Balanced fertilization for sustainable use of plant nutrients

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Introduction

Fertilizer best management practices (FBMPs) are methods and conditions established for using fertilizers, mainly to assure optimum plant growth, contribute to a profitable farming business and minimize adverse environmental effects. Some FBMPs could apply to a wide range of situations and cropping systems throughout a country, a region or the whole world, whereas others are designed for specific circumstances, such as reducing nutrient loads to enriched soils, protecting a low level of the ground water table, or building up the nutrient content of poor or very deficient soils. So, the best set of management practices for a specific cropping situation will depend on individual circumstances; no single set of best management practices applies to all situations.

Balanced fertilization is the proper supply of all macronutrients and micronutrients in a balanced ratio throughout the growth of crops. It aims at providing optimum plant development, obtaining good yields, providing the farmer with optimum profit and limiting or preventing damage to the environment. In this respect, balanced fertilization is a key component of FBMPs.

This paper will stress the importance of using nutrients in a balanced way for productive and profitable crop production. In particular, it will outline the importance of balanced fertilization for increased crop yield and farm incomes, improved nutrient use efficiency and the improved quality of crop products.

Essential plant nutrients

Many scientist agree that sixteen elements are essential for the growth and development of higher green plants (Roy *et al.*, 2006). These elements are: Carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P) and sulphur (S), which are the elements out of which proteins and protoplasm are made, the living substance of all cells. In addition to these six, there are ten other elements that are essential to the growth of some plants: calcium (Ca), magnesium (Mg), potassium (K), iron (Fe), manganese (Mn), molybdenum (Mo), copper (Cu), boron (B), zinc (Zn) and chlorine (Cl). Sodium (Na), cobalt (Co), vanadium (V), silicon (Si) and nickel (Ni) are also required by some lower plants. Other elements may be found to be essential in the future.

These 16 elements or plant nutrients are essential since:

- a deficiency in one of them makes it impossible for the plant to complete the normal vegetative and reproductive stages of its life cycle;
- such a deficiency is specific and can be prevented or corrected only by supplying it;

- each element is involved directly in the nutrition of the plant, apart from its possible effects in correcting some deficiency of the soil or some other culture medium.

Plants up take plant nutrients in different amounts and forms. With the exception of carbon, hydrogen and oxygen, they all must be obtained from the soil. Six elements are required in relatively high amounts; their concentrations in the plant tissue represent up to a few percent of the fresh plant weight: they are the **macronutrients** (nitrogen, phosphorus, potassium, calcium, magnesium and sulphur). Eight other nutrients are required in much smaller amounts, with a magnitude of mg per kg of fresh plant weight: they are called **micronutrients** (molybdenum, nickel, copper, zinc, manganese, iron, boron and chlorine).

All of these nutrients fulfil specific functions in plants and cannot replace each other. Regardless of the amount required physiologically, all of them are equally important. This means that the lack of one single nutrient will limit crop growth even if all the other nutrients are fully available. In consequence, the supply of all these nutrients is essential for growing healthy crops that produce high yields of good quality. Figure 1 represents the general relationship between yield and the supply of nutrients.

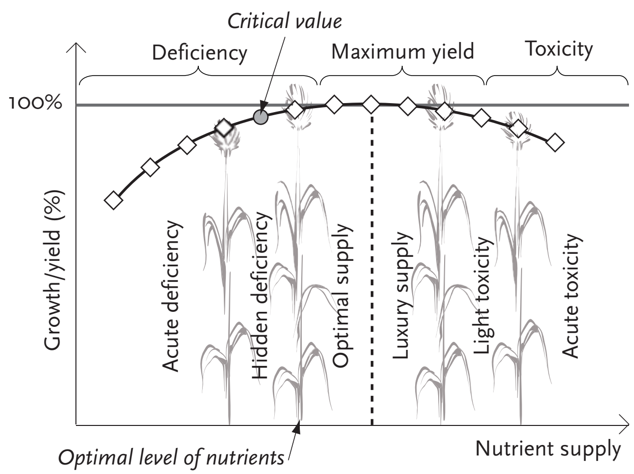

Figure 1. Plant growth and yield relationship with the supply of nutrients.

