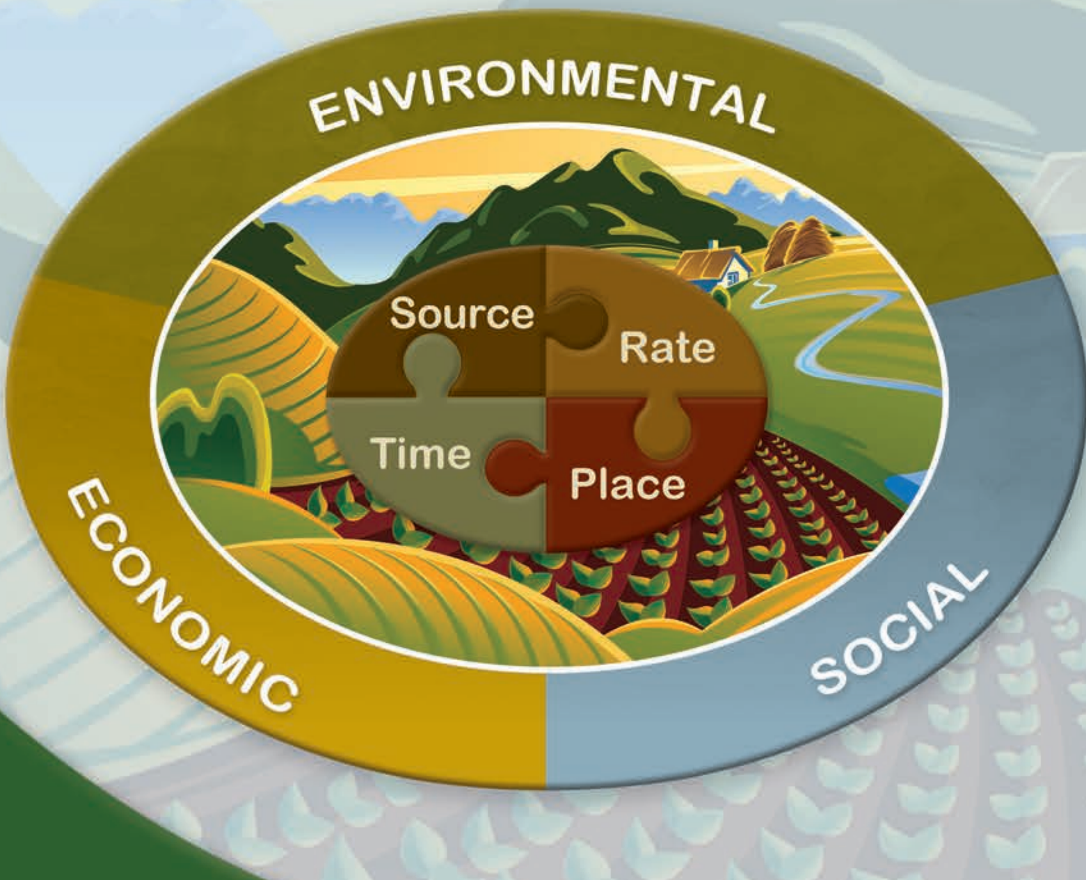
4R PLANT NUTRITION

A Manual for Improving the Management of Plant Nutrition

METRIC VERSION



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Metric Version

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Foreword

4R **NUTRIENT STEWARDSHIP** is a new innovative approach for fertilizer best management practices adopted by the world's fertilizer industry. This approach considers economic, social, and environmental dimensions of nutrient management and is essential to sustainability of agricultural systems. The concept is simple—apply the right source of nutrient, at the right rate, at the right time, and in the right place—but the implementation is knowledge-intensive and site-specific.

We developed this manual to explain the concept of 4R Nutrient Stewardship and to outline the scientific principles that define the four "rights". It is not intended to educate the reader on the basics of soil fertility and plant nutrition, but rather to help the reader adapt and integrate those fundamental principles into a comprehensive method of nutrient management that meets the criteria of sustainability.

The manual includes chapters on scientific principles behind each of the four Rs with supporting practices. We also discuss adoption of practices on the farm, approaches for nutrient management planning and measuring sustainability performance. Most of the chapters include modules outlining case studies from around the world illustrating various applications of the concept. The case studies presented demonstrate the universality of 4R Nutrient Stewardship application in diverse cropping systems from small enterprises to large commercial farms and plantations.

This material provides a foundation for the implementation of improved nutrient management based on the principles of the 4Rs. It is not a recipe or a guidebook…4R nutrient management is site specific. Detailed plant nutrition management practices will be dictated by the goals of the farmer, available resources, the cropping system, soil conditions, climatic conditions, and other factors that influence any management decision.

IPNI is dedicated to the development and promotion of scientific information about the responsible management of plant nutrition. 4R Nutrient Stewardship encompasses all the principles related to such management. We hope this manual will be a useful tool for farmers and their advisers, extension workers, researchers, regulators, and anyone with an interest in the management of plant nutrition.

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Additional Resources for the 4R Plant Nutrition Manual

IPNI encourages all users of the manual to consult the IPNI website http://www.ipni.net/4R for details on additional resources related to this manual including:

1. Our most up-to-date collection of Modules and Case Studies available for download.
2. Guidelines for those wishing to submit examples to our library of Modules and Case Studies.
3. Details on alternative eBook formats of the 4R Plant Nutrition Manual.
4. Details on accompanying PowerPoint slide sets.
5. Details on other related resources for 4R Nutrient Stewardship.

Feedback

We would appreciate feedback from users of this manual. Please send your responses to 4Rmanual@ipni.net

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Chapter 1

GOALS OF SUSTAINABLE AGRICULTURE

ABOUT 30 YEARS AGO, the Advisory Panel on Food Security, Agriculture, Forestry, and Environment (1987) was asked by Gro Harmlem Brundtland, then Chairman of the World Commission on Environment and Development (WCED), how humankind could be protected from hunger on an ecologically sustainable basis. In their report to the WCED, they stated: "The next few decades present a greater challenge to the world food systems than they may ever face again. The effort needed to increase production in pace with an unprecedented increase in demand, while retaining the essential ecological integrity of food systems, is colossal both in its magnitude and complexity. Given the obstacles to be overcome, most of them man-made, it can fail more easily than it can succeed." This sobering appraisal is as applicable today as it was then.

This Advisory Panel's report constituted the basis of the recommendations on food security and sustainability of Brundtland's WCED report, titled *Our Common Future* (1987). The report addressed the growing concern "about the accelerating deterioration of the **human environment** and **natural resources** and the consequences of that deterioration for **economic** and **social development**." The challenge to increase food production in an economically viable way while retaining the ecological integrity of food systems is the underlying aim of sustainable agriculture.

There are numerous characterizations of sustainable agriculture, but most emphasize a driving need to accommodate growing demands for production without compromising the natural resources upon which agriculture depends. Despite the multiplicity in definitions of sustainability, there is a generally agreed upon common denominator in the attributes that characterize it. One of those important traits is that of its multi-dimensionality. The concept of sustainability does not apply only to one dimension (e.g. social, economical, or environmental) in isolation, but rather to all of them simultaneously.

The application of such multi-dimensional vision to agriculture can be facilitated if the traditional classification into social, economical, and environmental components is further spelled out. One effective way of visualizing the multiplicity of resources involved in the functioning of agriculture is to group them as assets or capital in five categories as was suggested by UNCTAD-UNEP (2008):

- **Natural capital**. This capital comprises the resources that are used for food, fiber, and wood production—notably land, water, and energy, as well as those used in producing and transporting the necessary inputs (e.g. raw materials for fertilizers). Moreover, this capital is also the source of natural or wild food and of important environmental services, such as waste disposal, nutrient cycling, soil formation, biological pest control, climate regulation, wildlife habitats, storm protection and flood control, carbon sequestration, pollination, and landscape.

- **Social capital**. It is linked to the norms, values, and attitudes that prompt people to cooperate and that are reflected in mutually beneficial collective action. Poorly linked communities, lacking in trust and partnerships, are more exposed to environmental hardship and food insecurity. The organization of farmers in cooperatives or in technological development groups provides incentives for working together and sharing knowledge and resources.
- **Human capital**. This includes the total capability of individuals, which is based on their knowledge, skills, health, and nutrition. The contributions from these assets depend on the extent of use of people's expertise, which is favored through the promotion of participation and education—both formal and non-formal—and the provision of adequate health care. The involvement of farmers in the process of generating new technological alternatives (for instance through on-farm research) is an example of an approach that contributes to developing human capital. Better education is clearly essential when agricultural practices such as fertilizer management need to be improved.
- **Physical capital**. It is the stock of man-made material resources such as buildings, market infrastructure, irrigation schemes, communication networks, tools, machinery, and energy and transportation systems that increase the productivity of labor. Access to markets is often limited by the lack of proper communications infrastructure.
- **Financial capital**. This capital is related to the flow of money in the system, which is dependent on factors such as prices, costs, income, profit margins, savings, credit, and subsidies. Poverty remains as the largest stumbling block for agriculture development and food security—especially in developing countries—because it prevents people from having access to the means that could improve their lives.

The sustainability of agricultural systems can be assessed by their impact on the assets described above. Agricultural technologies that lead to a resilient growth in natural, social, human, physical, or financial capital can be deemed to be sustainable. In turn, since agricultural systems interact with the five types of capital through a feedback loop, having large stocks of those five kinds of assets further favors their functioning.

The 4R Nutrient Stewardship approach is an essential tool in the development of sustainable agricultural systems because its application can have multiple positive impacts in the assets mentioned above.

There is an immediate connection between applying the right nutrient source, at the right rate, right timing, and right placement, and beneficial impacts on components of the natural capital evidenced through better crop performance, improved soil health, decreased environmental pollution, and the protection of wildlife. Similarly, positive effects are expected on financial capital, as farmer profits improve, bringing about improvement in their quality of life and increased economic activity in their communities.

However, the implementation of 4R Nutrient Stewardship can also increase the social, human, and physical capital. The development of site-specific nutrient management practices, for instance, implies research work in farmer fields, requiring their active involvement, which normally results in better communication among stakeholders (farmers, researchers, and business and government representatives). Furthermore, the educational level of the participants will also increase through both formal and non-formal activities. There are numerous examples of successful organizations run by farmers that generate and disseminate agricultural technologies.

The adoption of new and winning technologies related to 4R Nutrient Stewardship can also have positive consequences on physical capital, because it usually encompasses better infrastructure to access markets—both for inputs and outputs—and for communication. Good roads are needed to bring in fertilizers and other inputs, and to take away the harvests. The growing access by members of the farming community to updated information through cellular telephones and digital communication tools reflects in better communication resources for society.

When viewed in a wide and integrated way, 4R Nutrient Stewardship can have potentially far-reaching effects on the sustainability of agricultural systems that extend beyond the immediate benefits in terms of crop nutrition.

***Sustainability** of agricultural systems can be assessed by their impact on natural capital, social capital, human capital, physical capital, and financial capital.*

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Chapter 2

THE 4R NUTRIENT STEWARDSHIP CONCEPT

PLANT NUTRITION MANAGEMENT applies to a wide range of systems, from extensive areas of rangeland and pasture used for grazing, to intensive production of annually seeded crops to plantations, and even to controlled greenhouse culture of fruits, vegetables, and ornamentals. Such systems around the world are located in diverse soils and diverse climates. This chapter aims to describe the common principles of plant nutrition across these diverse systems, and a framework for the continual improvement of practices involved in managing plant nutrients.

2.1 Right Source at the Right Rate, Time, and Place

Applying the right source of plant nutrients at the right rate, at the right time, and in the right place is the core concept of 4R Nutrient Stewardship. These four "rights" are all necessary for sustainable management of plant nutrition: management that sustainably increases the productivity of plants and crops. As described in the previous chapter, sustainability consists of economic, social, and environmental dimensions. All three dimensions need to be included in the assessment of any nutrient management practice to determine whether or not it is "right."

The fertilizer rights—source, rate, time, and place—are connected to the goals of sustainable development (**Figure 2.1**). For any given system, stakeholders need to define the general goals, but managers are best equipped to choose the practices. In order to define goals, stakeholders need to understand how the management of plant nutrition affects the performance of the plant system. Stakeholders include not only managers and their advisers, but also those who purchase the products and live in the environment of the system. Because plant-based production systems are widespread—and people rely on them for food, fuel, fiber, and aesthetics—essentially everyone is a stakeholder to some degree. Thus, their definition of performance will include the productivity and profitability of the system (the economic dimension), its impacts on soil, water, air, and biodiversity (the environmental dimension), and its impacts on quality of life and employment opportunities (the social dimension). Enterprise-specific goals need to align with general goals for sustainable development for a region.

Fertilizer management, to be considered "right," must support stakeholder-centric goals for performance. However, the farmer, the manager of the land, is the final decision-maker in selecting the practices—suited to local site-specific soil, weather, and crop production conditions, and local regulations—that have the highest probability of meeting the goals. Because these local conditions can influence the decision on the practice selected, right up to and including the day of implementation, local decision-making with the right decision support information would perform better than a centralized regulatory approach.

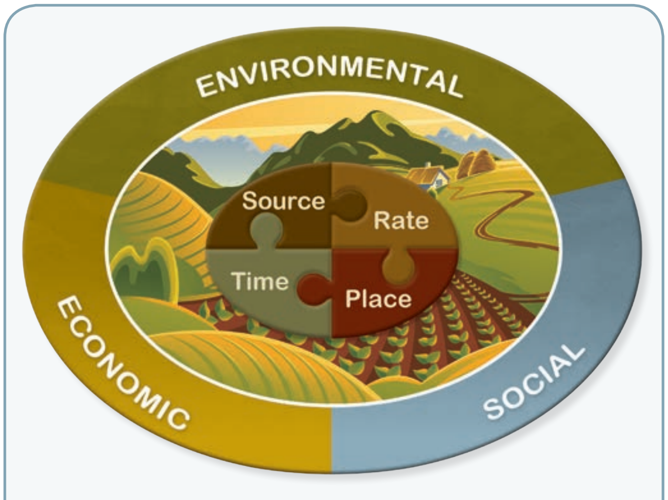

Figure 2.1 The 4R Nutrient Stewardship concept defines the right source, rate, time, and place for fertilizer application as those producing the economic, social, and environmental outcomes desired by all stakeholders to the plant ecosystem.

