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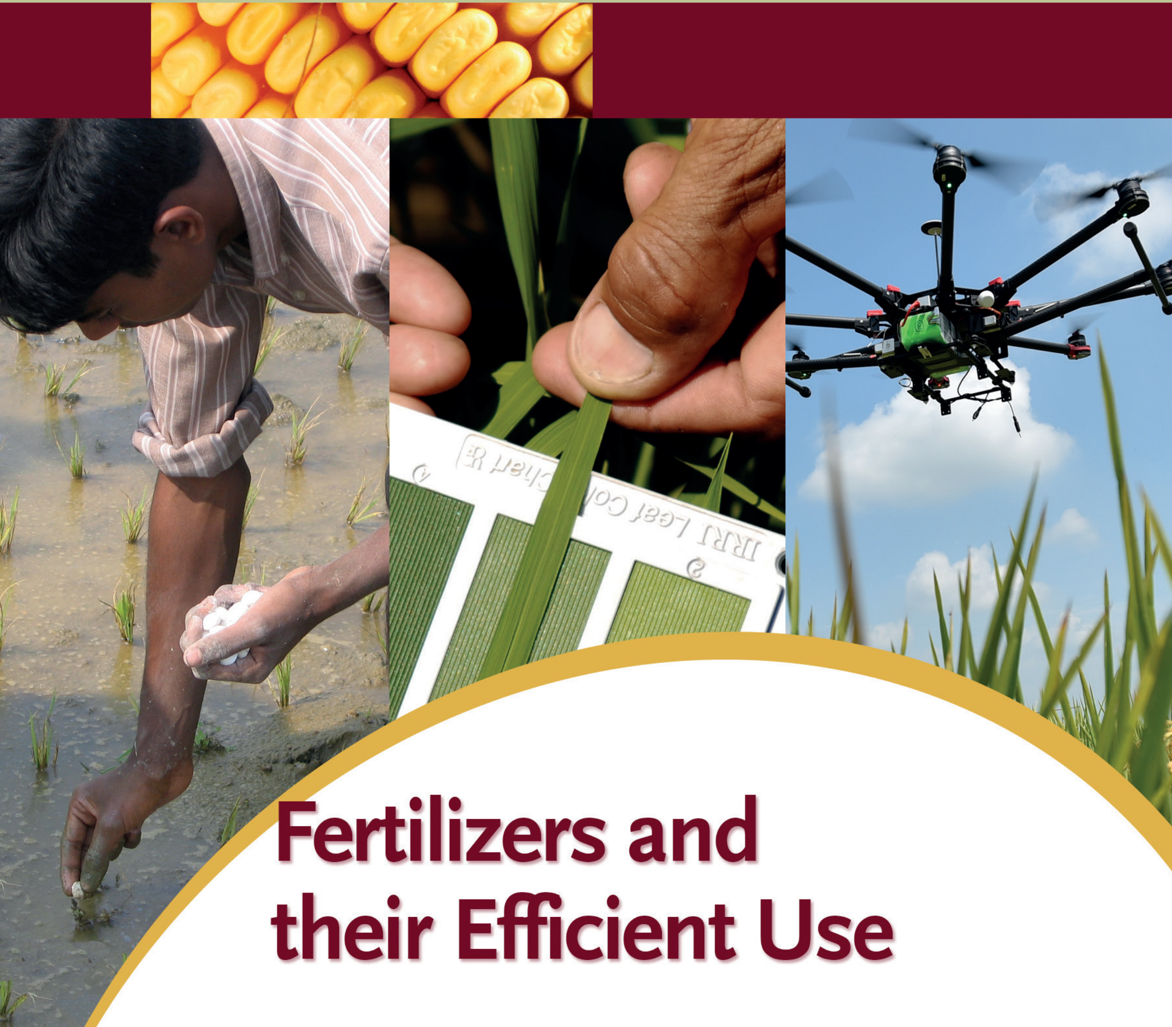

Fertilizers and their Efficient Use

Harold F. Reetz, Jr.

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A reference guide to improve general understanding of the best
management practices for fertilizer use throughout the world to enhance
crop production, improve farm profitability and resource efficiency, and
reduce environmental impacts related to fertilizer use in crop production

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About the book

This book is intended to serve as a reference guide to people throughout the world who need a general understanding of fertilizers and how they are most efficiently used to maintain or improve soil productivity, crop yields, farmers' profits, and environmental services. The focus of the book is around *nutrient stewardship*, which addresses nutrient management from economic, environmental, and social perspectives.

A brief outline of the 17 essential plant nutrients and their sources and functions in plants sets the stage for the discussion. The general soil nutrient management approaches of maintenance, build-up, and sufficiency are described. Characteristics and management of individual macro-nutrients (nitrogen, phosphorus, and potassium) most often needed as fertilizers are discussed in detail, and secondary nutrients and micro-nutrients are briefly reviewed, with some important examples.

The book should prove valuable for understanding the role of improved management practices on the efficient use of fertilizer. It is not a "how to..." guide, but more of a "why...?" guide to nutrient management.

The G*lobal Framework for Nutrient Management–the 4R Approach* is used to show how agronomic, economic, environmental, and social aspects of fertilizer use interact, and how changes in management practices affect all of these areas. Details of each of the components are discussed along with some of the performance indicators that can be used to monitor and evaluate these practices.

The development of *site-specific precision agriculture* over the past two decades has greatly improved the management of nutrients, our ability to practice nutrient stewardship, and the tools for monitoring and evaluation of the results. The technology and its role in both developed and developing economies is a critical component of improving nutrient management. Use of sensors, from hand-held data collectors to satellite imagery, have opened some new possibilities for fine-tuning nutrient applications. New formulations of fertilizer and various additives have created a variety of fertilizer options from which a farmer and his advisers can develop an integrated nutrient management plan.

Nutrient use efficiency (NUE) is a central component of the book, with an outline of different definitions of NUE, and the kind of data and analytical processes needed to evaluate NUE. Approaches used by governmental bodies, academics, industry, NGOs, and farmers are discussed with a specific review of the site-specific nutrient management (SSNM) approach developed for rice by the International Rice Research Institute (IRRI).

Having the right data is a critical factor in efficient use of fertilizer. Collection of data, managing and interpreting it with proper analysis and modeling, and communication with various advisers and stakeholders rounds out a solid fertilizer program.

Farmers, advisers, input suppliers can use this book to make better-informed decisions on crop nutrient management. Reviewing these concepts will help government agencies and NGOs better understand the "why...?" of nutrient management. Further, this information can be used to help the non-agriculture community to better understand the importance of fertilizer to their well-being in supporting the food, feed, fiber, and fuel production industries that depend upon a viable and sustainable agriculture worldwide.

Soil fertility and plant nutrition constitute a dynamic system. While it has been studied for over 100 years, there is still much to be learned. As global requirements for crop production continue to grow, fine-tuning of the nutrient management systems becomes more and more critical. Involvement of soil microbiology and interactions among plants and microbes need to be better understood and managed whenever possible. It has been attempted to introduce these interactions and learn how to manage them to enhance crop nutrition. Environmental stewardship related to nutrient management has also been discussed in terms of making decisions about fertilizer products, rates, timing, and placement.

About the author

Dr. Harold F. Reetz, Jr., is an agronomic consultant, and owner of Reetz Agronomics, LLC., providing consulting services in agronomy, high yield cropping systems, precision farming technology, conservation systems, and on-farm research.

Dr. Reetz spent most of his career with the International Plant Nutrition Institute (formerly the Potash & Phosphate Institute), where he served as Midwest Director (US) and Director of External Support and FAR, with 5 years as president of the Foundation for Agronomic Research (FAR). Dr. Reetz has focused his career on integrated crop and soil management systems for high yield crop production, promoting technologies for nutrient management and precision agriculture. He served as leader of the IPNI Global Maize Project to promote intensive crop production systems for high yields for all major maize production areas of the world. In 1995, he founded the InfoAg Conference series, providing international leadership and networking in the application of precision agriculture and information management technologies in crop production systems.

Dr. Reetz is a graduate of the University of Illinois (B.S., 1970) and Purdue University (M.S., 1972, Ph.D., 1976).

His professional career has included the following positions:

- 1974-1982—Purdue University—Extension Corn Production Specialist; research in high yield corn production, and crop simulation modeling; teaching crop production
- 1982-2004—Potash & Phosphate Institute (PPI)—Midwest Director
- 2004-2007—Foundation for Agronomic Research (FAR)—President
- 2007-2010—International Plant Nutrition Institute (IPNI)—Director of External Support and FAR.
- 2010-present—Reetz Agronomics, LLC—Owner and president

He is a Certified Professional Agronomist and a Certified Crop Adviser.

An active member of the American Society of Agronomy (ASA), Crop Science Society of America (CSSA), and Soil Science Society of America (SSSA), Dr. Reetz has held several leadership roles over the past 40 years. He was one of the founders of the Certified Crop Adviser (CCA) program, served several years on the International CCA Board of Directors, served as Chairman of the International CCA Board, and received the CCA Outstanding Service Award. He is a Fellow of CSSA, Fellow of ASA, and received the ASA Agronomic Service Award and the ASA Agronomic Industry Award. He has received numerous other awards for his service to the profession of agronomy and for public service.

Some of his current consulting clients and projects include the Conservation Technology Information Center (CTIC), Argonne National Laboratories, and several US and international agribusiness and technology companies that support more efficient nutrient management, precision farming, and new technology development.

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I am grateful for all the support given by my wife, Chris, while I worked through the screening of the world's literature on fertilizer's role in crop and soil nutrient management and weaving this information together with my own experience, to provide the grower a practical guide for the effective and efficient use of plant nutrients.

To all those who have kindly provided photos, either used or not in the book. To the staff of the International Plant Nutrition Institute for providing numerous illustrations and ideas for concepts used.

To the International Fertilizer Industry Association (IFA) for funding support which led to the publication of the book.

I would like to dedicate this book to my grandchildren and all of the children of the world, in hope that in some small way it will help to improve the productivity, efficiency, economics and resource stewardship related to nutrient management in the production of crops for meeting the food, feed, fiber, and energy for their generation and beyond.

Harold F. Reetz, Jr., May 2016

List of abbreviations, acronyms and symbols

ATV	all-terrain vehicle
B	boron
C	carbon
Ca	calcium
$CaCO_3$	calcium carbonate or lime
CaO	calcium oxide
CEC	cation exchange capacity
CH_4	methane
Cl	chlorine
CO_2	carbon dioxide
Cu	copper
DNA	deoxyribonucleic acid
EC	electrical conductivity
ESN	environmentally smart nitrogen
FBMP	fertilizer best management practice
Fe	iron
GIS	geographic information system
GPS	global positioning system
ICP	inductively coupled plasma emission spectroscopy
IFA	International Fertilizer Industry Association
IPNI	International Plant Nutrition Institute
IPNM	Integrated plant nutrient management
ISFM	Integrated soil fertility management
K	potassium
KCl	potassium chloride also known as MOP (muriate of potash)
kg/ha	kilogramme per hectare
K-Mag	potassium magnesium sulfate
LCC	leaf color chart
lb/A	pound per acre
MAP	monoammonium phosphate
Mg	magnesium
MOP	muriate of potash also known as KCl (potassium chloride)
mt/ha	metric tonne per hectare
N	nitrogen
N_2	nitrogen gas or dinitrogen
NGO	non-governmental organization
NH_3	ammonia
NH_4^+	ammonium
N_2O	nitrous oxide
NUE	nutrient use efficiency

P	phosphorus
PO_4^{-3}	inorganic phosphate ion
RNA	ribonucleic acid
RTK	real time kinematic (guidance)
S	sulphur
SOP	sulphate of potash or potassium sulfate
SSNM	site-specific nutrient management
TFI	The Fertilizer Institute
t/ha	tonne per hectare
UAN	urea ammonium nitrate
US	United States (of America)
Zn	zinc

Executive summary

Fertilizers are responsible for approximately half of the world's crop production, supplying food, feed, fiber, and fuel for a global population that is expected to reach 9 billion before the middle of the 21st century. Most fertilizer materials come from concentrated supplies of naturally-occurring minerals that are mined or extracted from various ore deposits. One exception is nitrogen (N) which is produced by combining N_2 from the air with natural gas (most common), coal, or naphtha to form anhydrous ammonia, which can be used directly as a fertilizer or converted to different other N fertilizers. Maintaining sufficient crop production depends upon a viable and efficient fertilizer industry throughout the world, to help provide the right nutrients, at the right rate, at the right time and in the right place. This challenge must be met in a way that is economical for all parties from mine or fertilizer plant to field, is respectful of the environment, and considers social concerns for maintaining various ecosystem services for the general public.

There are 17 essential nutrients for crop growth. Three of them—carbon (C), hydrogen (H), and oxygen (O)—are supplied from air and water. The three macronutrients—N, phosphorus (P), and potassium (K) are mostly supplied from the soil, but soil deficiencies and crop removal must be replaced with supplemental sources—mostly fertilizers. A third group of secondary nutrients—sulphur (S), calcium (Ca), magnesium (Mg)—are no less essential, but are usually needed in smaller amounts as fertilizers. Finally, the micronutrients—boron (B), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), chlorine (Cl), nickel (Ni)—are needed in very small amounts, but play essential roles as catalysts in metabolic processes of crop growth and development or play other key roles. Learning the way plants use each of the nutrients, and the source, rate, timing, and placement of each is important to nutrient management and optimizing crop production.

Technology is an important part of successful nutrient management. Various additives or coatings help maintain nutrient availability throughout the growing season. Other technologies assist farmers and their advisers in developing and implementing nutrient management plans. Global positioning systems (GPS) guide fertilizer applications and other field activities, and geographic information systems (GIS) allow farmers and their advisers to geographically reference information about the fields. Monitors and sensors for on-the-go adjustment of application rates, and various analytical processes to assess nutrient content of soil and plants are all part of the suite of technologies used in improving fertilizer use efficiency.

Putting all of the products and technologies together in an integrated system is the key to success. The fertilizer industry and the research and extension education community have developed protocols—or the best management practices—to guide farmers and their advisers in making nutrient management decisions. The strategic plans for nutrient management are built around a global framework for nutrient stewardship. This framework, in various adaptations, is used throughout the world to guide the development and implementation of nutrient management plans, and to help explain to people outside of agriculture why fertilizer use is essential.

Fertilizers are an important basic resource for crop production. The nutrients supplied by fertilizers are essential to the survival of plants, animals, and humans. Properly managing nutrients is the key to making efficient use of the supplies available and to the protection of the environment and ecosystem services.

Introduction

The widespread use of commercial mineral fertilizers is one of the major factors in ensuring global food security in recent times. Over 48% of the more than 7 billion people alive today are living because of increased crop production made possible by applying nitrogen (N) fertilizers. The extent to which world food production depends on fertilizer use will inevitably increase in future. Without fertilizers, the world would produce only about half as much staple food, and more forested lands would have to be put into production. The potential impact of fertilizers in meeting global crop production needs was illustrated by the ears of corn displayed by a farmer (Figure 1) from Nigeria at the Millennium Summit in 2000 at the United Nations in New York City. He had been growing maize without fertilizer and was unable to meet his family's food needs. When he started using fertilizer, the yields greatly increased and he was able to feed his family and had enough maize to sell to others. Globally, 180.6 Mt of nutrients were used for crop production in 2013; 70.2 % and 29.8 % were used in developing and developed countries. China and India, the two most populous countries in the world, consumed 42.8 % of the total amount of nutrients applied through fertilizers in the world.

It is projected that the world population will reach at least 9 billion people by 2050. As per FAO's revised projection on world agriculture, global agricultural production in

Figure 1. An African farmer at a UN meeting in New York, exhibiting the impact of fertilizer on maize, 24 April 2000 (Harold Reetz).

2050 should be 60% higher than that of 2005/2007. An improving standard of living in much of the world will further add to the demand for food and fiber. At the same time there is an ongoing reduction in productive arable land so that mineral fertilizers will play a critical role in the world's food security and will be important from both the yield and food quality perspectives. The challenge ahead is to manage fertilizers and soil in a sustainable way so as to continuously improve production of food and fiber crops through scientifically sound and efficient fertilizer use practices.

Fertilizer best management practices (FBMPs) are a part of an integrated farming system (Figure 2) that includes crop management and all of the soil and plant nutrient management components of a complete farming system. Based on nutrient stewardship principles, FBMPs not only fulfil the four management objectives of productivity, profitability, cropping system sustainability, and a favorable biophysical and social environment. Specific and universal scientific principles in the development and implementation of FBMPs have been described and discussed to enhance the efficiency of nutrient use through a variety of fertilizer materials and new technologies not only to enhance crop production but also to reduce the negative impacts of fertilizer use on air and water resources.

This book is not an exhaustive review of plant nutrition and fertilizer use. It aims to provide an overview of important concepts of nutrient management and the role fertilizers play in keeping the world fed, clothed, transported, and healthy. It is intended to be a guide for the farmers, planners and extension workers to understand why fertilizers are essential. It has also been attempted to dispel some of the myths that come from misunderstanding the nature of these important products. Further, this book serves as a reference for teachers and students in the process of learning about fertilizers, and as a general handbook to practitioners who need a quick reminder of the facts and concepts presented.

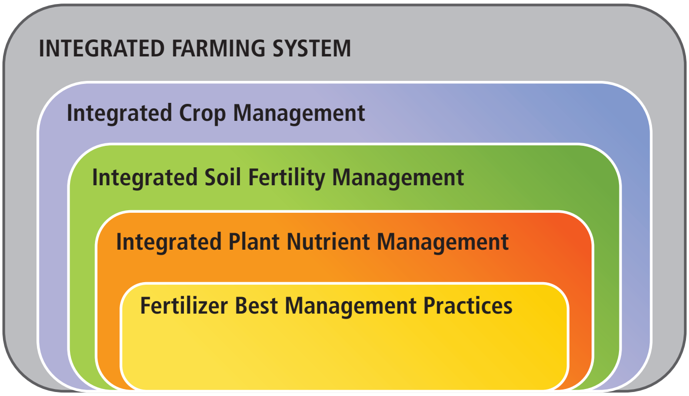


Figure 2. Different aspects of nutrient management are a part of integrated farming systems.

Why use fertilizers?

The goal of nutrient management is to provide an adequate supply of all essential nutrients for a crop throughout the growing season. If the amount of any nutrient is limiting at any time, there is a potential for loss in production. As crop yields increase and as increasing amounts of nutrients are exported from the fields where crops are grown, the nutrient supply in the soil can become depleted unless it is supplemented through application of fertilizers. Fertilizers need to be applied to all types of crop production systems in order to achieve yield levels which make the effort of cropping worthwhile. Modern fertilization practices, first introduced in the last half of the 1800s and based on the chemical concept of plant nutrition, have contributed very widely to the immense increase in agricultural production and have resulted in better quality food and fodder. Furthermore, the farmer's economic returns have increased substantially due to fertilizer use in crop production.

German agronomist, Carl Sprengel (1787-1859) was the first to publish on the *Law of the Minimum* around 1837 which states that plant yield is proportional to the amount available of the most limiting nutrient, and if that nutrient deficiency is corrected, yield will improve to the point of the next most limiting nutrient in the soil. German chemist, Justus von Liebig (1803-1873) is generally credited for promoting this concept, and for developing the first mineral fertilizer to be used as a part of sustainable agriculture production systems. The Law of the Minimum is commonly illustrated by the staves in a broken barrel (Figure 3), with each stave representing essential inputs for crop

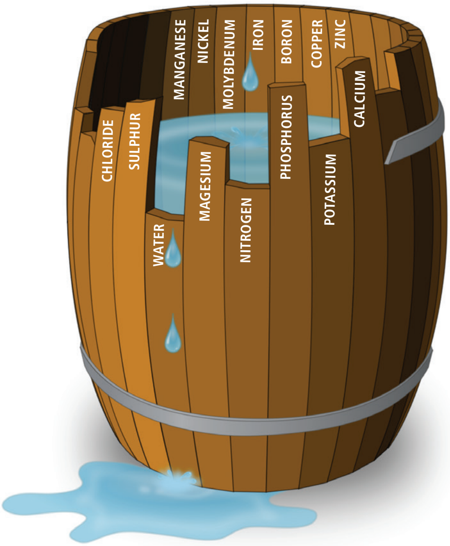


Figure 3. Barrel stave visualization of Liebig's Law of the Minimum (ca 1840). The nitrogen stave is the shortest, indicating that it is the limiting element.

growth. The barrel (representing yield) can only be filled to the point of the shortest stave (the most limiting input). The nitrogen stave being the shortest, it represents the most limiting nutrient. Other nutrients come next.

When fertilizers were introduced, they used to supply the primary nutrients N, P and K. In fields where primary nutrients are no longer the most limiting factor, fertilizers are

Box 1. Role of fertilizers in crop productivity

The main opportunities in increasing production are (1) to expand arable land use or (2) to increase yields on land currently in production. The potential for putting new land into production is limited, and if new lands are available these are often less productive. The need will probably be met by a combination of both approaches, but meeting future food needs with increased crop production through greater yields on existing farm land is a more favorable scenario.

- Cereal production accounts for about 50% of world fertilizer use.
    - Globally, commercial fertilizer has been the major pathway of nutrient addition, more than doubling the quantities of new N and P entering the terrestrial biosphere since the 1970s.
    - Of the gains in crop production world-wide, about half has been attributed to additional use of fertilizer.
- About 70% of global fertilizer consumption is in developing countries, and has been growing since the Green Revolution.
- Commercial fertilizer will continue to play a vital role in the future in closing the gap between actual and attainable crop yields.
- Except for Oceania and Eastern Europe/Central Asia, cereal yields in many industrialized regions have continued to increase in the past 30 years without significant increases in N fertilizer use (Dobermann, 2006), due to substantial increases in fertilizer use efficiency.
- Increasing agricultural production does not automatically mean a proportionate increase in fertilizer use is needed. Improvements in management and nutrient use efficiency allow productivity to grow relatively faster than the growth rate of inputs, except in regions where fertilizer is underused.
- Along with better genetics, improvements in agronomic practices and efficient management of fertilizers will be necessary to significantly increase crop yields.
- In both temperate and tropical climates, fertilizers serve the identical purpose of supplying adequate amounts of nutrients to crop plants to produce high yields. Fertilizers are applied to:
    - supplement the natural soil nutrient supply in order to satisfy the demand of crops with a high yield potential;
    - compensate for the nutrients removed by plants as well as lost from the soil-plant systems via mechanisms like leaching and volatilization;
    - improve and maintain soil fertility level.

used to supply secondary and micronutrients as well. In a large number of fields in both developed and developing countries, secondary and micronutrients are now becoming the limiting elements for crop production because farmers have started applying substantial amounts of primary nutrients. However, in several developing countries in Africa and Asia, N and P are still the limiting elements in crop production.

Soil fertility and its improvement

Fertile and productive soils are vital components of stable societies because they ensure growth of plants needed for food, fiber, animal feed and forage, industrial products, energy and for an aesthetically pleasing environment. Soil fertility integrates the basic principles of soil biology, soil chemistry, and soil physics to develop the practices needed to manage nutrients in a profitable and environmentally sound manner. Soils differ widely in their ability to meet nutrient requirements of plants; most have only moderate natural soil fertility. To achieve production objectives, more nutrients are usually required than can be supplied by the soil. High crop yields mean greater depletion of soil nutrient supplies, which eventually must be balanced by increased nutrient input to maintain the fertile soils needed by our societies. Thus a hallmark of high-intensity agriculture is its dependence on mineral fertilizers to restore soil fertility, and in the broader context of soil productivity, soil fertility regulates supply of nutrients inherently available in soils or applied as manures and fertilizers to plants.

Box 2. Soil fertility and soil productivity

- Soil productivity is a measure of the ability of soil to produce a particular crop or sequence of crops under a specified management system. Optimum nutrient status alone will not ensure soil productivity.
- Soil productivity encompasses soil fertility plus all the other factors affecting plant growth, including soil management.
- Soil fertility connotes primarily the combined effect of chemical and biological properties, and is probably the most important single soil factor affecting productivity.
- Factors such as soil moisture and temperature, soil physical conditions, soil acidity and salinity and biotic stresses (disease, insects, and weeds) can reduce the productivity of even the most fertile soils. Factors such as climate (including rainfall, evaporation, solar radiation, temperature and wind) are beyond farmers' control, but soil fertility is influenced by farmers' past and present activities such as manuring and fertilization and nature of crops grown.
- All productive soils are fertile for the crops being grown, but many fertile soils are unproductive because they are subjected to unsatisfactory growth factors or management practices.

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

There are a number of ways of making use of soil fertility in farming:

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

The large differences in fertility between different soil types and sub-types must be taken into account. Some soil characteristics important to nutrient management may be grouped geographically and general recommendations may be summarized as follows:

Soils of the humid tropics

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

Soils of the sub-tropics

- water shortage (without irrigation, fertilizer use must be suitably adapted to efficient water use);
- N is often the main critical nutrient, due to the low humus content;
- widespread P deficiency, especially in sandy soils;
- neutral soil reaction (therefore often a shortage of available Fe and Zn);
- a generally good supply of S, Mn, and B;
- risk of salinity due to lack of leaching of salts from the root zone.

Soils of humid temperate zones

- widespread soil acidity which requires liming;
- partly obstacles to root growth (e.g., hard layers in subsoil);

- often insufficient aeration (poor natural drainage of heavy soils);
- generally shortage of available N and often of P, K, Mg;
- low nutrient reserves in sandy soils, also only little storage and therefore considerable leaching with water surplus;
- partial fixation of P and Mo (due to natural soil acidity) and Cu (in organic soils);
- climatic cold stress retarding nutrient uptake.

Essential nutrients

Plants contain practically all (92) natural elements, but 17 elements have been identified as *essential* nutrients that are required for plant growth. These must be provided either by the soil or by plant and animal wastes and/or other organic sources or by mineral fertilizers. For an element to be proven essential, it must be demonstrated that a plant cannot complete its life cycle in the absence of the element, and that no other element can substitute for the test element. Three of these, carbon (C), hydrogen (H) and oxygen (O), are used in the greatest quantities and are provided by the air and water. The other 14 nutrients are *mineral elements* obtained from the soil through the plant roots.

The three *macronutrients* are required by plants in relatively large amounts. Nitrogen as N_2 gas forms 78% of the Earth's atmosphere and is non-reactive. It must be converted to reactive chemical forms (ammonium and nitrate) to be utilized by plants. This conversion is done by micro-organisms in the soil, by symbiotic bacteria living on plants, or by chemical reactions. Phosphorus (P) usually occurs in large quantities in the soil minerals and organic matter, and must be converted to inorganic phosphate ions ($H_2PO_4^-$ or HPO_4^{2-}) to be used by plants. Potassium (K) exists in large quantities in the soil minerals and adsorbed in the ionic form K^+ to soil particles and organic matter. It enters the plant roots as a K^+ ion, often by osmosis through cell walls as a companion to negatively charged ions. Potassium does not form any chemical compounds in plants, but plays a major role in transport of water and other ions across cell membranes.

Sulphur (S), calcium (Ca) and magnesium (Mg), the three *secondary macronutrients,* are no less necessary for plant growth than the macronutrients, but are needed in somewhat smaller amounts. Sulphur is found in soil organic matter, but it also occurs in some clay minerals. Sulphur is taken up by plants as a sulphate ion (SO_4^{-2}). Calcium and Mg are easily available in the soil and taken up as cations by plant roots. Calcium is an important structural component of cell walls and plant tissues while Mg plays a major role in photosynthesis as a central component of the chlorophyll molecule.

The eight essential nutrients needed by plants in small amounts are called the *micronutrients* and these are iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), molybdenum (Mo), chlorine (Cl), boron (B), and nickel (Ni). Cobalt (Co), and silicon (Si) are the two other nutrient that are essential, or at least beneficial, to some plant species, but not required by all.

Table 1 lists the 14 essential *mineral* nutrients, the form in which these are taken up by plants, their main form in soils, and the relative amounts found in plants (listed as atoms per plant).

Table 1. Essential and beneficial mineral nutrients for plants (IPNI 4R Manual).

Category	Nutrient	Symbol	Primary form of uptake	Main form in soil reserves	Relative # atoms in plants
Macronutrient	Nitrogen	N	nitrate, NO_3^-, ammonium, NH_4^+	organic matter	1 million
	Phosphorus	P	phosphate, HPO_4^{2-}, H_2PO_4	organic matter, minerals	60,000
	Potassium	K	potassium ion, K^+	minerals	250,000
	Calcium	Ca	calcium ion, Ca^{2+}	minerals	125,000
	Magnesium	Mg	magnesium ion, Mg^{2+}	minerals	80,000
	Sulphur	S	sulphate, So_4^{2-}	organic matter, minerals	30,000
Micronutrient	Chlorine	Cl	chloride, Cl^-	minerals, rainfall	3,000
	Iron	Fe	ferrous iron, Fe^{2+}	minerals	2,000
	Boron	B	boric acid, H_3BO_3	organic matter	2,000
	Manganese	Mn	manganese ion, Mn^{2+}	minerals	1,000
	Zinc	Zn	zinc ion, Zn^{2+}	minerals	300
	Copper	Cu	cupric ion, Cu^{2+}	organic matter, minerals	100
	Molybdenum	Mo	molybdate, MoO_4^{2-}	organic matter, minerals	1
	Nickel	Ni	nickel ion, Ni^{2+}	minerals	1

Additional beneficial nutrients useful for some plants, but not considered essential are:

- Sodium (Na): taken up as Na^+; can partly replace K for some crops;
- Silicon (Si): taken up as silicate; strengthens cereal stems to resist lodging;
- Cobalt (Co): involved in N-fixation by legumes, is being considered as the 18th essential crop nutrient;
- Aluminum (Al): found beneficial for some plants such as tea.

Availability of nutrients for uptake by plant roots is linked to ability of roots to reach adequate supplies of each nutrient either by the root growing to the nutrients in the soil (root interception) or by the nutrients moving to the roots in the soil water by the process of diffusion in the soil solution along a concentration gradient, or by mass flow of water to the roots. Topsoil drying decreases the plant's ability to absorb micronutrients from otherwise available forms (Holloway *et al.*, 2010) and plants must obtain micronutrients from the subsoil where availability is often low because of high pH and low density of roots. Under these conditions micronutrient-efficient genotypes express their superiority.

The following section provides a more detailed discussion on each of the essential crop nutrients, their fertilizer sources and formulations, their functions in plants, and other information to help better understand how each nutrient can best be managed.

Mineral and manufactured fertilizers

Numerous mineral fertilizers have been developed to supplement nutrients already available in the soil and to meet the high requirements of crops (Box 3). These are generally mineral salts, except for some organic compounds such as urea which are easily converted into salts. The customary classification into single- or multi-nutrient fertilizers usually refers only to the three major nutrients. Many so-called single-nutrient

Box 3. Types of mineral fertilizers (according to different criteria)

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

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

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

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

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

fertilizers actually supply more than one nutrient, e.g. ammonium sulphate contains both N and S.

Fertilizer grade is used to classify different fertilizer materials on the basis of the content of the 3 major nutrients. The nutrient content, or grade, may refer either to the total or to the available nutrient content, and may be expressed traditionally for some nutrients in oxide form (P_2O_5, K_2O) or in elemental form (N, P, K).

For example, a fertilizer grade of 7-28-14 is 7% N, 28% P_2O_5, and 14% K_2O.

Nitrogen (N)

Nitrogen is a key component of amino acids and proteins. It is also a part of the chlorophyll molecule, which controls photosynthesis, the solar energy capturing reaction of green plants. Nitrogen and Mg are the only elements in the chlorophyll molecule that come from the soil. Adequate supplies of N are needed to support photosynthesis and to produce proteins in harvested crops.

