NUTRIENT MANAGEMENT HANDBOOK

ifa
INTERNATIONAL FERTILIZER ASSOCIATION

WORLD FARMERS' ORGANISATION

GACSA
GLOBAL ALLIANCE FOR CLIMATE-SMART AGRICULTURE

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FOREWORD

Balanced and precise crop nutrient application - of organic as well as mineral fertilizers - is a prerequisite relevant tool for meeting the second Sustainable Development Goal to end hunger, achieve food security, improved nutrition and promote sustainable agriculture. It is also a crucial building block of climate-smart agriculture. Soil-and crop-specific plant nutrition increases agricultural productivity with a view towards providing food security for an expected global population of about 10 billion people by 2050, but also ensures a maximum uptake of nutrients by plants and a concomitant decrease of nutrient losses to the environment, including emissions of nitrous oxide. By sustainably increasing productivity on arable land, efficient and effective fertilization also safeguards the world's forests and help maintain or increase soil organic matter, two enormous carbon sinks. Last but not least, as one of the effects of climate change in the long run will be an increase of temperature and water stress, proper crop nutrition will help build resilience in agricultural crops, a prerequisite for climate change adaptation.

The world's farmers are on the frontline of the tremendous challenges facing the agricultural sector. With the unfortunate decline in extension services seen in many parts of the world, greater efforts to transfer knowledge on best management practices in the area of plant nutrition are required. Towards this end, WFO, IFA and GACSA are delighted to release this handbook, which is intended to outline the key principles of precise and balanced crop nutrition, to assist farmers in their invaluable work of feeding the growing global population, while improving and safeguarding soil health in a changing climate.

Building on the premises of climate-smart agriculture and the principles of integrated soil fertility management, which call for combining organic and mineral nutrient sources with appropriate soil management practices and crop variety selection, and on the "4Rs" of nutrient stewardship, namely the need to determine - based on crop-and soil-specific investigation - the 1) correct source of fertilizers (matching the fertilizer types with the crop needs); 2) the right rate (matching the amount of fertilizer with the crop requirements); 3) the right time (making nutrients available according to the crop production cycle); and 4) the right place (placing the nutrients where crops can best access them), this handbook provides useful and practical information intended to facilitate efficient and effective crop nutrition by agricultural practitioners.

This Nutrient Management Handbook provides farmers and farmers’ organizations with useful and straightforward practical information on the combination of fertilizers and their effects on plant growth and on soils, including guidelines on efficient nutrient management techniques, which should be tailored to the specificities of particular crops, soils and climatic conditions.

This joint effort by WFO, IFA and GACSA is a good example of a multi-stakeholder partnership to promote Sustainable Development Goal 2 and climate-smart agriculture, and our three organizations are committed to disseminating its recommendations to farm groups around the world.

1.

UNDERSTANDING CROP NUTRITION AND FERTILIZERS

(ORGANIC AND MINERAL)

1.1

ESSENTIAL NUTRIENTS FOR HEALTHY CROPS

As a precondition for growth, health and the production of nutritious food, plants require essential nutrients (macro and micronutrients) in sufficient quantities.

Seventeen elements have been shown to be essential for plants: carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), sulphur (S), magnesium (Mg), calcium (Ca), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), chlorine (Cl), nickel (Ni). Furthermore, additional elements may be essential to a few plant species, e.g. sodium (Na) and cobalt (Co).

Carbon, H and O are obtained from the atmosphere and water, and are not considered mineral elements. The remaining essential elements can be divided into three groups: primary macronutrients (N, P and K), secondary macronutrients (S, Mg and Ca) and micronutrients (Fe, Mn, Zn, Cu, B, Mo, Cl and Ni) based on average concentrations in plants.

If a single essential plant nutrient is available in insufficient quantity, it affects plant growth and thus the yield.

Illustration of Leibig's Law of the Minimum that states that yield potential is determined by the most limiting factor in the field.

Plant growth is limited by the essential element that is furthest below its optimum. Nitrogen, P and K are generally the most widely deficient elements but, nowadays, elements such as S, Zn and B are increasingly deficient in both soils and plants, becoming new limiting factors throughout the world.

1.2

WHAT ARE THE MAIN NUTRIENT SOURCES?

Nutrients can come from a variety of sources:

- **Rock weathering** is a slow process that releases small amount of nutrients annually. It is insufficient to achieve medium to high yields over time.

- Soil nutrients from **previous applications**, which have not been taken up by previous crops are either lost to the environment or stored in soils and potentially available to subsequent crops. Some nutrients such as N and S can be prone to significant losses in the year of application under wet conditions. Nutrients such as P and K remain in soils for longer periods of time, usually several years, subject to soil types, rainfall and management practices.

- **Atmospheric deposition** can be significant in some areas, especially for N and S. In response to regulations reducing S emissions to mitigate related acid rains, this input has been declining over time, S has become an increasingly limiting factor, and S fertilization is now becoming a common practice in developed countries and more and more in emerging and developing economies.

- **Added irrigation water** can also contain nutrients available to crops.

- **Crop residues**, such as leaves, stems and roots, when left on/in the soil, release the nutrients they contain. Crop residues are mainly rich in K. That is why residue incorporation has, over the years been the chief source of this element. However, burning and conversion into livestock feed has gradually depleted K reserves in the soil. Crop residues vary greatly in nutrient content, and the amount of plant available nutrients that are released in a specific time period can only be determined from local data.

- **Compost** (organic matter that has been decomposed) can be added to soils to supply nutrients and serve as soil conditioner. Quality of composts can vary with raw materials and processes used.

- **Livestock manure** is a valuable nutrient source. Nutrient content of manure varies widely between sources and farm management practices. It is widely recognized that poor quality feed for livestock results in manure with low nutrient contents. Manures should be analyzed for nutrient content.

NUTRIENT	CROP RESIDUES	POULTRY MANURE	LIVESTOCK MANURE
N	10-15	25-30	20-30
P	1-2	20-25	4-10
K	10-15	11-20	15-20
Ca	2-5	40-45	5-20
Mg	1-3	6-8	3-4
S	1-2	5-15	4-50

General nutrient content values (g/kg) of crop residues and poultry and livestock manures (Adapted from Barker et al., 2000).

- **Biosolids** (residual solids from urban wastewater treatment) can be recycled and provide significant quantities of plant nutrients. Nutrients in biosolids vary in quantity and forms, depending on the source, treatment, storage and handling processes. Their content in plant nutrients and in possible contaminants should be regularly analyzed.

- **Biological N fixation** (BNF) is the conversion of inert atmospheric dinitrogen molecules (N_2) into forms of N that can be utilized by plants. BNF is found in a number of crop-bacteria combinations. It is greatest in symbiotic systems developed between leguminous crops (e.g. beans, peas, alfalfa) and rhizobia. BNF rates range from 20 to 400 kg N/ha/year depending on plant species, length of the growing season and climatic conditions.

- **Manufactured fertilizers** are produced by the fertilizer industry. A wide range of products, supplying one or more essential mineral nutrients, are available to farmers. On average, world farmers apply some 180 million tons of fertilizers (on a nutrient basis) annually to supplement nutrient sources available on/near their farm, and achieve their sustainable yield and quality goals.

Fertilizers containing only one primary macronutrient are referred to as ‘straight’ fertilizers. Those with two or three primary macronutrients are called ‘multi-nutrient’ fertilizers. Multi-nutrient fertilizers can be either compounds/complexes (all nutrients in the same granule) or bulk blends (physical mixing of different granules). Each fertilizer product has its own advantages and disadvantages, which may depend on the local agro-ecological and economic conditions (See Reetz, 2016 for details).