If one of these elements is in a short supply (i.e. is a limiting element) then the **Law of the Minimum** (Liebig's law, Figure 2) determines the plant's development and yield. In short, this law states that if one crop nutrient is missing or deficient, plant growth will be poor, even if the other elements are abundant. Therefore, a **limiting nutrient** is an element necessary for plant growth, but available in a concentration insufficient to support continued growth. Meanwhile, it is known that plants may take up many elements that play no vital role in their own nutrition. They can consume high levels of certain elements, some of which are essential and some of which are not. They may accumulate low levels of elements which play no beneficial role in the plants themselves but which are important in the diet of animals that eat these plants. Plants can even take up elements, such as heavy metals, which may be extremely toxic when their availability exceeds certain levels in the soil.

Figure 2. Law of the minimum (Liebig's Law).

Dealing with plant nutrition, whether it is addressed through balanced fertilization, integrated fertilizer or nutrient management practices or integrated plant nutrition, requires that all the nutrients necessary to achieve good yields and food quality should be taken into account. Therefore, identifying and assessing these needs and requirements are central to any approach that aims at obtaining good yields and food quality.

Defining balanced fertilization

Basically, the law of the minimum governs balanced fertilization. Balanced fertilization is the proper supply of all macronutrients and micronutrients throughout the growth of a crop. It is not the supply of a single or a couple of nutrients but rather the complete supply to a crop or a cropping system, with optimum and adequate quantities of the required nutrients at appropriate times to achieve a target yield, which is profitable and sustainable. All available knowledge about the crop and the environment in which it will be grown, including the economics of plant nutrient applications, must be combined to establish the right combination of nutrients to be applied. As both the total amount of nutrients (macro and micronutrients) required and the right nutrient ratios vary from one type of crop to another, balanced fertilization should be based on the specific requirements of the crop that is grown.

Balanced fertilization is soil and crop-specific

Balanced fertilization not only guarantees optimal crop production, better food quality and benefits for the growers, but is also the best solution for minimizing the risk of nutrient losses to the environment. If the balance of nutrients applied is not appropriate, the crop will not be able to grow properly and its overall uptake of nutrients will be limited. The supply of other nutrients will then be of no or limited use, and these will accumulate in the soil, leading to potential environmental problems.

The nutrient ratios in a balanced fertilization recommendation give only an indication of the fertilizer requirement of a given crop. Any recommendation to supply a crop with balanced fertilization must first take into account the amount of nutrients supplied from the soil or from other sources such as the irrigation water, green or animal manure, residues from preceding crops, etc. Since these sources are very rarely sufficient, mineral fertilizer must be added to satisfy the remaining nutrient needs of the crop.

The balanced use of fertilizers should be aimed mainly at: (1) increasing crop yield, (2) increasing crop quality, (3) increasing farm income, (4) correction of inherent soil nutrient deficiencies, (5) maintaining or improving lasting soil fertility, (6) avoiding damage to the environment, and (7) restoring fertility and productivity of the land that has been degraded by wrong and exploitative practices in the past.

Balanced fertilization is not a static but a dynamic concept that can pave the way to a sustainable agriculture and which will provide the world population with high quality food while minimizing the impact on the environment. **A well-balanced fertilization also optimises the nutrient use efficiency of crops.**

Table1 gives examples of nutrients required to ensure a balanced fertilization of the selected crops and cropping systems.

Table 1. Examples of nutrients required for the balanced fertilization of certain crops and cropping systems.

Crops/cropping systems	Balanced nutrients requirements
Intensively cropped irrigated areas	N, P, K, Zn and S or N, P, S and Zn
Areas under oilseeds	N, P, K and S or N, P, Zn and S
Legumes in acid soils	N, P, K, Ca and Mo
Fruit trees in alkaline, calcareous soils	N, P, K, Zn, Mn and Fe
Cabbage, cauliflower and other crucifers	N, P, K, S and B
High-yielding tea plantations	N, P, K, Mg, S and Zn
Coconut in light soils	N, P, K and Mg
Immature rubber plantations	N, P, K and Mg
Mature rubber plantation	N, P and K

In practice, there are many reasons for the unbalanced use of plant nutrients. Among these are:

- The relative prices at which fertilizers are sold to farmers, with in general N fertilizers having very low prices compared with other fertilizers, in particular P, K and S;
- The availability in time of needed quantities;
- The perception by the farmers of the benefit associated with fertilizers;
- The financial return.