Nitrogen occurs in a variety of forms in the soil, and may be taken up in different forms by growing plants. Throughout the growing season, and even between seasons, N is transformed from one form to another by various chemical and biological processes. It can also be reacted by lightning and deposited in rainfall. Some of these processes make it more available to plants, while others reduce its availability. Nitrogen is also lost from the local production systems in various forms. It may be lost into the atmosphere from the soil or from growing plants as N_2 gas, ammonia (NH_3), nitrous oxide (N_2O), or NO_x gases; it may be lost as nitrate (NO_3^-) in soil water through leaching or runoff from the soil surface. In short, N is a very reactive element as summarized in the N cycle diagram, forms numerous biochemical compounds in plants, and plays a variety of significant roles in plant growth and development. This makes it complicated to manage, but also provides many opportunities for managing N. While it is one of the most studied nutrients, in many ways it remains one of the least understood. But its significance in crop production and in resulting animal and human food makes it a very important part of nutrient management. As a major component of amino acids and proteins, as well as other major food components, N deserves significant attention.

Nitrogen is also important because of its impact on the environment. In surface water bodies, nitrate-N is a major nutrient that supports growth of algae and aquatic plants, which as they die and decompose, tie up oxygen in the water, creating a hypoxic condition which starves aquatic animals for oxygen. Nitrogen in the soil can also be released into the atmosphere as N_2O which is over 300 times as potent as CO_2 as a greenhouse gas. An important goal of fertilizer best management practices (FBMPs) for N is to reduce the release of reactive forms of N (forms other than N_2) into the environment.

The "plow layer" of most soils contains between 0.08 and 0.4% N, with a representative average of 0.15% N. That equates to about 3,360 kg/ha of N naturally occurring in the soil, mostly in organic compounds, which are slowly broken down so that the N is available for plant growth. The total fertilizer N applied, while often more readily available, is a small fraction of the total N in the soil. Applied N fertilizer merely contributes to the total N pool in the soil. The dynamic changes in form of N in the soil make N management a very complex process. Separately accounting for which source of N contributes to crop growth, which to atmospheric losses, and which to water contamination, is nearly impossible. Since all of these processes draw from the same N pool, it is difficult to show conclusively how managing one N source can impact any of the processes or its outcomes. It is all part of one dynamic N system. This makes any attempts to monitor and control losses of N from production fields an extremely difficult task. But farmers still can benefit from making a serious effort to properly manage that portion for which they do have some control.

Figure 4 illustrates the relationships among some of the many forms, processes, and reactions of N in crops, soils, and the atmosphere. Nitrogen dynamics in soils are very complex. The important process of nitrification (transformation of ammonium to nitrate by bacteria) proceeds rather quickly when temperatures are warm. Denitrification, another bacterial process, converts nitrate into N_2 gas, which is released to the atmosphere.

The N Cycle (Figure 5) shows the interactions among the N forms in the soil-crop-atmosphere system of crop production. The reactive N in these systems is in a constant dynamic exchange among the various forms.

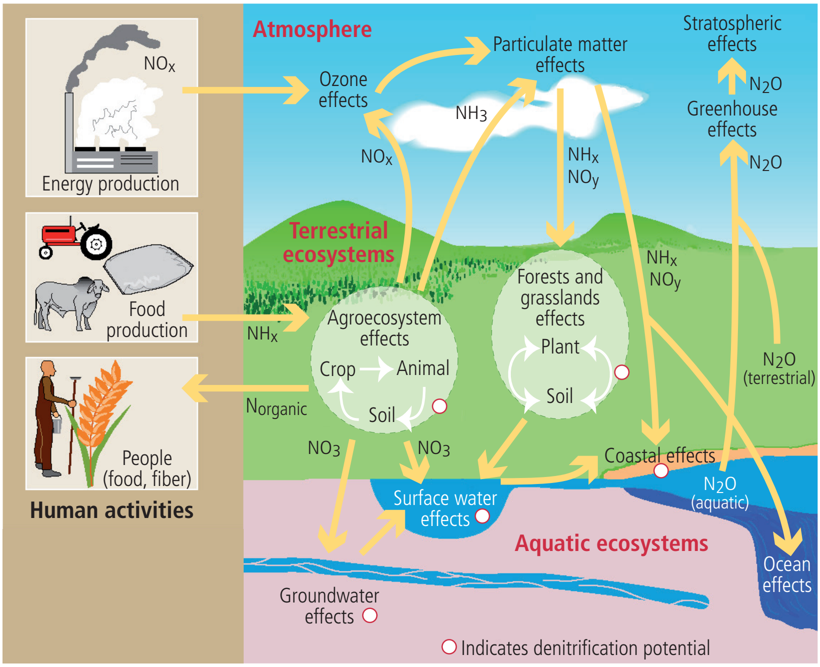


Figure 4. The "Nitrogen Cascade" illustrating the interaction of various N forms in the N cycle (adapted from Galloway *et al.*, 2003).

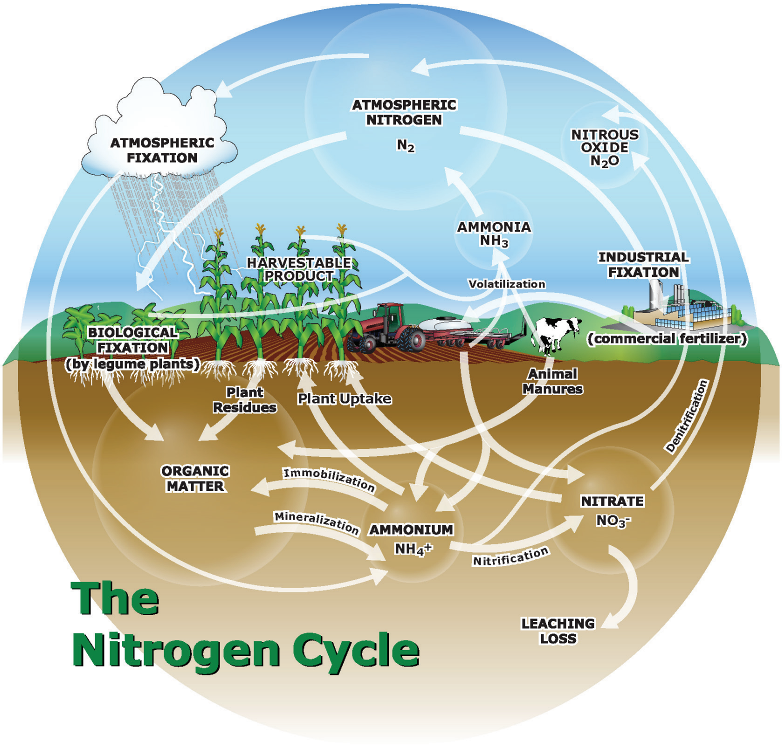


Figure 5. The Nitrogen Cycle–The dynamic interchange among various N forms in the soil-crop-atmosphere system (IPNI).

Nitrogen is dynamic, constantly shifting among the various reactive forms as a result of chemical and biological processes. This makes it important agriculturally, naturally, and environmentally. There are many management opportunities to affect these processes and impact the efficiency of use of this important nutrient in agriculture. Figure 6 shows the relative amounts of N commonly occurring in the various forms in the soil-crop-atmosphere system. Each of the transition points in the diagram represents potential N management decision opportunities.

N fertilizer sources and formulations

Nitrogen fertilizers are manufactured in a variety of formulations, each with different properties and uses for crop production systems. These all essentially begin with anhydrous ammonia which is manufactured from air and natural gas by the Haber-Bosch process through the chemical reaction [$3H_2+N_2 \rightarrow 2NH_3$] under high temperature and pressure. This process, developed in Germany just before World War I, is sometimes considered the most important technological development of the 20th

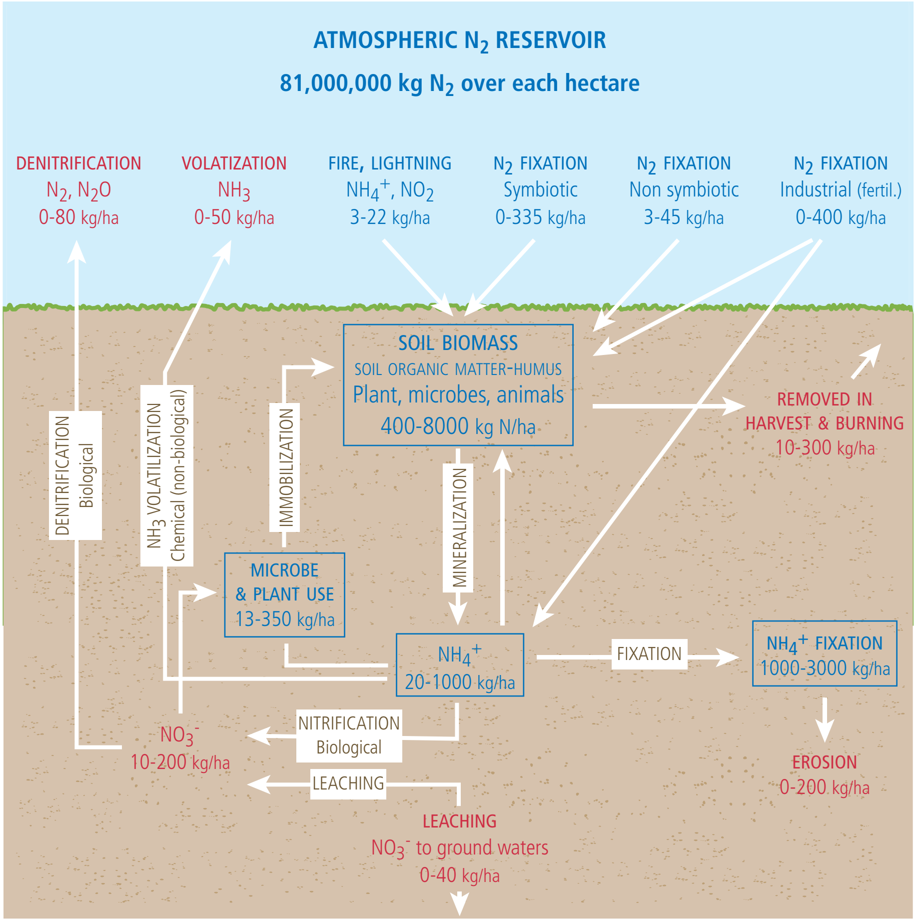


Figure 6. Amounts of N commonly found in each form in the N cycle (adapted from University of Florida).

century. The Haber-Bosch process supports a major part of the world's food supply by generating production of ammonia, the main raw material for most nitrogen fertilizers. Erisman *et al.* (2008) estimate that, in absence of N fertilizers, we would produce 48% less food. According to IFA, the global fertilizer-related ammonia output was of 137 million tonnes in 2014. Besides direct application as anhydrous ammonia fertilizer, ammonia is also used as raw material in the production of urea, ammonium nitrate and other N fertilizers, as well as in the production of MAP, DAP and other multi-nutrient fertilizers.

The Haber process is named after the German scientist Fritz Haber, and industrial chemist Carl Bosch. Haber was the first person to successfully complete the process. In 1909, Haber's process could produce about one cup of ammonia every two hours. Bosch helped develop the Haber process for Industry. In 1913, the German company BASF started *using the Haber process to make ammonia. During World War I, the Haber process was used to make explosives. The Germans kept this a secret until after the war. In 1918, Haber won the Nobel Prize in Chemistry, and in 1931, Bosch also shared a Nobel Prize.*

Anhydrous ammonia is then reformulated into several other N fertilizer sources to provide farmers a wide range of N source options for managing N to best meet their crop needs and meeting logistical requirements. Some of the more common N formulations are described below.

Anhydrous ammonia (NH_3) is the most concentrated commercial fertilizer N source (82% N). Since the most common source of energy for manufacturing ammonia is the natural gas (methane), ammonia production facilities are usually located near natural gas supplies. The ammonia is transported world-wide by pipelines, truck, railroads, and ships, as a liquid under pressure and/or refrigeration to keep it below its boiling point (-33°C, -27°F).

Ammonia is usually applied to the soil by injection at a depth of 10 to 20 cm (4 to 8 in) as a pressurized liquid that immediately vaporizes, and reacts with soil water to convert to ammonium (NH_4^+). This ion then gets attached to negatively charged cation exchange site on clay minerals and organic matter in the soil. **Aqua ammonia** (20 to 24% N) is produced by mixing ammonia with water. This form can be added to irrigation water as an alternate means of application.

Ammonium sulphate [$(NH_4)_2SO_4$] (21% N) is produced as an industrial byproduct and is one of the oldest manufactured N fertilizers. It comes from manufacturing of steel, nylon, and other processes that use sulphuric acid. It is often used as a carrier for herbicide application, helping to enhance efficacy. It also contains 24% S, making it a useful choice where S is needed.

Urea (46% N) is the most widely used solid N fertilizer in the world. The production of urea fertilizer involves controlled reaction of ammonia gas (NH_3) and carbon dioxide (CO_2) with elevated temperature and pressure. The molten urea is formed into spheres with specialized granulation equipment or hardened into a solid prill while falling from a tower. During the production of urea, two urea molecules may inadvertently combine to form a compound termed biuret, which can be damaging when sprayed onto plant foliage. Most commercial urea fertilizer contains only low amounts of biuret due to carefully controlled conditions during manufacturing. Urea is an excellent nutrient source to meet the N demand of plants. Because it readily dissolves in water, surface-applied urea moves with rainfall or irrigation into the soil. Within the soil, urea moves freely with soil water until it is hydrolyzed to form NH_4^+.

Nitrophosphate (variable grades) is made by treating rock phosphate with nitric acid instead of sulphuric acid. It has the advantage of not producing the calcium sulphate (gypsum) byproduct that becomes a disposal issue. Two additional byproducts, calcium nitrate and calcium ammonium nitrate, are also generated in the process. Nitrophosphates can be mixed with other nutrients to make uniform pellets of fertilizer containing multiple nutrients.

Ammonium nitrate (NH_4NO_3) was initially produced in the 1940s as a munition product. It contains 33 to 34% N. Ammonium nitrate is produced as a concentrated solution by reacting ammonia gas with nitric acid. The solution (95 to 99% ammonium nitrate) is dropped from a tower and solidifies to form prills, which can be used as fertilizer or made into granular ammonium nitrate by spraying concentrated solution onto small granules in a rotating drum. Since half of the N is in the ammonium form, it may be taken up directly by roots, or gradually converted to nitrate by microbes, providing a delayed-release of N. The other half of the N is in the nitrate form and is immediately available to plants. Its high solubility makes it well-suited for fertigation and foliar application.

Urea ammonium nitrate (UAN) (28% N) is commonly used as a liquid fertilizer N source, applied as a broadcast application, as a carrier for herbicides and as a side-dress application for row crops, such as maize.

Calcium cyanamide, in addition to its fertilizer value, has herbicidal and fungicidal properties due to intermediate decomposition products.

The different forms of N when applied to soil give almost similar crop yield responses. Efficiency of some products may be reduced due to leaching losses of nitrates or volatilization of ammonia under certain temperature and soil moisture situations. Surface applied urea or UAN solutions are especially susceptible to such losses. Most N fertilizers tend to be available quickly and are subject to loss before the N can be taken

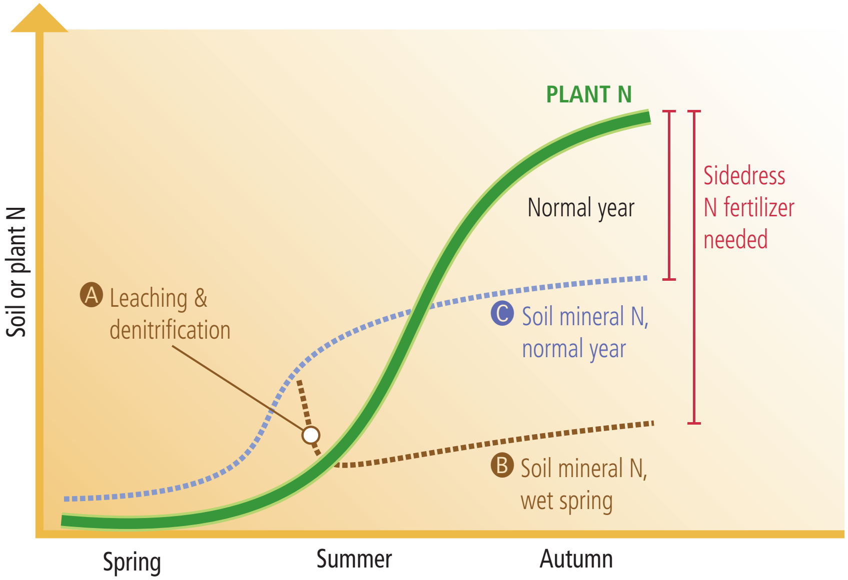


Figure 7. The need for supplemental N fertilizer depends on early season weather.

up by the crop. But slow-release or controlled-release enhancement products can help reduce those losses as well.

In a wet spring under tropical climate, soil N may be lost due to leaching and denitrification, resulting in a larger amount of side-dress N fertilizer being required to meet crop needs. Split-application of fertilizer N should be a good way to manage such situations (Figure 7).

The N supply from slow- and controlled-release fertilizers is theoretically better adapted to the curve of N uptake but depends on temperature.

Nitrogen fertilizer characteristics

Different N fertilizers are valued according to their total N-content, the different N-forms (which determine the rate of action), and side-effects if any (Box 4).

Regardless of the formulation of the fertilizer applied, most are converted in the soil to nitrate and ammonium, the predominant plant-available forms of N. Nitrate N in the soil solution is immediately available and thus acts quickly but is most liable to losses via leaching and/or denitrification. Plants take up N mainly in nitrate form. Ammonium-N, although fully available, has a somewhat slower effect, because it is first adsorbed on soil particles and then only gradually released and nitrified. This can be beneficial to N use efficiency, because N in the ammonium form attached to soil particles is much less susceptible to leaching and other losses. Some plants can absorb ammonium directly, while others require that it is first converted to nitrate. At a temperature of 20-25° C, an application supplying 50-100 kg/ha (20-40 lb/A) N would nitrify in about two weeks. Nitrification can be delayed for several weeks by adding nitrification inhibitors to the fertilizer. This can be useful for preventing undesirable accumulation of nitrate in vegetable crops or reducing loss by leaching.

Several different formulations, coatings, and additives are available to help farmers manage fertilizer N more efficiently. These are broadly classified as stabilizers, inhibitors, slow-release, and controlled-release products. The Association of American Plant Food Control Officials has defined these products as (Trenkel, 2010):

- Slow- or controlled-release fertilizer: A fertilizer containing a plant nutrient in a form which delays its availability for plant uptake and use after application, or which extends its availability to the plant significantly longer than a reference 'rapidly available nutrient fertilizer' such as ammonium nitrate or urea, ammonium phosphate or potassium chloride. Such delay of initial availability or extended time of continued availability may occur by a variety of mechanisms. These include controlled water solubility of the material by semipermeable coatings, occlusion, protein materials, or other chemical forms, by slow hydrolysis of water-soluble low molecular weight compounds, or by other unknown means.
- Stabilized N fertilizer: A fertilizer to which a N stabilizer has been added. A nitrogen stabilizer is a substance added to a fertilizer, which extends the time the N component of the fertilizer remains in the soil in the urea-N or ammoniacal-N form.
- Nitrification inhibitor: A substance that inhibits the biological oxidation of ammoniacal-N to nitrate-N.

Box 4. Types of N fertilizers (N content refers to total N)

- **Ammonium fertilizers**
    - ammonia (82% N), ammonium sulfate (21% N), ammonium bicarbonate (17% N), all moderately quick-acting. Uptake by plants can be retarded by addition of nitrification inhibitors.

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

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

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

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

- **Slow- and controlled-release fertilizers**
    - either derivatives of urea with N in large molecules, or granular water-soluble N fertilizers;
    - controlled-release urea (encapsulated in thin polymer film, slow- or very slow-acting according to type of polymer or thickness of film);
    - often includes a quick-acting component;
    - or other means of slow-release, e.g. sulfur coated urea (SCU).

- **Multi-nutrient fertilizers** containing N
    - NP: Nitrophosphate (20-23% N, 20-23% P_2O_5);
      Monoammonium phosphate (11% N, 52% P_2O_5);
      Diammonium phosphate (18% N, 46% P_2O_5);
      Liquid ammonium polyphosphates (e.g. 12% N, 40% P_2O_5);
    - NK: fertilizers containing both N and K (e.g., potassium nitrate);
    - NPK: fertilizers containing N, P, and K.

- Urease inhibitor: A substance that inhibits hydrolytic action on urea by the enzyme urease.

Nitrogen fertilizers tend to increase soil acidity, so as N fertilizer use is increased, pH may need to be adjusted through application of liming materials (Table 2).

Table 2. Acidification effect of selected nitrogen fertilizers.

Fertilizer	Amount of CaO to compensate the soil acidification induced by 1 kg N*
Calcium ammonium nitrate	0.6 kg
Ammonia, urea, ammonium nitrate	1 kg
Diammonium phosphate	2 kg
Ammonium sulphate nitrate	2 kg
Ammonium sulphate	3 kg

*On the basis of 50% utilization rate.

Enhancing nitrogen use efficiency

The utilization by crops of N applied through fertilizers varies from 30 to 50% depending upon nature of the crop, climate, soil and management practices. It can be 50-60% for wheat grown in temperate climates and around 30% for lowland rice grown in coarse textured soils. The energy required to produce fertilizer N to be applied per unit area is about one-third of the total energy requirement for raising the crop. More efficient use of N fertilizers therefore, means a net saving in energy.

Three types of processes affect excess N not utilized by the crop. Their relative impact on the supply of N to crops depends upon weather, soil conditions, and other factors. These processes are:

- microbial–e.g. nitrification, denitrification, immobilization;
- chemical–e.g. exchange, fixation, precipitation, hydrolysis;
- physical–e.g. leaching, run-off, volatilization.

Fertilizer best management practices (FBMPs) for the application of plant nutrients attempt to increase nutrient use efficiency and minimize unfavorable effects on the environment. The root system of most arable crops only explores 20-25% of the available soil volume in any one year. So the utilization of nutrients by plants will not only depend on the stage of growth and nutrient demand, but also on the rate of delivery of plant nutrients to the root by mass flow and diffusion in the soil solution.

Split application–the application of N fertilizers at multiple times during the growing season–can help improve N use efficiency and reduce losses. Applying N fertilizer as close as possible to the time of uptake requirement by the crop is a good management strategy to maximize efficiency. Similarly, site-specific fertilizer management leads to application of fertilizer N after taking into account the N supplying capacity of the soil and thus ensures high fertilizer N use efficiency. Any surplus mineral N remaining in soil at harvest is likely to be lost by leaching and denitrification. Use of cover crops and crop residue management can help keep the N in organic compounds in the soil and make it less susceptible to leaching and denitrification losses.

Several tools are available to help enhance the efficiency of N fertilizers. These include chemical additives, biological inhibitors, and coatings that physically constrain N activity in the soil. Some of the important conversion processes that occur in the soil are dependent on microbial activity. These provide a point of management through chemical or physical factors that control microbial activity. Some examples include:

- Nitrapyrin–used to inhibit the nitrification process.
- Urease inhibitors–used to slow down the conversion of urea to ammonium and nitrate.
- Encapsulation of urea granules–used to slow the solubility of urea and its release to the soil solution.

Phosphorus (P)

Phosphorus also plays a vital role in photosynthesis, functioning in the capture and transfer of energy into chemical bonds. New, rapidly growing plant meristematic tissues have a high concentration of P. The genetic materials, DNA and RNA, are built around a backbone of P atoms, and P plays a major role in the metabolism of sugars and starches, all critical to cell division and growth processes.

Environmentally, P is an important nutrient because excess P supplies in water bodies leads to excessive growth of plant materials (such as algae blooms), which subsequently die, and are decomposed by microorganisms, leading to depletion of oxygen in the water, creating a *hypoxic zone* that kills fish, shrimp, and other aquatic life. Soil erosion, runoff and leaching losses of P from agricultural fields are considered a major contributor to hypoxic areas around the world. Part of nutrient management is to minimize such agricultural losses of P. Sewage and industrial effluents are also major sources of the P that induces hypoxia. Best management practices for P are designed to help minimize losses of P to the environment and improve P use efficiency for growing crops.

The "life cycle" of P in the soil-crop system is illustrated in Figure 8. This dynamic cycle is affected by a variety of continuous physical, chemical, and biological processes affecting how much P is in each form at any given time.

Figure 9 provides a simplified schematic representation of the phosphorus cycle in the plant-soil system. Soil analysis to estimate the readily available soil P measures the small amount of P in the soil solution. The amount of P extracted varies with the extractant used. Using the analytical data soils are classified descriptively (e.g. deficient, sufficient) or by numerical indexes. These classes are related to the probable response of a crop to an application of an appropriate phosphatic fertilizer.

Figure 10 illustrates the relative distribution of P forms in the crop-soil-environment-atmosphere system. P is constantly shifting from one form to another according to the physical, chemical, and biological systems in which it is functioning.

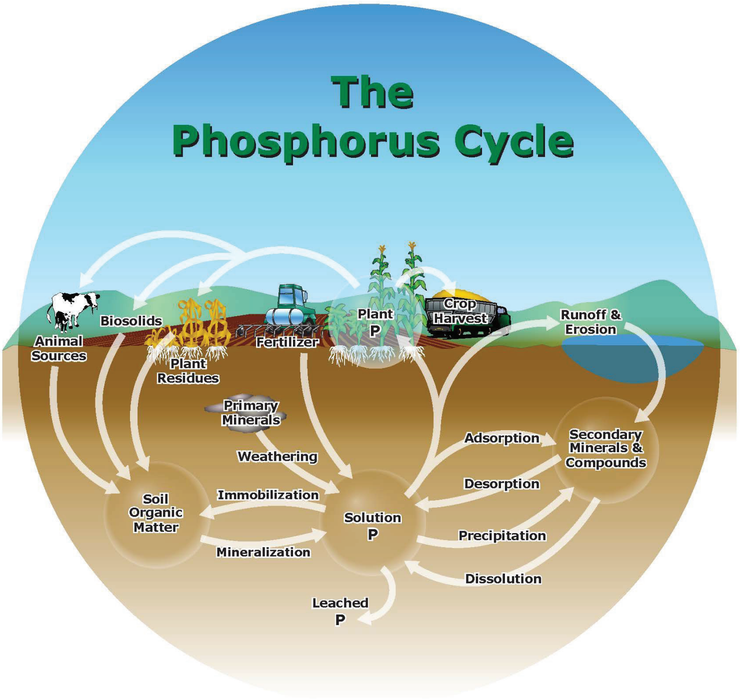


Figure 8. The phosphorus cycle. P is found in a variety of forms in the soil and in crops and is constantly cycling among these forms (IPNI).

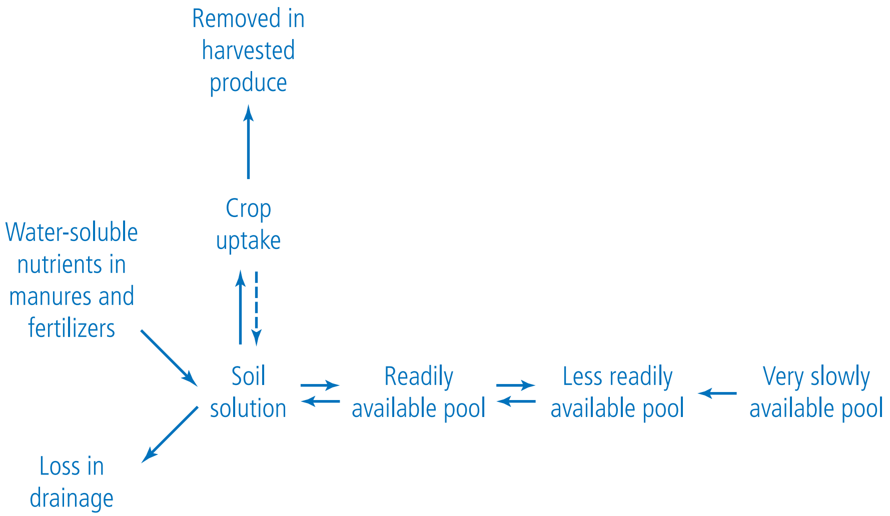


Figure 9. A simplified schematic diagram of the phosphorus cycle (IFA).

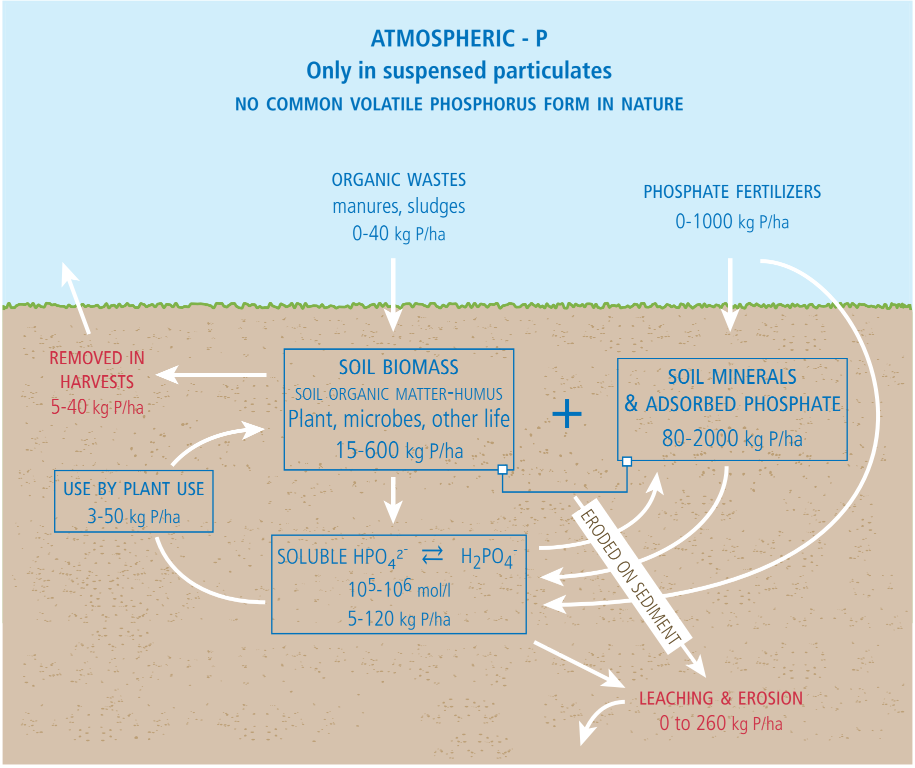


Figure 10. Relative amounts of P found in various forms in the crop, soil, atmosphere, and the environment (adapted from University of Florida).

P fertilizer sources and formulations

Phosphorus in fertilizer materials is usually expressed in the oxide form (P_2O_5). Although this form does not actually exist in fertilizer materials, it has been adopted as the standard form for comparison among different P fertilizers. The formula to convert P to P_2O_5 is: P x 2.29 = P_2O_5

Phosphate rock (PR). The world's P reserves exist in old marine deposits and PR must be processed to remove other materials. Unprocessed phosphate rock may be applied as a source of P nutrition under some situations, but most is processed for production of other phosphate fertilizers. When PR is applied directly, its water solubility may be too low to meet the needs of a growing crop. PR can be an effective P source if used on acidic soils (soil pH below 5.5). Today, over 90% of the PR used is processed into soluble P fertilizers by reacting it with acid, which makes it agronomically and economically effective as a crop nutrient source.

Single superphosphate (SSP) is produced by reacting rock phosphate with sulphuric acid. It was the first commercial mineral fertilizer and it led to the development of the modern plant nutrient industry. This material was once the most commonly used fertilizer, but other P fertilizers have largely replaced SSP because of its relatively low P content. The SSP fertilizer is a source of three different essential crop nutrients, in the following proportions: 7 to 9% P (16 to 20% P_2O_5); 18 to 21% Ca; and 11 to 12% S.

Triple superphosphate (TSP) [$Ca(H_2PO_4)_2 \cdot H_2O$] or mono-calcium phosphate was a popular P fertilizer in the early 1900s, but has been replaced by other P fertilizers in recent years. It has the highest P content of the dry fertilizers that do not contain N, and the P is over 90% water soluble. It is still popular for legume crops where N fertilizer is not needed.