COMMON NAME	N	P_2O_5	K_2O	S	PHYSICAL STATE
Ammonia	82	0	0	0	Gas
Urea	45-46	0	0	0	Solid
Ammonium sulphate	21	0	0	24	Solid
Ammonium nitrate	33.0-34.5	0	0	0	Solid
Calcium ammonium nitrate	20.4-27.0	0	0	0	Solid
Urea ammonium nitrate	28-32	0	0	0	Liquid
Monoammonium phosphate	11	52	0	0	Solid
Diammonium phosphate	18	46	0	0	Solid
Potassium nitrate	13	0	44	0	Solid
Ground rock phosphate	0	20-40	0	0	Solid
Single superphosphate	0	16-20	0	12	Solid
Triple superphosphate	0	46	0	0	Solid
Potassium chloride	0	0	60	0	Solid
Potassium sulphate	0	0	50	18	Solid

Average nutrient content of some important fertilizer materials (nutrients as % of product).

It is important to note that crops respond to plant nutrients from all sources but they can take up nutrients only in their inorganic form. Organic nutrient sources must be mineralized (converted from an organic to an inorganic form) before being taken up by plants. The amount of nutrients provided by the different sources varies greatly between and within agro-ecosystems. Sustainable crop nutrition identifies and utilizes all available sources of plant nutrients.

CARBON FERTILIZATION

Photosynthesis, thanks to light energy, combines carbon dioxide (CO_2) and water to produce carbohydrates. Through this process, CO_2 is the only C source for all organic matter, about half of which consists of C. This characteristic qualifies CO_2 as the most important element for life in quantitative terms, but efficient photosynthesis also requires all other essential nutrients.

The increase of atmospheric CO_2 since the beginning of industrialization, estimated between 0.03% and 0.04%, has been of global significance for improved water use efficiency and enhanced crop yields. The annual global fertilization value of man-made CO_2 has been estimated to US$ 140 billion.

Under confined systems such as modern greenhouses, increasing CO_2 concentration is a common practice to boost yield. However, to avoid dilution of other nutrients in the faster growing plant tissue and related loss of nutritive value, it is necessary to supply all the essential mineral nutrients in a balanced way and sufficient quantities.

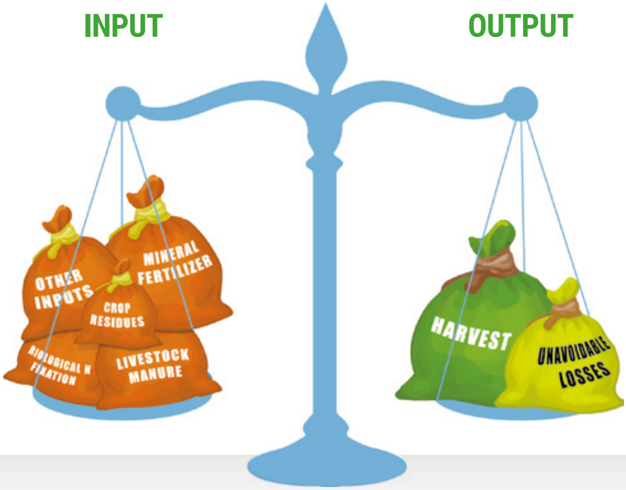
1.3

WHY ARE FERTILIZERS NEEDED FOR HEALTHY SOILS AND PRODUCTIVE AND NUTRITIOUS CROPS?

Nutrients are exported from the field when crops are harvested. This is called soil nutrient mining. The amount of nutrient removed by the harvest is specific to each crop and crop part and proportional to yield. To maintain soil fertility for sustainable crop yields and quality, nutrients exported from the field with the harvest and lost to the environment must be replaced by other organic and/or mineral sources.

In soils where fertility is suboptimal, and where this practice is economically viable, it may be useful to apply higher nutrient application rates, in combination with other necessary soil fertility management practices, to alleviate nutrient-related limiting factors, improve nutrient availability to crops and enhance soil health.

To achieve medium to high yields over time for improved food security and farmer's income, nutrients from indigenous sources, such as soil supply, atmospheric deposition, BNF and manure recycling, may not be sufficient. To maintain high yields, farmers usually require additional nutrient inputs, in the form of manufactured fertilizers or as purchased organic nutrient sources. Limiting nutrients will be replenished by applying mineral and/or organic inputs and, in the case of manufactured fertilizers, by using multi-nutrient fertilizers or combining various complementary fertilizer materials.



Nutrient inputs and outputs must be balanced to optimize crop yield, sustain productivity and minimize losses to the environment.
A positive balance increases risk of nutrient losses and a negative balance results in soil nutrient mining.

MANAGING FERTILIZERS TO IMPROVE NUTRITIONAL VALUE

Fertilizers can also be managed in ways that enhance the nutritional value of crops and, in turn, improve animal and human health. For instance, N and S fertilization influences protein content and quality; K fertilization can increase antioxidant concentration; and Zn fertilization can boost grain Zn density.

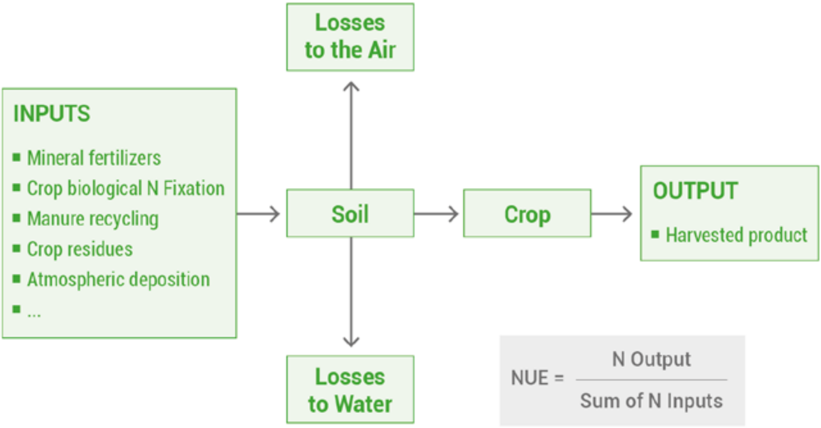
2.

MANAGING NUTRIENTS EFFICIENTLY AND EFFECTIVELY

2.1

WHAT IS NUTRIENT USE EFFICIENCY?

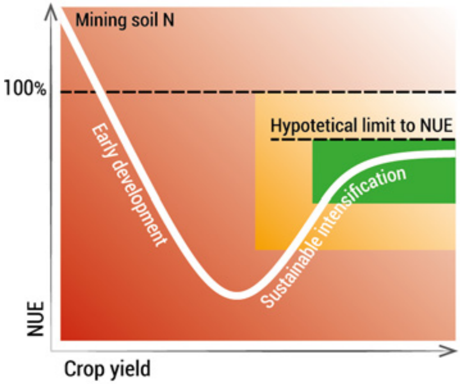
From a farmer's perspective, nutrient use efficiency can be defined as the proportion of the nutrients applied (from all sources) that are taken up by the crop, i.e. how to get the best from the nutrient input. For monitoring purposes, it is calculated as the output/input ratio, i.e. the proportion of the nutrients applied that end up in the harvested product.



$$NUE = \frac{\text{N Output}}{\text{Sum of N Inputs}}$$

Calculation of N use efficiency (NUE)

Low output/input ratios (e.g. below 50%) often reflect risks of nutrient losses to the environment, while high ratios (e.g. above 90%) may reflect soil nutrient mining practices that reduce soil fertility if practiced over several years. Both cases are unsustainable. The 'green zone', where crop productivity is high and where the nutrient output/input ratio is considered close to the optimum, is specific to each cropping system and nutrient.