At a time of economic pressures, farmers face the need to reduce production costs. In the case of fertilizers, they often tend to favor the use of N, particularly when their land tenure is insecure, which is the case of many countries of the developing world. But in many situations, the use of even appropriate levels of N fertilizer without adequate use or soil contents of P and K results in yield losses and inefficiency in the use of nitrogen, as illustrated in Figure 3.

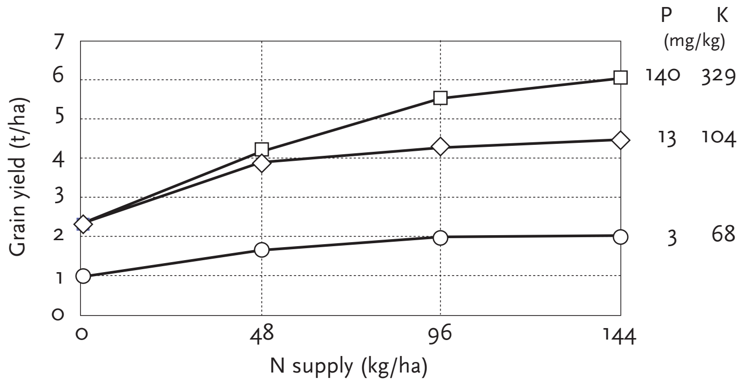

Figure 3. Spring barley responses to N on soil with different P and K contents, Rothamsted, UK.

Evolution of world fertilizer consumption and nutrient consumption ratios

World total fertilizer consumption increased from 27.4 million tonnes (Mt) nutrients in 1960 to 137.7 Mt and 151.4 Mt in 2000 and 2005 respectively. In 2015, world fertilizer consumption is projected to amount to 165.1 Mt nutrients.

Trends in fertilizer consumption show that, from 1960 to the early 1990s, developed countries accounted for more than half of world fertilizer use. In 1990, their fertilizer consumption was about 80 Mt nutrients. By 1992, fertilizer consumption in developing countries surpassed the consumption in developed countries. By the year 2020, it is forecast that fertilizer consumption in developing countries will be at least 40% higher than its level in developed countries.

Table 2 gives average nutrient consumption ratios of the world and in some of the major crop production regions.

Table 2. Nutrient consumption ratios (2002).

Region	N	P_2O_5	K_2O
World	1.0	0.4	0.2
Developed countries	1.0	0.4	0.3
Developing countries	1.0	0.4	0.2
Latin America & Caribbean	1.0	0.7	0.6
Africa	1.0	0.3	0.2
East & South-east Asia	1.0	0.3	0.3
South Asia	1.0	0.3	0.1
Europe	1.0	0.2	0.3

At the world level, the above table shows an unbalanced use of P and K with respect to N, in relation to a normal or generally accepted "balanced ratio" between N, P_2O_5 and K_2O of 1:0.5:0.5. It also shows a rather large variation between the selected regions, with Latin America and the Caribbean being the only region were P and K consumption, compared with N, is higher than the normal figure. This is not an indication of very high levels of P and K use compared with the needs of the crops grown, but rather a low level of N use that might limit the efficiency of the applied P and K fertilizers and the level of crop production. It also needs to be stressed that there are large areas of soybean and pastures planted with legumes that do not need high applications of N (Amar and Cissé, 2007).

In the other regions, from Africa through Europe and Asia, P and K applications are very unbalanced in relation to N. Data from countries of Asia, where the World Phosphate Institute (IMPHOS) is conducting several promotional activities on the balanced use of fertilizers, are presented below. NPK use ratios in India from 1980/81 to 2005/06 are given in Table 3.

Table 3. Ratios of N, P, K use in India.

Year	N	P_2O_5	K_2O
1980/81	1.0	0.3	0.1
1985/86	1.0	0.4	0.1
1990/91	1.0	0.4	0.2
1992/93	1.0	0.3	0.1
1993/94	1.0	0.3	0.1
2000/01	1.0	0.4	0.1
2005/06	1.0	0.4	0.2

In Pakistan, during the decade from 1996 to 2005, N, P and K consumption, while increasing substantially, in particular for N and P, was substantially unbalanced in the use of these three nutrients, as illustrated in Table 4 (Cissé , 2006a).