2.2 Principles Supporting Practices

The sciences of physics, chemistry, and biology provide fundamental principles for the mineral nutrition of plants growing in soils. The application of these sciences to practical management of plant nutrition has led to the development of the scientific disciplines of soil fertility and plant nutrition. The management components source, rate, time and place each have unique science which describes the processes important to plant nutrition.

Specific scientific principles guide the development of practices determining right source, rate, time, and place. A few examples of the key principles and practices are shown in **Table 2.1**. These and other important principles of plant nutrition will be described in more detail in the following four chapters.

The principles are the same globally, but how they are put into practice locally varies depending on specific soil, crop, climate, weather, economic, and social conditions. Farmers and crop advisers make sure the practices they select and apply locally are in accord with these principles.

Table 2.1 Examples of key scientific principles and associated practices.

	The Four Rights (4Rs)			
	Source	**Rate**	**Time**	**Place**
Examples of Key Scientific Principles	◆ Ensure balanced supply of nutrients ◆ Suit soil properties	◆ Assess nutrient supply from all sources ◆ Assess plant demand	◆ Assess dynamics of crop uptake and soil supply ◆ Determine timing of loss risk	◆ Recognize crop rooting patterns ◆ Manage spatial variability
Examples of Practical Choices	◆ Commercial fertilizer ◆ Livestock manure ◆ Compost ◆ Crop residue	◆ Test soils for nutrients ◆ Calculate economics ◆ Balance crop removal	◆ Pre-plant ◆ At planting ◆ At flowering ◆ At fruiting	◆ Broadcast ◆ Band/drill/inject ◆ Variable-rate application

Source, rate, time, and place are the necessary and sufficient components to describe any application of nutrients to any crop.

The four "rights" provide a simple checklist to assess whether a given crop has been fertilized properly. Asking "Was the crop given the right source of nutrients at the right rate, time, and place?" helps farmers and advisers to identify opportunities for improvement in fertilizing each specific crop in each specific field.

A balance of effort among the four rights is appropriate. It helps avoid too much emphasis on one at the expense of overlooking the others. Rate may sometimes be overemphasized, owing to its simplicity and direct relation to cost. Source, time, and place are more frequently overlooked and may hold more opportunity for improving performance.

2.3 The 4Rs Fit into Cropping Systems

The four "rights" are interconnected. They must work in synchrony with each other and with the surrounding environment of plant, soil, climate, and management. For most systems in which plants are managed to provide food, feed, fiber, fuel, and aesthetic benefits, soils are the medium in which the plants grow. Soil fertility is a basic need for plants to grow productively. Although fertility is vital to productivity, not all fertile soils are productive soils. Poor drainage, drought, insects, diseases, and other factors can limit productivity, even when fertility levels of all plant nutrients are adequate. To fully understand soil fertility, we must know other factors which support…or limit…productivity.

Plants depend on soil for mechanical support, water, air, and nutrients. They also depend on external factors like light and temperature. All of these factors are linked to each other and influence plant growth and nutrient uptake in numerous ways. Since water and air occupy the pore spaces in the soil, factors that affect water necessarily influence soil and air. In turn, water affects soil temperature. Nutrient availability is influenced by all three: air, water, temperature… and more, as plant root growth responds to additional stresses including soil compaction, soil depth, and the presence of many kinds of microbial organisms in the soil.

Table 2.2 Performance indicators reflect the social, economic, and environmental dimensions of the performance of the crop-soil-climate system. Their selection and priority depends on stakeholder values.

Performance Indicator	Relevance		
	Economic	Environmental	Social
Farmland Productivity	✓	✓	
Soil Health	✓	✓	
Nutrient Use Efficiency	✓	✓	
Water Quality		✓	✓
Air Quality		✓	✓
Greenhouse Gas Emissions		✓	✓
Food and Nutrition Security	✓		✓
Biodiversity		✓	✓
Economic Value	✓		✓

The nutrition of plants is therefore part of a dynamic system, varying from one place to another and from one time to another. The response to application of plant nutrients varies with all the above-mentioned factors, and thus managing plant nutrition is a site-specific activity. Within production systems, nutrients are constantly being removed from the soil in the form of plant and animal products, and by processes of leaching, volatilization, and erosion. Some forms of nutrients can be tied up by chemical reactions with clay minerals and other constituents of soils. Organic matter and soil organisms immobilize, then release, nutrients.

Plant nutrition practices thus interact with the surrounding plant-soil-climate system (**Figure 2.1**). For fertilizer use to be sustainable, it must enhance the performance of the plant system. The performance of the system is influenced not only by the 4Rs, but also by how they interact with other management practices such as tillage, drainage, cultivar selection, plant protection, weed control, etc. The plant-soil-climate system includes factors such as genetic yield potential, weeds, insects, diseases, mycorrhizae, soil texture and structure, drainage, compaction, salinity, temperature, precipitation, and solar radiation. They interact with management of plant nutrition.

Many aspects of performance are influenced as much by crop and soil management as they are by management of the nutrients applied. For example, nutrient use efficiency is increased when a higher yielding crop cultivar is grown. The performance indicators shown in **Table 2.2** illustrate the complexity of plant agriculture. Performance indicators show trade-offs: one may increase at the expense of others, particularly if plant productivity is reduced. Further detail on selected performance indicators can be found in Chapter 9.3. Plant production systems are complex and can respond in unanticipated ways to the application of nutrients. So the science backing a particular nutrient application practice needs to describe how the practice works at the basic level (for example, the chemistry) and measure outcomes relative to cropping system performance. Whole-system agronomic, environmental and social sciences that measure impacts on whole-system performance are important to the continuous refinement of management practices.

Questions ?

1. The most important aspect of sustainable development is
   a. economic.
   b. social.
   c. environmental.
   d. a balance of the three.

2. Scientific principles guide the development of
   a. stakeholder teams.
   b. site-specific combinations of source, rate, time, and place.
   c. nitrous oxide emissions.
   d. sustainability goals.

3. Right source, rate, time, and place are
   a. independent among themselves and of other practices.
   b. interconnected but independent of other crop management practices.
   c. interconnected and linked to other crop management practices.
   d. independent of fertilizer management.

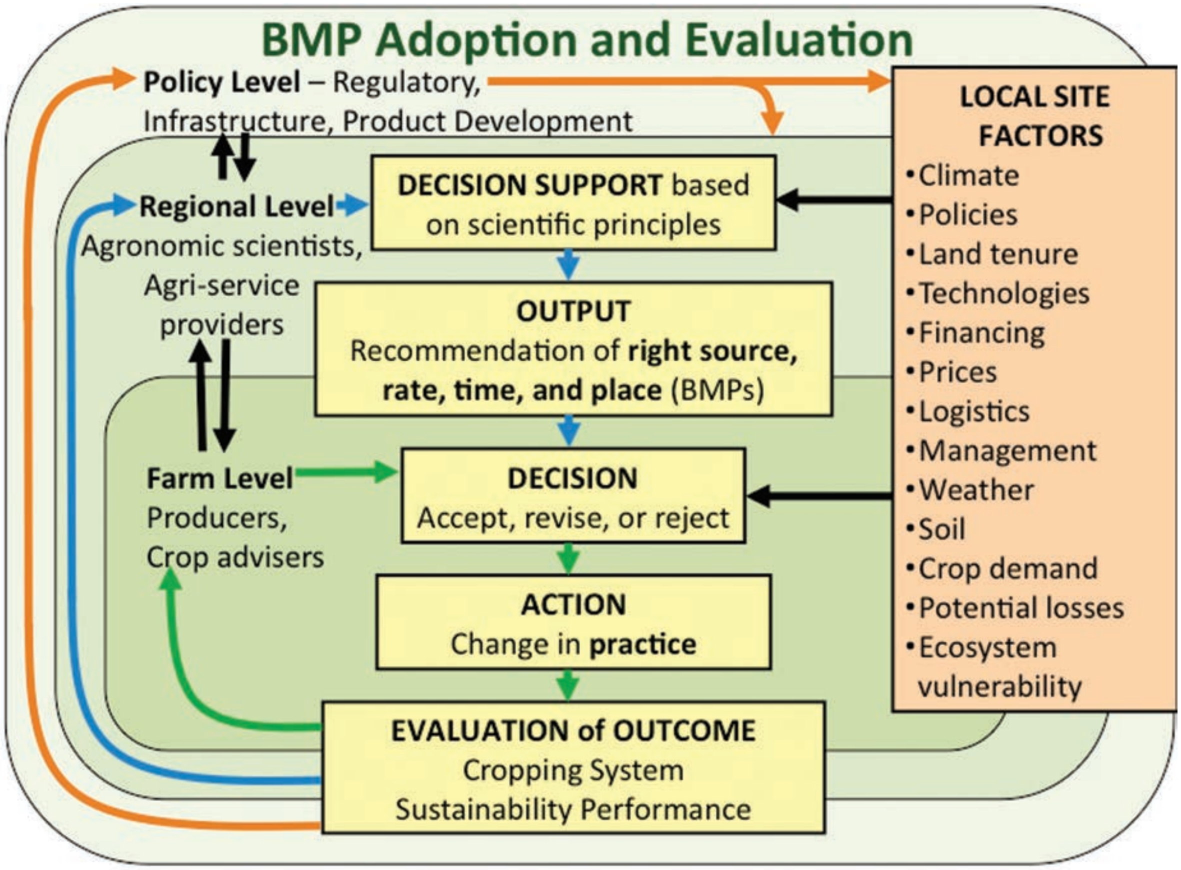

Figure 2.2 The 4R Nutrient Stewardship concept develops best management practices (BMPs) through continuous cycles of decision evaluation in the context of local site factors.

2.4 Continuous Improvement by Evaluating Outcomes

The foregoing, and **Figures 2.1** and **Table 2.2**, described the scope of plant nutrition management and the requirements for improvement of practices. At this point we need to give some more detailed attention to the activities of the people who make improvements happen. The 4R Nutrient Stewardship concept envisions cycles of action and evaluation of performance outcomes on several levels (**Figure 2.2**). These cycles may engage producers and crop advisers at the farm level, agronomic scientists and agri-service providers at the regional level, and government and industry leaders at the policy level. Each level strives to facilitate the adaptation of practices to local site-specific factors to meet sustainability performance goals.

At the farm or local production system level, producers and their advisers make decisions—based on local site factors—and implement them. They then evaluate the outcome of their decisions to determine what decision to make the next time in the cycle. Ideally the assessment of practice performance would be done on the basis of all indicators considered important to stakeholders. Essentially, this is the practice of adaptive management—an ongoing process of developing improved practices for efficient production and resource conservation by use of participatory learning through continuous systematic assessment.

For sound guidance in this process, it is important that crop advisers have some level of professional certification and training.

Farmers and managers recognize environmental and social aspects related to keeping their enterprises viable for future generations. Economic profitability, however, is essential for the sustainability of any enterprise, and may sometimes conflict with goals for environmental and social performance. Motivation for managers to more fully address all three aspects can be provided by programs that include recognition (e.g. carbon offsets related to greenhouse gas mitigation).

The regional level includes the agri-services industry (crop input dealers and agricultural service providers), since they make decisions affecting the capacity to deliver the right sources of plant nutrients, in the right volumes and at the right time and place to meet the demands of producers. There are logistical challenges in delivery and distribution of fertilizer nutrients, which the agri-services industry needs to meet.

The regional level also includes agronomic scientists who work to develop and deliver decision support to managers. Their output is a recommendation of the right source, rate, time, and place—again in relation to local site factors. Decision support systems need continual evaluation and improvement to accommodate changes in availability of technology, and changes in the plant-soil-climate system. The output of decision support systems requires validation in the real-world plant production system. Validation can include many of the same performance indicators as those used at the practical level. Agricultural service providers in the private sector can also participate in such validation through the establishment of regional crop response databases. The professional participation of their crop advisers with agronomic scientists can contribute towards improving the decision support provided by commercial crop advisers.

The policy level involves the regulatory and institutional framework within which producers, managers, advisers, the agri-services industry, and research-extension institutions operate. It includes decision-making on infrastructure enabling the transport and delivery of crop nutrients and crop commodities, and on support for education and research. Industry's activity in development of new fertilizer products also plays an important role at this level. This level would also include the forums in which stakeholder input is formulated into specific performance indicators and goals. Wherever possible, setting goals in terms of system performance, instead of applying regulations to specific practices, aligns better with current initiatives and is more likely to result in actual progress toward enhanced sustainability.

The 4R Nutrient Stewardship concept relates management practices to sustainability goals at all levels, including the farm level. Asking farmers to define their sustainability goals encourages a higher level of commitment and participation and diminishes the negative reactions that tend to result from the imposition of sustainability accounting systems from other parties. The adoption of a 4R nutrient management plan would include identification of such sustainability goals.

Indicators can be presented in many ways, influencing their perception by stakeholders. The time interval chosen for a trend is important. Short-term changes can be misleading. Since sustainability is a long-term issue, use of the longest feasible time interval should be encouraged. Context can be important. When a nutrient balance is presented showing only surplus, deficit, or ratio of output to input, the scope of the nutrient flows in and out of cropland is not apparent. Presentation of the full nutrient balance can lead to a different perception.

Questions ?

4. According to principles of sustainability, stakeholders need to provide input into selection of
   a. performance indicators.
   b. site-specific practices.
   c. source, rate, time, and place.
   d. fertilizer management practices.

5. The final decision on selection of a site-specific combination of source, rate, time, and place should be made by
   a. regulatory authorities.
   b. the crop manager.
   c. a qualified research scientist.
   d. stakeholder teams.

6. Fertilizer management practices should be validated by assessing performance on the basis of
   a. crop yield increases on research plots.
   b. crop yield increases in on-farm plots.
   c. all indicators considered important to stakeholders.
   d. environmental benefits.

7. A science-based fertilizer management practice is one that is
   a. based on past local experience.
   b. consistent with scientific principles and validated through field testing.
   c. specifically described in regulations.
   d. environmentally neutral.

Questions ?