Typical N use efficiency (NUE) trend relative to crop yield over time.

Farming systems progressively move from the red zone to the orange zone and, ultimately, the green zone, which reflects high yield and optimum N use efficiency (Adapted from Zhang et al., 2015)

Nutrient use efficiency is highly influenced by the way mineral fertilizers, other nutrient sources, crops and soils are managed. Nutrient use efficiency has been improving for about three decades in developed countries, where farmers have access to modern technology and information. It illustrates the move to sustainable intensification, where farmers increase agricultural productivity while preserving the resource base and reducing risk of environmental impacts associated with the nutrient surplus per unit output. In contrast, the situation is still deteriorating in most developing countries. Access to and adoption of best management practices (nutrient stewardship and integrated approaches) is required for reverting the trend in developing countries.

Because nutrients interact between each other, enhanced nutrient use efficiency can be achieved by better managing the nutrient in question, as well as by better managing the nutrients with which it interacts (through balanced fertilization). For instance, S is known to improve protein synthesis and thus N use efficiency.

2.2

EFFICIENCY AND EFFECTIVENESS GOALS ARE COMPLEMENTARY

While improving nutrient use efficiency is an important goal, it should not be to the detriment of other key performance areas such as crop yield[1], soil fertility, water productivity, etc., which reflect effectiveness of the farming system. For instance, it is possible to increase nutrient use efficiency by mining soil nutrient reserves but it is an unsustainable option because such a practice would impact soil fertility in the medium to long term.

Similarly, it is possible to achieve higher use efficiency by cutting fertilizer applications rates but that might be to the detriment of crop yield. While tracking nutrient use efficiency provides useful information, it should be part of a set of complementary indicators to ensure meaningful interpretation.

Best management practices recommended to farmers for their site- and crop-specific conditions should provide options that improve the overall performance and sustainability of the farming system, taking into account economic, social and environmental goals set by society.

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[1] Nutrient use efficiency (measured as the output/input ratio) is typically highest at very low nutrient application rates, which lead to low yield.


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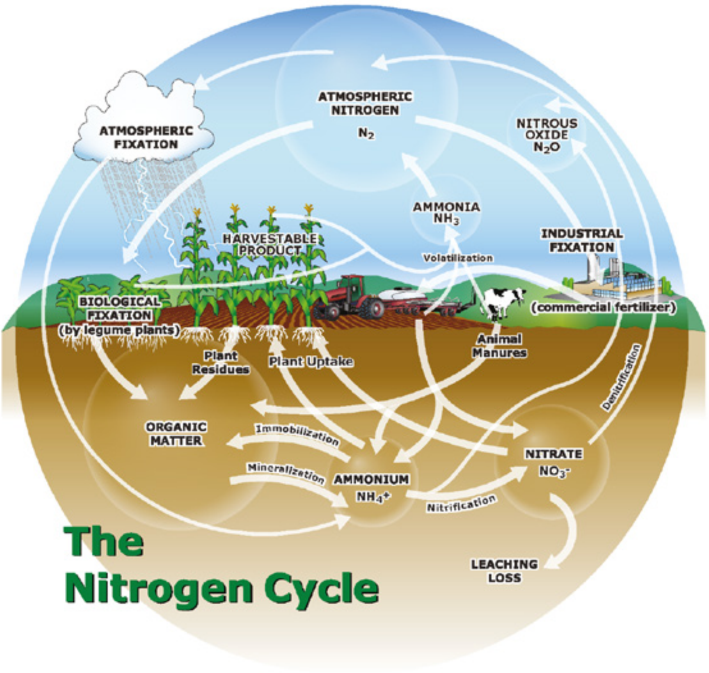
3.

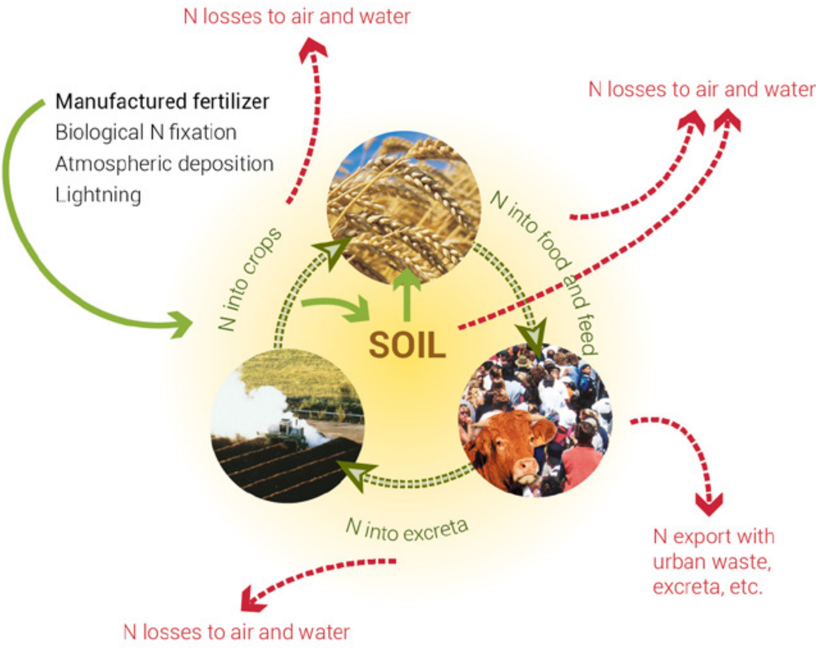
AGRICULTURAL NUTRIENT CYCLES AND LOSS PATHWAYS

The principal forms of N in the soil are organic N compounds and mineral N in the form of ammonium (NH_4^+) and nitrate (NO_3^-). Mineral N is only a small fraction of the total soil N. Most of the N in a surface soil is present as organic N. These different N fractions undergo various transformation processes, which may lead to various losses to the air and water.



In the case of P, the main losses occur through soil erosion and runoff of particulate matter. Leaching losses of P are small relative to those of N owing to the low mobility of P in soils. Potassium is also lost through erosion, runoff and leaching. Leaching losses are proportionally larger for K vs. P owing to K's greatest mobility in soils. The S cycle is more complex with, similarly to N, losses to both the air and water.

Because agricultural nutrient cycles are leaky, sustainable agricultural production relies on external nutrient inputs, through addition of organic forms (if available), mineral fertilizers and biological N fixation, in order to fill the gap caused by nutrient exports with the harvested product and nutrient losses at different stages of the nutrient cycle. The continuous challenge for the farmer is to apply the right nutrient source at the right rate, at the right time, in the right place in order to sustain optimum yields and, at the same time, minimize environmental impacts. Both lack and excess of nutrients may result in adverse effects on human health, the environment and farmer's income.



The actual agricultural N cycle: an open system with unavoidable losses

4.