Table 4. Ratios of N, P, K use in Pakistan.

Year	N	P_2O_5	K_2O
1996/97	1.0	0.2	0.004
1997/98	1.0	0.3	0.01
1998/99	1.0	0.2	0.01
1999/2000	1.0	0.3	0.01
2000/01	1.0	0.3	0.01
2001/02	1.0	0.3	0.01
2002/03	1.0	0.3	0.01
2003/04	1.0	0.3	0.01
2004/05	1.0	0.3	0.01

Also in China, the use of NPK nutrients is very unbalanced. In 2002, the $N:P_2O_5:K_2O$ ratio was 1.0:0.4:0.2.

Among the many consequences that result from the unbalanced use of nutrients are:

- Decreased fertilizer use efficiency, in particular for N. In China, results from a study covering 5.7 million hectares show that, on average, fertilizer use efficiency had fallen by 8.2%;
- Yield reduction, which in the above example ranged from 0.4 to 1 t/ha;
- Reduction in the farmer's income;
- Soil mining, in certain areas (India) of P and K on a very large scale;
- Lower response ratios: in India from 10 in the 1970s to 6 at present on cereals;
- Increasing N losses to the environment by leaching and volatilization.

This paper will focus mainly on balanced fertilization for the purposes of:

- Increasing crop production and financial returns;
- Improving nutrient use efficiency and avoiding unnecessary nutrient losses to the environment;
- Improving food quality.

Balanced fertilization for increased crop yield and financial return

In Asia, there is generally an over-application of N compared with P. This is well documented, from China to Pakistan. In China, wheat and corn yields increased by 15 to 20% in recent years as a result of balanced fertilization.

As indicated above, balanced fertilization refers to the application of all plant nutrients required by a given crop grown on a given soil to achieve established agronomic, economic and environmental goals. Therefore, the application of micronutrients, where needed, is required in addition to the application of macronutrients. There are many documented cases that clearly show the need to apply nutrients other than N, P and K to satisfy plant growth and obtain higher yields and better crop quality.

On rice, results show increased yields from the application of Zn, ranging from 1.9% to 13.5%. On rapeseed, yield increases following Mn applications ranged from 8% to about 40%. On wheat, yield increases due to the application of micronutrients (a single application of Fe, Zn, Cu or B, or the application of all together) amounted to 4% with B application alone; to 11% when all four were applied. Zinc application alone gave the highest increase, of about 10% (Malakouti, 2006).

IMPHOS has launched several projects in Asia to promote the balanced use of fertilizer nutrients. In Pakistan, the project conducted by IMPHOS, the Food and Agriculture Organization of the United Nations (FAO) and the National Fertilizer Development Centre (NFDC) from 1986 to 2005 gave many significant results that clearly demonstrate the important role of balancing N with P to increase crop production. This case will be used to illustrate the impact on crop production that can result from more balanced fertilization practices (Amar and Cissé, 2007).

In Pakistan, fertilizer use is highly biased in favour of N. Micronutrient use is negligible compared to the actual requirements, and is limited to Zn on rice, potato and citrus; B on cotton, potato and rice (Figure 4).

Over the course of the project in Pakistan, 712 demonstration trials were conducted on seven crops, comprising 412 trials on wheat, 159 on rice, 57 on cotton, 54 on maize, 9 on sugarcane, 11 on oilseeds and 10 on onions. Region-wise, the four agricultural pro-

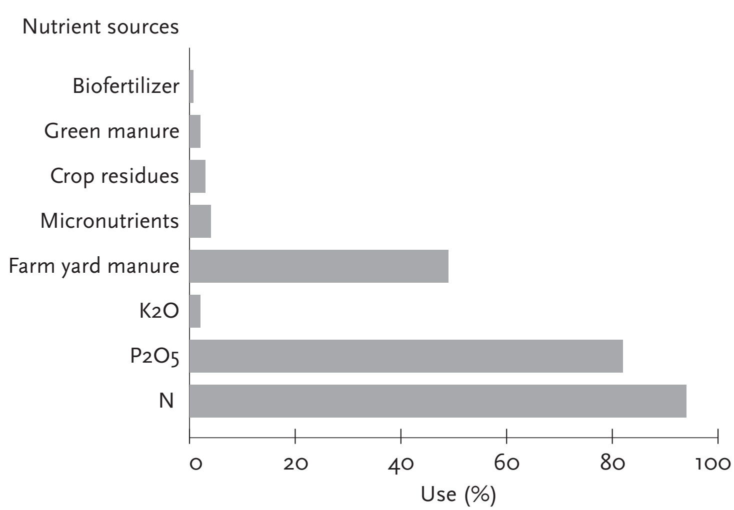

Figure 4. Source and level (%) of plant nutrient used by farmers in Pakistan, 2006.