8. The right combination of fertilizer source, rate, time, and place ensures the
   a. highest possible crop yields.
   b. minimum loss of nutrients to water.
   c. minimum loss of nutrients to air.
   d. best chance of achieving sustainability goals.

9. The most important performance indicator of fertilizer management is
   a. nutrient use efficiency.
   b. crop yield.
   c. crop quality.
   d. determined by stakeholders.

10. Performance indicators reflect the progress of fertilizer management in helping to improve
   a. water quality.
   b. air quality.
   c. crop yield.
   d. sustainability.

Conclusion

SOURCE, RATE, TIME, AND PLACE are completely interconnected in nutrient management. None of the four can be right when any one of them is wrong. It is possible that for a given situation there is more than one right combination, but when one of the four changes the others may as well. The 4Rs must work in synchrony with each other and with the cropping system and management environment. 4R Nutrient Stewardship emphasizes the impact of these combinations of management choices on outcomes, or performance, toward improved sustainability.

Every nutrient application can be described as a combination of source, rate, time, and place. The underlying scientific principles that govern the appropriate choice of each are specific to each category. The four chapters that follow this one, Chapters 3 through 6, separately describe the principles specific to each of the 4Rs. They are followed by Chapters 7 through 9, which again focus on the integration of the 4Rs in adaptive management of whole farming systems, in the practices supporting the decisions related to choice of 4R combinations, and in the accountability of such integrated management as expressed in nutrient stewardship plans.

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NOTES

Chapter 3

SCIENTIFIC PRINCIPLES SUPPORTING
RIGHT SOURCE

The core scientific principles that define right source for a specific set of conditions are the following.

- **Consider rate, time, and place of application.**
- **Supply nutrients in plant-available forms.** The nutrient applied is plant-available, or is in a form that converts timely into a plant-available form in the soil.
- **Suit soil physical and chemical properties.** Examples include avoiding nitrate application to flooded soils, surface applications of urea on high pH soils, etc.
- **Recognize synergisms among nutrient elements and sources.** Examples include the P-zinc interaction, N increasing P availability, fertilizer complementing manure, etc.
- **Recognize blend compatibility.** Certain combinations of sources attract moisture when mixed, limiting uniformity of application of the blended material; granule size should be similar to avoid product segregation, etc.
- **Recognize benefits and sensitivities to associated elements.** Most nutrients have an accompanying ion that may be beneficial, neutral or detrimental to the crop. For example, the chloride (Cl^-) accompanying K in muriate of potash is beneficial to corn, but can be detrimental to the quality of tobacco and some fruits. Some sources of P fertilizer may contain plant-available Ca and S, and small amounts of Mg and micronutrients.
- **Control effects of non-nutritive elements.** For example, natural deposits of some phosphate rock contain non-nutritive trace elements. The level of addition of these elements should be kept within acceptable thresholds.

These core principles are integrated into the concepts presented in the rest of this chapter.

All plants require at least 17 essential elements to complete their life cycle. These include the 14 mineral nutrients shown in **Table 3.1** and the three non-mineral elements carbon (C), hydrogen (H), and oxygen (O). The macronutrients are required in relatively large amounts by plants, while the micronutrients are used in much smaller quantities. Nutrient availability in many native soils is too low in at least one or more of the essential nutrients to allow crops to express their genetic potential for growth. In unfertilized ecosystems, native plants adapt to nutrient deficits by limiting their growth rate, a strategy not generally acceptable to farmers concerned with food production and economic returns.

Each plant nutrient has specific functions within the plant; some are relatively simple while others take part in extremely complicated biochemical reactions. Once within the plant, the original source of the mineral nutrient is no longer important.

Table 3.1 Important characteristics of plant mineral nutrients.

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
Macronutrient	Phosphorus	P	phosphate, HPO_4^{2-}, $H_2PO_4^-$	organic matter, minerals	60,000
Macronutrient	Potassium	K	potassium ion, K^+	minerals	250,000
Macronutrient	Calcium	Ca	calcium ion, Ca^{2+}	minerals	125,000
Macronutrient	Magnesium	Mg	magnesium ion, Mg^{2+}	minerals	80,000
Macronutrient	Sulfur	S	sulfate, SO_4^{2-}	organic matter, minerals	30,000
Micronutrient	Chlorine	Cl	chloride, Cl^-	minerals	3,000
Micronutrient	Iron	Fe	ferrous iron, Fe^{2+}	minerals	2,000
Micronutrient	Boron	B	boric acid, H_3BO_3	organic matter	2,000
Micronutrient	Manganese	Mn	manganese ion, Mn^{2+}	minerals	1,000
Micronutrient	Zinc	Zn	zinc ion, Zn^{2+}	minerals	300
Micronutrient	Copper	Cu	cupric ion, Cu^{2+}	organic matter, minerals	100
Micronutrient	Molybdenum	Mo	molybdate, MoO_4^{2-}	organic matter, minerals	1
Micronutrient	Nickel	Ni	nickel ion, Ni^{2+}	minerals	1

Additional elements—including sodium (Na), cobalt (Co), and silicon (Si)—have been shown to be essential or beneficial in some, but not all, plant species.

3.1 Where Nutrients Come From

Since the concentrations of some plant nutrients are often less than optimal in soil, farmers commonly supplement the native supply with on-farm and off-farm resources. On-farm resources may include legume cover crops, animal manure, and crop residues. Off-farm resources may include various processed and unprocessed nutrients and soil amendments.

Of the nutrients, all except N are derived from naturally occurring earth minerals. A sophisticated global industry has been developed to extract these nutrients and concentrate them into forms that are convenient to handle and transport, and that provide a readily available nutrient to plant roots. Some earth minerals can be used directly as sources of plant nutrients or soil amendments, but many others require processing to increase solubility or concentrate the nutrients for efficient transport. Insoluble minerals release plant nutrients very slowly into the soil solution.

Leguminous plants (such as alfalfa, clovers, vetches, and beans) are capable of hosting bacteria (*Rhizobia, Bradyrhizobia, Sinorhizobia, etc.*) in root nodules. These nodules are the site where atmospheric N_2 gas is converted into plant-available forms of N. Legumes that are removed from the field for hay or animal feed may not leave large amounts of residual N in soil. Legumes that are grown and left in place (called green manure) contribute fixed N to nourish the crops that follow and build soil organic matter. The residual N following a cover crop will vary tremendously depending on the plant species and the local conditions.

Animal manures and composts are excellent sources of plant nutrients when used appropriately. Manures contain all elements essential to plants, though their relative ratios often differ from the relative amounts needed. Because some of the N, P, and S forms are organic, they may require a period of breakdown (mineralization) before they are converted into forms that can be assimilated by roots. Composts undergo controlled decomposition during their incubation period, resulting in an organic product that is relatively stable and slower to decompose than animal manures. The nutrients in manures and composts came from feed and hay harvested fields that likely received fertilizer; nutrients added to crops cycle from fields both nearby and far away. Of course animals produce no nutrients during their digestion, but merely excrete what is not absorbed from their feed.

Almost all nutrients enter plants through the root system. The primary form of uptake is shown in **Table 3.1**. Foliar fertilization can be useful in some situations, such as overcoming a developing deficiency or supplementing the nutrient supply during periods of peak demand. However plants are adapted to acquiring most of their nutrients from the soil solution through their roots.

3.2 Selecting the Right Source

The idea of selecting the most appropriate nutrient source seems simple in concept, but many factors need to be considered when making this choice. In addition to the six core scientific principles mentioned earlier, factors such as fertilizer delivery issues, environmental concerns, product price, and economic constraints can all be important. Decisions may be influenced by the availability of various materials within reasonable distance. The accessibility of fertilizer application equipment may also narrow the options. It is tempting to rely on tradition and experience when making these decisions, but a periodic review of these factors helps farmers gain the maximum benefit from these valuable resources and the significant economic investment they represent and allows consideration of new fertilizer materials.

Selecting the right fertilizer source begins with determining which nutrients are actually required to meet production goals. Nutrients that are limiting can be determined through the use of soil and plant analysis, tissue tests, nutrient omission plots, leaf color sensors, or visual deficiency symptoms (see Chapter 8). All of these need to be done in advance of the fertilizer application decision. Merely guessing at the needed nutrients can lead to numerous problems associated with under- or over-fertilization and can lead to ignoring specific nutrients until shortages become severe. Guessing at specific nutrient requirements can also result in poor economic return if over-applied nutrients are already present in adequate concentrations.

It is common to focus on a single nutrient that is in short supply to the exclusion of other nutrients. For example, a lack of adequate N is easy to detect by observing stunted growth and chlorotic leaves. However, the maximum benefit from applied N fertilizer will not be obtained if other deficiencies (such as P or K) are not also corrected. Although we often focus on individual nutrients, all the nutrients function together to support healthy plant growth.

Each plant nutrient is available in different chemical forms and they undergo unique reactions after entering the soil. Regardless of their original source and their soil reactivity, they must be in a soluble and plant-available form before they can be taken up by plants.

Fertilizers are normally sold with a grade, or guaranteed minimum analysis. The grade is represented as a series of numbers representing percent nutrient content by weight. The first number represents total N; the second, available P as P_2O_5 equivalent, and the third, soluble K as K_2O equivalent. For example, 100 kg of a 10-15-20 fertilizer contains 10 kg of N, 15 kg of P_2O_5, and 20 kg of K_2O. For fertilizers containing other nutrients, additional numbers can be added with the chemical symbol of the nutrient; for example, a 21-0-0-24S fertilizer contains 21% N and 24% S.

Questions ?

1. One of the seven core scientific principles that define **right source** for a specific set of conditions is to
   a. apply only plant-available forms of nutrients.
   b. suit soil physical and chemical properties.
   c. ignore blend compatibility.
   d. avoid applying associated elements.

2. An element is considered essential to plant growth if
   a. the soil contains only small quantities of it.
   b. plants require it in its elemental form.
   c. all plants require it to complete their life cycle.
   d. it is capable of being taken up by plants.

3. Selecting the right source of fertilizer should be based on
   a. tradition and experience.
   b. price alone.
   c. focusing only on a single nutrient in short supply.
   d. determining which nutrients are limiting.

4. The chemical forms of P and K in fertilizers are
   a. expressed as P_2O_5 and K_2O equivalents.
   b. P_2O_5 and K_2O.
   c. P and K.
   d. converted to elemental form by multiplying by 2.29.

Questions follow standard exam format but are designed to review main points and stimulate group discussion. For answers, see page A-7.

Note that the chemical forms of P and K in fertilizers are not P_2O_5 or K_2O. Rather, the oxide form is the traditional unit used for these fertilizer expressions. Phosphorus and potassium contents of fertilizers are expressed as P_2O_5 and K_2O equivalents, respectively. To convert from the oxide form to the elemental form, use the following conversion factors:

$$P_2O_5 \times 0.437 = P$$
$$P \times 2.29 = P_2O_5$$
$$K_2O \times 0.830 = K$$
$$K \times 1.20 = K_2O$$

Figure 3.1 Three types of compound fertilizers (containing a combination of N, P, and K in each granule)

3.3 Forms of Fertilizer

The form of fertilizer to be used is frequently one of the first decisions to make.

Bulk blends consist of a mix of various granular fertilizers in a batch that will meet the specific needs of a customer. Blends are adjusted with differing ratios of nutrients for individual crop and soil conditions. They are popular because they are made from least-cost components and mixed with relatively simple and inexpensive equipment. The individual fertilizer components must be chemically and physically compatible for mixing and storing.

Attention needs to be given to possible segregation of the individual components that may occur during transportation and handling. Fertilizer blending operators are aware of this concern and try to match uniform particle sizes of different nutrients to minimize segregation of the blended materials during transportation.

Compound fertilizers are a mixture of multiple nutrients within a single solid fertilizer particle (**Figure 3.1**). This approach differs from a blend of individual fertilizers mixed together to achieve an average nutrient composition. Each particle of compound fertilizer delivers a mixture of nutrients as it dissolves in the soil and eliminates the potential for any segregation of particles during transport or application (**Figure 3.2**). A uniform distribution of micronutrients throughout the root zone is also possible when they are included in compound fertilizers. There are certain ratios of nutrients that are commonly available for various agronomic application and they offer simplicity in making fertilizer decisions.

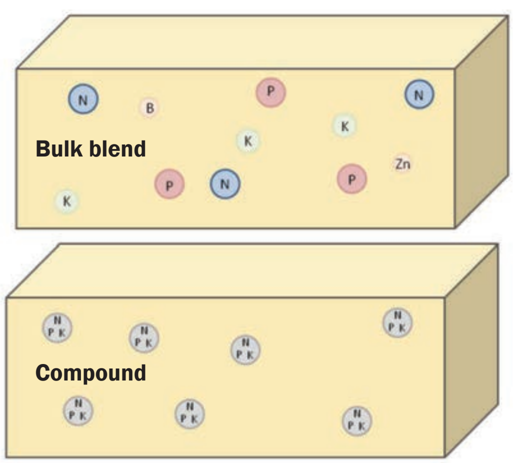


Figure 3.2 Nutrient distributions in soil comparing bulk blend and compound fertilizers. The more uniform distribution with compound fertilizers can be important for nutrients applied at low rates, the bulk blend offers more opportunity to match the recommended rate for each nutrient.

Fluid Fertilizers are popular because they allow for mixing many nutrients into a single homogeneous, clear liquid that can be applied uniformly in the field. These clear fluids can be custom blended and applied as a starter fertilizer, a subsurface concentrated band, or dribbled as a topdress application. They are very popular for addition to irrigation water. Fluids are easy to handle and are excellent carriers for a variety of micronutrients, herbicides, and pesticides. Blending several materials together can reduce the number of trips required in the field, thereby reducing soil compaction and fuel consumption.

Fluid fertilizer

Not all fluid fertilizers are compatible with each other when mixed. **Figure 3.3** provides guidelines for mixing compatibility when combining fluid materials. It is always recommended to mix a small amount of fertilizer or chemical in a jar to test the mixing suitability before blending large quantities.