THE NEED FOR INTEGRATED PLANT NUTRIENT AND SOIL FERTILITY MANAGEMENT

4.1

MINERAL AND ORGANIC NUTRIENT SOURCES ARE COMPLEMENTARY

Mineral fertilizers have a higher nutrient content than organic sources. They have a well-defined nutrient composition, and nutrients in mineral fertilizers are often readily available to crops. Organic nutrient sources are, by definition, rich in organic matter, which helps improving soil properties such as soil structure, water infiltration and retention capacity. In view of these respective benefits, mineral and organic nutrient sources are complementary. Best management practices take advantage of this synergy.

4.2

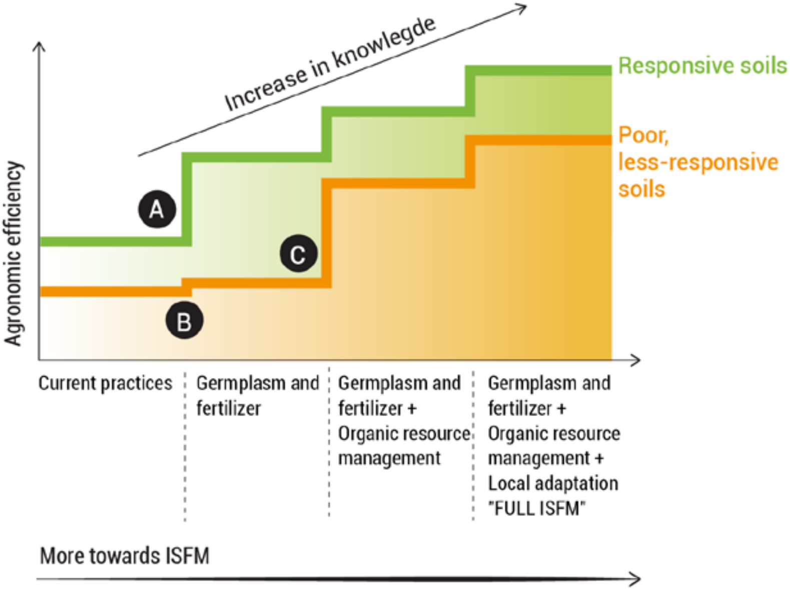
THE MULTIPLE BENEFITS OF INTEGRATED PLANT NUTRIENT AND SOIL FERTILITY MANAGEMENT APPROACHES

From a nutrient standpoint, integrated management can be considered at two different levels:

- Integrated Plant Nutrient Management (IPNM) aims at combining organic and mineral nutrient sources, building on the respective advantages of both sources. In IPNM, farmers apply organic sources available on the farm or in its vicinity and supplement them with manufactured fertilizers to achieve the farmer's yield and quality goals, and restore soil fertility where soil testing shows low available nutrient levels.

- While IPNM is an approach focusing on the nutrient supply aspects of crop production, Integrated Soil Fertility Management (ISFM) encompasses all dimensions of plant nutrient uptake, including selection of crop varieties and the biological and physical dimensions of soil health, which can enhance uptake. For instance, under drought stress conditions, a soil covered with organic matter can hold more soil moisture than a soil that does not have mulch, and this extra moisture may result in improved uptake of applied fertilizer nutrients and increased yields.

Integrated plant nutrient and soil fertility management share similar objectives, namely to ensure efficient nutrient uptake and plant growth with minimal adverse impacts on the environment.



Ⓐ Local adaptation also adjusts for variability in soil fertility status and recognizes that substantial improvements in agronomic efficiency can be expected on responsive soils.

Ⓑ On poor, less-responsive soils, application of fertilizer alone does not result in improved agronomic efficiency.

Ⓒ Fertilizer is better applied in combination with organic resources.

Conceptual relationship between the agronomic efficiency of fertilizers and organic resources as one moves from current practice to “full ISFM”. At constant fertilizer application rates, yield is linearly related to agronomic efficiency. Note that the figure does not suggest the need to sequence components in the order presented.

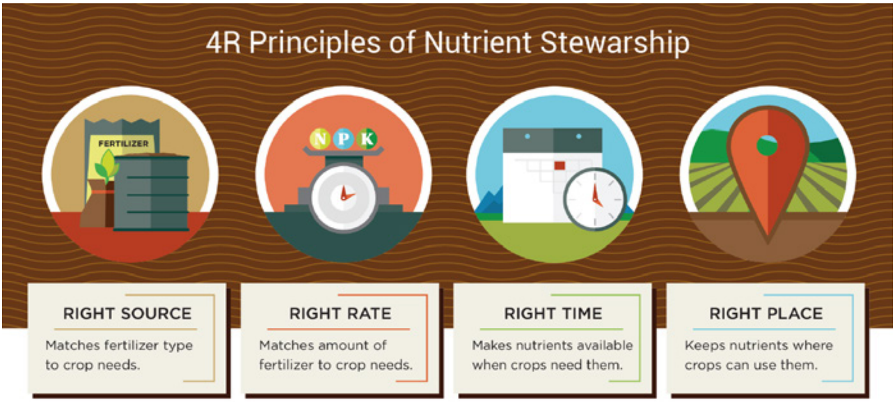
5.

NUTRIENT STEWARDSHIP

5.1

PRINCIPLES OF BEST MANAGEMENT PRACTICES AND NUTRIENT STEWARDSHIP

Practices shown by research and experience to be more productive, more profitable, more environment-friendly, and more socially-acceptable are designated as fertilizer (or nutrient) best management practices (BMPs). The goal of fertilizer BMPs is to match nutrient supply with crop requirements to optimize yield while minimizing nutrient losses to the environment. Application of fertilizer BMPs in each of the four areas of nutrient management (source, rate, time and place) provides the basis of "nutrient stewardship", a framework for the efficient and effective use of plant nutrients to achieve economic, social and environmental benefits.



An individual BMP may improve performance in one or two management areas. Because the four management areas should be paid equal attention, nutrient stewardship requires adoption of a set of complementary BMPs that will address the four areas. If any of the four areas are overlooked, on-farm nutrient management is unlikely to be efficient and effective. The weakest area of management will have the strongest influence on overall use performance.

Selection of BMPs varies by location, and those that work best for a given farm will meet local soil and climatic conditions, crop type, management system, and other site-specific factors.

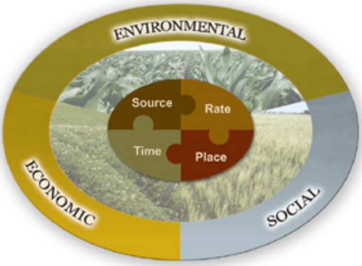


Diagram of the Global Framework for 4R Nutrient Stewardship.
The concept is centered on the interlocking 4Rs, which influence the cropping system's contribution to the three dimensions of sustainability (IFA, 2009; IPNI, 2012)

The following general scientific principles apply to fertilizer BMPs:

- **Be consistent with understood agronomic mechanisms.**
  Take into account the related scientific disciplines, including soil fertility, plant nutrition, soil physics and chemistry, hydrology, and agro-meteorology. For instance, moisture stress and, hence wilting may worsen under dry conditions as the nutrient concentration around the root zone draws water from the plant through osmosis. In this case, fertilizer application should be well timed with water or moisture availability in the soil.

- **Recognize interactions with other cropping system factors.**
  Examples include cultivar, planting date, plant density, crop rotation, etc.

- **Recognize interactions among nutrient source, rate, time and place.**
  For example, a controlled-release source likely should not be applied with the same timing as a water-soluble source.

- **Avoid detrimental effects on plant roots, leaves and seedlings.**
  For example, banded fertilizers need to be kept within safe distance from the seed to avoid possible damage to seedlings.