vinces of Pakistan were covered, with 366 trials conducted in Punjab, 152 in Sindh, 137 in NWFP (North West Frontier Province) and 57 in Baluchistan. Trials were conducted under irrigated and rainfed conditions, using simple non-replicated treatments applied on large plots of 1000 m^2 each.

In all locations, in addition to the control treatment (0-0-0), farmers' practice on their own fields was recorded and the yield they obtained was used to assess the effect of the balanced application of NPK on the crop grown.

When comparing the balanced treatment with actual farmers' practices, which are very unbalanced in favour of N, and scaling up the results to the country level, the aggregated data show very substantial effects of the balanced use of N, P and K on the production of the selected crops.

For example, the average yield of wheat obtained in Punjab for the period of 1987 to 2005, was 1370 kg/ha on the control, 2168 kg/ha for N and 3284 kg/ha for NP (the N and P_2O_5 doses per hectare were respectively 120 and 90 kg/ha). The increase per unit of nutrient was 6.6 kg for N and 12.4 kg for P.

Overall crop yields obtained by farmers compared with those obtained with balanced fertilization on irrigated wheat, rainfed wheat, rice (IRRI variety), rice (Basmati), cotton and maize are presented in Figure 5.

The impact of a balanced use of P with respect to N is quite substantial for the production of all the crops. Table 5 shows that the additional production with a 50% adoption of a balanced use of P vis-à-vis N. It represents an average increase of 30% over the national output of the selected crops, amounting to about 11.7 Mt.

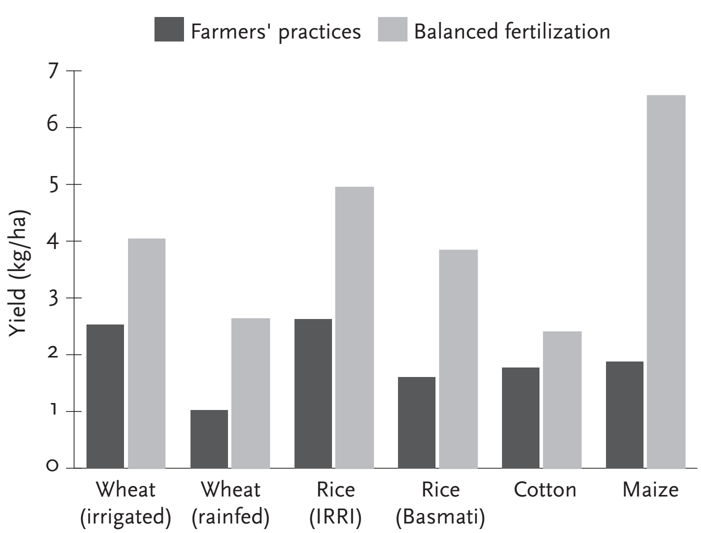

Figure 5. Average farmer's yields and yields obtained with balanced fertilization, Pakistan, 2006.

Table 5. Impact on the production of selected crops if balanced NP fertilization was adopted on 50% of the land planted to these crops in Pakistan.

	Wheat	Rice	Maize	Sugarcane	Total
Area (thousand ha)	7,333	2,156	335	206	10,030
Additional production (thousand tonnes)	4,422	2,895	350	4,014	11,681

The income associated with the adoption of balanced fertilization on 50% of the area planted to the above selected crops would amount to US$ 41.9 million per year.

Wheat is the staple food of the vast majority of Pakistanis; it is one of the most important crops of the country and production never matches the needs of the population. There is often a shortfall in wheat production, as was the case in 2005, with an 800 thousand tonne deficit. This deficit would have been covered by a 10% adoption of balanced NP fertilization in the country.

Since exports of cotton, rice and other products based on agricultural raw materials account for 80% of Pakistan's foreign exchange earnings, the impact of balanced fertilization on the country's balance of payment would be significant.

