriculture. LISA is supposed to optimize the management and use of internal production inputs (mainly on-farm nutrient resources) in order to obtain a satisfactory level of sustainable crop yields and profitable returns (Parr, 1993). It is in fact a production at a somewhat lower end of the crop response curve.

Low input agriculture may be required for compelling natural and economical reasons (extensive sustainable agriculture in vast areas of developing countries) or deliberately used because of ideological reasons (bio- or ecofarming in developed countries).

Extensive sustainable farming: In areas with strong yield limiting factors, e.g., in dryland farming, extensive farming with low input and low to medium yields holds still its place.

The main emphasis lies on the use of mobilized soil nutrients and internal nutrient cycling via organic substances, although a complete cycling is difficult to achieve because of some unavoidable losses. Some exceptions may occur on small subsistence farms. The input of mineral fertilizer is

kept low since their efficiency is known to be low under stress conditions induced by dryness, etc. Some information on yield limiting factors can be drawn from soil productivity studies on farmer's fields.

It has been pointed out, that many marginal ecosystems are not precisely sustainable because of low input (Miller and Larsen, 1990). Whereas, at least in some years, they could profit from an improvement of the yield limiting factor by fertilization, in general, a fertilizer input is risky because the V/C (value/cost-ratio) of 2 required for economic reasons may not be reached.

Bio- or ecofarming (deliberate extensive farming): In developed countries the term biofarming (organic farming, ecofarming) indicates special farming systems without application of chemicals such as factory-made fertilizers or pesticides, but with animal manures, compost, legumes as nutrient sources and with great care for nutrient cycling in order to produce better, i.e., allegedly non-contaminated food and to protect the environment against unwanted pollution from agricultural chemicals. Somewhat lower yields (30 to 50%) are compensated by corresponding higher product prices.

Although the claims for superior quality food by avoiding chemical fertilizers are not substantiated (Finck, 1992) nor those by avoiding chemical crop protection (Goring, 1990), a limited number of consumers maintain this production of so-called "natural" food.

The further claim that these types of bio- or ecofarming are less (water) polluting because of no chemical fertilizer input also needs correction. Although a lower amount

of N-leaching often is achieved per unit of land, it rarely holds true per unit of crop product (because almost twice an area of land is required for cropping than with conventional farming).

Sustainable agriculture at high yield level: Sustainability is not confined to low-input conditions. The input, however, should be adequate to the goal that may be even a very high yield level. Such systems could be called AISA (Adequate-Input Sustainable Agriculture). As demonstrated in Western Europe and elsewhere, a high but adequate use of fertilizers results in sustainable production with high yields and yet without significant adverse effects on soil fertility or environment (Finck, 1992). Farming systems of this kind are rather diverse (e.g., rainfed or irrigated), but have many similarities of nutrient management.

The goal is the same as of maximum yield experiments, i.e., obtaining as far as possible the yield potential of high-yielding crops by eliminating all nutritional minimum factors (via fertilization and maintaining a high soil fertility) while simultaneously protecting the crop against all kinds of diseases and insect damage.

The details need not be described here since they are presented in modern text books, but a certain negative aspect of practical nutrient management should be mentioned, namely the tendency for neglecting the soil nutrient reserves and those available in farm waste materials (e.g., slurry), especially if cheap chemical fertilizers are available. This has led to the misleading public opinion in the past that intensive cropping essentially is a "nutrient-wasting" system.

Sustaining crop productivity at a high yield level has proved to be possible in many progressive agricultural areas, e.g., in India by integration of chemical, organic and biological nutrient sources and their effective management, partly while even saving mineral fertilizer input (Hedge and Dwivedi, 1993).

Food production can certainly be increased by better nutrient cycling and prevention of losses; but for the food supply of an increasing population, demands cannot be met with the farm nutrient sources nor with the present use of mineral fertilizers, but require an increasing nutrient input (Angé, 1995).

In fact, the principles of modern comprehensive fertilization concepts and the basic principles of sustainability will have to be combined. Integrated plant nutrition systems, as part of integrated crop production, will be a decisive factor for the final goal: a sustainable high yielding and profitable crop production without avoidable negative effects on environment.