- **Recognize effects on crop quality as well as yield.**
  For example, N influences both yield and the protein content. Protein is an important nutrient in animal and human nutrition, and it influences bread-making quality in wheat. Nitrogen rates above those needed for optimum yield may increase protein content, but over-application has a negative impact on plant health, crop yield and quality, and environmental sustainability. Nitrogen utilization in N-efficient cultivars is to be paid

due attention: Some varieties growing under high N tend to grow lavishly i.e. greater vegetative part at the expense of the harvestable part. Therefore, proper choice of crop varieties and adapted fertilization programs is essential.

5.2

RIGHT NUTRIENT SOURCE

CHOOSE NUTRIENT SOURCES THAT PROVIDE A BALANCED SUPPLY OF ALL ESSENTIAL NUTRIENTS, WITH RELEASE MATCHING CROP DEMAND.

The right source for a nutrient management system must ensure that a balanced supply of all essential nutrients is present in plant-available forms, whenever required by the crop throughout the growing season. Selection of the right source (including organic sources) must also consider susceptibility to nutrient loss, any nutrient interactions or compatibility issues, potential sensitivity of crops to the source, and risk from any non-nutrient elements included with the source material. The right source may vary with the crop, climate, soil properties of the field, available products, economic considerations and options for method of application.

Scientific principles applying to the right source of plant nutrients include:

› **Supply nutrients in plant-available forms.**
The nutrient applied is water-soluble and plant-available, or is in a form that converts readily into a plant available form in the soil.

› **Suit soil physical and chemical properties.**
Examples include avoiding nitrate application to waterlogged soils and use of surface applications of urea without a urease inhibitor on high pH soils. Some fertilizer have acidifying effects on soils; they should be applied to alkaline soils only, or in combination with liming.

› **Recognize interactions between nutrient elements and sources.**
Examples include the phosphorus-zinc interaction, nitrogen increasing phosphorus availability, and fertilizer complementing manure.

› **Recognize blend compatibility.**
Certain combinations of sources/products attract moisture when mixed, limiting uniformity of application of the blended material; granule size should be similar to avoid product segregation; certain fluid sources may “salt-out” at low temperatures or react with other components to form gels or precipitate.

› **Recognize crop sensitivities to associated elements.**
Most nutrients have an accompanying ion that may be beneficial, neutral or detrimental to some crops. For example, the chloride accompanying potassium in muriate of potash is beneficial to maize but can be detrimental to the quality of some fruits and vegetables.

› **Control effects of non-nutritive elements.**
For example, raw materials used for fertilizer production may contain non-nutritive trace metals. Addition of these elements should be kept within safe limits.

5.3

RIGHT RATE

ENSURE AN ADEQUATE AMOUNT OF ALL LIMITING NUTRIENTS IS APPLIED TO MEET PLANT REQUIREMENTS IN RELATION TO YIELD AND QUALITY GOALS.

The right rate matches the plant-available supply of nutrients from all sources to the nutrient requirements of the plant. Understanding of the nutrient needs of the crop through the various growth stages is a first step to providing the right rate. Application rate should be selected to balance nutrient supply with crop demand throughout the growing season to avoid nutrient deficiency or excess. Crop yield and quality will be restricted if the rate is too low while excess application can lead to crop damage and negative environmental impacts. Both excess and insufficient nutrient application will decrease economic profitability.

› **Assess soil nutrient supply.**
Practices used may include soil and plant analysis, response experiments, omission plots, or saturated reference strips.

› **Assess all available nutrient sources.**
Includes quantity and plant availability of nutrients in crop residues, green manures, animal manure, composts, biosolids, irrigation water, atmospheric deposition and manufactured fertilizers.

› **Assess plant demand.**
The quantity of nutrient taken up in one season depends on crop yield and nutrient content. Accurate assessment of attainable yield is important, and design total crop production programs to achieve attainable yield.

› Predict fertilizer use efficiency.

Some losses are unavoidable. While losses should be minimized, unavoidable losses must be considered when determining the rate for meeting plant demand.

› Consider season-to-season variability in nutrient demand.

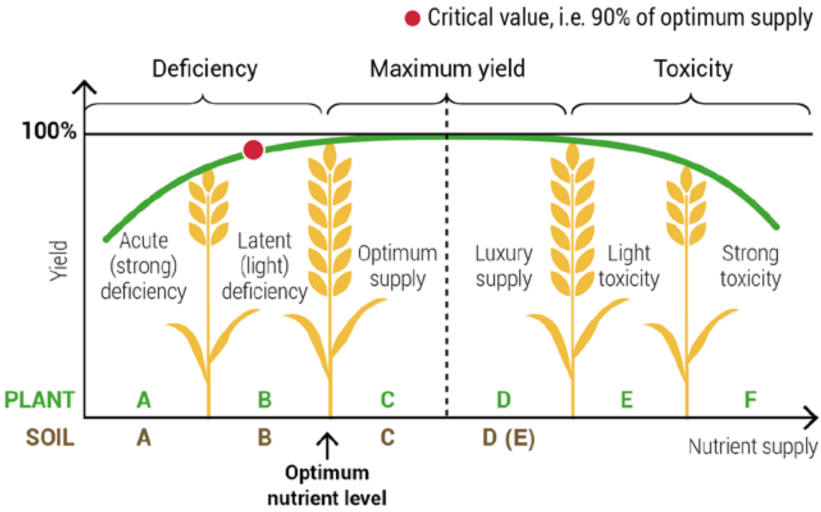
Yield potential and nutrient demand are affected by season-to-season variability in climate and other factors, including management, providing opportunities for real-time nutrient management with variable fertilizer rates (technologies include chlorophyll meter, leaf color chart, and other methods of in-crop nutrient assessment).

› Consider nutrient budgets.

If the output of nutrients from a cropping system exceeds inputs, soil fertility declines in the long term. In the opposite situation, if surplus nutrients are lost, environmental quality and economic performance are affected.

› Consider rate-specific economics.

Taking into account spatial and temporal yield variability, for nutrients unlikely to be retained in the soil, the most economic rate of application is where the last unit of nutrient applied is equal in value to the increase in crop yield it is anticipated to generate (law of diminishing returns). Residual value of soil nutrients to future crops should be considered.



Effects of nutrient rate on crop yield, showing potential deficiency and toxicity effects of not applying the right rate of nutrients.

5.4

RIGHT TIME

TIME NUTRIENT APPLICATIONS CONSIDERING THE INTERACTIONS OF CROP UPTAKE, SOIL SUPPLY, ENVIRONMENTAL RISKS, AND FIELD OPERATION LOGISTICS.

Crop nutrient uptake rates change throughout the growing season as the crop moves from emergence to vegetative growth, through reproductive stages, and on to maturity. To attain optimum productivity, sufficient plant-available nutrients must be present where the crop can access them to meet crop demand at all stages through the growing season. However, if the nutrient is present in the soil for an extended time prior to crop uptake, it may move out of the rooting zone or be converted to unavailable forms. The right timing of nutrient application will support crop yield and nutrition quality and minimize nutrient losses.

› **Assess timing of crop uptake.**
Depends on factors such as planting date, plant growth characteristics, sensitivity to deficiencies at particular growth stages. Nutrient supply must be synchronized with the crop's nutrient requirements, which usually follows an S-shaped curve.

› **Assess dynamics of soil nutrient supply.**
Mineralization of soil organic matter supplies a large quantity of some nutrients, but if the crop's uptake need precedes the release through mineralization, deficiencies may limit productivity.