Balanced fertilization for improved nutrient use efficiency

Worldwide, at least one-third of the gain in cereal production has been attributed to increased fertilizer consumption and, in many countries, the figure is 50%. The application of mineral fertilizers needed to obtain higher yields should complement nutrients available from other sources and match the needs of individual crop varieties. The increased use of fertilizer is becoming even more crucial in view of other factors, such as the impact on soil fertility of more intensive cultivation practices and the shortening of fallow periods, and the growing concern about improved food quality. Fertilization should ensure not only high yields per unit area but also high quality of the produce.

Many studies that have assessed the relationship between food grain production and fertilizer consumption during the period 1961 to 2006 show that the partial factor productivity of fertilizers has been declining regularly. Available data increasingly indicate a reduction in crop response to fertilizer application, especially when balanced fertilization is not practiced.

When nutrients are properly used they are very beneficial, but applied in the wrong place, at the wrong time and with an inappropriate rate, they lose much of their positive effects. Farmers can achieve increased nutrient use efficiency by adopting improved and more precise management practices. It is expected that this trend towards increasing efficiency of nutrient use through better nutrient management, by improving the efficiency of nutrient balances and the timing and placement of fertilizers, will continue and accelerate in the future.

There are several causes of the declining or lower crop responses to applied fertilizers or efficiency of fertilizer applications in developing Asian countries. One major cause of this decline is the continuous nutrient mining of the soils (particularly P and K) resulting from unbalanced fertilization practices.

The data from on-farm trials conducted in India during 1999-2003 showed that the average response of cereals to fertilizer was 8-9 kg grain/kg fertilizer. The efficiency of fertilizer N is only 30-40% on rice and 50-60% on other cereals, the efficiency of fertilizer P is 15-20% for most crops, and the efficiency of K and S is 60-80% and 8-12%, respectively. For micronutrients, the efficiency of most of them is below 5%.

In India, it is estimated that about 28 Mt of NPK are removed annually by crops, while only 18 Mt or even less are applied as fertilizer, leaving a net negative balance of about 10 Mt of NPK. An analysis of the data pertaining to the rice-wheat cropping system from 24 research stations revealed that rice yields are declining more rapidly than wheat yields, and soil P and K depletion seemed to be a main cause. Similarly, other sets of data showed that the yield decline of both rice and wheat was highest when N alone was applied at 120 kg/ha. Unbalanced fertilization is therefore affecting fertilizer nutrient use efficiencies.

In Hungary, work conducted by IMPHOS on wheat and maize, to develop and promote more balanced, efficient and profitable nutrient applications, showed that previous fertilizer recommendations were not balanced, they were very often above crop requirements for the yields obtained and had low profitability (Cissé, 2006b). On wheat, total NPK applications could be reduced from 320 to 240 kg/ha without any significant yield losses. On maize, with a more appropriate NPK amount and ratio, the yield could be maintained at 11 t/ha, with the total amount of nutrient application decreasing from 560 to 350 kg/ha. These results offered, in addition to improved nutrient use efficiency and profitability, the possibility of greatly reducing the risk of nutrient losses to the environment.

Balanced fertilization for improved food quality

The application of plant nutrients has greatly increased the resistance of plants to diseases and climatic stress. Plants which have been provided with an adequate supply of K and P, for example, respond with early root growth and increased water holding capacity, thereby ensuring better survival in dry spells. The resistance of plants to frost and cold, ultra-violet radiation, pests and fungal attacks also increases when they have a sufficient supply of the major plant nutrients, micronutrients and trace elements.

The health of farm animals and human beings is directly affected by the quality of their nutrition. High quality crops are those which do not suffer from deficiencies but contain the mineral and organic nutrients that are essential and beneficial to human and animal health. Fertilizer use must therefore take into account the nutritional requirements of the animals and human beings which consume the crops.

The issue of food quality has emerged in recent years and is of increasing concern, primarily in the developed countries, but it is becoming an issue also in the developing countries. High quality is important for almost every harvested product, whether it is food, fodder or industrial raw materials.

The quality of vegetal products depends on many factors, among them the optimal supply of all substances required for growth. Minerals occupy a central position for obtaining high quality products.