Nutrient management on arid lands

In rainfed dryland farming, the yield level is limited by shortage of water (rainfall being not only scarce but also variable and thus unreliable). Since better nutrition of crops reduces their water requirement, a proper management of farm nutrients is of far greater importance than in humid areas.

The main nutritional problem is the ubiquitous shortage of total and available N due to the rather low soil humus content. In order to make the best use of the scarce soil N-sources, the crop N-requirement should be adapted (via sowing time) as

far as possible to the nitrate flash occurring from rapid mineralization at the onset of the rainy season (although it must be admitted, that this suggestion is not easily put into action because of the uncertain progress of the rainy season). There is also a certain upward movement of nitrate from the subsoil by evaporation (formerly mistaken for a chemical N-fixation at the soil surface by a hypothesis of Dhar in India).

The natural N-supply may be sufficient for low yields, e.g., of 1 to 3 t ha⁻¹ of grain, but for medium yields additional N-sources like farm waste materials or even mineral N should be added (if there is sufficient moisture).

For adding organic material, depending on priority, there is the choice of mulching for soil protection or mixing it into the top soil as nutrient source. An increase of the very low soil organic matter level would be very desirable, but the possibilities are rather limited because of the high mineralization rate. The application of organic substances, however, is often limited by competitive use of crop residues, etc., for manuring, for animal feed or for fuel.

Another possibility to improve the natural nutrient supply (as well as of water) is the inclusion of a bare fallow period for storage of water and mobilized nutrients.

Besides N, also the phosphate supply is often insufficient, especially on sandy soils. Since P is specially required for (early) root growth and since deep rooting may be decisive for survival during dry spells, a good P-supply (from fertilization) is therefore important beyond the acute crop requirement. A good K-supply is also essential for reducing the transpiration of crops, but

for dryland farming on many arid soils (practically without leaching), there is often sufficient available K for at least low to medium yield levels. The same holds true for magnesium and sulfate.

As for micronutrients, due to immobilization at neutral soil reaction of arid soils, there is a frequent lack of available Fe or Zn. A certain improvement can be obtained by using strongly acidifying N-fertilizers such as ammonium sulfate or (to a lower extent) urea. In addition, special fertilization may be required, more effective by leaf spray than via soil. In some cases the problem of micronutrient deficiency can be solved by using crop varieties with high uptake efficiency.

Whereas many arid soils are rather coarse-textured, the vertisols represent the clay-type. Their natural supply of all nutrients is abundant even under intensive cropping with irrigation. The only exception is nitrogen because of the low soil organic matter content that therefore needs special nutrient management (Finck and Venkateswarlu, 1982; Dudal, 1989).

Although nutrient management on arid soils with many different crops includes a vast complex of problems in detail, only few can be mentioned in this overview.

Agrosystems in semi-arid regions with common agricultural practice may not be always sustainable, but can be made sustainable with the existing research knowledge and with producer's experience (Steward and Robinson, 1997; Ryan, 1997).

Saline soils: Since on parts of the arid lands the soil salinization adds even more problems, some comments may be added on the management of deleterious soil sub-

stances. If the excessive surplus of soluble salts (Na, Cl, SO₄, etc.) cannot be removed by amelioration, cropping must take into account a certain degree of soil salinization by adapting fertilization to this stress environment.

Whereas, the (salt-induced) water stress can hardly be reduced, at least the excessive uptake of Na may be lowered to a certain extent by (antagonistic) K-fertilization with the additional advantage of an improved K-status which reduces transpiration losses. K-fertilizers, however, should be chosen which cause the least increase of salinity stress, i.e., rather K-sulfate than K-chloride or even better, K-nitrate (if N is required in corresponding amounts).

As for the micronutrient situation, in addition to deficiencies often occurring on neutral soils, at some sites boron toxicity may prove to be a special problem because it is difficult to ameliorate. Detailed information on nutrient management under conditions of salinity is given by Oertli (1992).

Nutrient management in humid tropics

Of this wide topic only some problems may be selected. Since strategies of nutrient management must be based on soil fertility properties, these will be discussed briefly. The widespread ferralsols (oxisols of tropical forest), in spite of their diversity in many respects, have some common properties due to the hot and moist environment.