Applying fluid fertilizer with irrigation water (fertigation) is commonly done to save labor, increase the flexibility of timing nutrient application, and improve nutrient efficiency. This is done in both pressurized irrigation systems (such as drip, microsprinklers, or pivots) and in furrow irrigation. It is important that nutrients used for fertigation do not cause

Questions ?

5. Compound fertilizers can be useful for
   a. single-nutrient applications.
   b. supplying differing ratios of nutrients to meet specific needs.
   c. eliminating potential segregation of particles.
   d. macronutrients without micronutrients.

6. Fluid fertilizers are popular because they
   a. are blended with granular fertilizers.
   b. can easily be added to irrigation water.
   c. are made from least-cost components.
   d. combine multiple nutrients within a single particle.

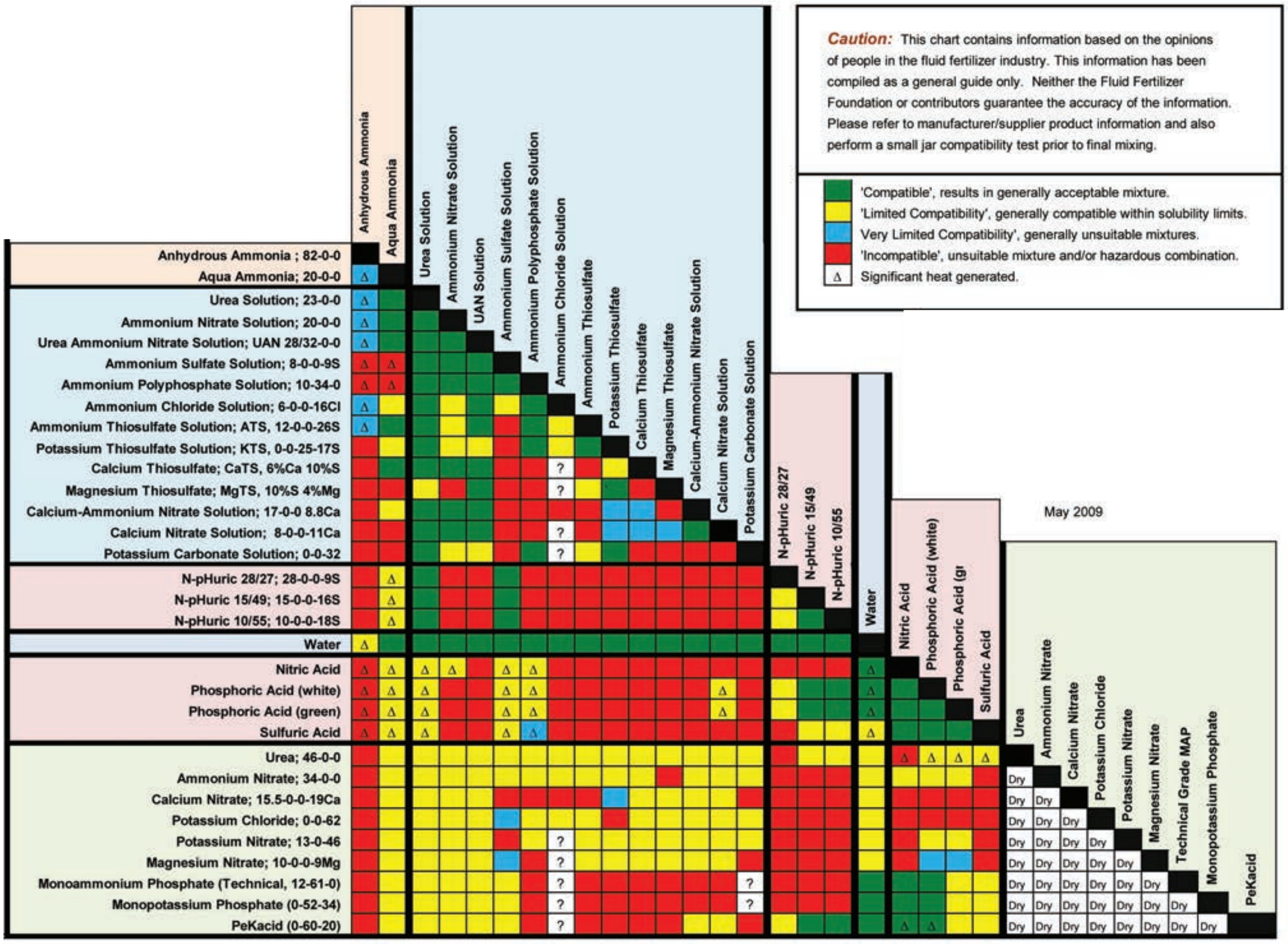


Figure 3.3 Compatibility of mixtures of fluid fertilizer (adapted from Fluid Fertilizer Foundation, 2009).

clogging of the irrigation equipment or chemically precipitate before reaching the target area.

There are many excellent fertilizers that are compatible with any type of irrigation system. Particular attention needs to be given when adding P fertilizers to any irrigation water that contains abundant Ca or Mg in order to avoid chemical precipitation and plugging in the pipes and emitters. Also remember that nutrient distribution through fertigation can be no better than the uniformity of the water delivery system in the field.

Foliarly applied fertilizer

Fluid fertilizers are also used for foliar nutrition, spraying a dilute nutrient solution onto leaves. This technique can be particularly effective in overcoming or preventing nutrient shortages or for meeting periods of peak nutrient demand when root uptake may be insufficient to meet plant needs. However, foliar nutrition is generally considered as a supplement to nutrient uptake through the root system. Many high solubility materials are used as foliar fertilizers to meet every potential nutrient deficiency. The solution sprayed onto the leaf surface is generally relatively dilute in order to avoid salt (osmotic) damage to the foliage. When the fertilizer concentration is too high in the foliar spray, the leaf tissue can become desiccated and damaged (commonly referred to as leaf burn). Product labels should be closely followed to achieve maximum nutritional benefit.

Suspension fertilizers are made by suspending very small particles within a solution. A suspending clay or gelling agent is used to keep the fertilizer particles from settling out of the liquid. Suspensions allow use of fertilizer materials lower in solubility than those that can be used with clear liquid fertilizers, and higher nutrient concentrations can be achieved. Larger quantities of micronutrients can be incorporated into suspensions, as well as herbicides and insecticides that are not suitable for clear fertilizers. Some type of agitation is commonly used in the tank to keep the suspension well mixed. Larger nozzles are used for application than with clear fluid fertilizers.

Enhanced-efficiency fertilizers are not a single group of materials, but consist of products or technologies that generally improve fertilizer use efficiency beyond standard practices and materials.

Slow-release and controlled-release fertilizers can be useful for improving nutrient use efficiency. There are several mechanisms for controlling nutrient release from a fertilizer particle. The most common is when a protective coating of polymer or S is added to a fertilizer in order to control the dissolution and release of nutrients (**Figure 3.4**). Typical release rates range from a few weeks to many months. Other slow-release fertilizers may have low solubility or a resistance to microbial decomposition to control nutrient release. Each of these products may be well suited to a specific set of conditions, but that does not mean that they are well suited to all conditions. Specific products must be matched with the proper soil, crop, and environmental conditions in order to get maximum benefit. Nitrogen is the nutrient generally targeted for controlled release, but there are circumstances when sustained release of other nutrients is also desirable.

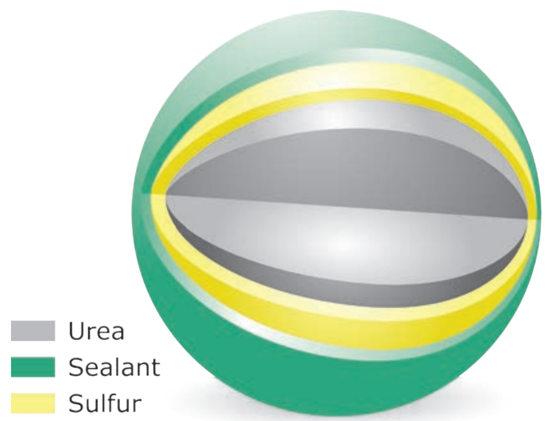


Figure 3.4 Coated enhanced fertilizer example.

Biological and chemical inhibitors are sometimes added to fertilizer to temporarily enhance or disrupt very specific soil reactions. Nitrification inhibitors are additives which slow the conversion of ammonium to nitrate in soil, which may reduce the possibility of nitrate leaching or denitrification. Urease inhibitors, another class of additives, can be used with urea fertilizer to temporarily delay its transformation to ammonium by inactivating urease, a common soil enzyme. This delay can reduce ammonia volatilization losses to the atmosphere, especially when urea is applied to the soil surface.

Polymeric materials are liquid polymers developed to temporarily bind with soil cations with the objective of reducing chemical reactions that can decrease P solubility.

3.4 Forms of Organic Amendment: Manures, Composts

Organic materials can be excellent sources of both macro and micronutrients for crop nutrition. Since these materials are extremely variable depending on their source, handling, and processing, only general principles are given here.

Much of the N in manure and composts is present in organic compounds which must be converted by soil microbes (mineralized) to ammonium or nitrate before uptake by roots. Mineralization rates are determined by microbial activity, which varies with environmental factors (such as temperature and moisture), the properties of the organic material (such as the C:N ratio and lignin content) and the placement (incorporation) of the organic material. Failure to synchronize N release with crop uptake can lead to N shortages and plant nutrient deficiencies, or lead to excessive N release beyond the growing season. (**Figure 3.5**). The ratio of N to P in many manures is not in proper balance with plant requirements. When manures are added to meet the N requirement of crops, P may be overapplied by 3 to 5 times the crop demand. Long-term manure application can result in P accumulation unless attention is given to this imbalance.

Animal manures vary tremendously in their chemical and physical composition due to specific feeding and manure management practices. Nitrogen in manures is present in both inorganic and organic compounds. Nitrogen in fresh manure can be unstable because ammonia can be readily lost through volatilization. Application of fresh manure or slurry on the soil surface can result in large losses of N by volatilization in some situations. Application timing and placement are important considerations for minimizing such losses. Estimating the correct application rate for manure should begin with an accurate chemical analysis of the nutrient content and prediction of N mineralization rates following application. The majority of P in manures and composts is in the inorganic phosphate form and all of the K is present as inorganic K^+, immediately available for plant uptake.

Composts generally contain low concentrations of nutrients. Properly composted materials typically decompose slowly and behave as a slow-release source of N over many months or years. Composts can vary tremendously in quality, maturity, and nutrient content based on the materials included, the conditions of the process, and their handling.

3.5 Nutrient Interactions

Interactions occur when the chemical form or the concentration of a specific nutrient influences the behavior of another nutrient. These interactions are not always well understood or documented, but they are known to occur in the fertilizer, in the soil, in the root zone, and within the plant. Favorable interactions (synergisms) are observed with some nutrients. Undesirable interactions (antagonisms) can

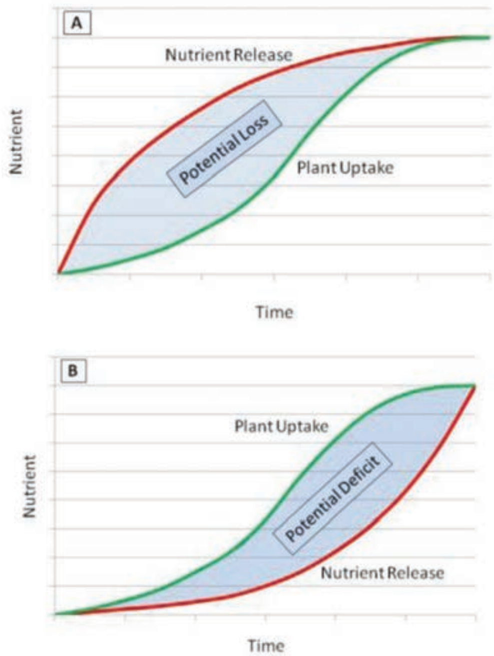


Figure 3.5 Synchronizing nutrient release with plant demand is a challenge with organic materials. Rapid release from organic sources with a low C:N ratio may supply nutrients more rapidly than the plant's demand (A). An organic material with a high C:N ratio may not release nutrients sufficiently rapid to meet the need of growing plants (B).

be avoided by monitoring nutrient status with plant and soil analysis to prevent extreme conditions.

A few examples of nutrient interactions include: (i) the presence of NH_4^+ can improve P availability to plants, thereby improving plant growth, (ii) excessive fertilization with K can lead to depressed uptake of Mg by some forages, resulting in nutritional problems for grazing cattle (grass tetany) or higher incidence of milk fever and retained placentas when fed to dry dairy cows, (iii) high concentrations of P in the soil can interfere with Zn assimilation in some plants, (iv) increases in soil pH following addition of limestone may improve the availability of P and Mo, but reduce the solubility of Cu, Fe, Mn, and Zn.

There is no one single right source of nutrient for all conditions. The need of specific nutrients should be established in advance of application whenever possible. Factors such as fertilizer product availability, nutrient reactions in soil, spreading equipment, and economic return, all need to be considered. These complex decisions should be continually re-evaluated in order to make the right fertilizer selection.

REFERENCES

Havlin, J.L. et al. 2005. Soil Fertility and Fertilizers: An Introduction to Nutrient Management. 7th edition. Pearson Prentice Hall. NJ, USA.

UNIDO-IFDC. 1998. Fertilizer Manual. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Questions ?

7. Controlled-release fertilizers can improve nutrient use efficiency
   a. under specific field conditions.
   b. equally for all nutrients.
   c. by inactivating the urease enzyme.
   d. under all field conditions.

8. Urease inhibitors reduce losses of ammonia most when applied with
   a. urea broadcast on the soil surface.
   b. urea incorporated into the soil.
   c. ammonium sulfate broadcast on the soil surface.
   d. urea ammonium nitrate incorporated into the soil.

9. For a short time after application, monoammonium phosphate (MAP) differs from diammonium phosphate (DAP) in that
   a. DAP provides phosphorus in a more plant-available form.
   b. the nitrogen in DAP will be used more readily by the plant.
   c. only MAP will convert to polyphosphate.
   d. the soil pH around a MAP granule will be lower.

10. Most potassium fertilizer sources
    a. contain potassium in different chemical forms.
    b. differ primarily in the accompanying anions.
    c. should be selected based only on price.
    d. are more effective than manure as a potassium source.