Monoammonium phosphate ($NH_4H_2PO_4$) is the most concentrated P source among solid fertilizers. It contains 10 to 12% N and 48 to 61% P_2O_5, most commonly produced as 11-52-0. It can be made using lower quality phosphoric acid than that used for producing other P fertilizers. Monoammonium phosphate is highly soluble and quickly becomes available to plants as NH_4^+ and $H_2PO_4^-$ in the soil solution. When made with purer forms of phosphoric acid, MAP can be made into a powdered form (usually 61% P_2O_5) and used in suspension or clear liquid fertilizers, or applied as a foliar spray or added to irrigation water.

Diammonium phosphate [$(NH_4)_2HPO_4$] (DAP) is the most widely used P fertilizer in the world. It is produced by reacting ammonia with phosphoric acid. The standard grade for DAP is 18-46-0. It is popular because it has a relatively high content of two commonly needed fertilizer materials and has properties that make it easy to handle and store. DAP first became available in the 1960s. Its high solubility makes the nutrients readily available to crops. The high ammonium-N content can damage seeds and roots near the fertilizer granules, so it is best placed in a band about 10 cm from the seed row, or broadcast and incorporated to avoid concentrating the nutrients too close to the seed or young roots.

Polyphosphate is a popular liquid phosphate fertilizer, produced by reacting ammonia with phosphoric acid, driving off water and linking the individual phosphate ions together in a chain. The single phosphate ions (orthophosphate) can form different lengths of chains, but they can be collectively called "polyphosphate". Most commonly produced as 10-34-0 or 11-37-0, these fertilizers form clear liquids that remain stable and crystal-free under a wide range of conditions. This makes them a popular P source throughout the world. Between 25 and 50% of the P in polyphosphate fertilizers remains in the orthophosphate (single molecule) form and is readily available for plant uptake. The remaining 25 to 75% of the P is in the polymers of different lengths that must be broken down by enzymes or organisms in the soil to be available to plants. Polyphosphate fertilizers offer the advantage of a high nutrient content in a clear, crystal-free fluid that is stable under a wide temperature range and has a long storage life. Polyphosphates are a popular carrier for mixing with micronutrients and other chemicals to aid in uniform distribution.

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

Under conditions of intensive farming on well-fertilized soils, the common P fertilizers give about an equal yield response per unit of "available" P_2O_5. Water-soluble P, however, is superior for crops with a short growing season and limited root system in deficient soils. The dynamics of different "pools" of P in the soil is illustrated in Figure 11. The P moves from one pool to another as factors such as soil pH and P concentration change.

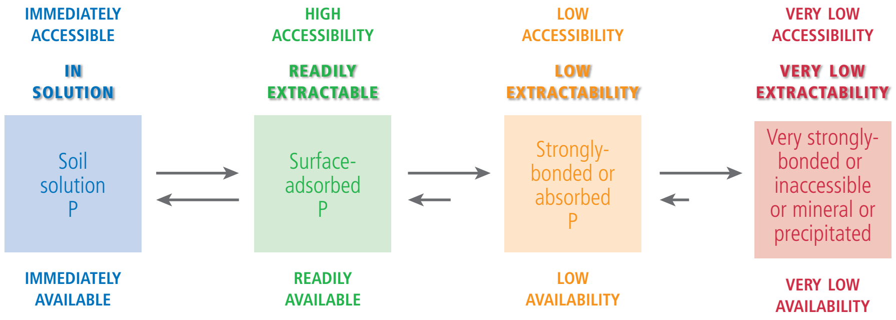


Figure 11. Relationship of different "pools" of P in the soil. As conditions, such as soil pH and P concentration change, the relative amounts of P in each pool will change.

Applying N and P fertilizers together in a band or as combined product sometimes offers advantages for nutrient utilization–the acidification from N helps prevent the P from becoming fixed in unavailable forms; gaseous losses of N may occur from surface-applied diammonium phosphate (DAP) on neutral soils. Phosphate fixation, i.e., the transformation of soluble fertilizer P into unavailable forms, is fortunately restricted to special soil conditions, e.g. high content of active Al and Fe or Ca and Mg, as defined by soil pH. The utilization rate of P in fertilizers is usually about 15 % in the first year but only 1-2% per year thereafter, with the result that only about two-thirds is taken up by the end of thirty years. The efficiency of P fertilizer utilization depends upon weather conditions, soil pH, type of crop, and timing and placement of P fertilizer application.

Fertilizer undergoes a number of reactions in the soil to be converted to the plant-available form (inorganic phosphate). Most modern P fertilizers are readily soluble, having been treated with sulphuric or phosphoric acid to increase solubility. Under some conditions, special treatments can be used to enhance solubility and uptake, or reduce fixation into insoluble compounds. Under very low or very high soil pH conditions, for example, P can be tied up in insoluble iron or calcium phosphates respectively. For organic P sources, the P is insoluble and microbial activity is required to convert the P to the inorganic, available form. As with N, the release of organic P may be managed by controlling this microbial activity. Box 5 shows characteristics of some important P fertilizers.

Box 5. Types of P fertilizers

P_2O_5 content refers to 'available' portion, except for rock phosphate where it means total content.

- **Water-soluble types** (quick-acting)
  - single superphosphate (18-20% P_2O_5);
  - triple superphosphate (45% P_2O_5).

- **Partly water-soluble types** (quick- and slow-acting)
  - partly acidulated phosphate rock (23-26% P_2O_5, at least one-third water-soluble).

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

- **Very slow-acting types**
  - rock phosphate (finely-powdered soft type, e.g. 30% P_2O_5), with reactivity indicated by formic acid-solubility; permitted minimum is about one-half of total P_2O_5 content).

- **Multi-nutrient fertilizers** containing P: like N, P
  - NP (see N fertilizers, Box 4);
  - PK (mixtures very commonly used);
  - NPK (may contain about one-third or more water-soluble P for quick supply and two-thirds slow acting P for continuous supply.

Potassium (K)

Potassium is found in all living cells. In the soil, it is found in relatively small amounts in soil solution as the positively-charged K^+ cation, and is taken up by plants in that form. At any given time, there may be only 12 to 15 kg per hectare of K in the soil solution, but there are large supplies of exchangeable K attached to the soil in various amounts of availability. The soil solution is constantly replenished through the cation exchange process as K^+ ions are taken up from the soil solution by plant roots. Potassium in its ionic form occurs in equilibrium in many processes in the soil (Figure 12).

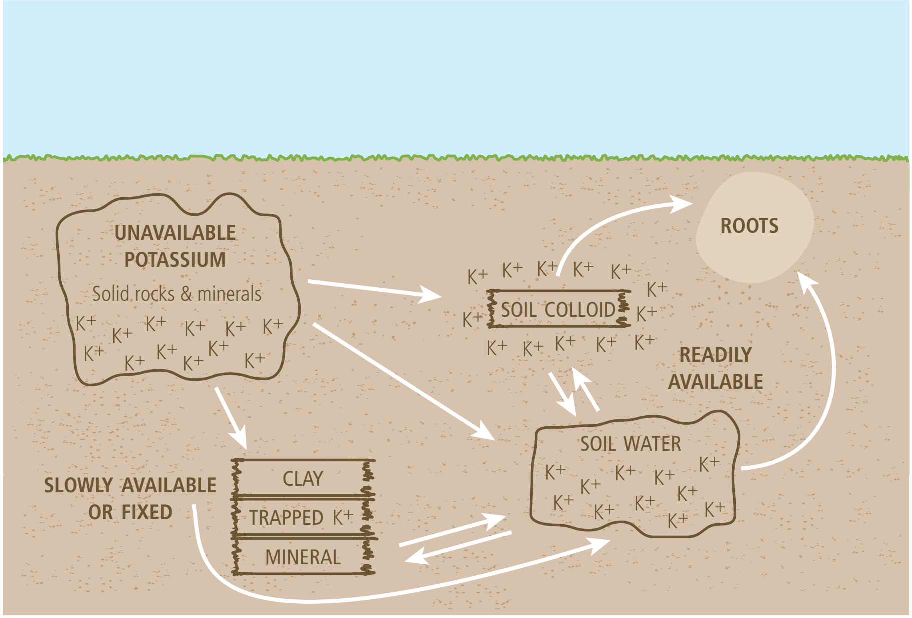


Figure 12. Illustration of K in various equilibrium positions in the soil. As K is taken up by plants, the equilibrium shifts to release more K into the soil solution (adapted from University of Minnesota).

In the plant, K regulates the flow of water and other materials across cell membranes, and helps regulate a wide variety of chemical and enzymatic processes. Potassium itself does not form any chemical compounds in plants, but rather serves to balance ionic electrical charges by moving back and forth across cell membranes. In doing so, K is essential to nutrient uptake and movement throughout the plant, and in maintaining water balance in the plant. It is thus essential for the utilization of other nutrients and water, even though it does not chemically combine with other nutrients. Much of the K used by a growing crop is not accumulated in the grain, but is left in the crop residue (stalks, leaves, and straw). When the plant dies, K is easily leached from crop residue, and may even leach from living plant tissue under heavy rainfall. For forage crops, where the entire plant is harvested, crop K removal rates are much higher. It is also true for sugarcane and some cereal crops grown in many countries in Asia where both grains and straw are harvested from the fields for human and animal consumption, respectively.

Potassium fertilizer is usually described in the oxide form (K_2O). As was the case with P, this form is a standard of comparison among K fertilizers, but it is not actually found in K fertilizer materials. The formula to convert K to K_2O is: K x 1.20 = K_2O. Potassium is constantly shifting among various parts of the soil-plant-animal-environment components as it functions in their physical, chemical, and biological systems as shown in Figure 13.

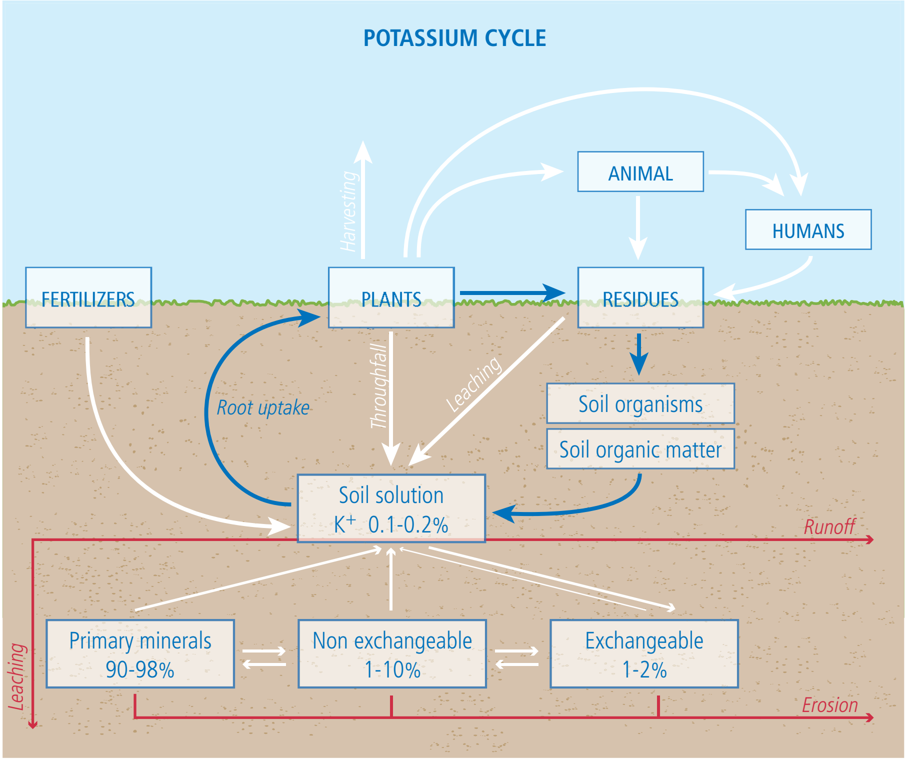


Figure 13. Relative amounts of K in the various pools in the soil-plant-animal system (adapted from University of British Columbia).

The Potassium Cycle (Figure 14) shows how swiftly K moves in the soil-plant system.

K fertilizers and formulations

Potash fertilizers are mainly derived from geological saline deposits. Although low-grade, unrefined materials can be used directly, most fertilizer products now in use are high concentration materials which are water-soluble and quick-acting.

Potassium chloride (KCl) (0-0-60) or Muriate of Potash (MOP): Most K deposits are found as KCl (sylvite) mixed with NaCl (halite) in the mineral sylvanite, often

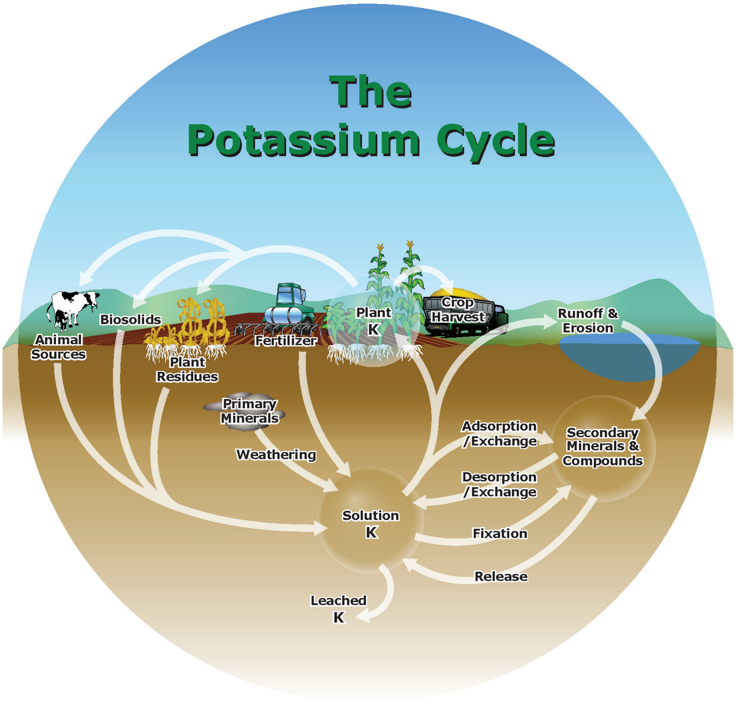


Figure 14. The Potassium Cycle. Potassium is readily leached from dead plant material, because K^+ doesn't form any chemical compounds in the plants (IPNI).

in ancient marine deposits buried deep beneath the Earth's surface. In processing, the ore is crushed and the KCl and NaCl are separated. In a few locations, the ore is dissolved with hot water and pumped to the surface as soluble sylvanite and then the water is evaporated. In the Dead Sea (Israel/Jordan) and Great Salt Lake (Utah, US), the K salts are recovered from brine water by solar evaporation. KCl is 60 to 63% K_2O (50 to 52% K and 45 to 47% Cl). It is usually surface applied prior to tillage, or banded near the seed row. Due to the high salt content, KCl should not be placed directly with the seed. It dissolves readily in the soil solution into K^+ and Cl^-. The K attaches to cation exchange sites in the soil clay and organic matter. Most of KCl fertilizers are white, but some K materials are reddish in color due to presence of trace amounts of iron oxide; but both are identical for agronomic use. Pure forms of KCl may be dissolved for use in fluid fertilizer or application in irrigation water.

Potassium sulphate (K_2SO_4), also called sulphate of potash (SOP), is 48 to 53% K_2O, and 17 to 18% S. Potassium sulphate is found in mineral deposits mixed with other minerals. The components are separated by rinsing them with water. The K in SOP functions similar to as in KCl, but SOP is also an important source of S where the soil is also S deficient. Potassium sulphate is less soluble than KCl, so it is not commonly used in irrigation water. But potassium sulphate is sometimes applied as a foliar spray if K and S are both needed. It is also used to supply K to Cl-sensitive crops such as tobacco and potatoes.

Potassium magnesium sulphate ($K_2SO_4 \cdot 2MgSO_4$) is also called Langbeinite, sulphate of potash magnesia, or commercially Sulpomag: Langbeinite is a unique mineral found in only a few locations in the world. Commercially it comes from underground mines near Carlsbad (Germany), New Mexico (US). Langbeinite is 21-22% K_2O, 10-11% Mg, and 21-22% S. It is a popular fertilizer where its three main nutrients (K, Mg, S) are needed. It is water-soluble, but slow to dissolve, and unlike other Mg and S fertilizers, it has a neutral effect on soil pH.

Potassium nitrate (KNO_3) or Saltpeter: It is a popular fertilizer for high-value crops that need nitrate form of N and also K. It is especially popular as a K source for crops that are sensitive to Cl. It is 13% N and 44-46% K_2O. It can be soil applied or applied as a foliar treatment to stimulate fruit development when root activity is declining, and is a common nutrient source for fertigation.

Several industrial residues containing K, e.g. filter dust, have been developed for use as slower-acting forms, especially where it is desired to avoid loss by leaching. Potash fertilizers should generally be applied at sowing time. The K^+ ions are adsorbed in the soil and thus remain available, yet largely protected against leaching. However, split application is advisable for some crops in soils and climates where higher leaching losses may be expected. Some immobilization into clay lattice layers reduces availability but strong fixation into completely unavailable forms is fortunately restricted to a few special soil types. The utilization rate of K in fertilizers is about 50-60% during the year of application.

Secondary nutrients

Sulphur, Ca and Mg are considered secondary nutrients, because while these are essential to crop development, seasonal crop uptake is usually lower than for the primary nutrients (N, P and K), but considerably higher than the micronutrients Zn, Fe, Mn, Cu, B, Mo and Cl.

Sulphur (S)

Sulphur is found in the soil primarily as inorganic sulphates and organic sulphur compounds. It must be mineralized to the sulphate anion (SO_4^{2-}) in order to be taken up by plants. Atmospheric sulphur in the form of sulphur dioxide (SO_2) supplies large amounts of sulphur (20 kg/ha or more) in areas where sulphur-containing fossil fuels are burned, but environmental clean-up from such sources has led to more need for sulphur fertilization in recent years. Similarly, a few decades ago fertilizers such as single super phosphate and some pesticides supplied some sulphur to crops, but changes in the manufacturing processes have reduced those sources as well. Sulphur in soils in the sulphate form can be leached out of the root zone, especially in coarse-textured soils. In irrigated production systems, irrigation water may be a significant source of S supply to the crop. The soil tests available for S are not very reliable for use in developing recommendations.

Sulphur can be supplied to field crops through a number of fertilizer materials.

Elemental sulphur (0-0-0-90 S) is a convenient form of sulphur that can be broadcast or band applied to a number of crops. Before applying to the soil, elemental sulphur must be broken down into small particles through purely physical processes. Once in the soil, it is transformed to sulphate ions through the activity of *Thiobacillus* and some other soil bacteria. Breakdown into small particles can more quickly be accomplished through mixing of the sulphur with bentonite clay in the formulating process. In water, a bentonite-sulphur particle swells, breaking it up into very fine particles. Once broken into small particles, the increased surface area allows soil bacteria to transform the sulphur to sulphate more quickly. However, even in the presence of small particles, transformation of sulphur to sulphate is a slow process often taking months. Therefore, for most crops in the initial sulphur fertilization year, a sulphate fertilizer like ammonium sulphate rather than elemental sulphur is recommended.

Ammonium sulphate (21-0-0-24 S) is produced as an industrial byproduct and is useful as an N source where S is also needed. Ammonium sulphate is a popular source of S because it is more available to plants and is less susceptible to leaching losses than many other sources. It also has the benefit of supplying part of the N requirement of the crop.

Calcium sulphate (Gypsum) (24% S) has been widely used for many years as a sulphur- and calcium-bearing material for fertilization and soil reclamation. It is a neutral salt and has no effect on soil acidity. Gypsum is far less soluble than ammonium sulphate and hard to handle.

Single superphosphate (SSP) (0-20-0); (8 to 10% S): Sulphur deficiencies seldom occur on land adequately fertilized for supplying P to crops with SSP. In the manufacture of concentrated superphosphates, such as triple superphosphate, however, the gypsum is largely removed and these materials therefore contain little or no sulphur.

Ammonium polysulfide (45% S) can be applied directly to the soil, added into irrigation water, or mixed with anhydrous ammonia or ammonia solutions. However, ammonia polysulfide is not completely compatible with liquid fertilizers that are highly acidic or have a high salt concentration. Used In some situations to reduce pH and to improve water infiltration into the soil.

Ammonium thiosulphate (26% S). Ammonium thiosulphate is another sulphur-containing material. It can be applied in irrigation water. It is also compatible with many fertilizers solutions such as aqua ammonia, N solutions containing ammonium nitrate, urea solutions, and most N, NP, or complete fertilizer solutions. It cannot, however, be mixed with anhydrous ammonia or acid solutions such as phosphoric acid, as these materials will decompose the thiosulphates.

Calcium (Ca)

Calcium makes up from 0.1 to 25% of soil, depending on the mineralogy. Liming to maintain pH in the proper range for plant growth will usually supply sufficient Ca to meet crop needs. Ca is a major component of cell walls in plants. Ca deficiency in plants is often masked by toxicity effects of other nutrients (such as aluminum, manganese, and copper) under low pH. Where Ca deficiency needs to be corrected, but pH is high, gypsum can be used to supply Ca.

Magnesium (Mg)

Magnesium is a part of the chlorophyll molecule. Thus Mg deficiency often shows up as yellowing between the veins of leaves. Applying dolomitic lime (11% Mg) is the most common means of correcting Mg deficiency. In acid soils or in regions with heavy rainfall that causes leaching of Mg from the root zone, more soluble forms of Mg (such as the $MgSO_4$) may be needed to get rapid correction of the deficiency.

Magnesium fertilizers are either quick-acting soluble salts (such as sulphates) or slow-acting (such as dolomitic lime). Magnesium sulphate, in the forms of Epsom salts (10% Mg) or keiserite (16% Mg), is the common Mg-supplying fertilizer for crops. Keiserite or magnesium sulphate monohydrate ($MgSO_4 \cdot H_2O$) is a natural mineral mined from deep underground geologic marine deposits in Germany. It provides a soluble source of both Mg and S for plant nutrition. The fine crystalline kieserite is sold for direct application to soil, or it is granulated to a larger particle size that is better suited for mechanical fertilizer spreading or for bulk blending with other fertilizers. Potassium magnesium sulphate (see under potash fertilizers) also constitutes an important source of Mg in situations where K is also deficient.

Magnesium carbonate (dolomitic lime). For soils that needs liming, the cheapest source of Mg is dolomitic lime or magnesium carbonate. A high rate of application of dolomitic lime can ensure a good supply of Mg for several years without any detrimental effects.

Micronutrients

Micronutrients are needed in very small amounts, but are still essential for growth of plants. Micronutrient deficiencies vary with regions, based upon soil mineralogy and climate, and often can be corrected by adjusting pH. Fertilizer sources for different micronutrients and their management are described in Table 3.

Table 3. Micronutrients essential to plant growth and some of their sources and characteristics.

Micronutrient	Sources for corrective action	Management functionality
Iron (Fe)	Usually applied as a foliar spray in the form of chelates such as Fe-EDTA (9% Fe) or Fe-EDDHA (6% Fe).	For soil application Fe-EDDHA has the advantage that it is more stable in neutral soils.
Manganese (Mn)	Deficiency occurs mainly in slightly acidic to neutral soils. Both Mn sulphate (24-32% Mn) and Mn-EDTA (13% Mn) are water-soluble and quick-acting, and are suitable for foliar or soil application.	Mn oxides may be used as a means of increasing the reserves. Indirect improvement of the soil supply may be achieved using acidifying additives.
Copper (Cu)	Deficiency may most easily be corrected for a longer period by soil application as Cu sulphate or oxides, etc.	Chelates or neutralized Cu sulphate (25% Cu) are suitable for foliar spraying of deficient crops.
Zinc (Zn)	Usually applied to deficient crops as a foliar spray of Zn sulphate (e.g. 23% Zn) or Zn chelate (e.g. Zn-EDTA).	High levels of P in the soil may result in reduced availability of Zn.
Chlorine (Cl)	Usually found in the soil as the Chloride ion (Cl^{-1}). Most commonly it is applied with K in potash fertilizer (KCl) or with other salts.	It is easily leached in drainage water.
Boron (B)	As a prophylactic treatment for crops with high demands, soil application of borax (11% or 22% B) is advisable.	Needs vary widely, the rate depending on the crop (0.5-2.0 kg/ha B); risk of a damaging surplus affecting a succeeding crop with a low requirement. A better distribution can be obtained by incorporating the boron in phosphate or multi-nutrient fertilizers. Polyborates seem to be superior to borax for foliar application (at about 1 kg/ha).
Molybdenum (Mo)	Required in only very small amounts.	Involved in the fixation of N by bacteria in association with legumes.
Nickel (Ni)	Nickel was confirmed as an essential plant nutrient in 1987.	One of its essential functions is in the urease reaction in soil N nutrition. It is thought to be important to grain development and maturation and in the movement of Fe into plant cells, and is a factor in grain quality.
Cobalt (Co)	Cobalt has recently been considered for addition as the 18th essential nutrient for plants, but has not been "officially" recognized. For now, it is considered beneficial, but not essential.	Cobalt is necessary for nitrogen (N) fixation occurring within the nodules of legume plants. In N-fixing bacteria, Co is a vital component needed to synthesize vitamin B12, which is necessary to form hemoglobin, which is directly related to successful N fixation in legume root nodules.

Other nutrients

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

Fertilizer use

As hardly any soil can supply all the nutrients needed in sufficient amounts to meet the demands of high-yielding crops, the deficit must be corrected by adding fertilizers and/or manures. The need for micronutrients often increases with higher yield levels due to the dilution effect of increased macronutrient levels in plant material.

Nutrient application should be timed to ensure that adequate supplies are available before the nutrient is needed by the crop. The total amount needed at a given stage can be estimated from the critical nutrient level required in plant tissue for the optimum functioning of biochemical processes at that growth stage. The actual nutrient contents of crops are usually somewhat higher than the critical levels, i.e. these are in the "normal" or optimum nutrient range. On the other hand, a large surplus or luxury supply is unwanted, not only because of the money wasted on excess fertilizer but also because it may upset the nutrient balance and reduce productivity, and it may trigger undesirable losses to the environment. Excess uptake of some micronutrients may have toxic effects on some plants.

Plants, in general, contain maximum amounts of nutrients in the later stages of growth shortly before maturity (usually more than is actually needed), but nutrient balance calculations are often based on the somewhat smaller amounts that are removed from the field at the time of harvest. Relevant nutrient removal data should be established for all crops and farming systems.

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

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

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

Fertilizer grade

Fertilizer grade refers to the legal guarantee of the available plant nutrients expressed as a percentage by weight in a fertilizer. A grade of 12-32-16 for an NPK fertilizer indicates the presence of 12% N, 32% phosphorus (P_2O_5) and 16 % potassium (K_2O).

Box 6. Forms of fertilizer

Fertilizer materials may be produced in a variety of forms. The decisions on which forms to use depend on when and how the fertilizer is to be applied, the crop to be grown, and which forms are available locally.

Individual nutrients

The simplest system is to apply nutrients individually, but that may not be the most efficient from the standpoint of labor and other resources, and may not result in the most efficient nutrient utilization. Sometimes it is the only choice. Anhydrous ammonia, for example, does not mix with other nutrients and is applied as a single nutrient.

Bulk blends

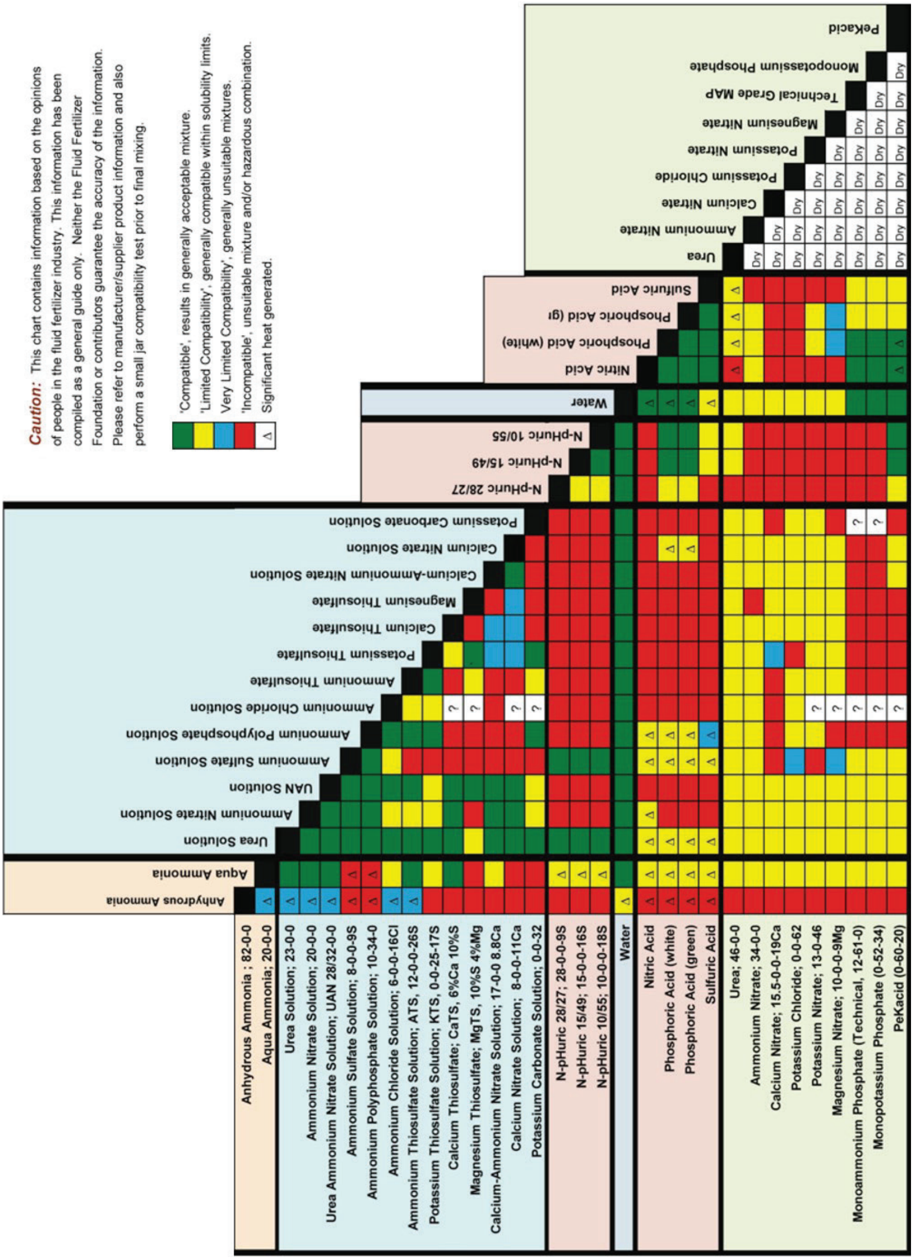
Dry granular fertilizer materials are often blended together in different ratios to meet the needs of the individual fields. By mixing the different component materials (usually N, P, and K sources, plus secondary and micronutrients if needed) in appropriate combinations, a nutrient management plan can be developed to match soil tests and crop requirements, usually with the least-cost combination of sources. Care must be taken to ensure chemical and physical compatibility of the component fertilizers. To avoid segregation during shipping, handling, and application, it is important that the different products in the blend have similar particle size. Bulk blending is practical for large operations where it is possible to handle large volumes of individual products and fertilizer is distributed to farmers in bulk. For many less-developed systems, it is often more practical to use compound fertilizers with standard nutrient contents, or fertilizer grades (N-P-K contents).

Compound fertilizers

Multiple nutrients may be combined into uniform granules, each containing the proper combination of nutrients and made in a uniform particle size to facilitate uniform spreading. Such fertilizers are manufactured in common ratios for the crop and soil requirements of the area. The disadvantage is that the ratios are fixed, so compound fertilizers generally do not work for variable-rate applications, unless supplemental sources of individual nutrients are used to balance the overall need. Compound fertilizers do offer an efficient way to uniformly apply micronutrients, by combining them in the compound granules, and using nutrients that are applied at higher rates as a carrier. Chemical compatibility is again important to consider.