› **Assess nutrient release and availability from fertilizer products.**
Release rate and availability of fertilizer nutrients are influenced by weather and soil moisture conditions at application, resulting in potential significant nutrient and yield losses if not synchronized with the crop's requirements.

› **Recognize timing of weather factors influencing nutrient loss.**
Specific forms of a nutrient can perform better than others under certain climate conditions and in certain seasons. For example, in temperate regions, leaching losses tend to be more frequent in the spring and autumn.

› **Evaluate logistics of field operations.**
For example, multiple applications of nutrients may or may not combine with those of crop protection products. Nutrient applications should not delay time-sensitive operations

such as planting or the need for insect or disease control. Under these constraints, foliar fertilizers which are compatible with most of the crop protection products can be used.

5.5

RIGHT PLACE

PLACE NUTRIENTS TO TAKE ADVANTAGE OF THE ROOT-SOIL DYNAMICS CONSIDERING NUTRIENT MOVEMENT, SPATIAL VARIABILITY WITHIN THE FIELD, AND POTENTIAL TO MINIMIZE NUTRIENT LOSSES FROM THE FIELD.

Having nutrients in the right place - vertically and horizontally - ensures that plant roots can absorb enough of each nutrient at all times during the growing season. Placement systems can be used to position fertilizer in relation to the growing roots. In recent years, availability of precision farming technology has made it also possible to fine-tune nutrient application, varying the rate of application within the field, to account for variability of soil test levels and yield potential.

› **Recognize root-soil dynamics.**
Roots of annual crops explore soil progressively over the season. Placement needs to ensure nutrients are intercepted as needed. An example is the band placement of phosphate fertilizer for maize, ensuring sufficient nutrition of the young seedling, increasing yields substantially even though amounts applied and taken up are small.

› **Manage spatial soil variability within fields and among farms.**
Soils do affect crop yield potential and vary in nutrient supplying capacity or nutrient loss potential.

› **Fit needs of tillage system.**
Recognize logistics of soil preparation. In conservation farming, ensure subsurface applications maintain soil coverage by crop residue and do not compromise seed-bed quality.

› **Limit potential off-field transport of nutrients.**
Identify fields and field areas most prone to nutrient losses. Keep nutrient losses through erosion, runoff, leaching, volatilization, nitrification and denitrification within acceptable limits.

› **Reduce risk of nutrient toxicity on seedlings.**
Avoid toxicity on seedlings from excess concentrations of nutrients in or near the seed.

› **Fix acute deficiencies by foliar applications.**

During drought or peak growth periods, temporary Mg or S deficiencies can be addressed by foliar applications. Crops' micronutrient requirements can be fully met by foliar sprays, e.g. in the case of Zn, B or Mn.

6.

NUTRIENT MANAGEMENT IN RELATION TO KEY SUSTAINABILITY CONSIDERATIONS

6.1

NUTRIENT MANAGEMENT, FOOD AND NUTRITION SECURITYSTEWARDSHIP

Nutrients, when available in insufficient quantities, limit crop yield. To produce enough food to meet the rising food, feed, fibre and bioenergy requirements of a fast growing and wealthier world population, while reducing agriculture's footprint on the environment, it is essential to enhance nutrient management. Nitrogen is the most limiting nutrient globally. In absence of fertilizers, especially N fertilizers, it is estimated that we would be able to produce only half of today's world food output (Erisman et al., 2008). With the world's population expected to exceed 9 billion by 2050, coupled with a steady shift to more livestock products in diets, the efficient and effective use of fertilizers will play a key role to feed the planet in the decades to come. This includes more balanced fertilization, including the appropriate use of secondary and micronutrients.

More recently, fertilization has been used to address micronutrient deficiencies in both animals and humans. As far as zinc (Zn) is concerned, the proportion of people at risk of Zn malnourishment, while varying regionally, is estimated at 21% globally (Hotz and Brown, 2004). Where low Zn levels in soils are at the origin of deficiencies in humans, fertilization interventions provide interesting options for increasing both crop yield and Zn density in grain, thus enhancing the Zn intake of populations that grow crops on those soils (Details on www.harvestzinc.org).

6.2

NUTRIENT MANAGEMENT AND SOIL HEALTH

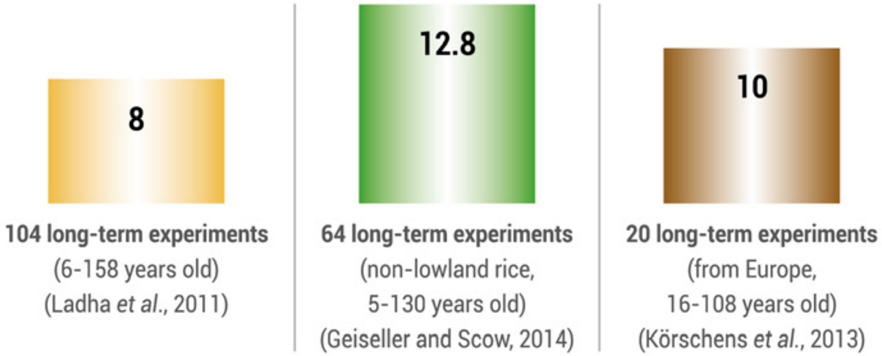
Many factors contribute to soil quality or health. A key property of soil health is the ability of the soil to provide all essential nutrients in adequate amounts and proportions for plant growth, often defined as soil fertility. Soil fertility is maintained by adding nutrient inputs that offset nutrient exports and losses. Physical factors such as texture and structure are also important components of soil quality. While human interventions can alter soil structure, texture is largely unchangeable. The key factor for soil quality is the soil organic matter (SOM) fraction, which although relatively small, has a strong influence on soil structure and the overall health of the soil and its beneficial functions.

Soil organic matter controls soil microbial populations and their many functions in soil such as organic matter decomposition and nutrient cycling. Organic matter can help increase soil aggregate stability and thus contribute to enhanced water infiltration and retention, with associated improved resilience to erosion and soil degradation.

Fertilizer use can have positive effects on soil health when best management practices are implemented, while fertilizer misuse can negatively impact some soil properties. Depending on the tillage system used, regular additions of fertilizer can enhance SOM levels by stimulating root and crop residue production. There is debate regarding the impact of mineral fertilizer use on SOM under tropical agro-ecological conditions, and whether it would stimulate organic matter turnover and thus lead to faster SOM breakdown. However, analysis of long-term experiments from all over the world shows that adequate and balanced use of mineral fertilizers results in an increase in SOM as compared to plots receiving no fertilizers.

If the wrong fertilizer product or blend is used, e.g. by applying an improper balance between N and the other essential nutrients, it can affect soil health negatively through faster depletion of non-added nutrients. With some fertilizer products, there is also a risk of acidifying soils; this may be beneficial for alkaline/calcareous soils, but may be detrimental to soils with a low pH if no lime is applied to offset the acidifying effect.

Percent increase in soil organic carbon due to fertilizer application compared to unfertilized control



The effects of fertilizer on soil microbial populations depend on the nutrient source, the application rate and method, soil pH and the timeframe considered. Negative effects are often localized and short-lived. For instance, next to fertilizer granules, total microbial activity may be reduced for a few weeks, after which levels return to normal. Long-term experiments show that long-term use of fertilizers generally leads to increases in soil microbial biomass (with a possible shift in microbial diversity), and microbial activity is generally further enhanced by integrated use of organic amendments along with mineral fertilizers.