Questions 9 and 10 refer to material in the modules for section 3.3 on the following pages.

Module 3.1-1 The right source of potash improves yield and quality of banana in India. Potassium is an important nutrient in banana production, for both yield and quality. Sulfate of potash (K_2SO_4 or SoP) has a lower salt index and supplies the plant nutrient S, as compared to muriate of potash (KCl or MoP) which supplies the plant nutrient chloride (Cl^-), in addition to K. A study on banana in the south Indian state of Tamil Nadu showed benefits to applying SoP as compared to MoP, as indicated in **Figure 1** below. **Adapted from:** Kumar, A.R. and N. Kumar. 2008. EurAsia J BioSci 2(12):102-109.

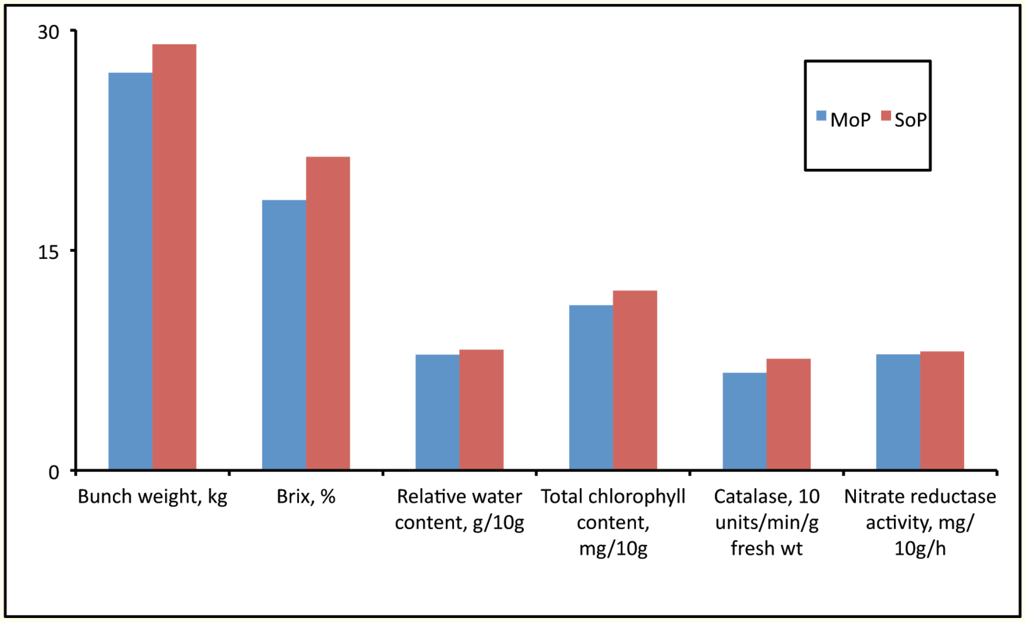
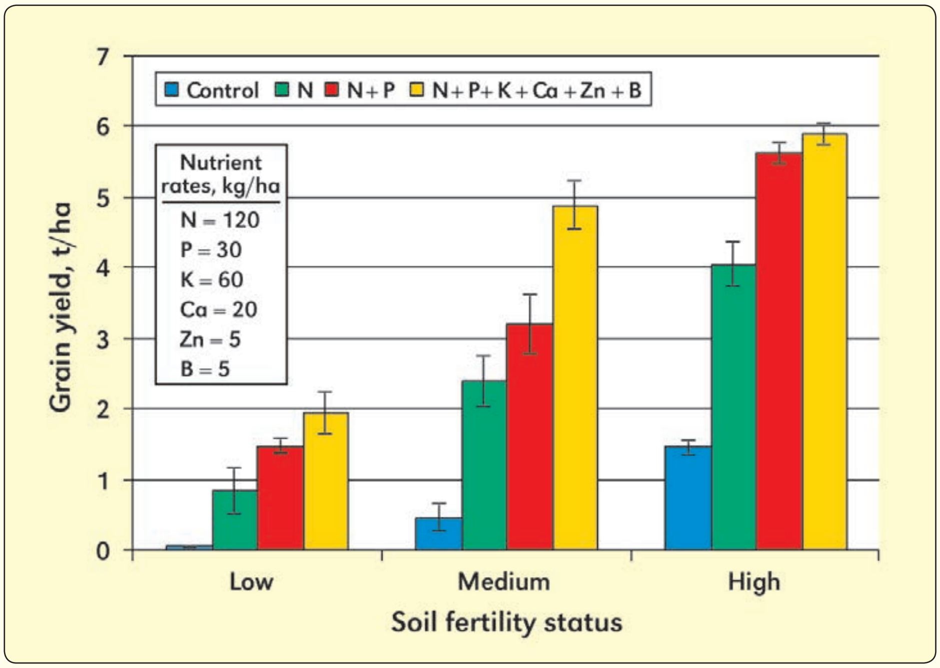


Figure 1. Banana bunch weight, Brix (total soluble sugars), relative water content, and photosynthetic parameters (chlorophyll content, catalase, and nitrate reductase activity) as affected by MoP and SoP as potassium sources.

Submitted by H.S. Khurana, IPNI, India, December 2011.

Module 3.2-1 Balancing organic and mineral nutrients for maize in Africa. Studies in sub-Saharan (SSA) show that fertilizer use is consistently more profitable and efficient on fertile fields. When soils are degraded, restoration of soil fertility through balanced fertilization and organic matter additions is necessary to achieve high crop productivity. Other options for managing soil fertility, such as manure, crop rotations, and improved fallows are most effective when strategically combined with fertilizer. In trials conducted on fields varying in soil fertility across many locations in SSA, application of N alone gave the largest maize yield increase under high and medium soil fertility conditions. Addition of P also led to a significant increase in yields on the high fertility fields, but in medium fertility fields, addition of base cations (K and Ca) and micronutrients (Zn and B) was required to significantly increase crop yields above the N treatment. On the low fertility fields, yields were increased to less that 1 t/ha by applying N and to less than 2 t/ha by applying N, P, K, Ca, Zn and B. Under such conditions, addition of organic resources to increase soil organic matter is required to increase retention of soil nutrients and water, better synchronize nutrient supply with crop demand, and improve soil health through increased soil biodiversity.
Source: Zingore, S. 2011, Better Crops with Plant Food 95(1): 4-6.



Submitted by S. Zingore, IPNI, Kenya, December 2011.

M

Urea

Module 3.3-1 Urea is the most widely used solid nitrogen fertilizer in the world. Urea is also commonly found in nature since it is expelled in the urine of animals. The high N content of urea makes it efficient to transport to farms and apply to fields.

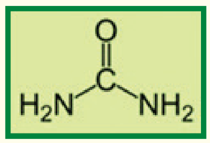
Production. The production of urea fertilizer involves controlled reaction of ammonia gas (NH_3) and carbon dioxide (CO_2) with elevated temperature and pressure. The molten urea is formed into spheres with specialized granulation equipment or hardened into a solid prill while falling from a tower.

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. However, special low-biuret urea is available for unique applications.

Urea manufacturing plants are located throughout the world, but most commonly located near NH_3 production facilities since NH_3 is the major input for urea. Urea is transported throughout the world by ocean vessel, barge, rail, and truck.

Chemical Properties

Chemical formula:	$CO(NH_2)_2$
N content:	46% N
H_2O Solubility (20°C):	1,080 g/L



Agricultural Use. Urea is used in many ways to provide N nutrition for plant growth. It is most commonly mixed with soil or applied to the soil surface. Due to the high solubility, it may be dissolved in water and applied to soil as a fluid, added with irrigation water, or sprayed onto plant foliage. Urea in foliar sprays can be quickly absorbed by plant leaves.

After urea contacts soil or plants, a naturally occurring enzyme (urease) begins to quickly convert the urea back to NH_3 in a process called hydrolysis. During this process, the N in urea is susceptible to undesirable gaseous losses as NH_3. Various management techniques can be used to minimize the loss of this valuable nutrient.

Urea hydrolysis is a rapid process, typically occurring within several days after application. Plants can utilize small amounts of urea directly as a source of N, but they more commonly use the ammonium (NH_4^+) and nitrate (NO_3^-) that are produced after urea is transformed by urease and soil microorganisms.

Management Practices. 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^+. Care should be used to minimize all N losses to air, surface water, and groundwater. Losses of ammonia by volatilization can be managed by careful attention to timing and placement. Avoid urea applications when the fertilizer will remain on the soil surface for prolonged periods of time. Undesired N losses may also result in loss of crop yield and quality.

Urea is a high N-containing fertilizer that has good storage properties and causes minimal corrosion of application equipment. When properly managed, urea is an excellent source of N for plants.

Non-agricultural Use. Urea is commonly used in a variety of industries. It is used in power plants and diesel exhaust systems to reduce emission of nitrous oxide (NO_x) gases. Urea can be used as a protein supplement in the diet of ruminant animals, such as cattle. Many common industrial chemicals are made using urea as an important component.

Source: http://www.ipni.net/specifics

M

Urea-Ammonium Nitrate

Module 3.3-2 Liquid fertilizer solutions or fluid fertilizers are popular in many areas because they are safe to handle, convenient to mix with other nutrients and chemicals, and are easily applied. A solution of urea [$CO(NH_2)_2$] and ammonium nitrate [NH_4NO_3] containing between 28 and 32% N is the most popular N fluid fertilizer.

Production. Liquid urea-ammonium nitrate (UAN) fertilizer is relatively simple to produce. A heated solution containing dissolved urea is mixed with a heated solution of ammonium nitrate to make a clear liquid fertilizer. Half of the total N comes from the urea solution and half from the ammonium nitrate solution. UAN is made in batches in some facilities or in a continual process in others. No emissions or waste products occur during mixing.

Since UAN is a concentrated N solution, its solubility increases as the temperature rises. To prevent the N components from precipitating as crystals, UAN solutions are made more dilute in regions with cold winter temperatures. Therefore, the N concentration in commercial UAN fertilizers will vary from 28% N to 32% N depending on geography. A corrosion inhibitor is usually added to the final solution to protect the steel in storage tanks.

Chemical Properties

	28% N	30% N	32% N
Composition (% by weight)			
Ammonium Nitrate:	40	42	44
Urea:	30	33	35
Water:	30	25	20
Salt-out temperature (°C):	-18	-10	-2
Solution pH:	- - - -	approximately 7	- - - -

Agricultural Use. Solutions of UAN are widely used as a source of N for plant nutrition. The NO_3^- portion (25% of the total N) is immediately available for plant uptake. The NH_4^+ fraction (25% of the total N) can also be assimilated directly by most plants, but is rapidly oxidized by soil bacteria to form NO_3^-. The remaining urea portion (50% of the total N) is hydrolyzed by soil enzymes to form NH_4^+, which is subsequently transformed to NO_3^- in most soil conditions.

Solutions of UAN are extremely versatile as a source of plant nutrition. Due to its chemical properties, UAN is compatible with many other nutrients and agricultural chemicals, and is frequently mixed with solutions containing P, K, and other plant nutrients. Fluid fertilizers can be blended to precisely meet the specific needs of a soil or crop.

UAN solutions are commonly injected into the soil beneath the surface, sprayed onto the soil surface, dribbled as a band onto the surface, added to irrigation water, or sprayed onto plant leaves as a source of foliar nutrition. However, UAN may damage foliage if sprayed directly on some plants, so dilution with water may be needed.

Management Practices. UAN makes an excellent source of N nutrition for plants. However, since half of the total N is present as urea, extra management of timing and placement may be required to avoid volatile losses. When UAN remains on the surface of the soil for extended periods (a few days), soil enzymes will convert the urea to NH_4^+, a portion of which can be lost as ammonia gas. Therefore, UAN should not remain on the soil surface for more than a few days in order to avoid significant loss. Inhibitors that slow these N transformations are sometimes added. When UAN is first applied to soil, the urea and the NO_3^- molecules will move freely with water in the soil. The NH_4^+ will be retained in the soil where it first contacts cation exchange sites on clay or organic matter. Within 2 to 10 days, most of the urea will be converted to NH_4^+ and no longer be mobile. The originally added NH_4^+ plus the NH_4^+ coming from urea will eventually be converted to NO_3^- by soil microorganisms.

Source: http://www.ipni.net/specifics

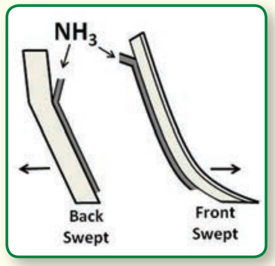
Ammonia

Module 3.3-3 Ammonia is the foundation for the nitrogen fertilizer industry. It can be directly applied to soil as a plant nutrient or converted into a variety of common N fertilizers. Special safety and management precautions are required.

Production. Almost 80% of the Earth's atmosphere is composed of N_2 gas, but it is in a chemically and biologically unusable form. In the early 1900s, the process for combining N_2 and hydrogen (H_2) under conditions of high temperature and pressure was developed. This reaction is known as the Haber-Bosch process:
[$3H_2 + N_2 \rightarrow 2\ NH_3$]

Chemical Properties

Anhydrous Ammonia (NH_3)	
N content:	82% N
Boiling Point:	-33°C
Aqua Ammonia (NH_4OH)	
N content:	20 to 24% N
pH:	11 to 12



A variety of fossil fuel materials can be used as a source of H_2, but natural gas (methane) is most common. Therefore, most NH_3 production occurs in locations where there is a readily available supply of natural gas.

Ammonia is a gas in the atmosphere, but is transported in a liquid state by compressing or refrigerating it below its boiling point (-33 °C). It is shipped globally in refrigerated ocean vessels, pressurized rail cars, and long-distance pipelines.

Agricultural Use. Ammonia has the highest N content of any commercial fertilizer, making it a popular source of N despite the potential hazard it poses and the safety practices that are required for its use. When NH_3 is applied directly to soil, it is a pressurized liquid that immediately becomes a vapor after leaving the tank. Ammonia is usually placed at least 10 to 20 cm below the soil surface, or in such a way to prevent its loss as a vapor back to the atmosphere. Various types of tractor-drawn knives and shanks are used to place the NH_3 in the correct location. Ammonia will rapidly react with soil water to form ammonium (NH_4^+), which is retained on the soil cation exchange sites. Ammonia is sometimes dissolved in water to produce aqua ammonia, a popular liquid N fertilizer. Aqua ammonia does not need to be injected as deeply as NH_3, which provides benefits during field application and has fewer safety considerations. Aqua ammonia is frequently added to irrigation water and used in flooded soil conditions.