As for soil acidity, in order to reach a normal pH-range of at least 5.5 to 6, considerable amounts of Ca-carbonate are required, which may, however, not always be available. The ash from burning the forest trees produces at least some transitory

effect of liming. Another source is fertilizers with an additional liming effect like rock phosphate.

Liming experiments, even if the pH is increased above the toxicity level of Al, sometimes give rather disappointing results due to some (not accounted for) yield limiting factor (whether major- or micronutrient), which has to be added in order to get satisfactory yields,

A typical example of very acid soils are the acid sulfate soils with often very low yields, sometimes less than 1 t ha⁻¹ of grain. However, even small amounts of lime in combination with rock phosphate may increase the yield level to 2 to 3 t ha⁻¹.

For compensation of the humus mineralized, crop residues should be left on the field. In farming systems with cash crops, there are often considerable amounts of residues from the processing factories that can be recycled. The nutrients of the added organic materials are rapidly mineralized (N- and P-source)

In order to reduce the losses by leaching, the period with bare soil between annual crops should therefore be kept as short as possible.

P-fixation results in a strong P-deficiency and an inefficiency of water-soluble P-fertilizers because the phosphate is quickly fixed and thus rendered unavailable. To overcome the P-fixation, large amounts must be applied, or rock phosphate may be more effective.

Sustainability of highly productive farming systems can be obtained by using a nutrient management that takes care of these problems caused by production limiting soil

properties and the humid hot climate. (For incoming information on sustainable crop production in Asia see Johnston and Syers, 1998).

The nutrient management of special annual or perennial crops on arable land or of tree plantations cannot be discussed here, except for a short comment on two topics.

Rice cropping on paddy soils: Irrigated rice presents special and large problems of nutrient management. A central and not yet really solved problem is the low efficiency of N-fertilizers (urea being the main source used). A recent review (De Datta and Buresh, 1989) pointed out that usually only less than half of the N added is taken up by the crop (compared with about 70% in intensive wheat cropping). Therefore, the losses by ammonia volatilization, denitrification as well as runoff and leaching should be reduced. However, in the paddy environment it is difficult to suggest a single superior method, but some progress seems to be possible by placement of urea, the use of nitrification inhibitors and top dressing at later stage.

The possibility of supplying N via the *Azolla/Anabaena* symbiosis appears to be very promising and could probably replace a large portion of mineral N-fertilizer.

Agroforestry: For the nutrient management, the advantages of agroforestry are protection against nutrient leaching and soil erosion, nutrient mobilization and transfer from trees to annual crops and pumping nutrients from deeper soil layers (Buresh, 1995).

The potential of alley-cropping systems has been critically reviewed by Lal (1991). The advantage of alleys of shrubs or trees

for erosion control is obvious, but obtained at the price of slightly lower yields from the annual crops (e.g., 10% for maize under special conditions). The tree cuttings (as an organic nutrient source) are less effective than mineral N. The general failure of alley-cropping to give higher yields than conventional cropping results from shading effects, root competition for nutrient and water, N-immobilization by the mulch, etc. Nutrients from deeper layers are only transferred to the surface soil if there are substantial nutrients in the subsoil.

In general, alley-cropping does not sustain production without substantial input in chemical fertilizer. Agroforestry has a potential to be a sustainable alternative to shifting cultivation, but its main advantage correlates with fertile soils.

Regional Nutrient Transfer

In smaller or greater regions there are natural nutrient flows and nutrient transfers by trade, e.g., into cities or even export into other countries. These mainly unilateral transfers are of environmental concern since they are not only the cause of nutrient losses from a farming area (and partly completely lost for production), but also unwanted from water eutrophication point of view.

Natural transfers (nutrient flows in landscapes)

A steady flow occurs naturally with surface or ground water movement in hilly or mountainous areas as part of the slow natural erosion process even under natural vegetation cover. The annual losses from the hilly part of the landscape are relatively small, and so are the gains for the low-lying

land. In geological periods, however, this transfer has produced many fertile alluvial soils in river basins that now belong to the best agricultural lands. If this process is accelerated by recent man-made strong soil erosion, it can lead to serious soil fertility decrease in the hilly area and to an excessive input of nutrient (especially N and P) into water.