Fluid fertilizers

Blending materials can be taken a step further by mixing nutrients in fluid form that can often be applied more uniformly in the field. These may be developed as clear liquids made of mixtures of dissolved nutrients that give a homogeneous product containing the desired nutrients, or as suspensions, which are composed of very small particles of fertilizer material suspended in a liquid in combination with suspending clay or a gelling agent. Micronutrients, herbicides, insecticides, and other additives may be included in fluid fertilizers. Sometimes these additions are more suitable for suspensions than for clear liquids due to interactions among the components. Some are made with nutrient sources that have a low salt content, so that it can be applied as a foliar fertilizer; some are added to irrigation water. Compatibility checking is critical to avoid formation of precipitates, clogging of nozzles, and crop injury. The compatibility chart (Figure 15) developed by the Fluid Fertilizer Foundation is a useful guide to which products can be successfully combined in fluid fertilizer mixtures.


Caution: This chart contains information based on the opinions of people in the fluid fertilizer industry. This information has been compiled as a general guide only. Neither the Fluid Fertilizer Foundation or contributors guarantee the accuracy of the information. Please refer to manufacturer/supplier product information and also perform a small jar compatibility test prior to final mixing.

- 🟩 'Compatible', results in generally acceptable mixture.
- 🟨 'Limited Compatibility', generally compatible within solubility limits.
- 🟦 'Very Limited Compatibility', generally unsuitable mixtures.
- 🟥 'Incompatible', unsuitable mixture and/or hazardous combination.
- Δ Significant heat generated.

Figure 15. Compatibility chart for mixing fluid fertilizers (Fluid Fertilizer Foundation, May 2009).

Enhancing fertilizer use efficiency

Fertilizers can be made more efficient by slowing the release of nutrients, inhibiting conversion to forms that are less stable in the soil, or enhancing availability of nutrients to plants. Whether to use these alterations to enhance fertilizer use efficiency depends upon potential benefits in terms of agronomic, economic, and environmental factors. In recent years, there has been an increasing interest in fertilizer formulations and additives that help to increase the efficiency of the applied fertilizer. A number of different processes and products are available to address this need. One approach is to create a physical barrier, or coating to protect the fertilizer granules from dissolving. Depending upon the thickness of the coating and its components, the protection can be for a few days to a few months. Another approach is to develop a chemical combination that enhances nutrient uptake. Several products are available that interfere with the biological processes of nutrients in the soil. These include nitrification inhibitors, urease inhibitors, and other chemicals that can be used to stop, or slowdown the conversion pathways that are regulated by soil bacteria.

Coatings and controlled-release fertilizers

A wide range of materials have been used as coatings on soluble fertilizers. Coatings are most commonly applied to granular or prilled N fertilizers, but multi-nutrient fertilizers are also sometimes coated. Since urea has the highest N content of common soluble fertilizers, it is the most commonly coated fertilizer. Elemental S was the first widely used fertilizer coating. It involved spraying molten S over urea granules, followed by an application of sealant wax to close any cracks or imperfections in the coating. An improvement in this process was later adopted when the S layer was covered with a thin layer of organic polymer. Polymer coatings can also be applied to fertilizer particles to control nutrient release and improve nutrient use efficiency. These coatings can protect the fertilizer particles for varying times from a few weeks to several months depending on the coating and the conditions in the soil. Some coatings protect the fertilizer particles from dissolving in the soil for a certain period of time.

An example of a coating that delays the release of N in urea is environmentally smart N (ESN). It is granular urea surrounded by a flexible polymer coating, which controls the permeability to water absorption and dissolved N release. The polymer coating can be applied at different thicknesses to adjust the rate at which water can be absorbed and the urea dissolved.

Coated products function by keeping the nutrient in a form that is less likely to be lost from the root zone, and releasing the nutrients at a time as close as possible to the time of uptake required by the plant. Just a few days in delayed release can often mean a significant reduction of nutrient losses, and thus a significant increase in nutrient use efficiency. By keeping more of the nutrient in the crop, losses to the environment are also reduced.

Inhibitors

A number of chemical and biological inhibitors have been identified which can be used to manage nutrient release or activity in the soil. These chemicals generally target a specific reaction in the soil to prevent its occurrence for a period of time. Again, nitrogen is the most common target nutrient. Example products are nitrification inhibitors, which slow the bacterial conversion of ammonium to nitrate, and urease inhibitors, which reduce the enzymatic breakdown of urea into ammonium. Additions of urease and nitrification inhibitors with urea allow applied N fertilizer to stay in the soil close to the root zone for a longer period thereby creating better opportunity for plant uptake than applying urea alone as well as reduce potential losses of N from the soil-plant system to the environment. However, the effectiveness of these inhibitors in increasing yield and improving grain protein content is affected by several soil and environmental factors. Thus, the optimal application method and timing of N fertilizer when applied along with inhibitors need to be worked out for different crops, soils and climates.

Others

Some micronutrients can be incorporated into glass beads, which make the nutrients easier to apply uniformly and also help control the rate of release. Liquid polymers are sometimes used to bind with soil cations and help maintain P solubility under some conditions. Several options are available to meet specific nutrient management needs. Adding these control systems usually adds to the costs, but may be justified if sufficient enhancement of nutrient efficiency and desired yield is obtained.

Organic fertilizers

A number of organic materials can be useful soil amendments and suppliers of nutrients (Box 7). Since many are waste products, they can sometimes be cheaply available, especially if used near to where they are produced. Some farm wastes are used because recycling is the only, and moreover beneficial, means of disposing of them. If waste material of any kind has to be bought in by the farmer, it must be comparatively cheap and have no detrimental or toxic effect, and it must be profitable. Organic fertilizers usually require handling and transporting large volumes of material to obtain relatively low levels of nutrients, so it is best to use them on fields near the source.

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

Box 7. Types of organic fertilizers

- **Naturally occurring material** (e.g. peat)

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

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

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

- **Urban wastes**
  - composted household refuse;
  - sewage sludge.

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

Important criteria for organic fertilizers are:

- dry matter content,
- total and easily mineralizable organic matter,
- total and quick-acting N,
- C/N ratio,
- total P and K contents,
- content of substances detrimental to plant growth or product quality (heavy metals in particular should be below established critical limits).

The rates at which organic materials are applied should take into account both the expected nutrient supply available to the crop (for N in farmyard manure, about 20-30% of the amount applied is available to the crop during the first year; it can be relatively high under tropical climates) and the need to minimize nutrient losses or other detrimental effects. There is no difference in the nutritional value of nutrients from organic sources compared to mineral fertilizers. Claims that organic nutrient sources are better for plants have no scientific basis. In addition to supplying nutrients, organic materials may provide other benefits to plant growth, particularly in improving soil physical and chemical properties (Box 8).

Box 8. Effects of organic materials on plant growth (via the soil)

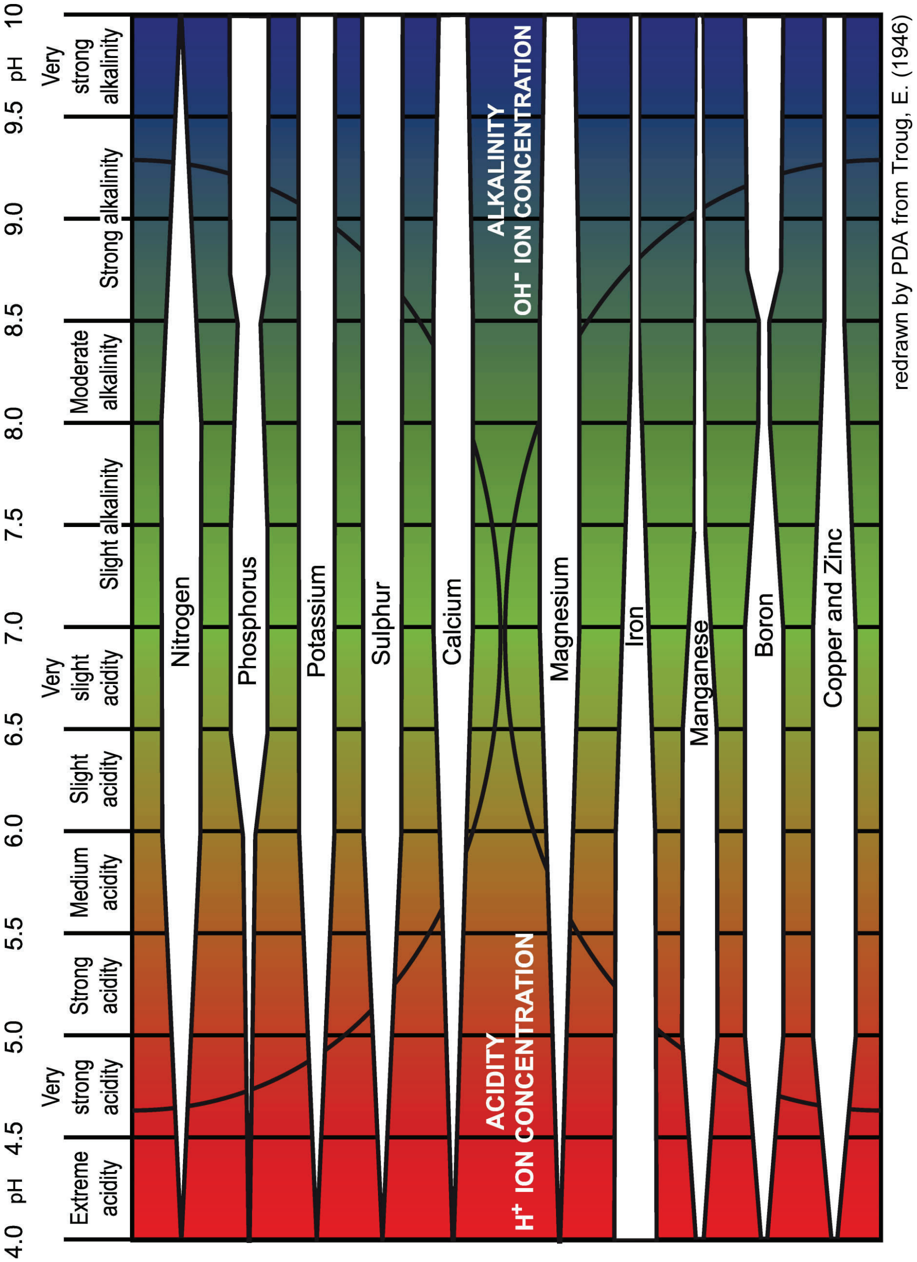
- Improvement of physical soil properties, either directly through addition of organic matter or by activating living organisms in the soil:
  - better soil structure as a result of soil loosening and crumb stabilization;
  - better water-holding capacity and soil aeration;
  - surface protection by mulch layer.

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

As with mineral fertilizer materials, efficiency-enhancing additives can be added to manures and other organic nutrient sources to reduce potential for nutrient losses either in storage or after application to the field. Placement and timing options may also improve management of nutrients from organic sources. Most build-up of organic matter is dependent upon plant growth, which depends upon nutrient balance in the soil. Organic matter produced from a fertile soil can hold nutrients in the soil until these are converted to plant-available forms, thus providing a slow-release mechanism for supplying nutrients to the next crop. So correcting nutrient deficiencies is really more important to building soil productivity than is increasing soil organic matter.

Soil reactions

A sound nutrient management plan must include careful monitoring of pH so that all of the other nutrients can be most efficiently used by the crop. For soils to be highly productive, they must first be in the optimum pH range (the values mentioned below refer to measurements in water suspension). The proper pH will ensure that all essential nutrients are available for plant uptake. Values under pH 4.5-5.0 can be very damaging to plants (soil acidity syndrome) by causing nutrient deficiencies (of P, Mg, etc.) and toxicities (of Al, Fe, Mn). Liming helps to raise the pH to at least about 5.5. A pH range of 5.5-6.5 seems to be satisfactory for moderate yields of most crops. Optimum pH values, or respective ranges, for high yields have been established for different soils, crops and rotations.



redrawn by PDA from Troug, E. (1946)

Figure 16. Availability of various nutrients as soil pH changes. The thickness of each nutrient bar represents its relative availability at the various pH levels (Potash Development Association, UK).

Figure 16 shows the effect of pH on relative availability of several nutrients. Many versions of this chart have been developed around the world. Adjusting pH by liming the soil can increase or decrease the availability of nutrients to plants. At pH between 6.5 and 7.0, most of the nutrients are at their maximum availability. As pH gets higher or lower, individual nutrients are tied up in compounds that make them unavailable.

Several kinds of liming materials may be used to increase soil pH. Limestone is the most commonly used material. Adjusting soil pH to between 6.5 and 7.0 will provide the soil condition for most nutrients to be in their most available form. For example, P reacts in acidic soil to form iron and aluminum phosphates, which are unavailable to plants. At high pH levels, P combines with calcium and magnesium to form insoluble compounds. Adjusting pH to the 6.5 to 7.0 range helps release the P from these compounds and makes it more available to plant roots. Thus P deficiency in crops may be corrected by addition of lime to raise the pH, releasing P that is already in the soil, rather than adding P fertilizer.

In many acid soils, lime containing magnesium carbonate provides a double benefit by adjusting pH and by supplying Mg. However, it is important for liming to be complemented with appropriate fertilizer use to correct other nutrient deficiencies.

In neutral to slightly alkaline soils under high yield conditions, use of acidifying N fertilizers can be advantageous resulting in a better supply of micronutrients such as Mn or Zn. On saline/sodic soils, gypsum is a useful soil amendment to help remove Na and supply structure-improving Ca, without changing the soil pH.

Fertilizer recommendation approaches

There are three primary approaches to fertilizer recommendations for crops. The sufficiency approach focuses on the plant needs whereas the build-up and maintenance approaches focus on the available amount of a nutrient in the soil.

The uptake of immobile nutrients (such as P and K) by crop plants is a function of the concentration of plant available nutrients in the soil, because the amount extracted by the plant is limited by the concentration at the root-soil interface. Percent sufficiency is based on soil test value expressed as a percentage of the potential yield when the nutrient is limited to that level. Each crop has a specific sufficiency index and a recommended application rate for each nutrient. The goal of the sufficiency approach is to apply enough fertilizer to maximize profitability in the *given year of application*, while minimizing nutrient applications and fertilizer costs at the same time. The sufficiency approach is commonly referred to as the “feed-the-crop” approach for efficient management of fertilizers.

The soil test levels must be calibrated by using yield response trials to determine sufficiency levels. In these trials, the point at which there is no increase in yield is identified as the *critical level*. A positive aspect of the sufficiency concept is that yields are maximized while annual inputs are minimized. However, applications will need to be made every year to maintain those yield levels. Fertilization based on sufficiency levels is well-suited for short term leases.

Maintenance approach

Using the *maintenance approach* to nutrient management, nutrients that have been removed with the crop at harvest should be replaced. Fertilizer is applied, based on the amount of nutrients removed from the field to maintain the soil nutrient level. The maintenance concept does not recommend application when soil nutrient levels are above the critical level. Above the critical soil test level, the soil will be able to supply the nutrients required by the crop and no fertilizer response would be expected. An assumption of the maintenance concept is that crop nutrient removal rate is accurate and allows maintaining soil tests at the critical level. To account for some of the applied nutrients being tied up in chemical interactions in the soil, the actual amount needed for maintenance may be slightly higher than the amount removed by the harvested crop.

Build-up approach

The *build-up approach* to nutrient management is based upon "feed-the-soil", rather than the plant. Nutrients are applied in excess of the amounts removed by the crop to build the concentrations to the point where they will not be limiting. This approach allows taking advantage of the exceptional 'good years', when weather and other conditions support above average yields.

The process to build-up soil test values is usually spread over four to eight years, depending upon the farmer's economic situation. Longer term build-up programs help farmers manage their finances by spreading build-up fertilizer costs over several years. But shorter build-up programs can provide earlier benefits from higher soil tests. For some soils, building soil test levels is not possible due to excessive leaching of the nutrients applied or having the nutrients 'tied-up' in unavailable forms. Soils with a high sand content or very high organic matter levels tend to have such limitations. In those cases, fertilizer should be applied as close as possible to the time of crop use in order to get the most efficient use of applied nutrients.

Build-up and maintenance approach

Usually the concepts of build-up and maintenance are used together. The build-up and maintenance philosophy means that fertilizer is applied over the selected time period until nutrient levels (such as P and K) are raised to the critical soil test levels, then applications are continued at a rate to maintain the nutrient levels to sustain that soil test. This approach requires a calibration data set that shows the relationship between fertilizer added and change in soil test level. The soil test provides an index of the productivity of the soil at different soil test levels for a selected soil test procedure.

The build-up and maintenance approach results in establishing soil test levels in a range where a yield response to applied fertilizer is not expected. Soil test levels are

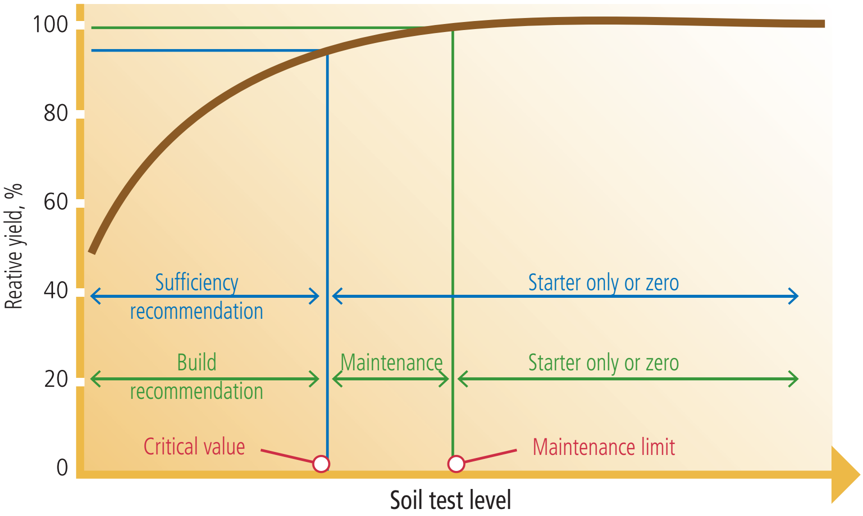


Figure 17. Build-up and maintenance approach to nutrient management (IPNI).

maintained to support optimum yields and ensure that nutrients are not limiting. This approach usually works well for P and K, but is not appropriate for N, since N soil tests cannot be built up or maintained.

Figure 17 shows a comparison for the critical value (sufficiency) approach and the build-up and maintenance approach to fertilizer recommendations. The most important component of this model is the establishment of a critical level. This critical level is the same value that is established as the 100 percent level for the sufficiency concept.

The main difference is that with the sufficiency approach, the goal is to apply fertilizer only up to the critical value. With the build-up and maintenance approach, the goal is to apply fertilizer up to the point where no further crop response is expected from further fertilizer application, and attempt to maintain the soil test at that level. With the sufficiency approach, it is critical that fertilizer is applied annually to reach the critical level needed to maintain yield. With the maintenance approach, there is more flexibility, because the crop is less dependent on the annual application. So if weather conditions or economics dictate cutting back on fertilizer application for one crop season, yield is not sacrificed.

When the soil test is above the “critical level” for the sufficiency approach or above the “maintenance limit” for the build and maintenance approach, the recommendation is to apply starter only or no fertilizer at all and wait for the next testing cycle.

The interpretation of soil tests depends upon the laboratory procedures used, and the calibration data used to relate the laboratory data to crop yield based upon extensive field studies for each crop and different soils. The relationship between expected yield and soil P is measured by the Bray P_1 or Mehlich-3 colorimetric procedures on neutral-to-acid soils, or by the Mehlich-3 procedure on soils with pH > 7.3. These values should not be used for the Olsen (soil bicarbonate) test or for Mehlich-3 extractions analyzed by inductively coupled plasma emission spectroscopy (ICP). Soil test results do not provide an actual measurement of the nutrient levels in the soil, but rather an index value that must be related to the appropriate calibration data relating the lab measurement to relative yield values.

Applications of phosphorus and potassium

Since P and K can usually build up in the soil and when applied as fertilizer, these tend to stay in the soil, farmers often choose to apply enough for more than one crop at a time. In a build-up and maintenance program, a common approach is to test the soil once every 4 years, and apply enough P and K to meet the anticipated needs for the crops for the following 4 years. The following are examples of how to calculate P and K fertilizer rates to be applied annually over a 4-year program.

Example 1: Build-up plus maintenance needed

Consider the fertilizer requirement for a continuous corn system, with a yield goal of 11.3 mt/ha grown in a region of soils with high P-supplying power and high CEC. The soil test levels were 36 kg/ha of P and 279 kg/ha of K.

Step 1: Calculate build-up rate

Phosphorus

This table shows the calculations of P_2O_5 fertilizer build-up requirement in English and metric units:

Value	Rate	Units
Desired soil test	45	kg/ha P
Current soil test	36	kg/ha P
Build-up required	9	kg/ha P
Build-up factor	9	kg/ha P_2O_5 to raise test by 1 kg/ha P
Fertilizer required	81	kg/ha P_2O_5
Years between applications	4	years
Annual application	20	kg/ha P_2O_5 per year

- The soil is 9 kg/ha below the desired level of 45 kg/ha (45-36 = 9);
- It takes 9 units of P_2O_5 to build the soil test level by 1 unit.
- 9 x 9 = 81 kg of P_2O_5 over 4 years to bring soil P to the desired level, or 81 ÷ 4 = 20 kg of P_2O_5 per year.

Potassium

This table shows the calculations of K_2O fertilizer build-up requirement:

Value	Rate	Units
Desired soil test	335	kg/ha K
Current soil test	279	kg/ha K
Build-up required	56	kg/ha K
Build-up factor	4	kg/ha K_2O to raise test by 1 kg/ha K
Fertilizer required	224	kg/ha K_2O
Years between applications	4	years
Annual application	56	kg/ha K_2O per year

- The soil is 56 kg/ha below the desired level of 335 kg/ha (335-279=56).
- It takes 4 kg of K_2O to build the soil test level by 1 kg.
- 56 x 4 = 224 kg/ha of K_2O over 4 years to bring soil K to the desired level, or 224 ÷ 4 = 56 kg/ha of K_2O per year.

Step 2: Calculate maintenance

Assume 11.3 mt/ha yield; nutrient content of 7.7 kg P_2O_5/mt and 5.0 kg K_2O/mt

Phosphorus maintenance:

7.7 kg of P_2O_5 per mt of corn x 11.3 mt = 86 kg/ha of P_2O_5 per year

Potassium maintenance:

5.0 kg of K_2O per mt of corn x 11.3 mt = 56 kg/ha of K_2O per year

Step 3: Sum build-up and maintenance values to determine yearly application rate

Phosphorus: 20 kg build + 86 kg maintenance = 106 kg/ha of P_2O_5 per year
Potassium: 56 kg build + 56 kg maintenance = 112 kg/ha per year

Nutrient supplying potential of soils

The natural nutrient content of soils provides large amounts of most essential nutrients. Variations in mineralogy, effects of weathering and leaching, nutrient removal by previous plant growth, and other factors may result in the need for some nutrients to be provided in supplemental fertilizers. The amounts applied in fertilizer are usually very small compared to the natural soil nutrient content. But the fertilizer sources may be more soluble, or positioned or timed to be more readily available to the plants.

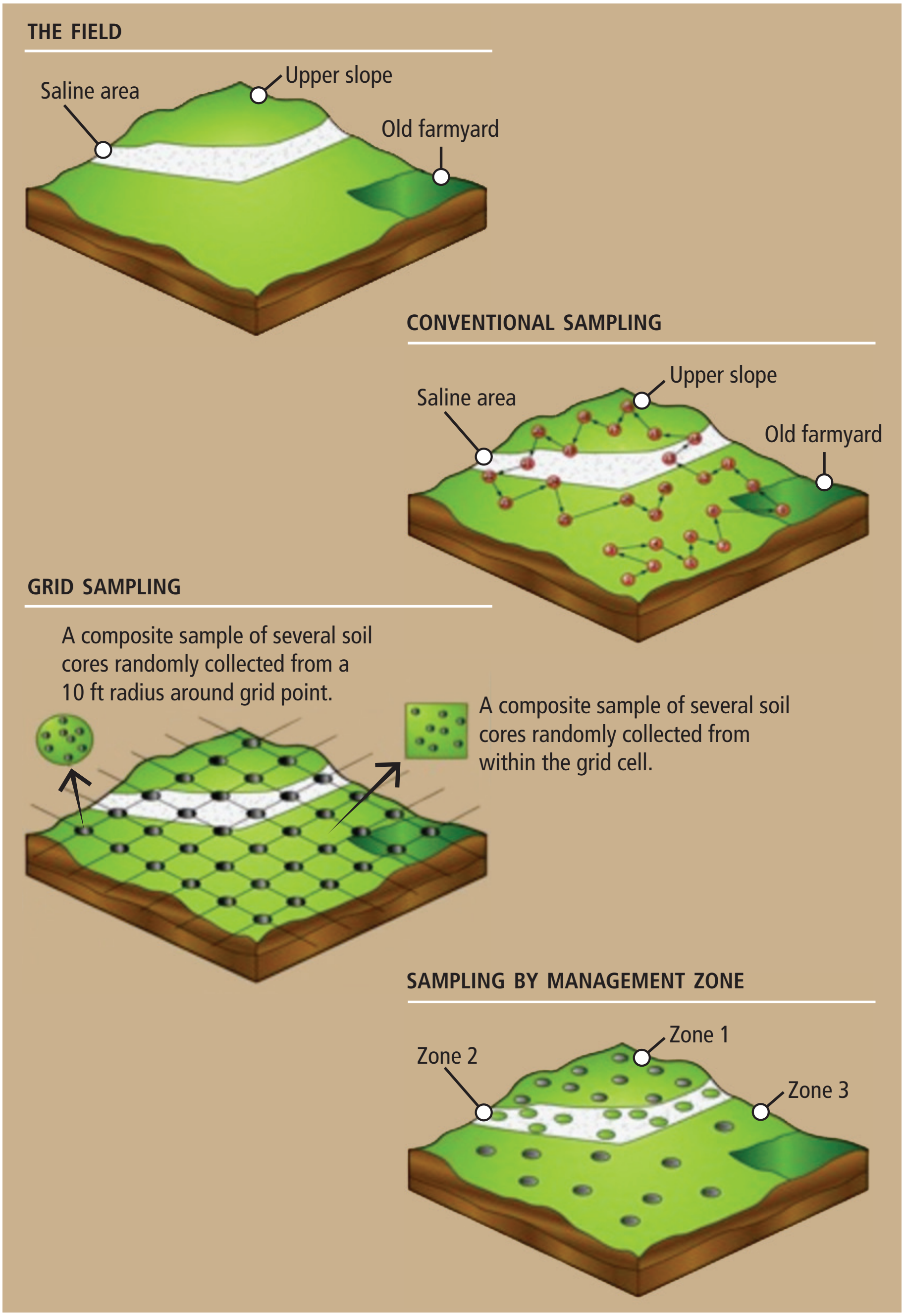
The ability of the soil to supply nutrients to plants involves more than just the content of that nutrient in the soil's chemical make-up. The interactions of the nutrients and other elements that make up the soil affect how and when those nutrients are made available to the plant. Soil texture, structure and other physical properties also influence nutrient release and availability. Most nutrients are available in the soil in much greater quantities than is needed to meet crop demand, but for various reasons they may not be readily available when needed by the crop. Soil water plays a major role in nutrient availability—either enabling nutrient release and transport or restricting it. Most nutrients move through the soil to the plant by *mass flow*, dissolved in the water that moves toward and into the plant. Some nutrients are more commonly supplied by *diffusion* of the nutrients across a concentration gradient to the plant. As the plant removes nutrients from the surrounding soil, the concentration is lowered and more nutrients move from a more concentrated supply in the soil to fill the void and attempt to equalize the concentration near the roots. An even smaller amount of nutrients may be available via *root interception* as the root physically comes into contact with the nutrients in the soil.

As the crop grows, roots tend to move downward in the soil, coming into proximity to fresh supplies of nutrients. Early in the growing season, the root system is limited and may benefit from a higher concentration of nutrients, such as is available through banded fertilizer application. As the plant grows and the root system becomes more extensive, the roots can explore a higher percentage of the soil profile and can more readily meet the plant's needs with less concentrated nutrient supplies. But even a fully-developed maize root system will physically contact only about 2% of the soil particles within the root zone, and thus will reach only about 2% of the nutrients attached to the soil particles. So most of the nutrients must be supplied by being released from the soil minerals and organic matter and moved in the soil solution (by diffusion and mass flow) to the roots.

Soil testing

Soil testing is the most common nutrient management diagnostic tool. A good soil testing program can help determine the nutrients available in the soil, the need for supplemental build-up applications, and the trends in nutrient levels over time as a result of crop removal, fertilizer addition, and other factors. It is important to understand that most soil tests are not a measurement of the nutrients in the soil, but rather an index of the soil supply. Thus the soil test numbers are only useful if linked to a set of calibration data that provides the relationship between the soil test index number and the probability of a response to added nutrients.

Scientists have developed a variety of soil test procedures to help identify the amount of nutrients in the soil and the *availability* of essential plant nutrients to growing crops. Since the actual amounts of each nutrient in the soil is substantially larger than what is available to the growing crop, the soil test must be calibrated through rate studies to develop an *index* of the plant-available nutrient supply. The calibration data are needed for different soil types and climate areas to account for responses to nutrients additions in each. The calibration data used to interpret soil tests should be derived from response data from the same soil type and climate as the field for which the recommendations are being made. Official university and government calibrations are available for general recommendations, but as we attempt to fine-tune nutrient management for specific field characteristics, it becomes important to recalibrate soil test recommendations to



THE FIELD

CONVENTIONAL SAMPLING

GRID SAMPLING

A composite sample of several soil cores randomly collected from a 10 ft radius around grid point.

A composite sample of several soil cores randomly collected from within the grid cell.

SAMPLING BY MANAGEMENT ZONE

Figure 18. Alternative soil sampling patterns for characterizing variability of soil nutrient levels in a field (IPNI).

the specific soils, climate, and management practices used on the farm. That means it becomes valuable to have local calibration data to be used in interpreting the soil test levels for a given field.

Farmers and their advisers are asking for more precision in soil testing and recommendations. The general recommendations of the past are no longer adequate. It is really not appropriate to use a “check-book balancing” approach to soil nutrients. There are many different efficiency factors that affect the availability of nutrients applied and the impact of nutrients removed. The soil has a major buffering ability that affects nutrient balance.

One of the most critical components of soil testing is to remember that *soil tests are only as good as the sample that is collected.* It is important that samples are collected carefully and systematically to best represent the area being sampled. Sample collection procedures should follow guidelines used to collect the samples used to calibrate the soil test.

Figure 18 shows some alternative recommended soil sampling patterns to use in collecting a representative set of samples for a field. A random pattern, with samples representing all of the different soil types or topographic features in the field is one approach. If variability in the field is minimal or unknown, a uniform grid (lower left) may be used. If there are known sources of variability, such as major soil type changes, significant changes in topography, or a history of specific patterns in yield variation across the field, it is more reasonable to use a zone sampling approach (lower right), defining zones by those known sources of variation. As more is learned over time, sampling patterns can be refined.

Perhaps the most critical step in soil testing is the collection of a representative sample. Samples may be collected by hand, using any tool that can produce a uniform-sized sample (top-to-bottom) and usually are collected to the depth of the tillage layer, or to the depth specified by the calibration database used by the soil testing laboratory that will analyze the samples. Alternatively, powered hydraulic samplers or various kinds may be used if the number of samples to be collected justifies such equipment. Figure 19 shows 3 types of hand sampling tools.

A standard hollow-core sampling tube helps collect a uniform-diameter core representing the soil profile to depth of sampling. The auger may be more useful in some soil conditions where a probe is difficult to use. If a spade is used, it is best to cut a narrow uniform slice from the center of the spade cut. It is recommended to collect 5

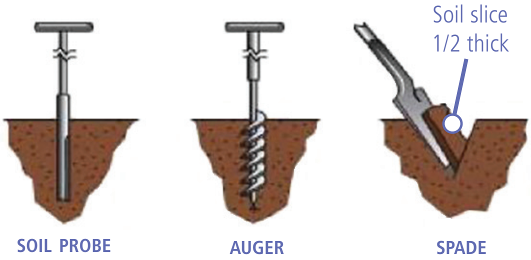


Figure 19. Three different types of soil sampling tools (IPNI).

to 10 cores from within a 3 to 5 meter radius, and mix them together for each sample point.