Management Practices. Handling NH_3 requires careful attention to safety. At storage facilities and during field application, appropriate personal protection equipment must be used. Since it is very water soluble, free NH_3 will rapidly react with body moisture, such as lungs and eyes, to cause severe damage. It should not be transferred or applied without adequate safety training.

Immediately after application, the high NH_3 concentration surrounding the injection site will cause a temporary inhibition of soil microbes. However, the microbial population recovers as NH_3 converts to NH_4^+, diffuses from the point of application, and then converts to nitrate. Similarly, to avoid damage during germination, seeds should not be placed in close proximity to a recent zone of NH_3 application. Inadvertent escape of NH_3 to the atmosphere should be avoided as much as possible. Emissions of NH_3 are linked to atmospheric haze and changes in rain water chemistry. The presence of elevated NH_3 concentrations in surface water can be harmful to aquatic organisms.

Non Agricultural Uses. Over 80% of NH_3 production is used for fertilizer, either for direct application or converted to a variety of solid and liquid N fertilizers. However, there are many important uses for NH_3 in industrial applications. Household cleaners are made from a 5 to 10% solution of NH_3 dissolved in water (to form ammonium hydroxide). Because of its vaporization properties, NH_3 is used widely as a refrigerant.

Source: http://www.ipni.net/specifics

M

Ammonium Sulfate

Module 3.3-4 Ammonium sulfate was one of the first and most widely used nitrogen fertilizers for crop production. It is now less commonly used, but especially valuable where both N and S are required. Its high solubility provides versatility for a number of agricultural applications.

Production. Ammonium sulfate (sometimes abbreviated as AS or AMS) has been produced for over 150 years. Initially, it was made from ammonia released during manufacturing coal gas (used to illuminate cities) or from coal coke used to produce steel. It is made from a reaction of sulfuric acid and heated ammonia. The size of the resulting crystals is determined by controlling the reaction conditions. When the desired size is achieved, the crystals are dried and screened to specific particle sizes. Some materials are coated with a conditioner to reduce dust and caking.

Most of the current demand for ammonium sulfate is met by production from by-products of various industries. For example, ammonium sulfate is a co-product in the manufacturing process of nylon. Certain by-products that contain ammonia or spent sulfuric acid are commonly converted to ammonium sulfate for use in agriculture. Although the color can range from white to beige, it is consistently sold as a highly soluble crystal that has excellent storage properties. The particle size can vary depending on its intended purpose.

Chemical Properties

Chemical formula:	$(NH_4)_2SO_4$
N content:	21%
S content:	24%
Water solubility:	750 g/L
Solution pH:	5 to 6


$(NH_4)_2SO_4$ crystals

Agricultural Use. Ammonium sulfate is used primarily where there is a need for supplemental N and S to meet the nutritional requirement of growing plants. Since it contains only 21% N, there are other fertilizer sources that are more concentrated and economical to handle and transport. However, it provides an excellent source of S which has numerous essential functions in plants, including protein synthesis.

Because the N fraction is present in the ammonium form, ammonium sulfate is frequently used in flooded soils for rice production, where nitrate-based fertilizers are a poor choice due to denitrification losses.

A solution containing dissolved ammonium sulfate is often added to post-emergence herbicide sprays to improve their effectiveness at weed control. This practice of increasing herbicide efficacy with ammonium sulfate is particularly effective when the water supply contains significant concentrations of calcium, magnesium, or sodium. A high-purity grade of ammonium sulfate is often used for this purpose to avoid plugging spray nozzles.

Management Practices. After addition to soil, the ammonium sulfate rapidly dissolves into its ammonium and sulfate components. If it remains on the soil surface, the ammonium may be susceptible to gaseous loss in alkaline conditions. In these situations, incorporation of the material into the soil as soon as possible, or application before an irrigation event or a predicted rainfall, is advisable.

Most plants are able to utilize both ammonium and nitrate forms of N for growth. In warm soils, microbes will rapidly begin to convert ammonium to nitrate in the process of nitrification [$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$]. During this microbial reaction, acidity [H^+] is released, which will ultimately decrease soil pH after repeated use. Ammonium sulfate has an acidifying effect on soil due to the nitrification process...not from the presence of sulfate, which has a negligible effect on pH. The acid-producing potential of ammonium sulfate is greater than the same N application from ammonium nitrate, for example, since all the N in ammonium sulfate will be converted to nitrate, while only half of the N from ammonium nitrate will be converted to nitrate.

Non Agricultural Uses. Ammonium sulfate is commonly added to bread products as a dough conditioner. It is also a component in fire extinguisher powder and flame-proofing agents. It is used for many applications in the chemical, wood pulp, textile, and pharmaceutical industries.

Source: http://www.ipni.net/specifics

M

Nitrophosphate

Module 3.3-5 The production and application of nitrophosphate fertilizers is largely regional, its use centered where this technology is advantageous. The process uses nitric acid instead of sulfuric acid for treating phosphate rock and does not result in gypsum byproducts.

Production. The majority of commercial P fertilizer is made by reacting raw phosphate rock with sulfuric or phosphoric acid. The sulfuric acid method of producing P fertilizer results in large amounts of calcium sulfate (gypsum) by-product that incurs additional disposal costs. Nitrophosphate differs because it involves reacting phosphate rock with nitric acid. Nitric acid is made by oxidizing ammonia with air at high temperatures. A primary advantage of this method is that little or no S inputs are required. With the nitrophosphate process, excess Ca from the phosphate rock is converted to valuable calcium nitrate fertilizer instead of gypsum. The nitrophosphate method was first developed in Norway and much of the global production still occurs in Europe.

The general reaction is: Phosphate rock + Nitric acid→Phosphoric acid + Calcium nitrate + Hydrofluoric acid. The resulting phosphoric acid is often mixed with other nutrients to form compound fertilizers containing several nutrients in a single pellet. The co-generated calcium nitrate or calcium ammonium nitrate is sold separately.

Chemical Properties

The chemical composition will vary depending on the combinations of nutrients used to make the final granule. Popular grades of fertilizer made with the nitrophosphate method include:

20-20-0, 25-25-0, 28-14-0, 20-30-0, 15-15-15, 17-17-17, 21-7-14, 10-20-20, 15-20-15, and 12-24-12

Nitrophosphate Granules

21-7-14 formulated with potassium sulfate *16-16-16 formulated with potassium chloride*

Agricultural Use. Nitrophosphate fertilizers can have a wide range in nutrient composition depending on their intended use. It is important to select the proper composition for each specific crop and soil requirement. Nitrophosphate fertilizer is sold in granular form to be used for direct application to soil. It is commonly spread on the soil surface, mixed within the rootzone, or applied as a concentrated band beneath the soil surface prior to planting.

Management Practices. Nitrophosphate fertilizer contains varying amounts of ammonium nitrate, which attracts moisture. To prevent clumping or caking, nitrophosphate fertilizers are generally packed in water-tight bags and protected from moisture before delivery to the farmer.

Source: http://www.ipni.net/specifics

M

Ammonium Nitrate

Module 3.3-6 Ammonium nitrate was the first solid nitrogen fertilizer produced at a large scale. It is an efficient N source because it contains both nitrate and ammonium and it has a relatively high nutrient content.

Production. Production of ammonium nitrate is an endothermic process that results from the reaction of ammonia gas with nitric acid to form a concentrated ammonium nitrate liquid solution. Considerable heat is co-produced, which is mostly recovered as energy in the fertilizer plant. Solid finished fertilizers are then made via a prilling or granulation process. Granular forms of ammonium nitrate are preferred by farmers for their superior mechanical spreading performance at large widths.

Since ammonium nitrate attracts moisture from air, it is produced with a coating that prevents moisture absorption and reduces caking to keep the particles free flowing during handling and field application.

Ammonium nitrate is often the nitrogen (N) source for NPK compound fertilizers when it is combined with phosphorus (P) and potassium (K). It can be enriched with sulfate to produce fertilizer with an excellent N to sulfur ratio for crops. Ammonium nitrate is sometimes enhanced with limestone to produce calcium ammonium nitrate (CAN), which provides additional calcium and magnesium to the crop and reduces the need for lime to compensate for soil acidification.

Chemical Properties

Chemical formula:	NH_4NO_3
Composition:	33 to 34% N
Water solubility (20°C):	1,900 g/L

HERINGER

Granular ammonium nitrate provides equal amounts of nitrate-N and ammonium-N, and its application has been highly suited to vegetable or forage crops.

Agricultural Use. Since plant roots do not directly absorb the urea form of N to a large extent, ammonium nitrate is an efficient and immediate source of plant nutrition. It provides half of the N in the nitrate form and half in the ammonium form. The nitrate form is mobile in the soil water and immediately available for plant uptake. The ammonium fraction is taken up if roots grow nearby or after it is converted to nitrate by soil microorganisms during nitrification.

Many farmers prefer an immediately available nitrate source for plant nutrition and choose ammonium nitrate as their N fertilizer. It is popular for pasture and broad acre crops since almost no ammonia volatilization losses occur, compared to urea-based fertilizers. Some 37 million metric tons (MMt) of fertilizer grade ammonium nitrate are consumed worldwide annually in agriculture, of which about 14 MMt are used as CAN. Because of its high crop recovery, its ease of use, and its suitability for in-season top dressing, ammonium nitrate is widely used, especially in many European countries.

Management Practices. Ammonium nitrate is a popular N fertilizer due to its agronomic efficiency and relatively high nutrient content. It is very soluble in the soil and the nitrate portion can be easily taken up by the crops. The ammonium portion provides a delayed supply of N to the crop. It is often used for in season top-dressing of N according to crop demand. Because of its high density it can be evenly spread across wide distances. Spreading widths of up to 36 meters are possible when using quality products having a quite large granular median size. Ammonium nitrate requires no special management practices, but efforts should always be made to minimize the loss of any nutrients to the environment.

Non Agricultural Uses. Ammonium nitrate is manufactured in both high density and low density forms. The low density prills (technical grade) are more porous than high density fertilizer prills or granules. The low-density materials are manufactured especially for use as an explosive in the mining industry. The intentionally porous nature of the particles allows rapid adsorption of fuel oil (termed ANFO). Concerns over illegal use of nitrate-containing fertilizer for explosives have caused strict government regulation in many parts of the world.

Source: http://www.ipni.net/specifics

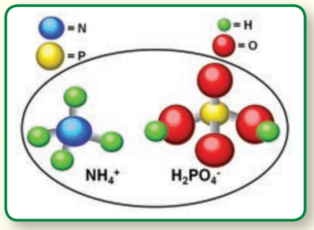
Monoammonium Phosphate

Module 3.3-7 Monoammonium phosphate (MAP) is a widely used source of phosphorus and nitrogen. In recent years its use has grown rapidly. It is made of two constituents common in the fertilizer industry and has the highest P content of any common solid fertilizer.

Production. The process for manufacturing MAP is relatively simple. In a common method, a one to one ratio of ammonia (NH_3) and phosphoric acid (H_3PO_4) is reacted and the resulting slurry of MAP is solidified in a granulator. The second method is to introduce the two starting materials in a pipe-cross reactor where the reaction generates heat to evaporate water and solidify MAP. Variations of these methods are also in use for MAP production. An advantage of producing MAP is that lower quality H_3PO_4 can be used compared with other P fertilizers that often require a more pure grade of acid. The P_2O_5 equivalent content of MAP varies from 48 to 61%, depending on the amount of impurity in the acid. The most common fertilizer composition is 11-52-0.

Chemical Properties

Chemical formula:	$NH_4H_2PO_4$
N content:	10 to 12%
P_2O_5 content:	48 to 61%
Water solubility (20°C):	370 g/L
Solution pH:	4 to 4.5



Agricultural Use. MAP has been an important granular fertilizer for many years. It is water soluble and dissolves rapidly in soil if adequate moisture is present. Upon dissolution, the two basic components of the fertilizer separate again to release NH_4^+ and $H_2PO_4^-$. Both of these nutrients are important to sustain healthy plant growth. The pH of the solution surrounding the granule is moderately acidic, making MAP an especially desirable fertilizer in neutral and high pH soils. Agronomic studies show that there is no significant difference in P nutrition from various commercial P fertilizers under most conditions.

Granular MAP is applied in concentrated bands beneath the soil surface in proximity of growing roots or in surface bands. It is also commonly applied by spreading across the field and mixing into the surface soil with tillage. In powdered form, it is an important component of suspension fertilizers. When MAP is made with especially pure H_3PO_4, it readily dissolves into a clear solution that can be used as a foliar spray or added to irrigation water. The P_2O_5 equivalent content of high-purity MAP is usually 61%.

Management Practices. There are no special precautions associated with the use of MAP. The slight acidity associated with this fertilizer reduces the potential for NH_3 loss to the air. MAP can be placed in close proximity to germinating seeds without concern for NH_3 damage. Band placement of MAP protects the P from soil fixation and facilitates a synergism between ammonium and phosphate uptake by roots.

When MAP is used as a foliar spray or added to irrigation water, it should not be mixed with calcium or magnesium fertilizers. MAP has good storage and handling properties. Some of the chemical impurities (such as iron and aluminum) naturally serve as a conditioner to prevent caking. Highly pure MAP may have a conditioner added or may require special handling to prevent clumping and caking. As with all P fertilizers, appropriate management practices should be used to minimize any nutrient loss to surface or drainage water.

A high purity source of MAP is used as a feed ingredient for animals. The NH_4^+ is synthesized into protein and the $H_2PO_4^-$ is used in a variety of metabolic functions in animals.

Non Agricultural Uses. MAP is used in dry chemical fire extinguishers commonly found in offices, schools, and homes. The extinguisher spray disperses finely powdered MAP, which coats the fuel and rapidly smothers the flame.