Proper fertilization improves food quality through a higher quality of the vegetal products (and indirectly of animal products); so it contributes not only to the nourishment of humans and animals but also provides them with healthier living conditions.

The many important roles of P in plant metabolism is the reason why the application of fertilizer P has significant effects on food quality.

Phosphate results in the following changes (Finck, 1982):

- Increased total P contents of plants; in the case of fodder this is an important quality criterion as an insufficient P content is detrimental to the fertility of cows, milk production and quality;
- Increased content of inorganic P in green plants, and that of phytin. Phytin increases particularly in the seeds, whereas inorganic P increases mainly in the straw;
- Higher content of nucleic P;
- Higher content of essential amino acids in the seeds;
- Increased content of carbohydrates (sugar, starch);
- Increased content of some vitamins, such as B1;
- Reduced content of nicotine in tobacco;
- Reduced content of oxalic acid; in leaf vegetables this product is harmful to humans and in sugar beet leaves it is harmful to cows;
- Increased content of coumarin in grass.

Even though new crop improvement technologies, such as biotechnologies, are increasingly addressing the issue of food quality by introducing into crops genetic traits that improve their quality, fertilization remains the main tool for enhancing food quality.

Data from experiments conducted by IMPHOS in Poland provide some examples of the effects of P application, along with sufficient levels of N and K application, on the quality of wheat and sugar beet.

On wheat, increasing P applications greatly increased the total content of proteins, from 9.4% to 16.3%, that is a 70% increase. Since this is very important for wheat used for bread production, farmers will further increase their incomes thanks to better prices in response to better grain quality.

On sugar beet, the sugar content increased with increasing P applications. In particular, in Wieszczyczyn, 15 P_2O_5 kg/ha and 60 kg P_2O_5/ha, the sugar yield increased from 4.5 to 9 to 10 t/ha. This clearly shows a dramatic sugar yield limitation if there is no P application or if it is not appropriate. So, in addition to facing reduced sugar beet yields, farmers also face losses in crop product quality and finally in incomes.

A long-term programme implemented in Finland consisting of the application of selenium (Se) enriched NPK fertilizers increased both the Se concentration in food crops and improved the daily intake of Se.

In Turkey, Zn application has given very large increases in yield of wheat and maize, along with increases in the grain Zn content. This has certainly improved the Zn intake of rural populations, whose diets are mainly cereal-based.

Therefore, balanced fertilization practices not only increase crop yields and farmers' incomes but it can also greatly improve the quality of food products and, finally, benefit human health.

Conclusion

During the past few decades, the use of mineral fertilizers has been growing rapidly in developing countries starting, of course, from a low base. This has been particularly the case in the developing countries of East and South Asia, following the introduction of high yielding varieties. East Asia (mainly China) and South Asia (mainly India and Pakistan) are likely to continue to dwarf the fertilizer consumption of the other developing regions.

The demand for food will continue to increase in many regions of the world, particularly in developing countries, driven by the increasing world population. Further, the need for high value quality food will be more and more a concern, not only in developed countries but also in developing countries.

Since the agricultural land area is shrinking, due to the increase in population and land being removed from agriculture by industrial and other human activities, increasing global food production to meet the needs of the world population will more and more require an increased use of fertilizers. However, this must be accompanied by the promotion and the increased use of practices such as balanced fertilization that ensure a more efficient use of plant nutrients, of natural resources (e.g. the soils) and of financial resources, while enhancing the environment.

Balanced fertilization should ensure not only high yields per unit area but also high quality produce, either by improving the low quality of the food due to insufficient nutrient supplies, or by maintaining the high quality together with increased yields. High quality is important in almost every harvested product, whether it is food, fodder or industrial raw materials. Balanced fertilization improves food quality through a higher quality of vegetal products (and indirectly of animal products); so it contributes not only to the nourishment of humans and animals but it also provides them with healthier living conditions.

Therefore, balanced fertilization contributes greatly, or even has a pivotal role, in achieving the goals of FBMPs.

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Papers presented at the IFA International Workshop
on Fertilizer Best Management Practices
7-9 March 2007, Brussels, Belgium

International Fertilizer Industry Association
Paris, France, 2007

Fertilizer Best Management Practices
First edition, IFA, Paris, France, August 2007

ISBN 2-9523139-2-X

The publication can be downloaded from IFA's web site.
To obtain paper copies, contact IFA.

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