Care must be taken to be sure all cores are collected to the same depth. Otherwise uneven representation of the profile will result. Careful documentation of the exact location of each sample is also important. Recording GPS coordinates of each sample is an easy way to track sample points. Then all of the results of the analysis will be georeferenced, and the data may be used with GIS mapping software to develop maps of soil test variability.

Vehicle-mounted soil sampling systems

Traditionally soil sampling has been done with a hand soil probe. More recently, tractor, truck, or ATV mounted hydraulic soil probes (Figure 20) have been used to reduce labor costs and improve uniformity and efficiency.

In 2014, a new automated sampling system (Figure 21) was introduced that offers even more improvements to the soil sampling process. With one sampling probe positioned on the outer rim of the 5-foot diameter stainless steel wheel/drum, the Falcon Automatic Soil Sampler collects one core of soil every 15.5 feet as the stainless steel wheel rolls across the field. Soil is deposited inside the drum and consecutive cores are mixed as the unit continues across the field. When the desired number of cores (possibly 10) is collected, the wheel is raised and a 12 volt electric motor spins the drum to mix the soil and deposit it in a soil sample bag or box. A carousel holding 12 boxes rotates to the next position and the next series of soil cores is started. This process continues until 12 samples are completed, without ever stopping. Then the carousel is replaced and the next 12 samples are collected in the same way. On-board wireless camera display the entire operation on the operator’s computer screen, and GPS mapping guides the movement of the unit through the field. The carriage holds 12 different carousels, so that 156 total samples can be collected without leaving the field. Travelling across the field at 8 to 10 mph, the unit can collect up to 40 soil cores per minute. The stainless steel

Figure 20. Hydraulic samplers mounted on a pickup truck or ATV help to reduce the workload in collecting soil samples, especially for deep sampling (Cropsmith).

Figure 21. The Falcon automated soil sampling system included a stainless steel drum, with an attached soil probe, that collects samples as it rolls across the field, collecting samples, packaging, labeling, and cataloguing them, and transmitting sample site data to the internet "cloud" (Falcon Soil Technologies).

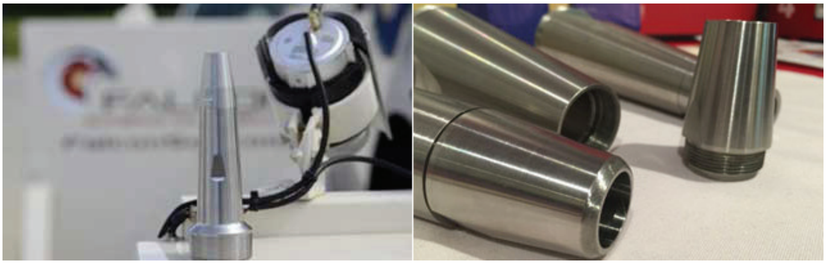


Figure 22. The interchangeable chamfered stainless steel probes (4 inches to 12 inches long) with a replaceable tip collects and deposits one soil core on each revolution of the stainless steel drum (Falcon Soil Technologies).

sampling probe (Figure 22) is chamfered inside and out, so that the soil slips easily from the probe into the drum. Interchangeable probes ranging from 4 inches to 12 inches in length can be selected depending upon the desired sampling depth.

Plant analysis

Soil testing is often the best approach to determining the availability—and the fertilizer requirement—of macro-nutrients (N, P, K), but soil test for micronutrients are not as effective as a diagnostic tool. Plant analysis is usually a better indicator of micronutrient availability and needs. Calibration data for micronutrient plant tests are usually based upon specific sampling times, commonly during active growth periods near anthesis. For some micronutrients, specific sampling periods are recommended for collection of most recently fully developed leaves.

Real-time assessment of nutrient status

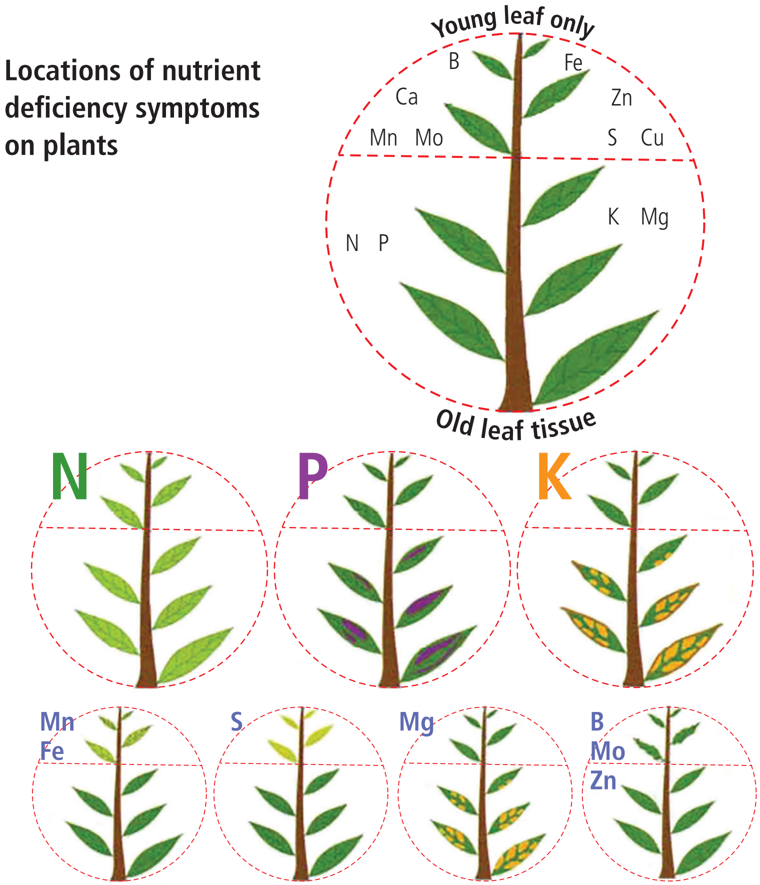
In order to manage nutrients and to be able to take immediate action to correct deficiencies during the growing season, it is helpful if a quick and inexpensive means of determining nutrient deficiencies in the field is available. Visual observation through regular field scouting is perhaps the best approach. Knowing the normal visual characteristics (color, developmental stages, and morphology) of healthy plants and the ability to identify abnormalities is step one. It is very effective and inexpensive, and can be used in broad-acre high-tech production systems as well as small-plots systems managed manually. Various visual aids are available to help identify specific nutrient deficiencies for individual crops or for plants in general. Some examples follow.

Anyone working with plant nutrition should learn to know the basic nutrient deficiencies for common crops. The deficiencies often are caused by failure of a particular plant function that is affected and location reflects whether the nutrient is mobile in the plant (translocated from older to younger plant tissues) or immobile (not translocated). Of course the nutrient's role in the plant will determine if visual symptoms are possible as a diagnostic tool. Figure 23 shows a general diagram of common coloration and location of symptoms for various plant nutrient deficiencies; fortunately coloration of deficiency symptoms is often similar for different plants.

Figure 24 shows images of different nutrient deficiency symptoms and other leaf abnormalities in maize (corn). The colors and patterns of the symptoms can be helpful in diagnosing these problems during the growing season. It is always helpful to confirm the diagnosis with plant analysis and soil tests.

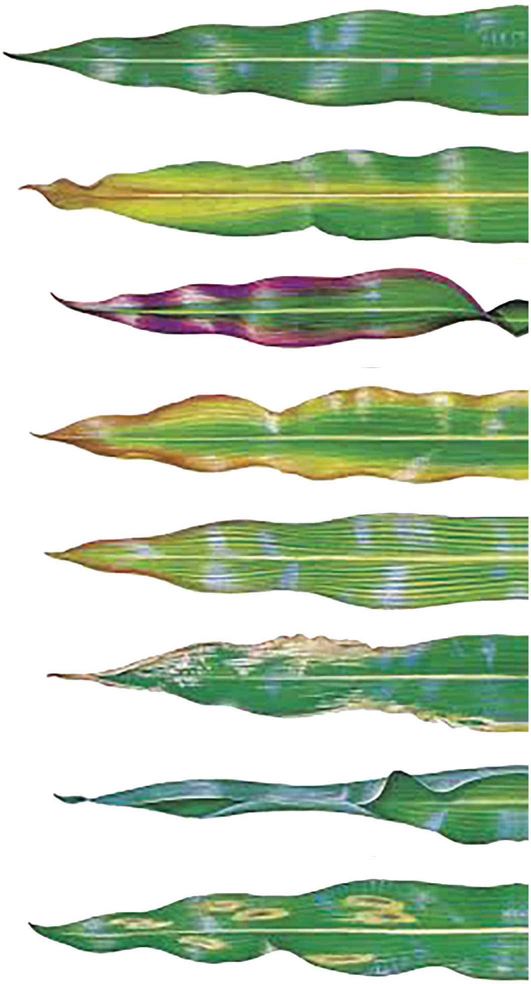
The International Rice Research Institute and other cooperators have developed a leaf color chart (LCC) for N management in rice (Figure 25). The LCC is an inexpensive and simple tool to monitor leaf greenness and guide the application of fertilizer N to maintain optimal leaf N content. Leaf color charts with four or six panels, ranging in color from yellowish green to dark green, have been developed and promoted across Asia. A big advantage of the LCC is that it is inexpensive and easy to understand and use. The LCC can be used to determine the relative rate of N fertilizer needed by the rice, wheat and maize crops; or it can be used to determine the timing for N fertilizer application.

Rice requires sufficient N during the tillering stage to ensure a sufficient number of panicles and then at panicle initiation to ensure enough filled spikelets per panicle to achieve the target yield. Inbred rice normally does not require fertilizer N at heading when N application at panicle initiation was adequate. Hybrid rice in high-yielding seasons can require fertilizer N application at early heading when leaf color is yellowish green. The leaf N content of rice is closely related to photosynthetic rate and biomass production, and can serve as an indicator of N status of the crop during the growing season. Leaf N content is reflected in the relative greenness of a rice leaf. Dark green leaves indicate enough N, whereas yellowish leaves indicate N deficiency. Therefore, the LCC is being successfully used to guide fertilizer applications to rice, particularly in several Asian countries. In rice, either a prescribed amount of fertilizer N (generally



Nutrient	Location of symptoms	Chlorosis?	Leaf margin necrosis?	Leaf color, shape
N	All leaves	Yes	No	Yellowing of leaves, leaf veins
P	Older leaves	No	No	Purplish patches
K	Older leaves	Yes	Yes	Yellow patches
Mg	Older leaves	Yes	No	Yellow patches (in oil palm) or interveinal chlorosis (in rice and maize)
S	Young leaves	Yes	No	Yellow patches
Mn, Fe	Young leaves	Yes	No	Interveinal chlorosis
B, Zn, Mo	Young leaves	–	–	Deformed leaves

Figure 23. Diagrammatic representation of common important nutrient deficiencies in plants (Canpotex Planters' Diary 2010).



Healthy leaves are dark green in color. High levels of chlorophyll are essential for trapping the sun's energy and producing sugars for growth and development.

Yellowing that starts at tip and spreads along the middle of the leaf indicates nitrogen deficiency.

Reddish-purple marks (particularly on young plants) indicate phosphorus deficiency.

'Firing' or drying along tips and edges of lowest leaves indicate potassium deficiency.

Whitish stripes along the veins and often purplish undersides of lower leaves indicate magnesium deficiency.

Burned tips and edges, and whitecap leaves may be caused by herbicide damage.

Grayish-green color and laeves rolling up to the size of a pencil indicate drought stress.

Small spots that gradually spread acroos the leaf indicate diseases such as helminthosporium blight.

Figure 24. Some common nutrient deficiency and injury symptoms for maize leaves. (IPNI (Original artwork by Maynard Reece, 1954, Curtis Publishing Company) From "Be Your Own Corn Doctor" Revised by H. F. Reetz, IPNI)

25 to 30 kg N/ha) is applied whenever the color of rice leaves falls below a critical LCC value or the LCC is used at critical growth stages to decide whether the recommended standard N rate would need to be adjusted up or down based on leaf color (Singh, 2014).

In South Asia, farmers have been recommended to use LCC to guide fertilizer N application to wheat based on leaf greenness at maximum tillering stage when adequate amounts of N have been applied at planting and crown root initiation stages of the crop. In maize, the LCC is used to manage fertilizer N starting from six-leaf (V6) stage up to

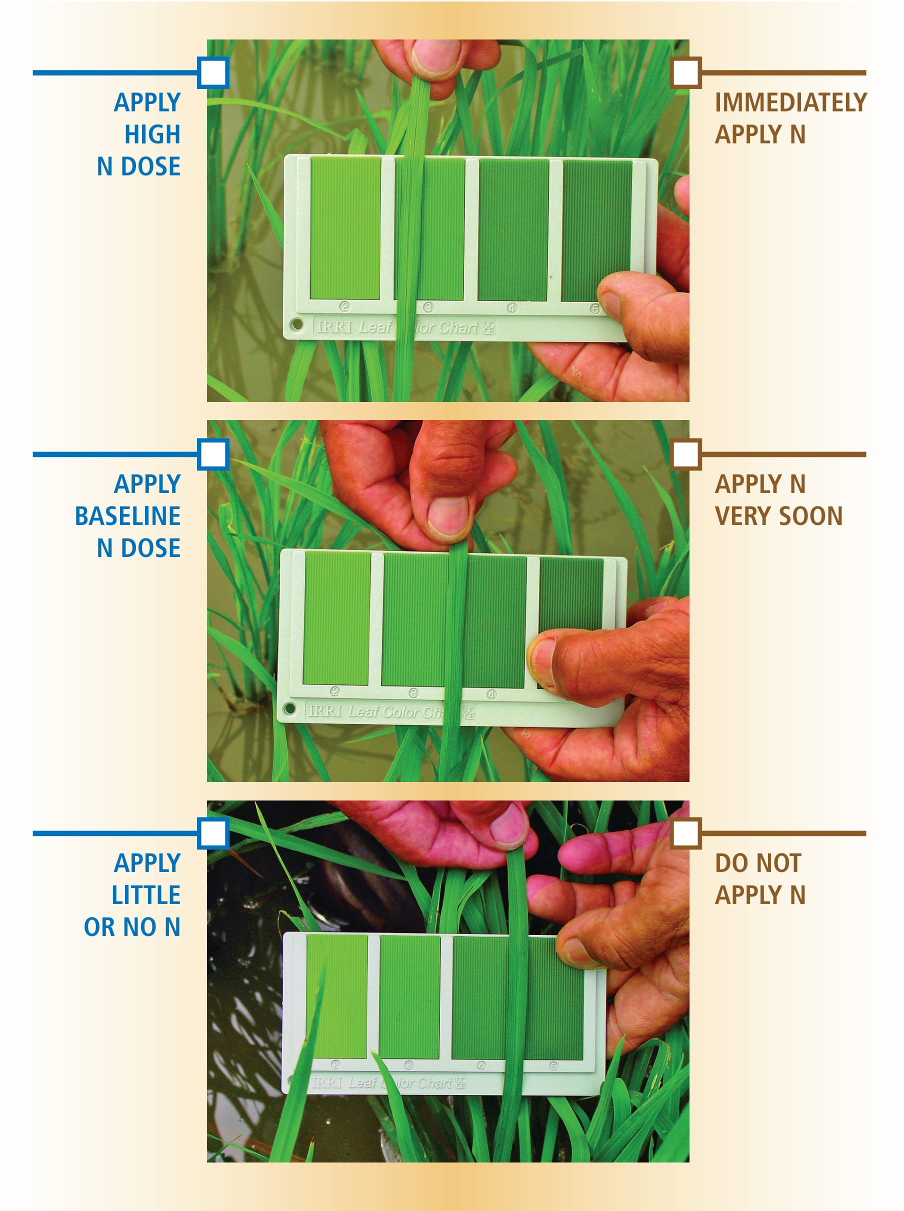


Figure 25. Nitrogen leaf color chart (LCC) for rice (IRRI).

R1 stage by applying a prescribed dose of N whenever leaf color was found to be less greenish than a threshold LCC shade (Singh, 2014).

Sensor systems

Site-specific nutrient management (SSNM) is very much a systems approach to management, involving decisions by the farmer and all of his input suppliers and advisers, each contributing his experience and training to the process. Extension workers, crop advisors, and farmers require easy-to-use tools that enable rapid identification of best management practices for specific rice-growing conditions. Decision support softwares, sensor systems and the LCC are among the tools that now help farmers pursue and determine best management practices based on SSNM.

New technologies are making various types of sensors available for determining status of some nutrients. These may be hand-held sensors, in-field plant exudate monitors, or machine-mounted canopy sensors. Some experimental work with remote sensing imagery, using scanners mounted on aircraft or satellites has been done, and more recently sensors mounted on unmanned aircraft (miniature airplanes or helicopters) have been used for in-field sensing of nutrient status. All of these tools depend upon having a good spectral signature of some plant nutrient response and a good set of calibration data to use in interpretation of the imagery.

To precisely estimate leaf color, new sensor technologies have come into play in the form of a SPAD chlorophyll meter. The SPAD chlorophyll meter has been used since the 1990s by researchers and crop consultants to help estimate the N status of plants (Figure 26). It instantly measures chlorophyll content or "greenness" of plants to reduce the risk of yield-limiting deficiencies or costly over-fertilizing. The SPAD quantifies subtle changes or trends in plant health long before these are visible to the human eye. Noninvasive, non-destructive measurement is made on green plants, by simply clamping the meter over leafy tissue, and receiving an indexed chlorophyll content reading in less than 2 seconds. Thus SPAD is used to assess N needs by comparing in-field SPAD readings to university guidelines or to adequately fertilized reference strips. Research shows a strong correlation between SPAD measurements and leaf N content.

Figure 26. The SPAD chlorophyll meter is a tool for estimating "greenness" of leaves, an indicator of relative N content (Spectrum Technologies).

The SPAD meter can provide an indication of the N status of plants and then be used to manage fertilizer N in rice, wheat and maize on the lines as explained in the case of the LCC. However, unlike the LCC the SPAD mater can guide fertilizer N applications to crops when a sufficiency index (defined as SPAD value of the plot in question divided by that of a well-fertilized reference plot or strip) falls below 0.90 in rice or 0.95 in maize. This approach has the advantage that a critical SPAD value need not be worked out for different cultivars, climates or regions.

Other electronic tools that have become important for N management guidance include the GreenSeeker (Figure 27), the CropCircle, and the RapidScan CS-45 sensors. Commonly used as a single handheld unit, or mounted on a tool bar as a gang of multi-row sensors, these tools emit standard wavelength light beams and measure the reflected light coming back to the unit from the leaves. Recently, smaller handheld versions of these tools have become available.

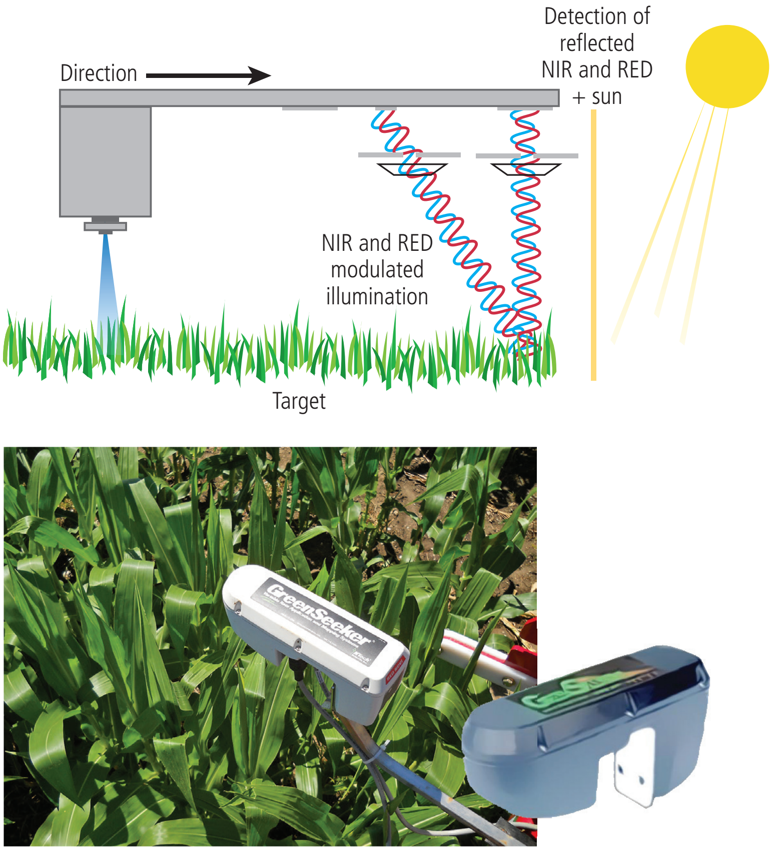


Figure 27. Photo of the system in use in the field. Diagram of the operation of the GreenSeeker on-the-go sensing system (top).

DGCI 0.560
SPAD Equivalent 33.1
End and Log Average
Picture Count 16
Average DGCI 0.565
Average SPAD Equivalent 33.5
Change N Reference from 55.0 to 33.5
N RECOMMENDATION TOOLS
Penn State Method 103 lb/ac
Iowa State Method 100 lb/ac

Figure 28. FieldScout GreenIndex + Nitrogen App and Board (Spectrum Technologies).

The GreenSeeker sensor, emits light in two wavelengths, and then measures the reflectance from the crop canopy, and computes the NDVI value (Normalized Differential Vegetation Index) that relates to the amount of plant material in the field of view and its general vigor. The NDVI value is then compared to a calibration dataset, such as an N rate comparison strip, to provide a relative indication of plant condition that can be used to predict response to additional N fertilizer. The GreenSeeker may be used as a stand-alone, hand-held system for small areas or crop scouting, or a bank of multiple sensors may be mounted on a tractor or sprayer system and used for mapping or real-time variable-rate fertilizer application.

By calibrating with standard color references and "non-limited" N reference plots, an estimate of the N status of plants can be made and used to predict potential response to added N fertilizer. This is a variation on the color chart concept, but with the added feature of potentially geo-referencing the measurement, electronically storing the information, and wirelessly transmitting the results via the mobile telephone network. As cellular phone networks spread across rural areas throughout the world, tools such as this can potentially be used to improve N management wherever crops are grown.

A less expensive technology to aid in N management is based upon leaf images collected using a mobile "smart-phone" (Android or Apple) camera and reference board (Figure 28) to scan plants in the field and assess their N status. The FieldScout GreenIndex application on the smart-phone interprets the "greenness" of the leaf, which can be used with calibration data to estimate N status of the plant. Recommendations for whether additional N fertilizer would be beneficial can then be made from the results.

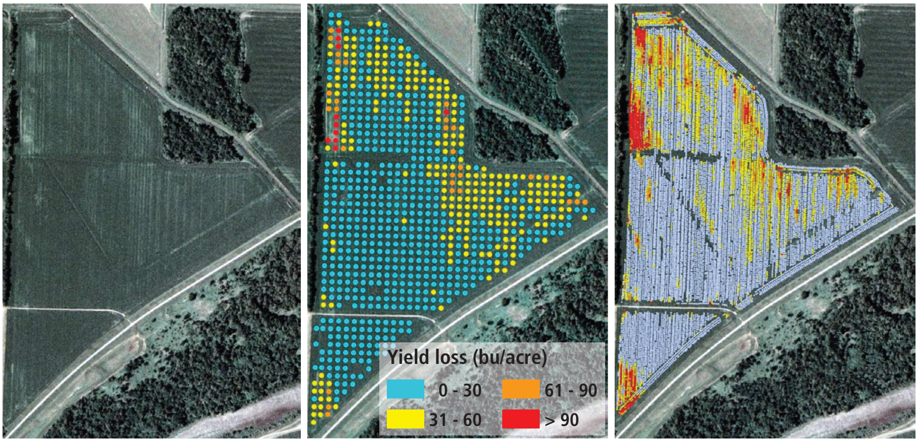
With the GreenIndex system, a leaf is placed over the reference board, and photographed with a smart-phone. An area of the leaf photo is selected to compare with the reference colors. Then the images are processed by the phone software application, and results are presented based upon the recommendation algorithms stored in the smart-phone application. It is a very quick and simple procedure. Calibrations and recommendations can be developed for different crops and recommendation databases.

Remote sensing

In addition to in-field sensors to monitor crops, there are also *remote sensing* systems that use airplanes, satellites, and various kinds of drones to monitor crop conditions. Shown in Figure 29, aerial imagery is being used to assess N status variability in areas of the US Corn Belt. Color and infrared aerial photography is used to photograph fields at critical growth stages for N deficiency. The photos are then analyzed to determine areas which appear to be N-deficient. The photos geo-referenced along with soil maps, yield maps, and other information can be analyzed with GIS tools to determine possible points for additional scouting, sampling, or for N application.

Nitrogen stress shows up in aerial photographs as higher reflectance in the green and red (and sometimes blue) wavelengths. Excessive rainfall can cause loss of fertilizer and soil N, resulting in N deficiency. In Figure 29 showing photograph of maize at a late vegetative

PREDICTING YIELD LOSS: AN EXEMPLE



June 24 aerial photo

Yield loss map predicted from June 24 aerial photo

Yield loss map based on yield monitor data (September 30)

Figure 29. Processed image based upon aerial photography compared to yield monitor map at harvest, showing that N deficient areas identified in the early season aerial photograph accurately predicted yield losses (Images provided by Peter Scharf, University of Missouri).

stage, excessive rain caused N deficiency in the wetter regions of the field, which are visible as lighter-colored areas. The width of the narrower streaks visible in the photo correspond to the width of the anhydrous ammonia applicator used in this field, confirming that light-colored areas are due to N deficiency and suggesting problems with uneven N fertilizer application. A quantitative relationship between relative greenness and yield loss is used to convert the aerial photograph into the yield loss map shown in the middle frame. This information about yield loss could be used to assess the economic impact of N deficiency, in support of a decision about whether to apply additional N fertilizer. The figure on the right shows yield loss (relative to the yield of the darkest areas in the aerial photograph) estimates derived from yield monitor data. The level of agreement between the predicted and observed yield loss maps suggests that remote sensing of N stress can provide a sound basis for making decisions about rescue N applications. Missing points in the predicted yield loss map are due to low certainty of canopy cover based on spectral properties.

Satellite-based systems

Satellite-based remote sensing has been studied since the 1970s as a potential tool to aid in crop management. It has the advantage of being able to cover large areas rapidly. It has several disadvantages that have kept it from being widely useful. The “revisiting” schedule for any point on Earth was too long, especially when cloud cover prevented images from being collected in many cases. Turnaround time between imagery collection and availability of processed data was too long for use in short-term management decisions. The whole process was too expensive compared to the potential benefits of the data for management decisions. Steady improvements in satellite imaging technology, and an increase in the number, spectral pattern, and resolution of the satellites available have renewed interest in how satellite-based remote sensing can be used as a diagnostic and management tool. Several companies are exploring and developing the commercial potential of such systems. Satellites have the advantage of being able to cover large geographies very quickly, and images can be analyzed to sort out specific spectral signatures, which in turn can be correlated to ground truth observations of crop identification, land-area showing that specific signature, and field observations to link to this information.

Sensing and communication tools are opening new possibilities for real-time monitoring and interpretation of plant nutrient status. Some of the technology is limited to large-area, intensively managed production systems. But an increasing amount of the technology is equally applicable to small-farm and economically stressed farming systems and provides modern tools that can benefit all farmers throughout the world.

Mapping soil EC in agricultural fields

One of the important considerations in developing a nutrient management plan for a field is to understand the within-field variability in the soil. Soil tests along with soil survey and topography maps are important tools to help define variability. Determining soil variability in agricultural fields can be guided through measurement of electrical conductivity (EC) (Figure 30) at different soil depths, which is affected by variation in several soil properties of importance to nutrient management. Mapping of soil EC requires a field vehicle that is equipped with both a GPS receiver and an EC measuring device. Ideally, the vehicle should be equipped with a differentially corrected GPS receiver. The vehicle traverses the field in a series of closely-spaced passes, collecting input from both devices. It is recommended to set up the GPS receiver to collect data at one-second intervals. EC measurements provide much greater detail in variability than most other measurements that are made. Typically, EC readings are collected at about 125 data points per hectare. This results in a much denser data set than is feasible with

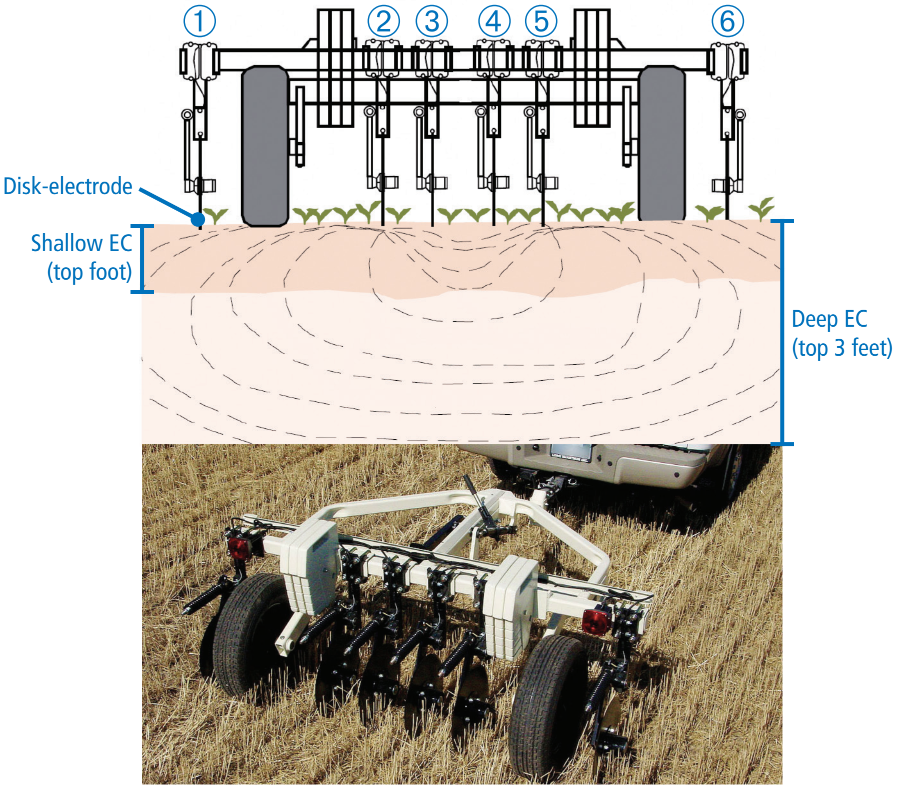


Figure 30. Sampling cart for taking electrical conductivity soil samples (Veris Technologies).

grid soil sampling (usually one sample per hectare), producing a type of soil map with much greater resolution than is possible with a typical nutrient soil test map. Mapping at this density will identify soil inclusions that are 0.1 ha in size or larger.