	NUMBERS OF DATA SETS	SOIL MICROBIAL BIOMASS CARBON ($mg\ kg^{-1}$) - N	+ N
All data sets	107	238	268
pH in +N treatment <5	17	240	213
pH in +N treatment 5-7	39	234	253
pH in +N treatment 7 or higher	17	139	205
Duration of long-term experiment 5-10 years	18	300	239
Duration of long-term experiment 10-20 years	34	227	270
Duration of long-term experiment 20 years or longer	55	224	276

Soil microbial biomass in treatments with (+N) and without (-N) N fertilization.
Unweighted averages are based on analysis of 107 data sets from 64 non-lowland rice long-term experiments from all over the world (adapted from Geiseller and Scow, 2014).

6.3

WATER x NUTRIENT INTERACTIONS

Fertilizer best management practices can enhance water productivity, just as an adequate water supply is a requirement for improved nutrient use efficiency. Often, water and nutrient management are addressed separately, although they are intimately linked. Improvements in nutrient use efficiency should not be viewed only as a fertilizer management issue. The same is true for water.

Water stress hinders the transport of nutrients from the soil to the crop's roots, as well as the chemical and biological processes in the soils, required for optimal nutrient uptake by plants. Nutrient deficiencies reduce root development and, in turn, the ability of crops to use water efficiently. Improvements in agronomic practices are essential for increasing agricultural output per unit of land, water and nutrients, which contributes to sustainable agricultural intensification.

The influence of nutrients on yield depends on available water, and there is often a positive interaction between these two components, and their relative importance varies depending on the degree of stress imposed by each factor. Often, interactions between nutrients and water have a greater impact on yield than the impact of each factor separately. Hence, these two factors should be addressed in an integrated way.

6.4

NUTRIENT MANAGEMENT AND CLIMATE CHANGE

By managing nutrients efficiently and effectively, farmers can:

- improve adaptation to climate change;
- prevent further expansion of cropping into sensitive valuable habitats;
- reduce nitrous oxide (N_2O) emission intensities; and
- sequester carbon (C) in their soils.

Expansion of agricultural land to forests, pastures or wetlands releases significant amounts of carbon dioxide (CO_2). Large emissions of CO_2 are due to burning of cleared bushes and destruction of carbon sinks. By boosting yields, fertilizers have the potential to prevent expansion of cropping into sensitive areas and related greenhouse gas emissions and biodiversity losses.

When N fertilizer is applied, part of it is taken up by crops, part remains in the soil, some of which is incorporated into soil organic matter, and part is lost to the environment. One of the loss pathways is denitrification, which releases both dinitrogen (N_2) and N_2O. Nitrous oxide is a greenhouse gas with a global warming potential about 300 times higher than CO_2.

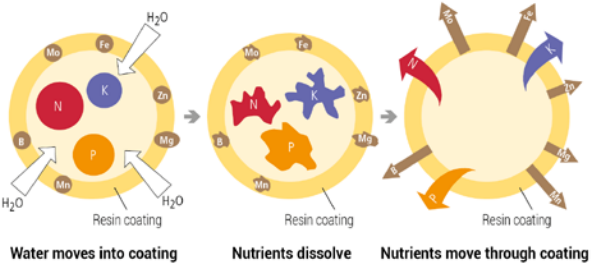
N_2O EMISSIONS FROM MANAGED ECOSYSTEMS AND N INPUTS

The Intergovernmental Panel on Climate Change (IPCC) Tier-1 method to calculate direct N_2O emissions from managed soils assumes that 1% of the added N (organic or inorganic) eventually is lost to the environment as N_2O. Even though this method is quite a simplification of realities, it is based on some extensive data sets, which relate measured N_2O emissions to N inputs. It thus seems difficult to reduce total N_2O emissions if agricultural systems are to be (further) intensified.

Some best management practices (e.g. avoid N applications on waterlogged soils, use slow- or controlled-release fertilizers or fertilizers stabilized with nitrification inhibitors), have the potential to minimize N losses in the form of N_2O while improving overall N use efficiency and effectiveness.

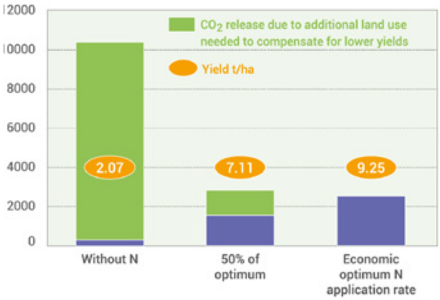
SLOW- AND CONTROLLED-RELEASE AND STABILIZED FERTILIZERS

Several additives and treatments are commercialized to modify availability of the nutrients. These include 'slow-release fertilizers' that break down gradually to release plant available nutrients (e.g. methylene urea), 'controlled-release fertilizers' that are physically encapsulated in a protective coating (e.g. polymer-coated fertilizers), and 'stabilized fertilizers' that slow N cycling in the soil (e.g. fertilizers treated with urease and/or nitrification inhibitors). All these products aim at extending the release of the nutrients from the fertilizer materials to better match crops' requirements.



Mode of action of a coated/encapsulated controlled-release fertilizer

Besides, there is a potential to decrease emission intensities, i.e. total greenhouse gas emissions (in CO_2 equivalent) per ton of harvested product. Even if N_2O emission quantities increase, this rate of increase may be smaller than the accompanying increase in crop production, which - dividing the one by the other - reduces emission intensities. By combining a reduction of emission intensities with no or limited expansion of cropping systems, future food can be produced with comparably less greenhouse gas emissions.



Greenhouse gas emissions (kg CO_2-eq/ha) for producing 9.25 tons of winter wheat in the United Kingdom under three different N fertilization regimes.
Results based on the Broadbalk experiment at Rothamsted Research, average 1996 to 2000 (Adapted from Brentrup and Pallière, 2008).

Fertilization can increase soil organic matter (SOM) by stimulating plant and root growth, if crop residues are left in the field. Because soil N and C cycles are closely linked, an increased input of C through residues may tie up soil N, reducing its availability to plants. On the other hand, excessive additions of N fertilizers may accelerate decomposition of SOM. Long-term experiments from all over the world show that adequate and balanced use of mineral fertilizers result in an increase in SOM as compared to plots receiving no fertilizers. Highest increases in SOM are generally achieved by integrating organic and mineral nutrient sources.

Reforestation can sequester large quantities of C, especially in developing countries. The sole option to liberate the necessary land for C sequestration without threatening food security in those countries is intensification of agricultural production on some of the best lands by increased fertilizer inputs, use of improved crop varieties, and adoption of good crop and soil management practices. Calculations show that C sequestration far outweighs emissions associated with the production and use of the extra fertilizer needed (Vlek et al., 2004).

Soil management, especially changes in tillage practices, also greatly influences SOM levels. Proper fertilization practices offer an interesting option for simultaneously sequestering C in agricultural soils and improving soil fertility and, in turn, mitigating climate change and improving food security.

Climate change is expected to increase temperature and water stress. Nutrient management provides options to address some of these stresses. Phosphate application stimulates root growth and, as a result, resilience to dryness. Cations such as potassium and zinc also improve stress tolerance through different mechanisms. Balanced fertilization is therefore an important tool available to farmers to adapt to climate change.