Source: http://www.ipni.net/specifics

M

Diammonium Phosphate

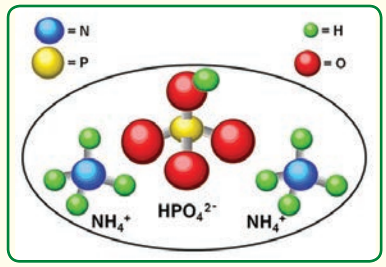
Module 3.3-8 Diammonium phosphate (DAP) is the world's most widely used phosphorus fertilizer. It is made from two common constituents in the fertilizer industry and it is popular because of its relatively high nutrient content and its excellent physical properties.

Production. Ammonium phosphate fertilizers first became available in the 1960s and DAP rapidly became the most popular in this class of products. It is formulated in a controlled reaction of phosphoric acid with ammonia, where the hot slurry is then cooled, granulated, and sieved. DAP has excellent handling and storage properties. The standard grade of DAP is 18-46-0 and fertilizer products with a lower nutrient content may not be labeled as DAP.

The inputs required to produce one ton of DAP fertilizer are approximately 1.5 to 2 t of phosphate rock, 0.4 t of S, to dissolve the rock, and 0.2 t of ammonia. Changes in the supply or price of any of these inputs will impact DAP prices and availability. The high nutrient content of DAP is helpful in reducing handling, freight, and application costs. DAP is produced in many locations in the world and is a widely traded fertilizer commodity.

Chemical Properties

Chemical formula:	$(NH_4)_2HPO_4$
N content:	18%
P_2O_5 content:	46%
Water solubility (20°C):	588 g/L
Solution pH:	7.5 to 8



Agricultural Use. DAP fertilizer is an excellent source of P and N for plant nutrition. It is highly soluble and thus dissolves quickly in soil to release plant-available phosphate and ammonium. A notable property of DAP is the alkaline pH that develops around the dissolving granule.

As ammonium is released from dissolving DAP granules, volatile ammonia can be harmful to seedlings and plant roots in immediate proximity. This potential damage is more common when the soil pH is greater than 7, a condition that commonly exists around the dissolving DAP granule. To prevent the possibility of seedling damage, care should be taken to avoid placing high concentrations of DAP near germinating seeds.

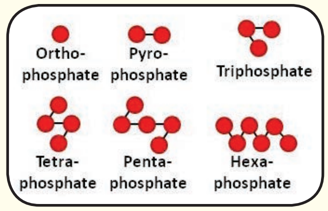
The ammonium present in DAP is an excellent N source and will be gradually converted to nitrate by soil bacteria, resulting in a subsequent drop in pH. Therefore, the rise in soil pH surrounding DAP granules is a temporary effect. This initial rise in soil pH neighboring DAP can influence the micro-site reactions of phosphate and soil organic matter.

Management Practices. There are differences in the initial chemical reaction between various commercial P fertilizers in soil, but these dissimilarities become minor over time (within weeks or months) and are minimal as far as plant nutrition is concerned. Most field comparisons between DAP and monoammonium phosphate (MAP) show only minor or no differences in plant growth and yield due to P source with proper management.

Non Agricultural Uses. DAP is used in many applications as a fire retardant. For example, a mixture of DAP and other ingredients can be spread in advance of the fire to prevent a forest from burning. It then becomes a nutrient source after the danger of fire has passed. DAP is used in various industrial processes, such as metal finishing. It is commonly added to wine to sustain yeast fermentation and to cheese to support cheese cultures.

Source: http://www.ipni.net/specifics

Polyphosphate



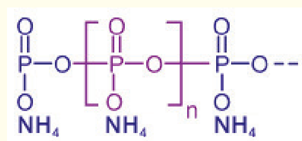
Module 3.3-9 Phosphorus deficiency limits the growth and productivity of plants in many parts of the world. Since many soils are low in P, this nutrient is commonly added to improve crop yield and quality. Phosphorus is derived from geologic deposits distributed across the globe. Polyphosphate is an excellent liquid fertilizer that is widely used in agriculture.

Production. Phosphoric acid is the starting material for most commercial phosphate fertilizers. However, the acidity and some of the chemical properties make this material difficult to use directly. When phosphoric acid and ammonia are reacted, water is driven off and individual phosphate molecules begin to link together to form a polyphosphate fluid fertilizer.

A single phosphate molecule is called orthophosphate. "Poly" refers to multiple phosphate molecules linked in a chain. Each linkage of phosphate molecules has a name depending on its length, although polyphosphate is the general term that includes all of these linked molecules.

The most common ammonium polyphosphate fertilizers have N-P_2O_5-K_2O composition of 10-34-0 or 11-37-0. 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. A variety of other nutrients mix well with polyphosphate fertilizers, making them an excellent carrier for micronutrients that may be needed by plants.

Chemical Properties	Fertilizer Grade	
Name	10-34-0	11-37-0
Density, kg/L	1.39	1.43
pH	5.9	6.1



Agricultural Use. In polyphosphate fertilizer, between half and three-quarters of the P is present in chained polymers. The remaining P (orthophosphate) is immediately available for plant uptake. The polymer phosphate chains are primarily broken down to the simple phosphate molecules by enzymes produced by soil microorganisms and plant roots. Some of the polyphosphate will decompose without the enzymes. The enzyme activity is faster in moist, warm soils. Typically, half of the polyphosphate compounds are converted to orthophosphate within a week or two. Under cool and dry conditions, the conversion may take longer.

Since polyphosphate fertilizers contain a combination of both orthophosphate and polyphosphate, plants are able to use this fertilizer source very effectively. Most P-containing fluid fertilizers have ammonium polyphosphate in them. Fluid fertilizers are commonly used in production agriculture, but not widely used by homeowners. Fluids are convenient for farmers since they can be easily blended with many other nutrients and chemicals and each drop of fluid is exactly the same. For most situations, the decision to use dry or fluid fertilizers is based on the price of nutrients, fertilizer handling preferences, and field practices rather than significant agronomic differences.

Management Practices. Ammonium polyphosphate is primarily used as a source of P nutrition for plants. Since P has limited mobility in most soils, efforts should be made to place the material as close to developing roots as practical. Practices should be adopted to minimize the movement of P from the soil into adjacent water. Excess P in surface water can stimulate the growth of undesirable algae.

Non-agricultural Use. Phosphate is an essential component in human nutrition. Polyphosphate is an approved additive for food and requires no special precautions in handling. Polyphosphate compounds are widely used as a flame retardant on many products, including wood, paper, fabric, and plastic. It is also used as a commercial retardant for forest fires. The mode of action involves the ammonium polyphosphate forming a charred layer after burning, thereby preventing further flames.

Source: http://www.ipni.net/specifics

M

Single Superphosphate

Module 3.3-10 Single superphosphate (SSP) 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.

Production. The modern fertilizer industry was launched in the 1840s with discovery that the addition of sulfuric acid to naturally occurring phosphate produced an excellent soluble fertilizer, given the name superphosphate. Ground animal bones were first used in this reaction, but natural deposits of rock phosphate (apatite) soon replaced the limited supply of bones. Making SSP is similar to what naturally occurs with bones or apatite in acid soils. The basic technique has changed very little in the past century. Ground phosphate rock is reacted with sulfuric acid to form a semi-solid which cools for several hours in a den. The plastic-like material is then conveyed to a storage pile for several weeks of additional curing. The hardened material is then milled and screened to the appropriate particle size or granulated. The general chemical reaction is:

$Ca_3(PO_4)_2$ [rock phosphate] + 2 H_2SO_4 [sulfuric acid] → $Ca(H_2PO_4)_2$ [monocalcium phosphate] + 2 $CaSO_4$ [gypsum]

SSP can easily be produced on a small scale to meet regional needs. Since SSP contains both monocalcium phosphate (MCP, also called calcium dihydrogen phosphate) and gypsum, there are no issues with phosphogypsum by-product disposal as occurs with the manufacture of other common P fertilizers.

SSP is also known as ordinary superphosphate and normal superphosphate. It is sometimes confused with triple superphosphate (TSP) production, which is made by reacting rock phosphate with phosphoric acid.

Chemical Properties

P_2O_5 content:	16 to 20%
Ca content:	18 to 21%
S content:	11 to 12%
pH:	< 2

Granular single superphosphate

Agricultural Use. SSP is an excellent source of three plant nutrients. The P component reacts in soil similarly to other soluble fertilizers. The presence of both P and S in SSP can be an agronomic advantage where both of these nutrients are deficient. In agronomic studies where SSP is demonstrated to be superior to other P fertilizers, it is usually due to the S and/or Ca that it contains. When locally available, SSP has found wide-spread use for fertilizing pastures where both P and S are needed. As a source of P alone, SSP often costs more than other more concentrated fertilizers, therefore it has declined in popularity.

Management Practices. No special agronomic or handling precautions are required for SSP. Its agronomic effectiveness is similar to other dry or liquid phosphate fertilizers.

The loss of P in surface runoff from fertilized fields can contribute to water quality problems. Farm practices that minimize this loss should be implemented.

Non Agricultural Uses. SSP is primarily used as a crop nutrient source. However MCP and gypsum (the two primary ingredients in SSP) are widely used in many products. For example MCP is commonly added to enrich animal feed. It is also routinely used as a leavening agent to cause baked goods to rise. Gypsum is widely used in the construction industry, as well as in the food and pharmaceuticals.

Source: http://www.ipni.net/specifics

M

Triple Superphosphate

Module 3.3-11 Triple superphosphate (TSP) was one of the first high analysis phosphorus fertilizers that became widely used in the 20th century. Technically, it is known as calcium dihydrogen phosphate and as monocalcium phosphate, [$Ca(H_2PO_4)_2 \cdot H_2O$]. It is an excellent P source, but its use has declined as other P fertilizers have become more popular.

Production. The concept of TSP production is relatively simple. Non-granular TSP is commonly produced by reacting finely ground phosphate rock with liquid phosphoric acid in a cone-type mixer. Granular TSP is made similarly, but the resulting slurry is sprayed as a coating onto small particles to build granules of the desired size. The product from both production methods is allowed to cure for several weeks as the chemical reactions are slowly completed. The chemistry and process of the reaction will vary somewhat depending on the properties of the phosphate rock.

Chemical Properties

Chemical formula:	$Ca(H_2PO_4)_2 \cdot H_2O$
P_2O_5 content:	44 to 48%
Ca content:	13 to 15%
Water-soluble P:	Generally >90%
Solution pH:	1 to 3

Triple superphosphate is available in granular (shown) and non-granular forms.

Agricultural Use. TSP has several agronomic advantages that made it such a popular P source for many years. It has the highest P content of dry fertilizers that do not contain N. Over 90% of the total P in TSP is water soluble, so it becomes rapidly available for plant uptake. As soil moisture dissolves the granule, the concentrated soil solution becomes acidic. TSP also contains 15% calcium (Ca), providing an additional plant nutrient.

A major use of TSP is in situations where several solid fertilizers are blended together for broadcasting on the soil surface or for application in a concentrated band beneath the surface. It is also desirable for fertilization of leguminous crops, such as alfalfa or beans, where no additional N fertilization is needed to supplement biological N fixation.

Management Practices. The popularity of TSP has declined because the total nutrient content (N + P_2O_5) is lower than ammonium phosphate fertilizers such as monoammonium phosphate, which by comparison contains 11% N and 52% P_2O_5. Costs of producing TSP can be higher than ammonium phosphates, making the economics for TSP less favorable in some situations.

All P fertilizers should be managed to avoid losses in surface water runoff from fields. Phosphorus loss from agricultural land to adjacent surface water can contribute to undesired stimulation of algae growth. Appropriate nutrient management practices can minimize this risk.

Non Agricultural Uses. Monocalcium phosphate is an important ingredient in baking powder. The acidic monocalcium phosphate reacts with an alkaline component to produce carbon dioxide, the leavening for many baked products. Monocalcium phosphate is commonly added to animal diets as an important mineral supplement of both phosphate and Ca.

Source: http://www.ipni.net/specifics

M

Phosphate Rock

Module 3.3-12 Phosphorus additions are needed in most areas of the world to improve soil fertility and crop production. Direct application of unprocessed phosphate rock (PR) to soil may provide a valuable source of plant nutrients in specific conditions, but there are several factors and limitations to consider.

Production. Phosphate rock is obtained from geologic deposits located around the world. Apatite, a calcium phosphate mineral, is the primary constituent of PR. It is primarily extracted from sedimentary marine deposits, with a small amount obtained from igneous sources. Most PR is recovered through surface mining, although some is extracted from underground mines.

The ore is first screened and some of the impurities removed near the mine site. Most PR is used to produce soluble phosphate fertilizers, but some is used for direct application to soil. While PR can be a valuable source of P for plants, it is not always appropriate for direct application. Its suitability depends partly on naturally occurring mineral impurities, such as clay, carbonate, iron, and aluminum (Al). The effectiveness of PR for direct application is estimated in the laboratory by dissolving rock in a solution containing a dilute acid to simulate soil conditions. Sources classified as highly reactive are the most suitable for direct soil application.

Direct use of PR avoids the extra processing associated with converting apatite to a soluble form. The minimal processing may result in a lower-cost nutrient source and make it acceptable for organic crop production systems.

Agricultural Use. When a water-soluble P fertilizer is added to soil, it quickly dissolves and reacts to form low solubility compounds. When PR is added to soil, it slowly dissolves to gradually release nutrients, but the rate of dissolution may be too slow to support healthy plant growth in some soils. To optimize the effectiveness of PR, these factors should be considered:

- **Soil pH:** PR requires acid soil conditions to be an effective nutrient source. Use of PR is not usually recommended when the soil pH exceeds 5.5. Adding lime to raise soil pH and decrease Al toxicity may slow PR dissolution.
- **Soil P-fixing capacity:** The dissolution of PR increases with a greater P-fixing capacity of soil (such as high clay content).
- **Soil properties:** Low calcium and high organic matter in the soil tend to speed PR dissolution.
- **Placement:** Broadcasting PR and incorporation with tillage speeds the reaction with the soil.
- **Species:** Some plant species can better utilize PR due to their excretion of organic acids from the roots into the surrounding soil.
- **Timing:** The time required for the dissolution of PR necessitates its application in advance of the plant demand.