Interpreting soil EC maps

Soil EC has no direct effect on crop growth or yield. The utility of EC mapping comes from the relationships that frequently exist between EC and a variety of other soil properties highly related to crop productivity. These include such properties as water holding capacity, topsoil depth, cation exchange capacity (CEC), soil drainage, percent organic matter, soil nutrient levels, salinity, and subsoil characteristics. With adequate field checking or field calibration, soil EC can be used as a substitute way to measure soil properties that affect crop yield. In general, the correlation between soil EC and yield will be the greatest when yields are primarily influenced by the soil's available water holding capacity. The patterns of soil EC within a field do not tend to change significantly over

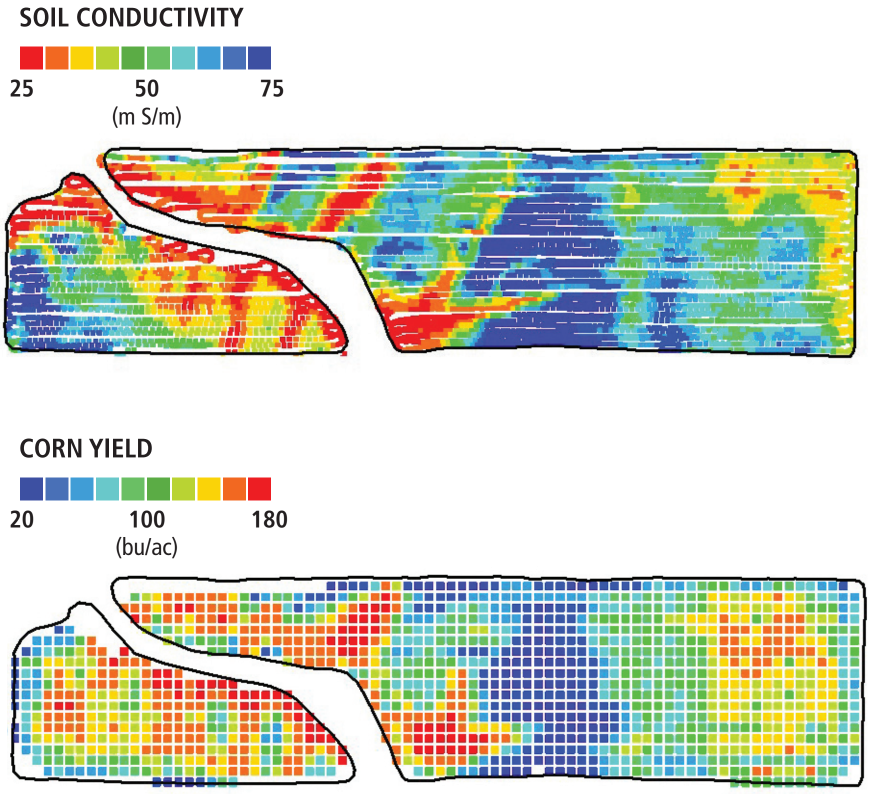


Figure 31. Comparison of a soil electronic conductivity map and a maize yield map, showing that EC variability is a good predictor of yield variability (Newell Kitchen, USDA ARS, University of Missouri).

time. Generally, once an EC map has been made, it will remain relatively accurate unless significant soil movement occurs such as with land leveling, terrace construction, or some type of natural occurrence. Seasonal variations in EC values can occur due to phenomena such as changes in temperature, soil water content, or vertical movement of salts in the soil profile. Most of these changes are temporary, however, although long term changes in EC values may occur if salts are added to the profile via irrigation water or an increase in size of saline seep discharge areas. There are many ways to visually present soil EC data in map form. One convenient way is to divide or classify the data into five value ranges that contain about the same number of points in each range (equal count). This will effectively differentiate between soils with distinctly different textural, organic matter and drainage properties.

The simplest way to interpret a soil EC map is to visually compare it to yield or soil survey maps from the same field, as illustrated in Figure 31.

Average EC values from grid cells can be compared to the yield values from the corresponding cells using linear regression and other statistical techniques. Statistical methods such as these can help to determine the level of correlation between EC values and other parameters such as yield or a soil property. The EC results can also be correlated to other quantitative site properties that have been measured and mapped using a similar sized grid system. These site properties include elevation, plant population, surface curvature, or remotely sensed soil and crop canopy images. A note of caution: Comparing two spatial data layers that were measured at a much different resolution from each other can lead to erroneous correlations.

Influence of soil microbiology on management of plant nutrients

The soil and plant system is very dynamic. In addition to the chemical aspects, there is a complex biological system associated with nutrients that is normally overlooked in most nutrient management planning. Figure 32 illustrates the complex biological system associated with plant nutrition. The interactions of the plant root, soil mineral and organic particles, and the various kinds of micro-organisms (bacteria, fungi, protozoa, etc.) all play a role in determining the availability of nutrients from the soil to the plant.

The symbiotic relationship of rhizobium species with leguminous plants is the most common plant/microbe system that affects N management because it converts atmospheric N into plant available N. But the total soil-plant-microbe system is much more complex. Many aspects have not been fully studied. This is at least partly due to the lack of a significant economic engine to support the research, reproduction or mass production and marketing of any products associated with microbes.

As fine-tuning of the dynamic soil-plant nutrition system continues, more economic benefits of some microbial interactions may be identified, and potential for managing some of these may be developed. This could open new aspects of plant nutrition in coming years. Some of the areas to be explored in detail include:

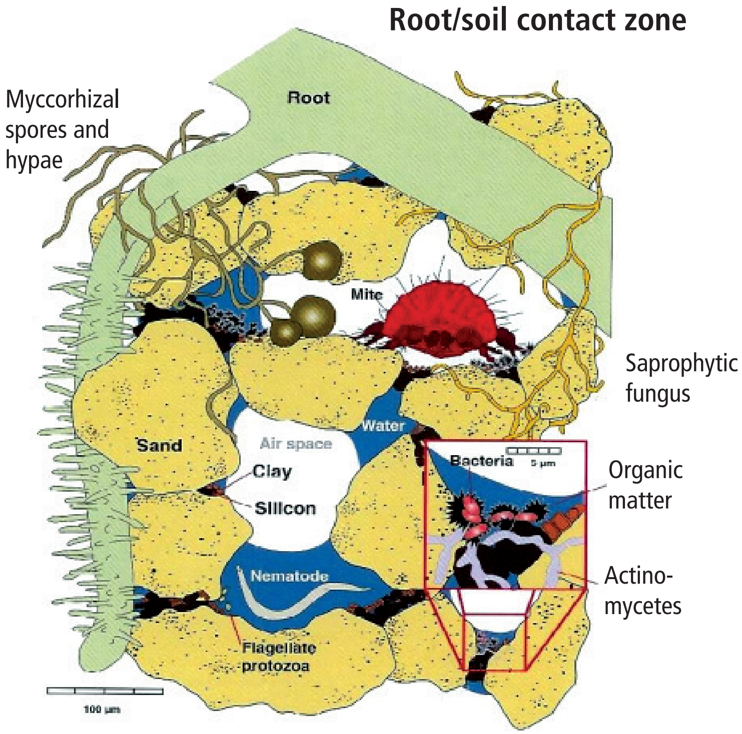


Figure 32. Microbial life in the root/soil contact zone. (Principles and Applications of Soil Microbiology (2nd Edition), Prentice Hall, 2004)

- How does the presence and amount of crop residue in the “off-season” affect microbe species and populations?
- How does presence and type of cover crops affect microbe species and populations during the fallow season?
- Which nutrients are affected by microbial activity and how?
- How does fertilizer application and timing influence microbial species and populations?

Detailed discussion of the role of soil microbiology in nutrient management is beyond the scope of this book, but its importance in future works and applications in management systems must be noted. Soil microbiology no doubt holds the keys to unlocking some of the important new opportunities to enhancing nutrient management and crop production.

Integrated plant nutrient management (IPNM)

The use of organic manures as source of nutrients dates back to the beginning of settled agriculture but after the introduction of widespread use of mineral fertilizers, organic manures were thought of as a secondary source of nutrients. However, with increasing awareness about soil health and sustainability in agriculture, organic manures and many diverse organic materials, have gained importance as components of integrated plant nutrient management (IPNM) strategies. The basic concept underlying IPNM is the maintenance and possible improvement of fertility and health of the soil for sustained crop productivity on long-term basis and use fertilizer nutrients as supplement to nutrients supplied by different organic sources available at the farm to meet the nutrient requirement of the crops to achieve a defined yield goal.

As Alley and Vanlauwe described in detail in *"The Role of Fertilizers in Integrated Plant Nutrient Management"*, IPNM concentrates on a holistic approach to optimizing plant nutrient supply. It includes the following considerations:

- Assessing residual soil nutrient supplies, as well as acidity and salinity;
- Determining soil productivity potential for various crops through assessment of soil physical properties with specific attention to available water holding capacity and rooting depth;
- Calculating crop nutrient requirements for the specific site and yield objective;
- Quantifying nutrient value of on-farm resources such as manures and crop residues;
- Calculating supplemental nutrient needs (total nutrient needs minus on-farm available nutrients) that must be met with "off-farm" nutrient sources;
- Developing a program to optimize nutrient utilization through selection of appropriate nutrient sources, application timings and placement.

The overall objective of IPNM is to adequately nourish the crop as efficiently as possible, while minimizing potentially adverse impacts on the environment. The trend globally is to find a balance of nutrient sources that takes advantage of the recycling of nutrients in manures and crop residues, supplementing them with commercial fertilizers. If this requires processing and transportation of the organic sources, those expenses must be considered. But it is also important to consider the costs and environmental consequences of not finding a way to utilize the organic materials. Recycling of available organic nutrient sources should be included in the nutrient planning whenever it is practical.

IPNM is part of the wider concept of Integrated soil fertility management (ISFM). Full implementation of ISFM includes proper attention to not only nutrient sources, but also other factors such as weed and insect control, selecting the appropriate crop varieties, and adapting to local conditions and seasonal weather events. The resources available to the farmer, government policies, and market conditions are also a part of the decision process in full ISFM implementation. The goal of ISFM is to maximize the interactions that result from the potent combination of fertilizers, organic inputs, improved germplasm, and farmer knowledge. The ultimate outcome is improved productivity, enhanced soil quality, and a more sustainable system through wiser farm investments and field practices with consequent minimal impacts of increased input use on the environment. Since the beginning of the 21st century, the ISFM concept has used fertilizer as the main entry point for nutrient management, but has integrated the use of available organic sources. This has led to improvement of agronomic efficiency in nutrient use and productivity of all types of soils. The IPNM and ISFM approaches are holistic and seek to optimize plant nutrient supply with an overall objective of adequately nourishing the crop as efficiently as possible, and improve and maintain the health of the soil base while minimizing potentially adverse impacts to the environment.

Successful implementation of IPNM requires a team effort among all stakeholders:

- *Policy makers* are needed to provide funding for research and extension activities and support for training, research, data management, and advisory activities.
- *Research institutions* provide the local science to adapt practices, develop tools for implementing and monitoring results, analyze and interpret data collected, and provide educational programs to improve the decision process.
- *Extension and agribusiness* dealers are the front-line contact with the farmers and help provide guidance and answer questions about adapting technology and practices to the local conditions and culture.
- *Fertilizer manufacturers* play an important role in supplying the right products for each area in sufficient quantities and at the right time. They support local research and training for local input suppliers, advisers, and farmers.
- *Farmers* may be the most important members of the team. They make the final decisions and take the final steps to implement IPNM, assess the final result, and reap the rewards of successful IPNM implementation.

4R Nutrient Stewardship for fertilizer management

There are four management objectives associated with any practical farm level operation, including management of fertilizers. These are productivity, profitability, cropping system sustainability, and a favourable biophysical and social environment. Best management practices for fertilizer support the realization of these objectives in terms of cropping and the environmental health. A strong set of scientific principles guiding the development and implementation of fertilizer best management practices (FBMPs) has evolved from a long history of agronomic and soil fertility research. When seen as part of the global framework, the most appropriate set of FBMPs can only be identified at the local level where the full context of each practice is known.

Through cooperative efforts of the International Plant Nutrition Institute (IPNI), The Fertilizer Institute (TFI), Fertilizer Canada, and the International Fertilizer Industry Association (IFA), along with their members and other organizations, a *Global Framework for Fertilizer Management* has been developed and is being adopted to guide nutrient stewardship. While this system has not yet been adopted in all parts of the world, it provides a good outline of the interactions of the scientific, economic, and social aspects of nutrient management. Described as "*4R Nutrient Stewardship*" (Table 4), it provides a framework to achieve cropping system goals of increased production, increased farmer profitability, enhanced environmental protection, and improved sustainability. It is presented here to provide a complete life cycle perspective of nutrient management, including the economic factors, the environmental consequences of nutrient management practices, and considers the social implications of different practices.

Table 4. Components of the 4R Nutrient Stewardship system.

Component	Goal
Right source	Provide plant-available forms, and a balanced supply of all essential nutrients. Take advantage of various formulations that offer improved efficiency and reduce environmental consequences.
Right rate	Ensure an adequate supply of all essential nutrients to meet plant demand.
Right time	Manage nutrient applications to match the interactions of crop uptake, soil supply, environmental risks, and field operation logistics.
Right place	Consider root-soil dynamics and nutrient movement, and manage spatial variability within the field to meet site-specific crop needs and minimize potential losses from the field.

This system is often illustrated as in Figure 33, showing the importance of considering environmental, economic, and social concerns in developing a complete nutrient management program.

The 4R Nutrient Stewardship requires the implementation of FBMPs that optimize the efficiency of fertilizer use. The goal of FBMPs is to match nutrient supply with crop requirements and to minimize nutrient losses from fields. Selection of FBMPs varies by location, and those chosen for a given farm are dependent on local soil and climatic conditions, crop management conditions and other site-specific factors.

For each of the 4R components, a series of performance indicators related to the economic, environmental and social goals have been identified to serve as measures of performance. These are represented around the Global Framework illustrated in Figure 34.

The Global Framework for 4R Nutrient Management provides a nutrient stewardship plan for implementing best management practices. The framework relates to individual practices and their interactions for nutrient management in a cropping system. The selected FBMPs are most effective when applied with other agronomic and conservation

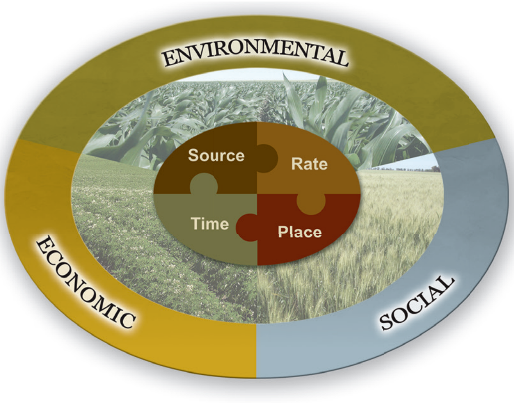


Figure 33. The Global Framework for 4R Nutrient Stewardship. The concept is centered on the interlocking 4Rs, which are determined by the economic, social and environmental goals related to nutrient management (IPNI, 2012).

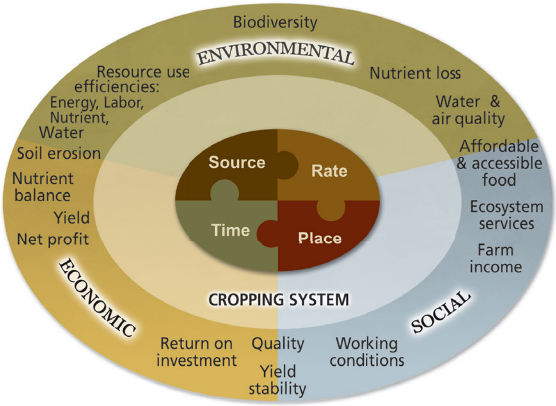


Figure 34. Performance indicators reflect the social, economic, and environmental aspects of the performance of the plant-soil-climate system. Their selection and priority depends on stakeholder values (IPNI, 2012).

practices, as a part of a complete system of crop management. Poorly managed nutrient applications can decrease profitability and increase nutrient losses, potentially degrading water and air. Due to multiple interactions of factors, it is essential that the entire system be considered when making management adjustments.

Performance measures and indicators will often include crop yields and sufficient information to calculate economic returns. In addition, they will need to reflect environmental and social performance. Those chosen may vary depending on stakeholder priorities, but will often include either nutrient balances or nutrient use efficiencies.

Following are a few examples of 4R FBMPs for nutrient management to illustrate how the "system" fits together.

Right source

The right source for a nutrient management system must provide a balanced supply of all essential nutrient elements in plant-available forms. The right source must also consider any nutrient interactions or compatibility issues, potential sensitivity of crops to the source, and any non-nutrient elements included with the source material. The right source may vary with the crop, the soil properties of the field, and options for method of application. Sources of nutrients were described earlier. In addition, several additives and treatments for nutrients are available to provide modifications in availability of the nutrients. These include fertilizer products of various kinds that slow chemical conversions, encapsulate fertilizer materials in some kind of protective coating (Figure 35), or in other ways modify the rate or release of the nutrients from the fertilizer materials.

Several different options are available for slow- and controlled-release fertilizer materials. For example, the urea granule in Figure 35 is coated with sulphur, and surrounded with a polymer sealant. This coating allows water to slowly enter the granule and dissolve the urea. Then the urea slowly moves through the coating to the

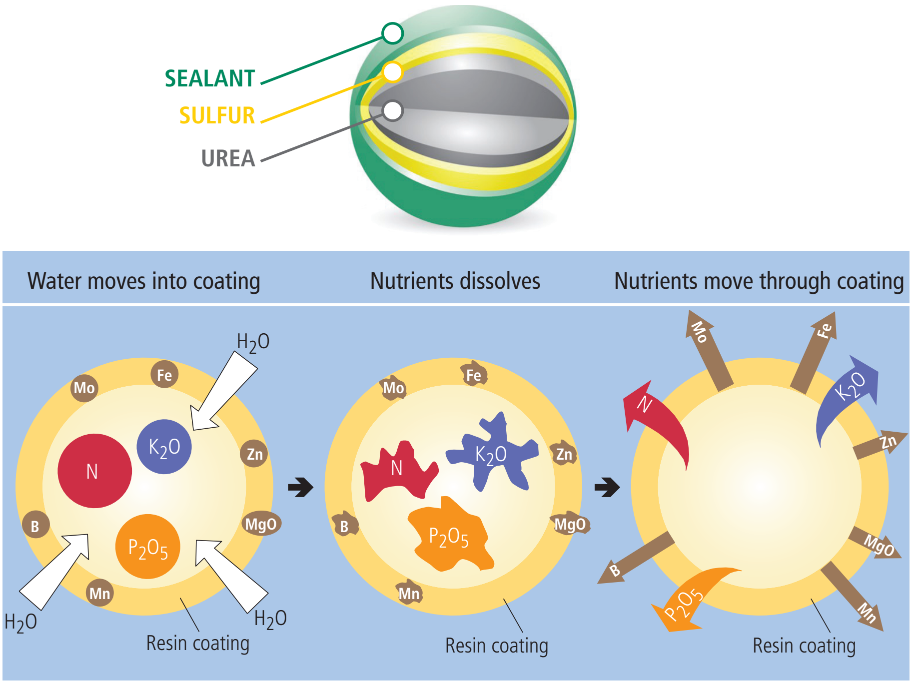


Figure 35. Example of one type of controlled-release fertilizer granule and its mechanism of nutrient release (Agrium Advanced Technologies).

soil solution where it is available to the plant roots. The nature and thickness of the coating can be adjusted to regulate the rate of release of the nutrients as desired. While this formulation adds to the expense of the fertilizer, it also significantly adds to the farmer's ability to manage the timing and rate of nutrient release, for better management of nutrient availability to the crop and also help control losses to the environment.

A nutrient management system may also include the use of organic nutrient sources, such as manure and sludge. These materials often contribute to increase in soil acidity and usually require chemical or biological degradation in order to release the nutrients for crop use.

Right rate

The right rate considers the supplying power of the soil in relation to the nutrient requirement of the crop. Soil testing and plant analysis are important tools to help with such decisions. Understanding of the nutrient needs of the crop is a first step to providing the right rate. Plants require different rates of different nutrients at different stages of the growing season. Rate should be adjusted to help balance nutrient supply with crop removal at all times to avoid deficiency stress and economic loss. Excessive rates may lead to inefficiency in nutrient use and economic losses and environmental problems. In some cases excess nutrients may also result in toxicity to the crop (Figure 36).

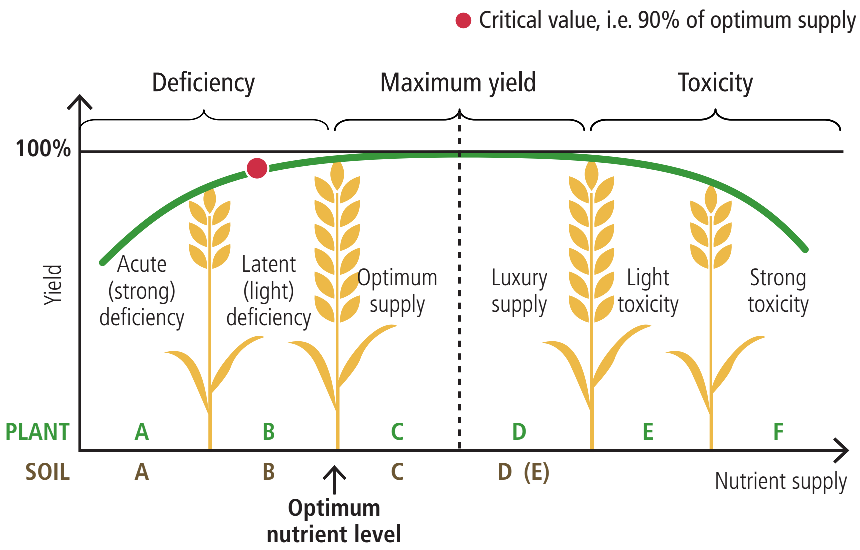


Figure 36. Effects of rate on wheat, showing potential deficiency and toxicity effects of not applying the right rate of nutrients.

The right rate should take into account all sources of nutrients, including soil supply (soil test), manure and other organic sources, crop residues, irrigation water, atmospheric deposition, etc. Rate comparison studies are an important part of determining the right rate. Rate studies are best done under the conditions for which the rate decision is being made, preferably on-farm rate studies. With precision farming technologies, such as GIS-referenced soil testing, variable-rate fertilizer application, and harvest with yield monitors, on-farm rate studies can be easily done and can guide site-specific, variable-rate fertilizer application to provide the most efficient and most profitable fertilizer nutrient management system, applying different rates of fertilizer on different areas within an individual field.

Right time

Crop nutrient requirements change throughout the growing season as the crop grows from vegetative stages, through reproductive stages, and on to maturity. The slow- and controlled-release and enhanced efficiency fertilizer products and additives help to provide a broader choice of options for timing the nutrient availability to crop requirements, and thus options for the time and method of application.

One of many examples of timing fertilizer applications based on stage of crop growth and nutrient needs is *split-application of N*. An increasingly popular system for applying N to maize in the US is to divide the application into 2 or 3 different times, and often different application methods and fertilizer sources. For example, a small amount of N may be surface applied as UAN solution in the fall to stimulate soil micro-organisms and help support decomposition of previous crop residues. A second, pre-plant, application using banded anhydrous ammonia or UAN solution may then provide the majority of the N requirement, followed by a supplemental side-dress or top-dress application to fine-tune the total N program based on in-season monitoring, or predetermined total N rate plans. By saving some for a final application after emergence, allows for a more informed final decision on total application rate, reduces potential for loss to the environment, and take advantage of available precision technologies for making the final application. Some farmers may even make a final top-dress N application of urea even later in the season if additional N need is indicated.

The maize crop has a very high N requirement at the stage when the stalk starts to elongate (about V8 growth stage), as show in Figure 37. After pollination, the effectiveness of the roots to take up N begins to decline, so it is important to have most of the total N requirement met and taken up by the plant at that time. Much of the N needed for the developing grain is provided by remobilizing N from lower leaves and stalk. Farmers and their advisers can benefit with a clear understanding of crop growth stages, and the timing of crop nutrient requirements, as they make plans for fertilizer application for most efficient nutrient utilization. Applying N fertilizer as close as possible to the time of uptake will help avoid losses to the environment and increase N use efficiency. Crop size, logistics of getting the fertilizer applied at the ideal time, and weather conditions often force application to be made at other less-than-ideal times.

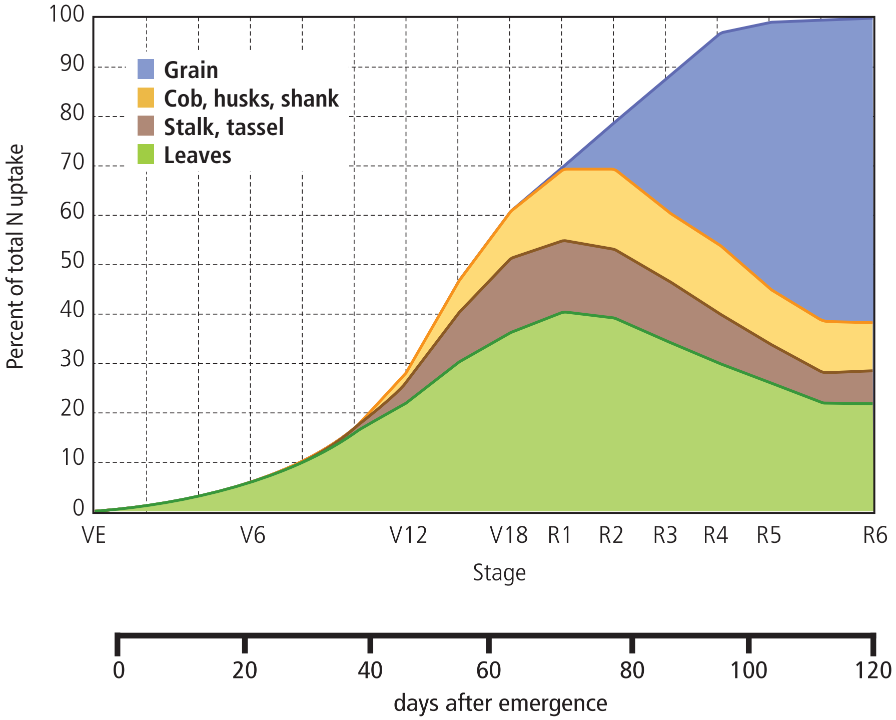


Figure 37. Nitrogen uptake by the corn crop at different growth stages and region of accumulation within the plant (adapted from "How a Corn Plant Develops", Iowa State University Extension Special Publication #48).

Right place

Having the nutrients in the right place helps to ensure that plant roots can absorb enough of each nutrient at all times during the growing season.

For placement with respect to the seed row and growing plant roots, there exist several options:

- Surface broadcast or band application
- Starter fertilizer application with the traditional 5 cm x 5 cm placement
- Deeper banding (usually 10 to 15 cm below the surface, providing a concentrated nutrient source lower in the root zone).

Strip-till systems are also becoming popular in some regions. A narrow strip (about 1/3 of the surface) is tilled and nutrients are concentrated in a band below the surface, maintaining a predominantly untilled surface residue environment to help reduce erosion and conserve soil moisture.

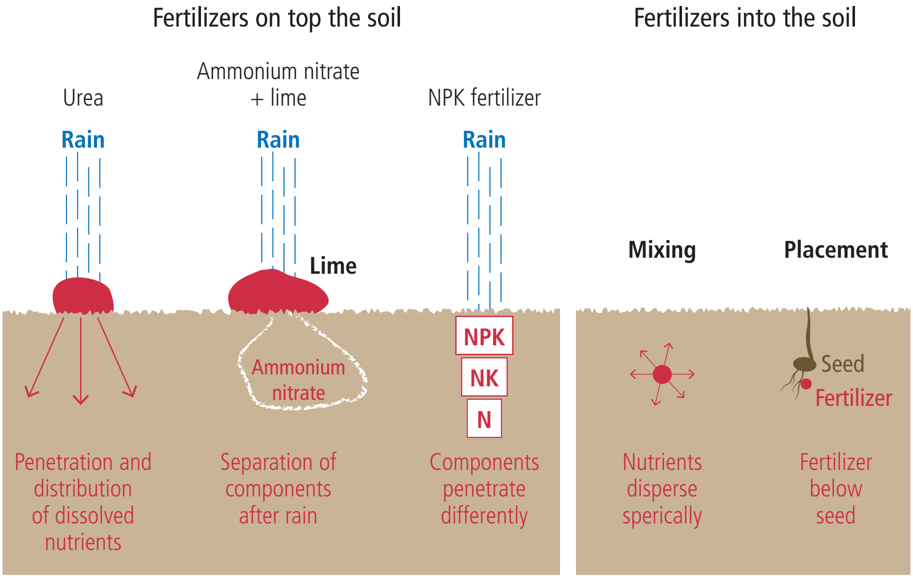


Figure 38. Diagram showing the impact of different fertilizer placement practices for movement of nutrients into the soil (adapted from IFA, 1992).

The right place also depends upon the characteristics of the fertilizer material being applied (Figure 38).

Anhydrous ammonia, for example must be injected into the soil deep enough to seal the gas from being lost to the atmosphere. Fertilizers applied to the soil surface are subject to potential losses in surface runoff. Other materials, such as urea or UAN solution, may be surface applied, but volatilization losses can be substantial without sufficient rainfall within a few days to move the fertilizer into the soil.

Another aspect of placement is with respect to addressing spatial variation in nutrient needs within the field. With precision farming tools, variability in nutrient needs based upon soil tests and other yield potential factors can be met with variable-rate application to match fertilizer applied to varying crop needs on a site-specific basis within the field. The placement of fertilizer affects both the current crop and subsequent crops. Figure 39 illustrates the effect of different fertilizer placement systems over time.

Broadcast application over time results in a uniform distribution of nutrients, which gradually move down the soil profile deeper into the root zone. Band application in the same location over time (as in recent years, availability of precision farming technology has made it possible to fine-tune nutrient placement within a field) accounts for specific variability of soil test levels, and in relationship to the growing roots with precision guidance and placement systems. Strip-till systems are especially useful in conjunction with Real Time Kinematic (RTK) guidance systems to ensure the fertilizer band is placed in an exact relationship with

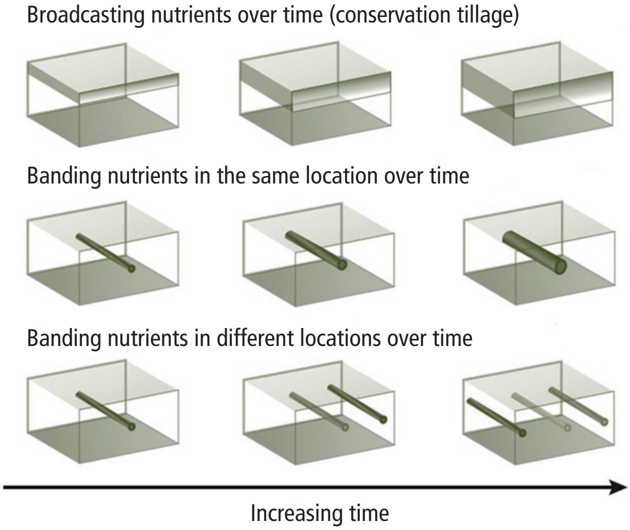


Figure 39. Volume of soil profile fertilized with different placement methods (IPNI, 2012).

the seed row, even though the fertilizer may be applied several months in advance of planting. With RTK guidance systems, farmers can apply starter fertilizer in the fall, and then plant the seeds the following spring, with the seed row accurately placed in the desired relationship with the starter fertilizer band. Thus, RTK provides accuracy in placement of fertilizer wherever it is needed, as well as providing options for timing of application with respect to the cropping season. Using a controlled traffic systems and RTK guidance, results in a fixed band that tends to expand in size over time, but stays relatively in the same place. Band application, without controlled guidance, results in multiple bands, and over time approximates the effect of broadcast application.

Precision farming and site-specific nutrient management

Applications of precision farming technology in fertilizer management

Developments in computer technology, geographic information systems (GIS), global positioning system (GPS), electronic sensors and controllers, and a wide variety of communication tools during the 1990s and into the 21st century have provided exciting new technologies that can be applied in agriculture. Under the collective term, precision farming, these technologies have opened many new opportunities for improving crop and soil management on a site-specific basis.

While initially designed and developed for broad-acre, large-scale producers in the US, West Europe and South America, precision farming has many applications that fit equally well for the small farmer. In Asia, for example, the International Rice Research Institute (IRRI) has promoted site-specific nutrient management (SSNM) since the 1990s, with some of the research dating before that. Their program has integrated research and education/outreach, using simple technologies such as a leaf color chart, to be sure the practices and information get to the farmer level. The tools may be different, but the approach is the same. Recently, a software called Nutrient Expert (NE) has been developed and introduced in several Asian countries to help crop advisors with a simpler and faster way to use SSNM. Paying attention to details and making decisions on a small area is an approach that any farmer can use, and one whose benefits can be realized regardless of farm size.