6.5

NUTRIENT MANAGEMENT AND THE ENVIRONMENT

In addition to the global warming potential of N_2O, nutrient applications (from mineral and organic sources) can impact the environment in the following ways:

- Acid deposition from anthropogenic emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_X) and ammonia (NH_3);
- Eutrophication of aquatic (and terrestrial) systems by increasing N and P flows from agricultural land to these systems;
- Stratospheric ozone depletion by N_2O emissions;
- Particulate matter formation following NH_3 emissions;
- Nitrate (NO_3^-) accumulation in groundwater.

Taking tradeoffs into account, agronomists are working hard to develop fertilizer BMPs that minimize the overall environmental impact while maximizing benefits. By developing and disseminating a range of BMPs (in the four areas of nutrient management) that address the diversity of agro-ecologies and farming systems, there is still tremendous scope for increasing efficiency and effectiveness at different scales.

As an example, the following table illustrates the advantages and limitations of selected P fertilizer application practices, combinations of source (S), rate (R), time (T) and place (P) for the maize-soybean rotation in the Lake Erie watershed in North America (Bruulsema et al., 2012).

P APPLICATION PRACTICE	ADVANTAGES	LIMITATIONS
OPTION 1 S – MAP or DAP R – Removal rate for rotation T – Fall after soy before corn P – Broadcast	• Minimal soil compaction • Allows timely planting in spring • Lowest-cost fertilizer form • Low cost of application	• Risk of elevated P in runoff in late fall and winter • Low N use efficiency
OPTION 2 S – MAP or DAP R – Removal rate for rotation T – Spring before corn P – Broadcast	• Minimal soil compaction • Better N use efficiency • Low-cost fertilizer form • Low cost of application	• Risk of elevated P in spring runoff before incorporation • Potential to late planting • Retailer spring delivery capacity
OPTION 3 S – MAP or fluid APP R – Removal rate for crop T – Spring P – Planter band	• Best N efficiency • Low risk of elevated P in runoff • Less soil P stratification	• Cost and practicality of planting equipment with fertilizer capacity • Potential to delay planting • Retailer delivery capacity • Cost of fluid versus granular P
OPTION 4 S – MAP or DAP R – Removal for crop or rotation T – Fall after soy before corn P – Zone placement in bands	• Low risk of elevated P in runoff • Better N and P efficiency • Maintain some residue cover • Allows timely planting in spring • Less soil P stratification	• Cost of RTK GPS guidance • Cost of new equipment • Requires more time than broadcast
OPTION 5 S – Fluid APP R – Removal for crop or rotation T – Fall after soy before corn P – Point or spoke injection	• Low risk of elevated P in runoff • Better N and P efficiency • Maintain good residue cover • Allows timely planting in spring • Less soil P stratification	• Cost of RTK GPS guidance • Cost of new equipment • Cost of fluid versus granular P • Requires more time than broadcast

MAP = Granular monoammonium phosphate
DAP = Granular diammonium phosphate
APP= Fluid ammonium polyphosphate
RTK GPS = Real-time kinematic global positioning system

7.

HIGHLIGHTS

Essential nutrients are required for growing healthy, productive and nutritious crops.

Agricultural nutrient cycles are open systems with unavoidable losses, which have negative impacts on crop productivity, farming profitability and environmental services. The objective is to reduce those losses while steadily increasing crop yield. More efficient nutrient use, through adoption of nutrient best management practices, optimizes benefits and reduces risks associated with human interference on agricultural nutrient cycles.

A range of fertilizer best management practices is available to farmers. These practices should address the four areas of nutrient management (source, rate, time and place) and provide options that meet the diversity of site- and crop-specific conditions, to improve overall sustainability of cropping systems considering economic, social and environmental perspectives (‘nutrient stewardship’ approach).

Mineral fertilizers should not be considered in isolation. For optimizing fertilizer use sustainability and performance, mineral fertilizer should be combined with the use of organic nutrient sources, together with the selection of appropriate crop varieties and crop, water and soil management practices (‘integrated soil fertility management’ approach).

Beyond food security and farm income, plant nutrient management can influence a number of sustainability goals such as human nutrition, soil health, water productivity, climate change mitigation and adaptation, and environment health as a whole. When properly managed, nutrients can positively impact these goals.

REFERENCES

Barker, A.V., M.L. Stratton and J.E. Rechcigl (2000). p. 169-213. In J.M. Bartels (ed.) Land Application of Agricultural, Industrial, and Municipal By-Products. Soil Science Society of America. Madison, Wisconsin, USA.

Brentrup, F. and C. Pallière (2008). GHG emissions and energy efficiency in European nitrogen fertiliser production and use. Proceedings 639, International Fertiliser Society, York, UK.

Bruulsema, T.W., R. Mullen, I.P. O'Halloran and H. Watters (2012). Reducing loss of fertilizer phosphorus to Lake Erie with the 4Rs. IPNI Insights, International Plant Nutrition Institute, Norcross, GA, USA.

Erisman, J.W., M.A. Sutton, J. Galloway, Z. Klimont and W. Winiwarter (2008). How a century of ammonia synthesis changed the world. Nature Geoscience 1, 636 – 639.

Geiseller, D. and K.M. Scow (2014). Long-term effects of mineral fertilizers on soil microorganisms – A review. Soil Biol. Biochem. 75: 54-63.

Glatzle, A. (2014). Severe Methodological Deficiencies Associated with Claims of Domestic Livestock Driving Climate Change. Journal of Environmental Science and Engineering B 2: 586-601.

Hotz, C. and K.H. Brown (2004). Assessment of the risk of zinc deficiency in populations and options for its control. Food Nutr. Bull. 25: 94–204.

IFA (2009). The Global "4R" Nutrient Stewardship Framework for Developing and Delivering Fertilizer Best Management Practices. International Fertilizer Industry Association, Paris, France.

IPNI (2012). 4R Plant Nutrition Manual: A Manual for Improving the Management of Plant Nutrition, metric version. Bruulsema, T.W., P.E. Fixen and G.D. Sulewski (eds.), International Plant Nutrition Institute, Norcross, GA, USA.

Körschens, M., E. Albert, M. Armbruster, D. Barkusky, M. Baumecker, L. Behle-Schalk, R. Bischoff, Z. Čergan, F. Ellmer, F. Herbst, S. Hoffmann, B. Hofmann, T. Kismanyoky, J. Kubat, E. Kunzova, C. Lopez-Fando, I. Merbach, W.Merbach, M.T. Pardor, J. Rogasik, J. Rühlmann, H. Spiegel, E. Schulz, A. Tajnsek, Z. Toth, H. Wegener and W. Zorn (2013). Effect of mineral and organic fertilization on crop yield, nitrogen uptake, carbon and nitrogen balances, as well as soil organic carbon content and dynamics: results from 20 European long-term field experiments of the twenty-first century. Arch. Agron. Soil Sci. 59: 1017-1040.

Ladha, J.K., C. Kesava Reddy, A.T. Padre and C. van Kessel (2011). Role of nitrogen fertilization in sustaining organic matter in cultivated soils. J. Environ. Qual. 40: 1756-1766.

Reetz, H.F. Jr. (2016). Fertilizers and their Efficient Use. International Fertilizer Industry Association, Paris, France.

Vlek, P.L., G. Rodriguez-Kuhl and R. Sommer (2004). Energy use and CO_2 production in tropical agriculture and means and strategies for reduction or mitigation. Environment, Development and Sustainability 6: 213-233.

Zhang X., E.A. Davidson, D.L. Mauzerall, T.D. Searchinger, P. Dumas and Y. Shen (2015). Managing nitrogen for sustainable development. Nature, doi: 10.1038/nature15743.