The extent of nutrient transfers in small watershed areas or whole river basins is difficult to determine because of many factors involved (sources not only from agriculture, but also from towns, industry, etc.). Anyhow, several studies of this kind are conducted in Europe in order to estimate those amount of nutrients transferred into rivers or lakes for which the agricultural production of this area is held responsible (e.g., as a basis for restrictive regulations on fertilization).

Nutrient transfer into cities

With food and other farm products plant nutrients are transferred from farm areas to villages, towns, big cities and megacities. The rate of recycling usually decreases with increasing size of the settlement and depends on the disposal system for sewage and garbage. Many cities are proud of their perfect sewage disposal system (leading biologically treated sewage water into rivers or the sea and filling garbage into deposits). This system of just getting rid of the waste materials, however, means an enormous loss of plant nutrients with the unwanted secondary effect of eutrophication (by N and P).

Very few cities have a direct recycling of treated sewage onto fields, because re-

cycling of sewage sludge as compost seems to be more adequate. But even so, farmers are increasingly reluctant to apply composted sewage or garbage as nutrient source (even if offered free of charge) because of the well-known problem of toxic heavy metals (and possibly even toxic organic substances), not only in view of decreasing food quality, but as a potential danger for soil fertility. With the past experience of environmental laws getting ever stricter, farmers suspect, that the critical limits for soil contamination might be decreased for political reasons and thus putting otherwise fertile land out of production by law. In addition, farmers dislike being accused by city people of "poisoning" the soil and thus decreasing food quality while helping them to dispose their waste products.

Theoretically, the measures required for an adequate recycling, are well known and feasible, namely to provide (almost) uncontaminated organic materials via separating the different waste materials and excluding toxic ones. Although this poses many problems in detail, a more or less quantitative recycling will be essential from the big cities in the future.

Export into other countries

The nutrient export with feedstuff and food into other countries can reach substantial amounts that are lost from the national nutrient budget (although not from the global one). Many developed countries with high animal production, even those which could produce sufficient feedstuff by their own agriculture, import substantial amounts of feedstuff and corresponding plant nutrients because of the cheaper price.

For the Netherlands this import is outstandingly high, namely about 2/3 of P and K of the total fertilizer import (Cooke, 1989).

On the other hand, as long as this unilateral transfer with agricultural products can be compensated by re-import of mineral fertilizer, the nutrient loss of the developing countries will not really be a serious problem since there seems to be no urgent need for self-sufficiency of countries in plant nutrients.

General and Future Aspects

What should be done and by whom?

First, there are the scientists concerned with agriculture chemistry who produce research data and present theories. The validity of their information is 'usually taken for granted, however, some conclusions from field experiments and regional studies are not as reliable as claimed by the authors. Some yield increases attributed to better N-supply correspond in fact to secondary effects (problem of wrong x-axis), the result being an over-estimation of the required N-amounts and higher avoidable losses. As another example, there seems to be a tendency to over-estimate the part of river pollution that must be attributed to the agriculture of the region (whereas other sources tend to be underestimated). Consequently, the scientific information on fertilization, nutrient flows and losses should be critically examined and evaluated.

Second, advisors are supposed to 'translate' the theoretical suggestions into a practical 'know-how'. Unfortunately, the

information obtained from experts is not always very precise (especially as for the conditions under which the results are valid) or not really prepared for this purpose. Anyhow, advisors have to combine the information available with their own experience, express it in terms of farmer's knowledge and formulate it for practical use.

Third, there are the farmers, eager to produce as high crop yields as possible and who, if they care for their land as owner or tenant, want to maintain its production potential for crops and animals for a long time. In addition to their own experience, they want intelligible and definite guidelines rather than sophisticated models with plenty of vague factors. They know about the difficulties, uncertainties and disappointments of primary production on the field and do their best to get along with the information available for sustainable crop production. On the other hand, farmers are also entrepreneurs, living in a world where economical considerations have priority over correct farming practice. It would be a long list describing the deviations from what farmers might want to do and what they are forced to do for economical reasons (in order to maintain their income and their farm).