SSNM fits anywhere in the world, and often may be easier to implement on small-scale farms where each field is more carefully monitored and managed. It is not limited to large fields and large equipment. The concept of SSNM attempts to match best management practices to the individual location, considering that location has unique soil and climate, and the unique management skills and experience of the grower. It is matching management decisions to the resources of the site, the knowledge base of farmer about his fields and the needs of his crops, and any information about previous management responses unique to the farm. The unique combination of these resources allows each farmer to use them to his advantage in optimizing yields and profits for his production system.

A small farmer with only one field probably does not have a GPS system—and probably doesn't need one. But he can still use SSNM. His knowledge of his fields and the crops he grows, and his experience and records of past production, all can be used to compile the unique information he can use to meet crop needs and optimize profits. Making observations, keeping records, analyzing resources (such as soil characteristics and soil tests), and employing his best knowledge of practices for his farm are all a part of SSNM.

Building a nutrient management GIS database for each field

Details of nutrient management and maintaining records of fertilizer use, crop yields, and nutrient removal should be kept for every field on every farm in the world. The goal should be to develop a database for each field with geographically-referenced data that can be analyzed for nutrient balance, productivity, profitability, and environmental impacts. Where GPS and GIS technology are not available, other methods of documenting location can be used, but GPS/GIS is the best approach for larger production areas. The important point for all is to begin keeping records to document production and fertilizer use.

GIS analysis allows the data from different layers (Figure 40) (years, crops, yields, soil characteristics, nutrient additions, pest problems, etc.) to be analyzed for each part of a field. This allows for interpretation of the cause-effect relationships among the various variables for which data are available. It becomes a very powerful management tool that gets better with each year of data that is added.

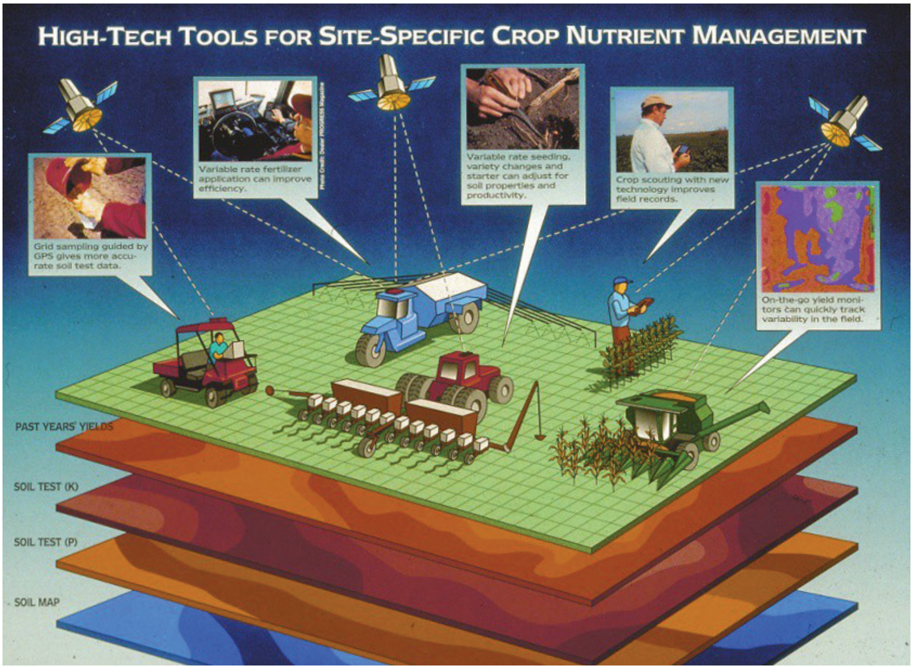


Figure 40. Illustration of various component practices and technologies commonly associated with specific precision agriculture systems (IPNI, Reetz, Better Crops, 1994).

For the individual grower, such a database is a valuable tool to guide future management decisions. For advisers and input suppliers it can be used to summarize local activities and guide training and product supply needs. For government agencies it can help guide policies for improving the production systems for the area. In all cases, better data, linked to GIS, has great potential for guiding better-informed decision making for all stakeholders. A variety of data management software programs and services are available for farmers and their advisers to use in collecting, organizing, and interpreting their data, and range from individual farmer data systems, to data systems that allow sharing of data among many farmers. Data privacy issues, potential for marketing of data, values gained by sharing information, and other factors must be considered in determining which data system is used.

Documentation of needs, rates of application and yield responses

Soil testing, either on a uniform grid basis, or based upon management zones, is the best way to determine and document variability in nutrient supplying power of the soil in a field. Along with documentation of variability in crop nutrient removal (such as by use of a yield monitor), soil test data can be used to estimate the nutrients needed from fertilizer and manure to maintain or improve the soil productivity. These data then guide the development of a site- specific nutrient application map to make most efficient use of the nutrients applied and protect against over-application that can cause environmental problems and excess expense, as well as prevent under-application that can affect yield potential and also lead to environmental problems.

How site-specific management fits all scales of operation and all parts of the World

SSNM enables farmers to tailor nutrient management to the specific conditions of their field and provides a framework for best management practices. The total fertilizer needed to achieve a profitable target yield is determined from the anticipated yield gain, applied fertilizer, and a targeted efficiency of fertilizer use. Fertilizer is supplied to match the crop's need for supplemental nutrients. SSNM is an important nutrient management concept for all parts of the world.

Managing the right source at the right rate, right time, and in the right place may be best accomplished with the right tools. Various technologies are available to help farmers and crop advisers make decisions related to nutrient management, from soil sampling to fertilizer application to yield measurement. These tools enhance the ability to fine-tune nutrient management decisions and develop the SSNM plan for each field. Farmers and the farm employees, management and agronomic advisers, and input suppliers are all part of a team, each contributing to the decision process in different ways.

Right management means site-specific management. Making management decisions with information collected on the specific field helps produce efficient, economical, and environmentally appropriate nutrient management plans. Costs of being wrong can be high. That means the price paid for technology to fine-tune those decisions is easy to justify. Plus, the costs have gone down for many of the tools, so the components of SSNM technology do not require as much investment.

Employing global positioning system (GPS) technology to geo-reference input and yield data is a good first step. In developed countries, most fertilizer and chemical dealers now have GPS-guided application equipment, and harvesting equipment now comes with GPS as a standard or easily added feature. Similar GPS systems are used on planting equipment for collecting geo-referenced planting data, starter fertilizer application, and other inputs. With proper controllers, variable-rate application of inputs can be added to the management plan. Each of these steps can be added over time, increasing the value of the initial investment. High-accuracy RTK GPS guidance systems help avoid costly skips and overlaps, saving on input costs for seed, fertilizer, and pesticides. Reduced operator stress and fatigue are major added benefits.

Geo-referenced records are a key element

On-board sensors, monitors and controllers make huge amounts of data available to help farmers and their advisers refine the management system. To best utilize the information collected on the farm, a geographic information system (GIS) is important. GIS is a powerful tool for managing and analyzing large amounts of geo-referenced data–the kinds of data generated by modern agriculture's tools and practices. Decision-support services for farmers, consultants, and input suppliers help interpret the GIS data for better-informed decisions. GIS-based records enable all members of the management team to have access to the details for each field, so that they can help choose the right sources, rates, timing, and placement for best results.

Comprehensive shared data management systems

Software and communication systems have continued to improve. New outside databases, such as digitized soil surveys and weather information are now available to complement the farm data for use in decision-support tools. More farmers with more data leads toward the "critical mass" of customers needed to sustain a support service offering, either as an independent operation or as an add-on support service offering by an input supplier. Managing and interpreting those data often require outside help. Farmers can gain much more benefit by sharing the data with their adviser partners. Farmers who share their data with other farmers have a broader base of information upon which to make decisions. Each can still benefit from his unique experience and resources to make decisions on his own farm. Programs being implemented by seed, fertilizer, and chemical companies, or by technology data service providers, may be the answer to the growing information management needs of 21st century farmers–helping them to put the right nutrient source on at the right rate at the right time in the right place.

Thus precision farming takes nutrient stewardship to another level, adding the provisions of using the right tools with the right information in the hands of the right people to fine-tune the nutrient management plan for a given field.

SSNM for rice in Asia

The International Rice Research Institute (IRRI) has developed a SSNM program, based on scientific principles for supplying rice with optimum levels of essential nutrients at the critical growth stages of active tillering and panicle initiation. SSNM helps farmers apply adequate fertilizer for their rice crop in a specific field and season, for efficient nutrient use, and high yields, translating to high cash value of the harvest.

The concept of SSNM in rice was developed in cooperation with researchers across Asia, and tested on farms in eight rice growing regions in six countries. It consists of three steps as shown in Figure 41. In the first step, an attainable yield target is established. The yield target for a given location and season is the estimated grain yield attainable when N, P and K constraints are overcome. As the amount of nutrients taken up by a rice crop is directly related to yield, the yield target indicates the total amount of nutrients that must be taken up by the crop. The second step consists of effectively using the indigenous nutrients coming from the soil, organic amendments, crop residues, manure and irrigation water. An estimate of the nutrients taken up by the crop from indigenous sources can be obtained from the grain yield of a crop not fertilized with the nutrient of interest but fertilized with other nutrients to ensure they do not limit yield. In the third step, the quantity of required fertilizer is applied to fill the deficit between the crop's total needs for nutrients as determined by the yield target and the supply of these nutrients from indigenous sources. The total quantity of fertilizer to be applied is determined by the efficiency of fertilizer use by the crop. The required fertilizer N is distributed in several applications during the crop growing season using tools like the leaf color chart.

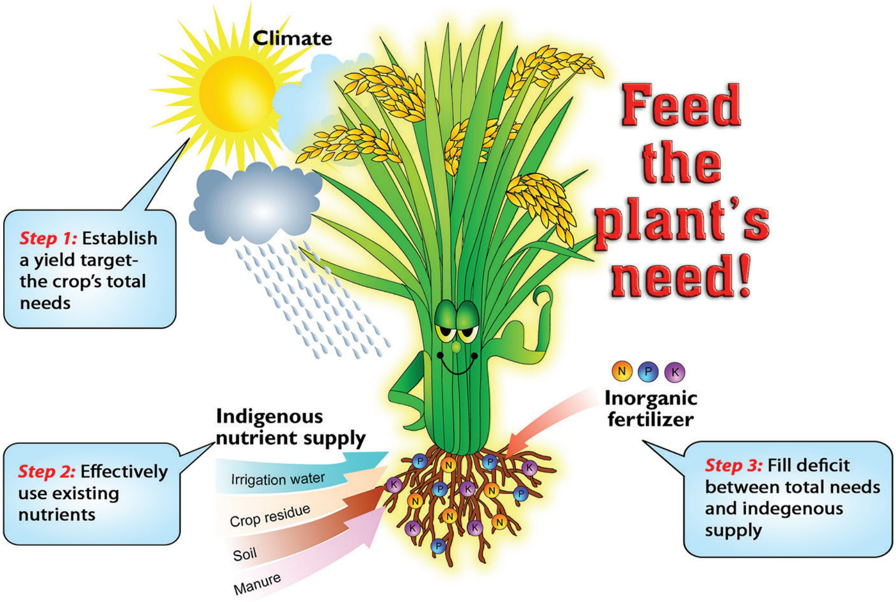


Figure 41. The three steps of SSNM (site-specific nutrient management) in rice in Asia (IRRI).

Spatial variability and SSNM of spring wheat production in China

Following is an example of the use of SSNM on wheat in Northeast China *(Better Crops* 94:7-9). Spatial variability of soil fertility (soil organic matter and available P, K, S and Zn) and water in different parts of the study area were the main factors influencing spatial variability of grain yield. The SSNM treatments applied significantly more N and less P for relatively high soil fertility plots, and more N and K for low soil fertility plots than with collective contract cropping practice. The SSNM for N, P and K increased yields by 8 to 19% and improved income by 455 to 520 Yuan/ha.

The strong visual relationships among the maps in (Figures 42-44) can be documented numerically through the use of GIS analysis. GIS analysis can also be used to determine relationships among other layers of information, such as soil texture, depth of root zone, water holding capacity, etc., and predict how these might be integrated to determine variability in yield potential. As more years of data are collected for a field, the power and benefit of using GIS analysis increases. Building a geo-referenced data base for each field is a critical first step to being able to use this powerful tool for decision making.

Nutrient Expert software

Nutrient Expert is a simple nutrient decision support tool developed on the principles and guidelines of SSNM to enable crop advisors develop fertilizer recommendations tailored to a farmer's field or growing environment. It takes into account the most important factors affecting nutrient management recommendations, which enables crop advisors to provide farmers with fertilizer guidelines suited to their farming conditions. Thus, Nutrient Expert helps farmers in their decision making because it reduces the uncertainty associated with highly variable conditions.

The algorithm for calculating fertilizer requirements in Nutrient Expert is determined from a set of on-farm trial data using SSNM guidelines. Nutrient Expert estimates the attainable yield and yield response to fertilizer from site information using decision rules developed from on-farm trials. Nutrient Expert recommendations are generated with attainable yield as yield target for the season. For the determination of fertilizer rates, Nutrient Expert uses information about the field's nutrient supply (soil, crop) that is derived either in omission plots or from site and management characteristics that serve as proxies for nutrient supply. Specifically, Nutrient Expert uses characteristics of the growing environment: water availability (irrigated, fully rainfed and rainfed with supplemental irrigation) and any occurrence of flooding or drought; soil fertility indicators: soil texture, soil color and organic matter content, soil test for P or K (if available), historical use of organic materials (if any) and problem soils (if any); crop sequence in farmer's cropping pattern; crop residue management and fertilizer inputs for the previous crop; and farmers' current yields. Data for specific crops and geographies are required in developing the decision rules for Nutrient Expert.

Nutrient Expert for inbred maize, hybrid maize and wheat are already available for regions in South Asia, Southeast Asia and China. Performance of Nutrient Expert

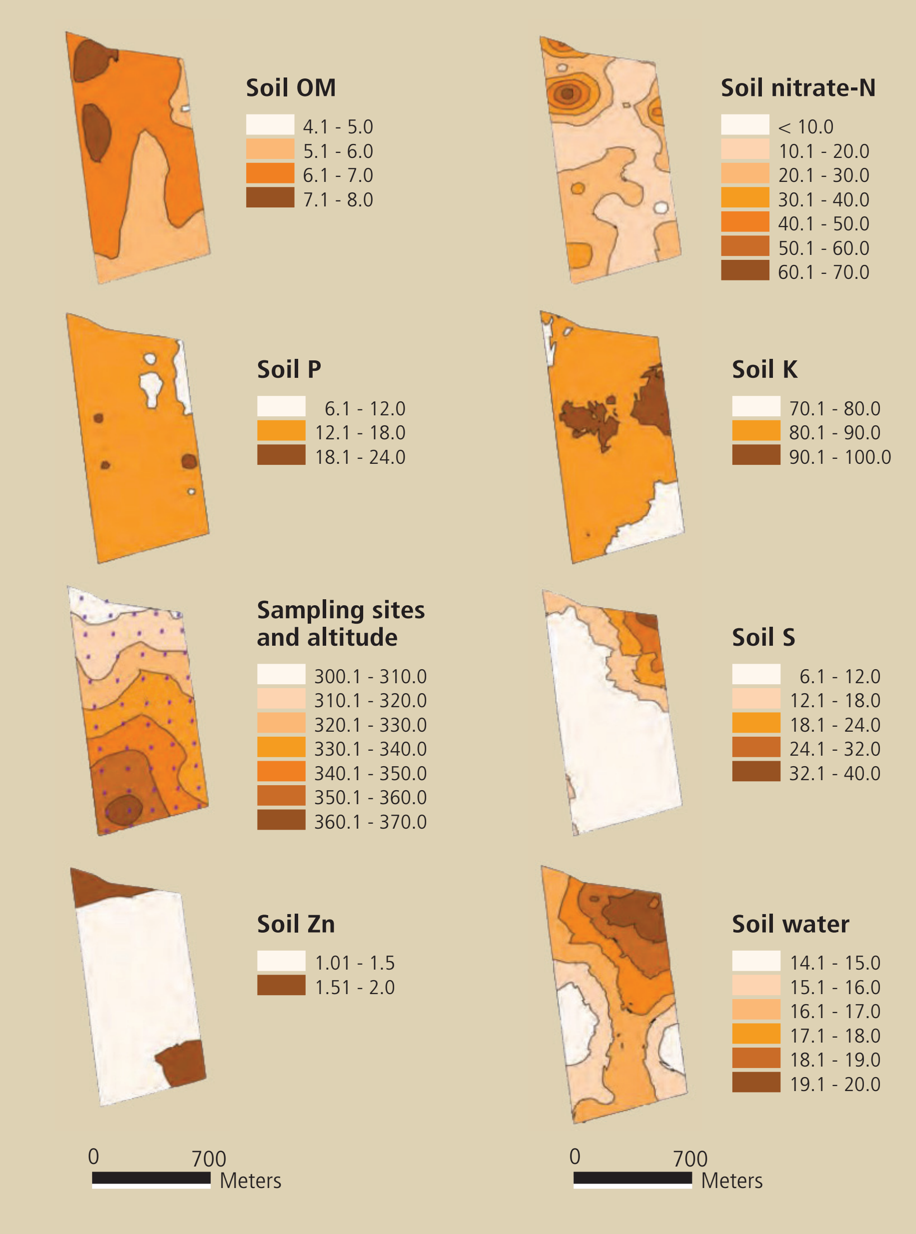


Figure 42. Maps of variability of selected available soil nutrients, % soil water, and % soil organic matter from sampling sites on a 156 hectare field.

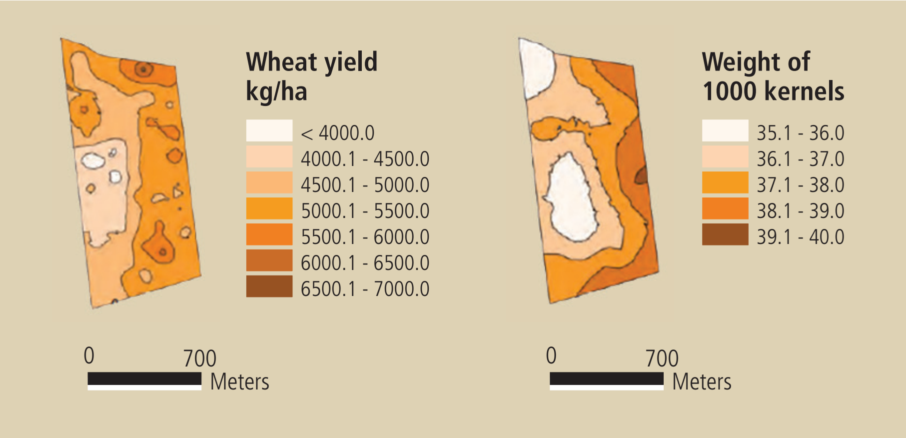


Figure 43. Grain yield (kg/ha) and kernel weight (g) shown by maps illustrate the spatial variability in crop production in the study area.

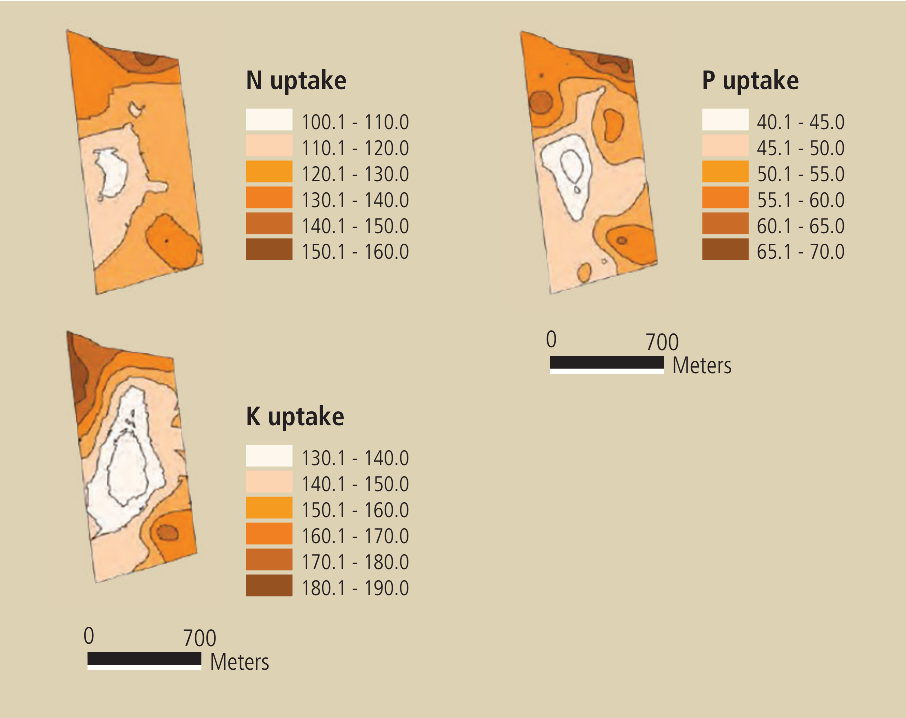


Figure 44. Spatial distribution of total N, P and K uptake.

fertilizer recommendations for all the crops and in different regions always turned out to be better than the farmers' fertilization practice, which would either rely on generalized "one-size-fits-all" regional recommendations, or are estimates that usually do not consider precise site-specific indigenous nutrient supply.

One of the challenges in use of the Nutrient Expert tool is the absence of any long-term use by farm advisors. Given that most of the smallholder farmers in Asia and Africa have little access to soil tests, it is believed that Nutrient Expert can meet the requirements for nutrient recommendations of large numbers of farmers. One of the important plus point of Nutrient Expert is that local science of nutrient management can readily be incorporated into the Nutrient Expert recommendations.

Nutrient use efficiency (NUE)

A variety of definitions are used to describe *nutrient use efficiency* (NUE). At global or regional scales, partial factor productivity (PFP) is the only index of nutrient use efficiency that can be estimated more easily, although not very precisely because of uncertainties about the actual use of different nutrients by different crops and about crop production statistics. Being a ratio, PFP declines from large values at small nutrient application rates to smaller values at high N application rates and differences in the average cereal PFP among world regions depend on which cereal crops are grown, their attainable yield potential, soil quality, amount and form of nutrient applied, and the overall timeliness and quality of other crop management operations.

Globally, PFP for fertilizer N (PFP_N) in cereal production has decreased from 245 kg grain/kg N in 1961/65, to 52 kg/kg in 1981/85, and to about 44 kg/kg in 2005/06 (Dobermann, 2007). An initial decline in PFP_N is an expected consequence of the adoption of N fertilizers by farmers because PFP decreases when yields increase along a fixed response function unless offsetting factors, such as improved management that remove constraints on yield, shift the response function up. In many developed countries, a steady increase in PFP_N has been observed because cereal yields have continued to increase during the last 2-3 decades. Evidence of improved PFP_N is available from the US, where it increased from 42 kg grain per kg N in 1980 to 57 kg grain/kg N in 2000, during a time when maize yields increased by 40%. Since the mid-1980s, a steady increase in PFP_N has also been observed in Western Europe (rainfed cereals systems), North America (rainfed and irrigated maize), Japan and South Korea (irrigated rice) (Dobermann and Cassman, 2005). In developing Asia, due to rapid increase in fertilizer N use, which started during the course of the Green Revolution in the 1960s and 70s, a steep decrease in PFP_N has been observed. According to Dobermann and Cassman (2005), PFP_N continues to decline in all developing regions at rates of 1 to 2% per year. In some countries like India, PFP_N seems to have levelled off in recent years, but in many it continues to decline because public and private sector investments in better technologies, services, extension and education are far below those made in developed countries.

Agronomic/economic/environmental aspects of NUE

The increased demand for fertilizer nutrients to meet global food demand, along with the finite resources of fertilizer materials available and the growing public concerns related to nutrient use side effects, all lead to the conclusion that NUE must be improved but not at the cost of decline in productivity. There are many different ways to evaluate and calculate NUE. The method to use depends upon the goals of efficiency to be evaluated, data availability, and the time frame for which NUE is to be determined. The data collected in precision farming and the use of on-farm research makes it possible to compute different NUE values for individual fields, and thus to further fine-tune management decisions.

In the short-term, efficiency can be improved by reducing inputs, even at the expense of yield. But the short-term efficiency gains may actually reduce the long-term efficiency and productivity of the cropping system, because the nutrients depleted must be replaced to restore full productivity. The long-term NUE can best be improved by careful attention to the entire nutrient management system, considering all management practices and how they relate to nutrient use for the crop. Best management practices for nutrient management must be selected considering the source of nutrients, the time of needs by the crop, the rate of application, and the placement of the nutrients relative to the growing crop. All of these components interact with one another, with the growing crop, the environment, and the other management practices. Efficiency depends upon the entire system.

The optimal and balanced use of nutrients ensures adequate agricultural production with reduced impact on the environment. The NUE is an important measure of the beneficial impact on economic, social and environmental performance of agricultural systems. It is important to note that sustainability performance of nutrient management cannot be reflected through NUE alone, and that a number of complementary indicators are needed.

Components of NUE

There are many different methods of calculating nutrient use efficiency (NUE) depending upon the goal of the production system and the comparisons being made. Snyder and Bruulsema (2007) selected four definitions of nutrient use efficiency (Table 5). These represent two different types of nutrient use efficiency calculations. *Production efficiencies* are used when the harvested crop product is the factor of interest, and *Recovery efficiencies* are used when the interest is in the nutrients recovered in the crop.

These subtle differences in efficiency calculations provide different ways to look at NUE. Long-term trends are usually more relevant than short-term trends if sufficient data are available.

Table 5. Calculation and definition of selected terms used to represent NUE.

NUE term	Calculation	Definition
Partial factor productivity	kg product/kg nutrient applied	crop yield per unit nutrient applied
Agronomic efficiency	kg product increase/kg nutrient applied	crop yield increase per unit nutrient applied.
Recovery efficiency	fertilized crop nutrient uptake - unfertilized crop nutrient uptake/ nutrient applied	increase in nutrient uptake by the crop per unit nutrient applied
Removal efficiency	often called partial nutrient balance; crop nutrient removal/nutrient applied	nutrients removed by the harvested portion of the crop per unit nutrient applied.
Physiological efficiency	kg product increase/kg fertilizer nutrient taken up	crop yield increase per unit fertilizer nutrient taken up

Partial factor productivity, an index that can be applied in absence of experimental results, can be useful for describing mega trends such as the evolution over several decades of average NUE in cereal production in a specific country or region. It can also be used to compare different regions of the world. However, partial factor productivity values depend on cropping systems, because crops differ in their nutrient and water needs. Therefore, different cropping systems are difficult to compare with this indicator. Partial factor productivity benchmarks and data exist mostly for cereals.

Agronomic efficiency and recovery efficiency are the two different ways of using the 'difference method' for expressing NUE. They require a record of nutrient inputs and outputs, and data on plots without nutrient inputs. Recovery efficiency is the most logical measurement to calculate NUE for environmental aspects, because it looks at the nutrient uptake by the crop. The difference method is, however only appropriate for long-term trials, because the indigenous fertility of soils ('zero nutrient plot') can only be estimated over long periods of time. If it is used for annual trials, NUE will be underestimated because the crop yield in the unfertilized treatment is supported by nutrient applications from previous years. For long-term trials (of at least 10 years), the difference method gives an accurate estimate of the long-term contribution of fertilizer to crop yield. Single-year agronomic efficiency and recovery efficiency can be useful in some fertilizer recommendation systems but have limitations as NUE indicators.

Nutrient recovery efficiency is used in two forms. The simple form, "nutrient output per unit of nutrient input", is sometimes termed a *partial nutrient balance* (PNB). It is calculated as nutrient in the harvested portion of the crop per unit of nutrient applied. Reported as a ratio of "removal to use", it is fairly easily measured by and useful to crop producers. It can be reported for any number of growing seasons. The more complex form—preferred by scientists—is often termed as recovery efficiency and defined as the increase in crop uptake of the nutrient in above-ground parts of the plant in response to application of the nutrient. Like agronomic efficiency, its measurement requires the implementation of plots with no nutrient applied. Operationally, it is limited to the description of the result of either a single nutrient application, or of a single cropping season. The PNB answers the question, "How much nutrient is being taken out of the system in relation to how much is applied?" The recovery efficiency, on the other hand, answers the question, "How much of the nutrient applied did the plant take up?" For nutrients that are retained well in the soil, PNB may be considerably higher than recovery efficiency.

Removal efficiency uses the 'balance method' to calculate NUE. This method is more appropriate for systems that have been cultivated for long periods where fertility levels have been monitored. This can be better illustrated for P, but it is also valid for N and the other nutrients. Since P is not very mobile in the soils, there are usually large amounts of residual P, which will increase the yields of subsequent crops for a number of years or even decades. If P removal efficiency is measured over a sufficiently long period when soil fertility levels have been stable –at least for a decade, it provides a realistic estimate of P use efficiency. However, when soil fertility levels change (e.g., changes in soil organic matter content or soil available P), removal efficiency calculated over short periods of time may either underestimate or overestimate NUE. The same is true with respect to N and soil organic matter changes.

Nutrient balance (nutrient inputs – nutrient outputs) is another expression of the balance method, expressed per unit area rather than as a ratio. It may provide an estimate of nutrient surpluses available for loss, but do not equate to losses or loads. In some soils, nutrient surpluses can be retained, and there can be multiple pathways of loss, some more benign than others, and the load to critical endpoints such as water or air is not the same as the nutrient balance or surplus. Inputs and outputs should be shown with the balance, to convey an appreciation for the scale of nutrient flows managed by agricultural producers. Nutrient balance and removal efficiency provide different information and are complementary indicators.

Physiological efficiency is a useful indicator in crop nutrition research and represents ability of a plant to transform nutrients acquired from fertilizer into economic yield. It depends on genotype, environment and management. Low physiological efficiency suggests sub-optimal growth due to nutrient deficiencies, drought stress, heat stress, mineral toxicities or pests.

No single measure or indicator provides a complete reflection of nutrient performance. Ideally, a set of indicators is required to properly reflect performance. Calculating removal efficiency, i.e. the nutrient output/input ratio, is often the most appropriate method to estimate N and P use efficiency because it is relatively easily actionable and scalable from the farm to the global level and the required data are usually available. Calculating removal efficiency does require good crop removal data. These data may need to be regionalized since the average nutrient content of the harvested produce often varies among regions.

Many environmental impacts are minimized when nutrient surpluses are avoided and when nutrient use efficiencies are improved. For example, in sandy soils, loss of nitrate by leaching can amount to a considerable fraction of the fertilizer N applied, so practices chosen to improve NUE will simultaneously reduce nitrate losses to groundwater. Such practices may include using split application to reduce losses, or using products that keep the N in the ammonium form. Actual direct measurement of N loss from the field is difficult and expensive. Measuring and computing N use efficiency and nutrient balance is much more practical and can provide a good, reliable estimate of the balance of N applied, used by the crop, and left in the soil.

Nutrient budgets and balances

The balances of nutrient inputs and outputs from a crop production agro-ecosystem are determined through nutrient budgets (Table 6). Such balances help farmers and policy makers assess whether nutrients are being lost from the agro-ecosystem or these are accumulating to excessive levels that may cause environmental problems. Perhaps even more important, nutrient budgets and balances help determine whether nutrient management practices are allowing nutrients to be depleted and thus reducing productive potential of the farms.

As an example, nutrient budgets in some states in the US are shown in Table 6. It is important to include all sources of nutrients in such balances. Note that for Illinois, removal of P is 1.54 times input, meaning that the soil P level is being depleted under current management. North Carolina, by comparison, is only removing 28% of the P input, reflecting the high level of manure being used.

Table 6. Nutrient balance for selected states in the US (IPNI).

State	Nutrient	Fertilizer	Recoverable manure	N fixation	Harvest removal	Balance*	
						R/U	Cropland A
			Thousand tonnes			lb/A	
Florida	N	167	13	4.5	102	0.55	56
	P_2O_5	56	13		33	0.47	25
Illinois	N	1,018	21	727	1,531	0.87	19
	P_2O_5	332	37		567	1.54	-16
North Carolina	N	187	94	75	197	0.55	61
	P_2O_5	101	148		69	0.28	70
South Dakota	N	450	17	333	679	0.85	13
	P_2O_5	212	29		219	0.91	2
US	**N**	**12,594**	**1,405**	**6,643**	**15,847**	**0.77**	**23**
	P_2O_5	**4,337**	**1,809**		**5,484**	**0.89**	**3**

*Balance = Farm fertilizer + Recoverable manure + N fixation - Harvest removal
R/U = ratio of harvest removal to nutrient use
Cropland A = net balance on a per acre of cropland basis

Nutrient budgets and balances can be developed for individual fields, farms, watersheds, or geographic areas. At the individual farm level, budgets help guide production decisions. The watershed or regional level budgets may be used to assess overall nutrient balance of the ecosystem and do not involve individual field assessments. Policy decisions may be looking for assessments of nutrient balance on a much larger geographic area. What data are collected, how, and when are determined by the level of decision-making needed. Data collected on a finer detail may be aggregated and summarized to fit a larger-scale need, but that may result in unnecessary cost and labor for data collection if it is not needed at that detail.

Box 9 describes a nutrient balance system developed by the International Plant Nutrition Institute (IPNI), which is an excellent model for collection and interpretation of nutrient use and removal data to help better inform decision makers and policy developers on the balance of nutrients for individual watershed and political regions, so that they can work with realistic data. While the data collection requires a lot of cooperation, the results can provide all users with a better basis upon which to take action.

Box 9. The IPNI NuGIS Program: an example of using the budget/balance approach

While nutrient management systems are necessarily focusing on the local field level through site-specific technology and precision farming in the adoption of nutrient stewardship, it is important to keep track of the aggregate effects of nutrient management at the more regional geographic scale. A good model for this has been developed by IPNI. The Nutrient Use GIS (NuGIS) system developed by IPNI summarizes nutrient inputs and crop removal for each crop and each county in the US. NuGIS makes it possible to calculate partial nutrient balances at different scales (county, watershed, and state) for the US. NuGIS takes into account inputs in the form of fertilizers, recoverable manure and biological N fixation. As similar data sources become available for other countries, the NuGIS system can be adapted to those areas as well. It provides solid background information for many decisions on nutrient management policies and recommendations, for the geographic area and watersheds involved.

Data are GIS-referenced, so that different data collected from the same location can be matched and correlated, and geographic summaries developed. The fertilizer use and nutrient removal data show agronomists and farmers trends and guide educational or advisory programs to optimize fertilizer use. An increase of soil organic matter over time may result in a decline of N removal efficiency if the incorporation of N into soil organic matter is not taken into account in the calculation where there is a progressive build-up of soil organic matter.

Omission plots and long-term trials

One of the most useful, and simple methods for determining the right fertilizer program for a field is the use of omission plots. This is simply a series of small plots with each plot receiving a complete set of all nutrients being evaluated, except for one nutrient being omitted. This is repeated for each nutrient. Then one plot is added with all nutrients present and one plot with no nutrients added.

By observing these plots and comparing yields at the end of the growing season, the farmer and his advisers can determine which nutrients are deficient and limiting yield potential. If the plot with a missing nutrient yields the same as the one with all nutrients present, it can be assumed that the soil has an adequate supply of that nutrient. If a plot without a nutrient yields less than the one with all nutrients present, it proves that the field needs additional fertilizer of that nutrient. Those nutrients shown to be limiting can then be studied in rate comparisons to determine the most appropriate rate of the nutrient to be applied. Omission plots are useful where little past information is available about local nutrient needs.

Long-term trials (Box 10) are particularly useful because they integrate the effects of year, climate, pest and disease stress, etc. Fertility management is often management of

Box 10. Long-term fertility trials

Founded in 1843, the Broadbalk Experiment at Rothamsted Research, Herpenden, England, is the world's oldest soil fertility experiment.

The Morrow Plots at the University of Illinois, in Urbana, Illinois, US, were started in 1876, and have some plots that have been in continuous corn since that time, without fertilizer.

Corn yields on plots with a standard fertilizer plan now average about 4 times those of the never fertilized plots.

Soil organic matter declined for about 60 years, then leveled off at a steady-state plateau.

These trials prove that fertilizer is needed to maintain productivity on fields under continuous cropping.

Data from long-term trials can be used to identify trends in yield and soil test levels that help guide future nutrient management. Maintaining these long-term trials provides a scientific resource that cannot be duplicated, and is thus an important resource for future scientific studies.

Long-term trials are often difficult to maintain because they may not have direct relevance to current research. But they provide irreplaceable data on long-term trends, and archived samples of soil and plant tissue provide useful insights into trends in nutrient content over long periods of time. Such samples and data are a resource that can never be replaced.

We should be grateful to the visionary scientists who have noted the value of these resources and worked to maintain them. We should encourage today's scientists to protect and maintain these resources and data sets for future generations.

trends, rather than absolutes. Long-term studies are necessary to establish trends, and to monitor effects of management changes.

Economics of fertilizer use

One of the major goals of 4R nutrient management is to manage the profitability of the crop production and nutrient management system. To be sustainable, a production system must be profitable in the long-term.

Figure 45 illustrates the general concepts of fertilizer economics. The maximum profit is usually achieved when fertilizer application (and general crop management) is set at slightly below the maximum yield level. This level, sometimes called *maximum economic yield*, makes the most efficient use of land, water, and labor resources, and produces optimum return on investment in inputs such as fertilizer. As an additional benefit, managing at this level also tends to result in lower potential loss of nutrients to the environment. *Better agronomy means better economics and better environment.*

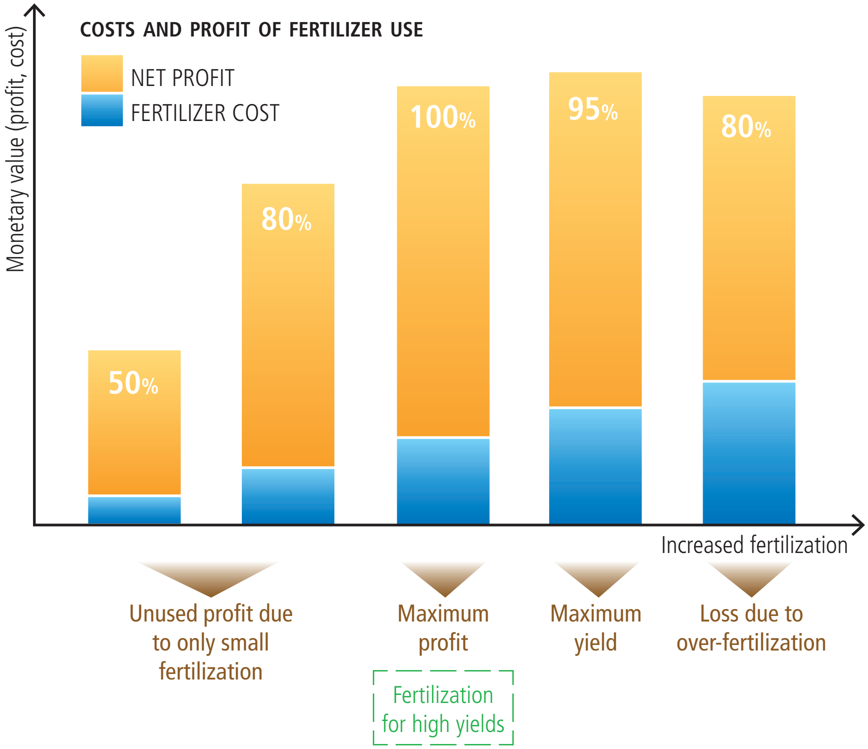


Figure 45. Generalized diagram of economic analysis of fertilizer use (IFA, 1992).

One of the most common limitations to farmers adopting better management practices and technology is that they do not have information on the economic benefit associated with different operations. Research reports and marketing information usually focus on the agronomic benefits, such as increased yield and the potential positive environmental benefits. But the final step of demonstrating the costs and benefits to an individual farmer's operation are often not explained. Individual set of costs and income based upon local input suppliers and local markets, may make a significant difference in individual profits. This seems to be a universal problem, in large-scale production systems in developed countries and in small-plot farms of developing countries. So taking a few extra steps to address the site-specific economics of better management practices could be a key to broader acceptance and adaptation of new practices and technologies.

4R nutrient management system trials

With the increasing concern for nutrient effects on water and air quality, more attention is being given to how to manage nutrients to improve productivity, yet reduce the environmental "footprint" of the production system. Following is an example of a public-private partnership project in central Illinois, US. The Indian Creek Watershed project was established to demonstrate 4R Best Management Practices (BMPs) that will help reduce N loss to the local surface waters and help support the Nutrient Loss Reduction Strategy for addressing water quality problems downstream from the project area.

The project is coordinated by the Conservation Technology Information Center (CTIC) with support from the Illinois Environmental Protection Agency, along with several local, state and national agribusiness companies, and farmer and dealer organizations. Since 2010, a series of on-farm nutrient management field demonstrations have been in place on individual farms to demonstrate BMPs and collect data for NUE analysis. This is a cooperative effort involving local farmers and fertilizer dealers, agricultural and environmental government agencies, agribusiness companies, and local citizens who serve on a local Steering Committee that directs the project.

Two different types of nutrient use efficiency studies are used in these demonstrations. One uses small plot techniques and equipment, and the other using the farmer's own field-scale equipment. Each involved establishing a set of N rate plots within the demonstration field, with application rates from zero (no N applied) to a rate higher than the expected optimum. In these trials, five rates were selected, ranging from zero to 240 pounds N per acre (269 kg N/ha).

For the small plot example, the NUE trial plots (each 15 feet x 40 feet (4.5 m x 12 m)) are established with 5 rates and 4 replications, in a randomized complete block experimental design (Figure 46). Fertilizer is applied with small plot equipment, and the crop is harvested with a small plot combine. Because this type of trial requires small plot equipment, extra labor and possibly a crop adviser's assistance, the farmer would likely not conduct it by himself. However, the farmer benefits from testing a smaller area

	N Rate (lb/A)				
Product	0	80	120	160	200
	Corn yield (bu/A)				
Check (No. N)	92				
Super U		141	160	145	174
Urea		158	145	143	168

Figure 46. An example of the plot layout and yield results from a Nitrogen NUE demonstration comparing two different N sources. (Reetz Agronomics and Cropsmith, CTIC Project).

of the field, which minimizes the risk of yield loss on the low-rate plots. And, because a small plot contains less soil variability, yield differences are less likely to be due to factors other than the fertilizer treatments.

Small plots were established to compare two sources of N at 5 different rates. The yields from these plots were used to compute the NUE for the two products, using the IPNI Crop Nutrient Response Tool (CNRT). The data in the table are the average corn yields for each treatment. These results can be used to estimate the most efficient N rate for meeting yield, profit and environmental stewardship goals.

Farmer-implemented NUE trials

A simple data collection system relies on varied plot application rates implemented with standard farm equipment. The plots (Figure 47) are established by the on-board controllers and monitors, so no measuring, staking, or hand application or harvesting is required. With this kind of system, every farmer's field could be used as a "research"

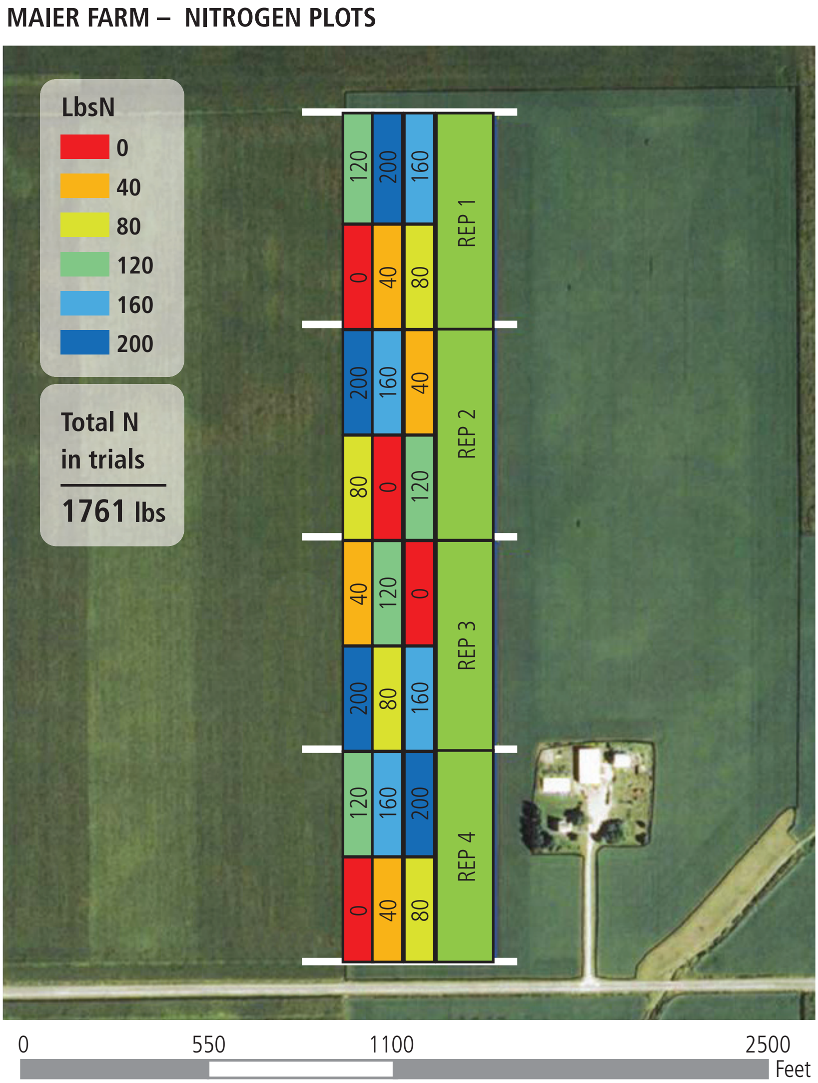


Figure 47. Example plot layout for an on-farm N rate comparison with 6 N rates and 4 replications. All established and harvested using conventional field equipment with RTK GPS guidance and variable-rate systems (Reetz Agronomics).

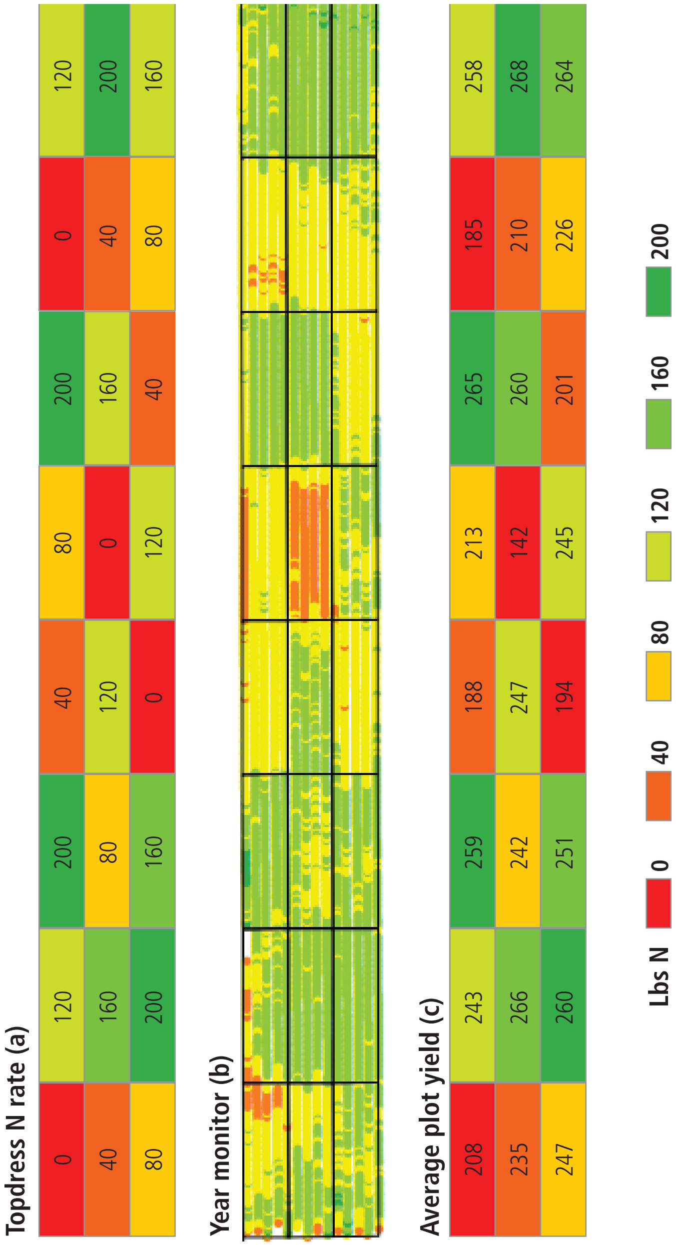
plot. And it is scalable to any size field, so it can be used anywhere in the world. The map below shows the replicated N rate and source treatments overlaid on an aerial image of the NUE trial plots. This type of plot layout is similar to those used in small plot research studies. The replication helps account for site variability. This system does not require special plot-scale equipment and requires very little interference with the farmer's normal field operations (Figure 48).

Figure 48. Variable rate fertilizer applicator used to establish plots illustrated in Figure 42 (Reetz Agronomics).

Maps of the layout for this example field demonstration are shown in Figure 49. In this split application, the first application was done prior to planting and the final top-dress application was made after the crop was established. When applying fertilizer, the dealer was provided with a data card with the treatments prescribed. The fertilizer was applied using RTK GPS guidance, with rates automatically adjusted to the plot plan, and the "as applied" information was recorded on the data card, thus incorporating trial plots into normal fertilizer application. At harvest, the farmer's yield monitor recorded yield variability across the field, and the plot data could then be extracted and analyzed. Using GIS positioning, any observations or samples gathered during the growing season could be linked to the plots and yield data.

Data gathered through trials like this can help farmers make better-informed fertilizer management decisions. The farmer may choose to share information with fertilizer dealers, crop advisers and others to document the economic and environmental impacts of improved nutrient use efficiency.

At the field or farm level, removal efficiency can be calculated taking all the inputs and outputs into account. At a larger scale (e.g. watershed, national), because of data availability constraints (e.g. on biological N fixation, manure, P erosion losses), a simpler model may be appropriate, focusing on nutrients applied with fertilizers and nutrients exported with the harvested product. The magnitude of error introduced in this simplification can vary considerably with regions and cropping systems. The method of calculation should always be clearly stated.



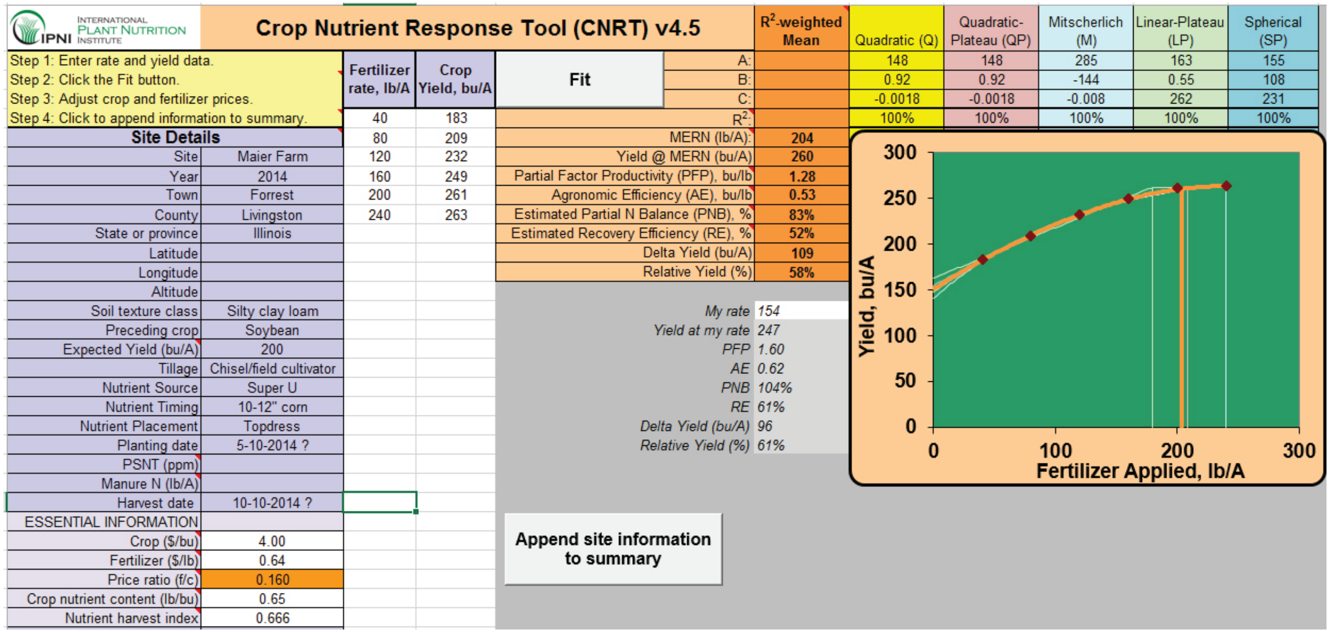
Topdress N rate (a)

0	120	200	40	80	200	0	120
40	160	80	120	0	160	40	200
80	200	160	0	120	40	80	160

Average plot yield (c)

208	243	259	188	213	265	185	258
235	266	242	247	142	260	210	268
247	260	251	194	245	201	226	264

Figure 49. Maps of top-dress N plots, yield monitor data, and average plot yields for Top-dress N rate demonstration. Yield monitor data were compared to as-applied N plot data. These data and current N and grain prices were analyzed with the CNRT (Reetz Agronomics).



INTERNATIONAL PLANT NUTRITION INSTITUTE IPNI

Crop Nutrient Response Tool (CNRT) v4.5

Step 1: Enter rate and yield data.
Step 2: Click the Fit button.
Step 3: Adjust crop and fertilizer prices.
Step 4: Click to append information to summary.

Site Details	
Site	Maier Farm
Year	2014
Town	Forrest
County	Livingston
State or province	Illinois
Latitude	
Longitude	
Altitude	
Soil texture class	Silty clay loam
Preceding crop	Soybean
Expected Yield (bu/A)	200
Tillage	Chisel/field cultivator
Nutrient Source	Super U
Nutrient Timing	10-12" corn
Nutrient Placement	Topdress
Planting date	5-10-2014 ?
PSNT (ppm)	
Manure N (lb/A)	
Harvest date	10-10-2014 ?
ESSENTIAL INFORMATION	
Crop ($/bu)	4.00
Fertilizer ($/lb)	0.64
Price ratio (f/c)	0.160
Crop nutrient content (lb/bu)	0.65
Nutrient harvest index	0.666

Fertilizer rate, lb/A	Crop Yield, bu/A
40	183
80	209
120	232
160	249
200	261
240	263

Fit

	R²-weighted Mean	Quadratic (Q)	Quadratic-Plateau (QP)	Mitscherlich (M)	Linear-Plateau (LP)	Spherical (SP)
A:		148	148	285	163	155
B:		0.92	0.92	-144	0.55	108
C:		-0.0018	-0.0018	-0.008	262	231
R²:		100%	100%	100%	100%	100%
MERN (lb/A):	204					
Yield @ MERN (bu/A)	260					
Partial Factor Productivity (PFP), bu/lb	1.28					
Agronomic Efficiency (AE), bu/lb	0.53					
Estimated Partial N Balance (PNB), %	83%					
Estimated Recovery Efficiency (RE), %	52%					
Delta Yield (bu/A)	109					
Relative Yield (%)	58%					

My rate	*154*
Yield at my rate	*247*
PFP	*1.60*
AE	*0.62*
PNB	*104%*
RE	*61%*
Delta Yield (bu/A)	*96*
Relative Yield (%)	*61%*

Append site information to summary

The last 5 columns in the table show different statistical models calculated from the data for the plots. The vertical orange line on the graph indicates the most efficient rate of N for this demonstration at the prices listed

Figure 50. Calculations from the Crop Nutrient Response Tool for the small-plot N rate comparison (Reetz Agronomics).

Nutrient management decisions affect input costs, profitability, and potential nutrient losses to the environment. The IPNI CNRT (Figure 50) may be used to interpret the effects of varied rates of nutrient application. This tool computes NUE using several different formulas for efficiency. For example, NUE may be determined for different application rates and associated yields. By including crop and fertilizer prices, the optimal nutrient rate can be determined for the management system. The farmer can use these results to plan an improved nutrient management system. Economic analysis of the NUE calculations carried out by CNRT helps compare the profitability of different N management systems.

GIS analysis and the CNRT were used to show the relationship between the top-dress N rate and the corn yield.

Performance measures and indicators will often include crop yields and sufficient information to calculate economic returns. In addition, these will need to reflect environmental and social performance. Selected performance measures may vary depending on stakeholder priorities, but will often include either nutrient balances or NUE. Many environmental impacts are minimized when nutrient surpluses are avoided and when NUE is improved. For example, in sandy soils, loss of nitrate by leaching can amount to a considerable fraction of the fertilizer N applied. Thus practices chosen to improve NUE will simultaneously reduce nitrate losses to groundwater. Such practices may include using split application of fertilizer N to reduce losses, or using products that keep the N in the ammonium form. Many of the losses impacting the environment are difficult to measure. Nutrient balances and NUE are not as difficult to calculate, estimate, or measure. Demonstrations as discussed above can be used as a surrogate for actually monitoring nutrient losses. They can be done at less cost than most monitoring systems, and they generate solid data on the impact of the practice being evaluated. These provide estimates of the proper nutrient rates to be used in the production system to avoid over application that could lead to nutrient losses to the environment, and the optimum rate also gives economic guidance for assessing profitability at those optimum rates.

Environmental aspects of fertilizer use

Fertilizer is often targeted as a contributor to environmental problems, particularly elevated nitrate levels in water supplies, nitrate and phosphorus levels in water bodies leading to eutrophication, and more recently greenhouse gas emissions (especially N_2O) from agricultural operations. All of these occur, and are controllable, to a varying degree. But it is difficult to determine on a sound scientific basis the answer to: *"What is the real fertilizer contribution to these environmental problems vs. other nutrient sources?"* Box 11 offers some guidelines.

Government policy guiding or regulating fertilizer use should be based on sound science. Balance of trade and other economic issues, and lack of awareness, sometimes overpower science in formulating policy. It is important that good science be made available and explained to policy makers wherever possible. Resource protection and

Box 11. Management of fertilizer for maximum economics and minimum environmental impact

- Follow good science and best management practices:
    - right product, at the right rate, at the right time, in the right place;
    - take precautions to minimize the contributions of fertilizers to environmental degradation.
- Fertilizer cost alone is often a deterrent to excess applications.
- Variable-rate technology has helped more farmers to use only what is needed and where it is needed.
- New fertilizer materials designed to help control losses are another positive step.
- Most farmers in developed countries do not over-apply fertilizer beyond the rates required for optimum crop growth.
- All farmers should make a serious effort to reduce the potential environmental effects of their nutrient management.
- The use of high-yield, economical nutrient management is often the most environmentally sound system as well.

future food security can only be possible if decisions are made at all levels with good science taken into account.

Most environmental consequences of nutrient management result from having excess nutrients in the soil above the amount used by the crop at a given time. Excess nutrients lead to potential losses, resulting in water and air pollution. The adoption of FBMPs can reduce environmental impacts. Cutting back on fertilizer is not the answer. Changes in the whole crop production system may be needed to realize the environmental benefits of changing nutrient management practices. In fact, a well-balanced fertilizer program coupled with a high yield management production strategy, in general, will keep more of the available nutrients in the crop. Site-specific management following a good soil testing plan can help design the right fertilizer program to optimize applications for high yields, optimum profits, and minimum environmental degradation that leads to sustainable agriculture systems, resource efficiency and food security.

Nutrient trading

Concerns about nutrient pollution of air and water resources have been gaining interest in many areas of the world, especially in the developed countries. While sources of the problems include industry and municipal sources, along with agriculture, management of nutrients in agriculture has been targeted in many countries as a way to mitigate the problem. A new market is developing in some countries, where farmers can adopt improved practices, often centered around 4R Nutrient Stewardship, and sell "nutrient credits" according to values established to match the amount of pollution "prevented" by that practice. The buyers would be other sources of nutrient pollution who are interested in purchasing these credits instead of cleaning up their own nutrient losses. This market has led to the establishment of Nutrient Credit Exchanges, which put buyers and sellers together for these transactions similar to the way commodity exchanges handle sale of grain stocks. Currently operational in Europe and beginning a testing phase in the US, the nutrient credit market may eventually become another significant factor to consider in nutrient management decisions.

Nutrition security

Food security, in both quantity and quality, is a major concern as world population is increasing. In addition to yield, plant nutrition affects other important components of human nutritional needs, including the amounts and types of carbohydrates, proteins, oils, vitamins and minerals in food products. As production of staple food crops increases, the extra yield is most often due to added carbohydrates, and leads to dilution of the micronutrient content. Many of the healthful components of food are boosted by the application of mineral nutrients. Since most farmers fertilize for optimum yields, these benefits are easily overlooked. Trace elements important to human nutrition can be optimized in the diet by applying them to food crops.

Most attention has been given to the crucial role of N, P and K fertilizers in increasing crop production, but secondary nutrients and micronutrients are also critically important. Roughly one-third of the world's population is at risk of one or more micronutrient deficiencies. The most common mineral trace element deficiencies are Fe, I and Zn (in 1.5 to 2 billion people each), most likely followed by Se and Cu. Specific fertilizer management practices have been or are being developped to increase grain density in Zn, Se and I and address deficiencies in these essential nutrients in humans. Micronutrient-rich crops, particularly pulses, have not benefited as much from the Green Revolution, and now comprise a smaller proportion of the diets of the world's malnourished poor.

Conclusions

Plant nutrients, their importance in crop production, and some insights into how to best manage them for sustainable production systems are discussed. Although fertilizer management is broadly described by the four "rights" of the 4R Nutrient Stewardship, determining which practice is right for a given field is dependent on the local soil and climatic environment, crop, management conditions, and other site-specific factors, including the education, skills, and experience of the farmer and his advisers.

Improving management of plant nutrients is key to meeting the global requirement of food, feed, fiber, and fuel for the growing world population. Hunger and malnutrition can be reduced by improving crop nutrient management through the use of nutrient stewardship, and by providing the right people with the right information to improve nutrient use.

Maximizing input use efficiency and profitability means fine-tuning decisions using site-specific information from individual fields. Precision farming tools for assessing needs, adjusting application, and monitoring results can provide the data to help farmers and their advisers make better-informed decisions to make farming sustainable, and provide for optimum yields, most efficient use of resources, and least negative impact on the environment. The importance of improving NUE will increase in the coming years due to the dependence on non-renewable raw materials and the need to minimize impacts on the air, soil and water. NUE is a dynamic indicator of nutrient management that can be applied at different levels of evaluation (e.g. country, region and farm), but it must be associated with other indicators to reflect the performance of the whole system.

Competition for food, feed and biofuels are putting greater pressure on alleviating global hunger as more grain is needed for direct consumption and for producing the animal-based protein diets, and the growing demand for biofuels in developed countries. Biotechnology and genetic advances will be critical to increasing crop yields, but meeting the world's escalating food needs cannot be achieved by biotechnology alone. Without mineral fertilizers, the world would produce only about half as much staple foods and more forested lands would have to be converted to crop production. Plant nutrients from both organic and inorganic sources are needed for higher crop production. Inorganic fertilizer plays a critical role in the world's food security, but the highest yields are often the result of using organic and inorganic sources together. Integrated soil fertility management (i.e. optimizing fertilizer and organic resources, along with improved genetics, and using modern technology) is critical to optimizing food production and efficient use of plant nutrients. Using the *right source,* at the *right rate*, at the *right time*, and in the *right place,* is a basic principle of nutrient management and can be adapted to all cropping systems throughout the world to ensure productivity, profitability and environmental stewardship are optimized. Putting the *right information* in the hands of the *right people* further ensures achieving efficient use of plant nutrients.

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