Least, but not last, there is the general public that is more and more represented by city people. Most of them live rather far away from agriculture and are hardly aware of biological and chemical crop production principles. These consumers demand a lot of good and cheap food, pure

drinking water, etc. They try to impose on the farmers their ideas of nature, landscape and farming, as well as their demands for town waste recycling. There should be limits to these demands, however, because many deplorable developments in agriculture are the result of the consumer's pressure. Consumers should realize, that farming has its own rules and that high soil productivity is a man-made valuable property that must be sustained, especially by proper plant nutrient management for generations to come. The world population can be fed in much higher numbers than today, but the pollution problems will set stricter limits.

Conflicts of interest due to future nutrient shortages

The customary approach of agronomists is to adapt the essentials of food production (especially nutrient use) to the requirements of the population being determined by prevailing socio-economic conditions. In many areas, an increasing number of people must be fed according to their nutritional habits, their location, mainly in cities and their desire for cheap food.

If this finally happens on a global scale, there will be shortages of at least some plant nutrients in the not so far future. However, long time before nutrient shortages become really acute (which may first be the case for P, the bottle-neck of world hunger) within a few hundred years, the remaining reserves should rather be used more to replace unavoidable losses than to comply with wasteful nutrient use and to serve an over-extending food demand.

In the long run, instead of adapting the plant nutrient consumption to food de-

mand, the food demand may have to be adapted to the amount of nutrients that can be annually used from the remaining reserves. Sustainable agriculture is not a matter of decades or centuries, but should go on indefinitely. The future agricultural production must not only be sustainable, but its extent and form should also be adapted to the limited resources. With increasing awareness of limited global plant nutrient resources, some conflicts of interest are unavoidable in different respects.

First, the necessity for farmers to produce as much and cheap in order to be competitive on the market may lead to a certain disregard of many well-proven agronomic principles, and even more of good animal husbandry (a list of society-induced "sins" of agriculture would be rather long).

Second, due to the high demand of animal protein, much more grain and other crops must be produced for vegetative food (e.g., the production of 1 kg of meat requires 3 to 4 kg of grain). This is a well-known fact, of course, but rarely regarded from the nutrient supply point of view.

In this context it may be quoted, that promoting long-term sustainable nutrient management will ultimately require radical changes in the way agriculture and society are organized. These include reintegration of livestock and crop farms and the encouragement of closer physical association of people with farmland. Establishing and implementing performance expectations for contemporary patterns of nutrient flow is especially difficult because the scale of transactions is broad and control of most aspects is far removed from the farm level (Magdoff *et al.*, 1997).

Finally, in a distant future, the old "chinese village" principle may have to be applied to the whole world. If food production (even on all available land and by using all possible means) is limited and there is no population outlet neither to east nor to west nor to other planets, the eating habits may have to shift to predominantly vegetarian food - and even the population number may have to be adapted to the remaining resources.

Summary

The common concept of fertilization should be widened into a more comprehensive concept of nutrient management being integrated with other production factors.

The natural nutrient supply, the flows and the nutrients added should be managed properly in order to achieve as high crop yields as possible under the climatic circumstances without avoidable environmental pollution.

This goal requires an optimum use of soil nutrient sources, a sustainable soil fertility, recycling of nutrients and a comprehensive fertilization in order to supply the crops with all nutrients in sufficient amounts.

An improved nutrient management also includes the adaptation of crops to the nutrient supply available and better use of nutrients from previous crops in rotations.

The heterogeneity of the nutrient supply in large fields, especially of N, should be compensated by precision fertilization.

Nutrient management should not only care for high yields, but also for good

product quality, stress resistance and reduction of nutrient losses.

Different farming systems in different climatic regions require special nutrient management ranging from exploitation cropping to sustainable agriculture at low, medium or high yield level. The claim that the nutrient management of biofarming produces better food is not justified.

Of the regional nutrient transfers, those into cities should be recycled to a far greater extent in order to stop wasteful flows.

Optimum nutrient management requires not only good expertise, but also knowledge and engagement of the farmers as well as an appreciation of the special problems involved in primary production by the general public.

In the near future, several modifications of nutrient management are required for saving nutrients, at least those with a limited global supply, whereas, in a distant future, the food production may have to be adapted to a sustainable nutrient use level.

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