Management Practices. Not all sources of unprocessed PR are suitable for direct application to soil. Additionally, many soils are not suitable for PR use. The total P content of a material is not a good predictor of the potential reactivity in the soil. For example, many igneous PR sources are high in total P, but are of low reactivity and provide minimal plant nutrition because they dissolve so slowly. However, mycorrhizal fungi may aid in the acquisition of P from low-solubility materials in some environments.

Over 90% of PR is converted into soluble P fertilizer through reaction with acid. This is similar to the chemical reaction that PR undergoes when it reacts with soil acidity. The agronomic and economic effectiveness of PR can be equivalent to water-soluble P fertilizers in some circumstances, but the specific conditions should be considered when making this choice.

Source: http://www.ipni.net/specifics

M

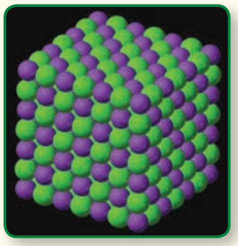
Potassium Chloride

Module 3.3-13 Potassium fertilizers are commonly used to overcome plant deficiencies. Where soils cannot supply the amount of K required by crops, it is necessary to supplement this essential plant nutrient. Potash is a general term used to describe a variety of K-containing fertilizers used in agriculture. Potassium chloride (KCl), the most commonly used source, is also frequently referred to as muriate of potash or MOP (muriate is the old name for any chloride-containing salt).Potassium is always present in minerals as a single-charged cation (K^+).

Production. Deeply buried potash deposits are found throughout the world. The dominant mineral is sylvite (KCl) mixed with halite (sodium chloride), which forms a mixed mineral called sylvinite. Most K minerals are harvested from ancient marine deposits deep beneath the Earth's surface. They are then transported to a processing facility where the ore is crushed and the K salts are separated from the sodium salts. The color of KCl can vary from red to white, depending on the source of the sylvinite ore. The reddish tint comes from trace amounts of iron oxide. There are no agronomic differences between the red and white forms of KCl.

Chemical Properties

Chemical formula:	KCl
Fertilizer analysis:	0-0-60
K_2O content:	60 to 63%
Cl^- content:	45 to 47%
Water solubility (20°C):	344 g/L
Solution pH:	approx. 7



Potassium chloride contains a one- to-one ratio of the two elements.

Some KCl is produced by injecting hot water deep into the ground to dissolve the soluble sylvinite mineral and then pumping the brine back to the surface where the water is evaporated. Solar evaporation is used to recover valuable potash salts from brine water in the Dead Sea and the Great Salt Lake (Utah).

Agricultural Use. Potassium chloride is the most widely used K fertilizer due to its relatively low cost and because it includes more K than most other sources...50 to 52% K (60 to 63% K_2O) and 45 to 47% Cl^-.

Over 90% of global potash production is used for plant nutrition. Potassium chloride is often spread onto the soil surface prior to tillage and planting. It may also be applied in a concentrated band near the seed. Since dissolving fertilizer will increase the soluble salt concentration, banded KCl is placed to the side of the seed to avoid damaging the germinating plant.

Potassium chloride is found in various shades and particle sizes.

Potassium chloride rapidly dissolves in soil water. The K^+ will be retained on the negatively charged cation exchange sites of clay and organic matter. The Cl^- portion will readily move with the water. An especially pure grade of KCl can be dissolved for fluid fertilizers or applied through irrigation systems.

Management Practices. Potassium chloride is primarily used as a source of K nutrition. However, there are regions where plants respond favorably to application of Cl^-. Potassium chloride is usually the preferred material to meet this need. There are no significant impacts on water or air associated with normal application rates of KCl. Elevated salt concentrations surrounding the dissolving fertilizer may be the most important factor to consider.

Non-agricultural Use. Potassium is essential for human and animal health. It must be regularly ingested because the body does not store it. Potassium chloride can be used as a salt substitute for individuals on a restricted salt (sodium chloride) diet. It is used as a deicing agent and has a fertilizing value after the ice melts. It is also used in water softeners to replace calcium in water.

Source: http://www.ipni.net/specifics

M

Potassium Sulfate

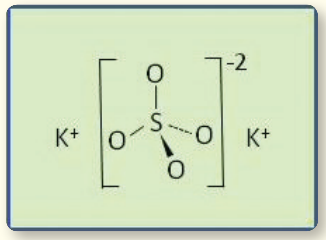
Module 3.3-14 Potassium fertilizer is commonly added to improve the yield and quality of plants growing in soils that are lacking an adequate supply of this essential nutrient. Most fertilizer K comes from ancient salt deposits located throughout the world. The word "potash" is a general term that most frequently refers to potassium chloride (KCl), but it also applies to all other K-containing fertilizers, such as potassium sulfate (K_2SO_4, commonly referred to as sulfate of potash or SOP).

Production. Potassium is a relatively abundant element in the Earth's crust and production of potash fertilizer occurs in every inhabited continent. However, K_2SO_4 is rarely found in a pure form in nature. Instead it is naturally mixed with salts containing Mg, Na, and Cl. These minerals require additional processing to separate their components. Historically, K_2SO_4 was made by reacting KCl with sulfuric acid. However, it was later discovered that a number of earth minerals could be manipulated to produce K_2SO_4 and this is now the most common method of production. For example, natural K-containing minerals (such as kainite and schoenite) are mined and carefully rinsed with water and salt solutions to remove byproducts and produce K_2SO_4. A similar process is used to harvest K_2SO_4 from the Great Salt Lake in Utah, and from underground mineral deposits.

In New Mexico (USA), K_2SO_4 is separated from langbeinite minerals by reacting it with a solution of KCl, which removes the byproducts (such as Mg) and leaves K_2SO_4. Similar processing techniques are used in many parts of the world, depending on the raw materials accessible.

Chemical Properties

Chemical formula:	K_2SO_4
K_2O content:	48 to 53%
S content:	17 to 18%
Solubility (25°C):	120 g/L
Solution pH:	approx. 7



Agricultural Use. Concentrations of K in soil are often too low to support healthy plant growth. Potassium is needed to complete many essential functions in plants, such as activating enzyme reactions, synthesizing proteins, forming starch and sugars, and regulating water flow in cells and leaves.

Potassium sulfate is an excellent source of nutrition for plants. The K portion of the K_2SO_4 is no different than other common potash fertilizers. However, it also supplies a valuable source of S, which is sometimes deficient for plant growth. Sulfur is required for protein synthesis and enzyme function. There are certain soils and crops where the addition of Cl^- should be avoided. In these cases, K_2SO_4 makes a very suitable K source. Potassium sulfate is only one-third as soluble as KCl, so it is not as commonly dissolved for addition through irrigation water unless there is a need for additional S.

Several particle sizes are commonly available. Fine particles (<0.015 mm) are used for making solutions for irrigation or foliar sprays since it dissolves more rapidly. Foliar sprays of K_2SO_4 are a convenient way to apply additional K and S to plants, supplementing the nutrients taken up from the soil. Leaf damage can occur if the concentration is too high.

Management Practices. K_2SO_4 is frequently used for crops where additional Cl^- from more common KCl fertilizer is undesirable. The partial salt index of K_2SO_4 is lower than some other common K fertilizers, so less total salinity is added per unit of K. The salt measurement (EC) from a K_2SO_4 solution is less than a third of a similar concentration of a KCl solution (10 mmol/L). Where high rates of K_2SO_4 are needed, it is generally recommended to divide the application into multiple doses. This helps avoid surplus K accumulation by the plant and also minimizes any potential salt damage.

Source: http://www.ipni.net/specifics

M

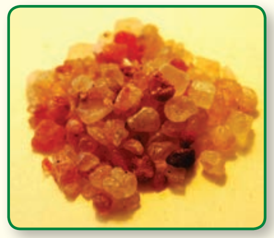
Potassium Magnesium Sulfate: Langbeinite

Module 3.3-15 Langbeinite is a unique source of plant nutrition since three essential nutrients are naturally combined into one mineral. It provides a readily available supply of K, Mg, and S to growing plants.

Production. Langbeinite is a distinctive geological material found in only a few locations in the world. Commercial supplies of langbeinite come from underground mines near Carlsbad, New Mexico (USA), which were first commercially developed in the 1930s. These deposits were formed millions of years ago when a variety of salts, including langbeinite, were left behind after the evaporation of ancient ocean beds. These salt deposits were buried deep beneath hundreds of meters of sediment. The langbeinite deposit is currently mined with large boring machines, washed to remove impurities, and then crushed to various particle sizes. Langbeinite is considered a potash (or K-containing) fertilizer, even though it also contains valuable Mg and S. Traces of iron oxide impurities give some langbeinite particles a reddish tint.

Chemical Properties

Chemical formula:	$K_2SO_4 \cdot 2MgSO_4$
K_2O content:	21 to 22%
Mg content:	10 to 11%
S content:	21 to 22%
Water solubility (20°C)	240 g/L
Solution pH:	approx. 7



Agricultural Use. Langbeinite is a popular fertilizer, especially where several nutrients are needed to provide adequate plant nutrition. It has an advantage of having K, Mg, and S all contained within a single particle, which helps provide a uniform distribution of nutrients when it is spread in the field. Due to economics, langbeinite may not be recommended to meet the entire K requirement of a crop. Instead, application rate may be based on the need for Mg and/or S.

Underground mining operation

Langbeinite is totally water soluble, but is slower to dissolve than some other common K fertilizers because the particles are denser than other K sources. Therefore, it is not suitable for dissolving and application through irrigation systems unless finely ground. It has a neutral pH, and does not contribute to soil acidity or alkalinity. This differs from other common sources of Mg (such as dolomite) which will increase soil pH and from elemental S or ammonium sulfate which will lower the soil pH.

It is frequently used in situations where a fertilizer free of Cl^- is desirable, such as with crops sensitive to Cl^- (some vegetables and certain tree crops). Langbeinite is a nutrient-dense fertilizer with a relatively low overall salt index. Particular sources of langbeinite have been certified for use in organic crop production in some countries.

Management Practices. Langbeinite has no restrictions for environmental or nutritional use when used at typical agronomic rates. One form of langbeinite is sold as a feed grade dietary source of K, Mg, and S for animals and poultry. All three of these nutrients are required for animal nutrition and each has a specific metabolic role required for optimal animal health. This feed material is recognized as safe by government agencies. As with all plant nutrients, best management practices should be observed to properly utilize this resource. A particular particle size should be matched with the specific need.

Non-agricultural Use. There are no major industrial applications for langbeinite outside of agriculture.

Source: http://www.ipni.net/specifics

M

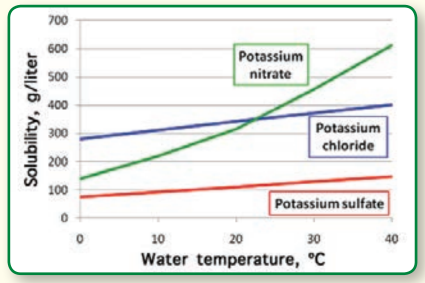
Potassium Nitrate

Module 3.3-16 Potassium nitrate (KNO_3) is a soluble source of two major essential plant nutrients. It is commonly used as a fertilizer for high-value crops that benefit from nitrate (NO_3^-) nutrition and a source of potassium (K^+) free of chloride (Cl^-).

Production. Potassium nitrate fertilizer (sometimes referred to as nitrate of potash or NOP) is typically made by reacting potassium chloride (KCl) with a nitrate source. Depending on the objectives and available resources, the nitrate may come from sodium nitrate, nitric acid, or ammonium nitrate. The resulting KNO_3 is identical regardless of the manufacturing process. Potassium nitrate is commonly sold as a water-soluble, crystalline material primarily intended for dissolving and application with water or in a prilled form for soil application. Traditionally, this compound is known as saltpeter.

Chemical Properties

Chemical formula:	KNO_3
N content:	13%
K_2O content:	44 to 46%
Water solubility (20°C):	316 g/L
Solution pH:	7 to 10



Water solubility of common K fertilizers

Agricultural Use. The use of KNO_3 is especially desirable in conditions where a highly soluble, chloride-free nutrient source is needed. All of the N is immediately available for plant uptake as nitrate, requiring no additional microbial action and transformation in the soil. Growers of high value vegetable and orchard crops sometime prefer to use a nitrate-based source of nutrition in an effort to boost yield and quality. Potassium nitrate contains a relatively high proportion of K, with a N to K ratio of approximately 1:3. Many crops have high K demands and can remove as much or more K than N at harvest.


KNO_3 crystals & prills

Applications of KNO_3 to the soil are made before the growing season or as a supplement during the growing season. A diluted solution is sometimes sprayed on plant foliage to stimulate physiological processes or to overcome nutrient deficiencies. Foliar application of K during fruit development can be advantageous for some crops, since this growth stage often coincides with high K demands during the time of declining root activity and nutrient uptake. It is also commonly used for greenhouse plant production and hydroponic culture.

Management Practices. Both N and K are required by plants to support harvest quality, protein formation, disease resistance, and water use efficiency. Therefore, KNO_3 is often applied to soil or through the irrigation system during the growing season to support healthy growth.

Potassium nitrate accounts for only a small portion of the global K fertilizer market. It is primarily used where its unique composition and properties are able to provide specific benefits to growers. It is easy to handle and apply, and is compatible with many other fertilizers. This includes usage for many high-value specialty crops, as well as grain and fiber crops.

The relatively high solubility of KNO_3 under warm conditions allows for a more concentrated solution than for other common K fertilizers. Careful water management is needed to keep the nitrate from moving below the root zone.

Non Agricultural Uses. Potassium nitrate has long been used for fireworks and gunpowder. It is now more commonly used in food to maintain the quality of meat and cheese. Specialty toothpastes often contain KNO_3 to alleviate tooth sensitivity. A mixture of KNO_3 and sodium nitrate ($NaNO_3$) is used for storing heat in solar energy installations.

Source: http://www.ipni.net/specifics

M

Kieserite

Module 3.3-17 Kieserite is a naturally occurring mineral that is chemically known as magnesium sulfate monohydrate ($MgSO_4{\cdot}H_2O$). It is mined from geologic marine deposits and provides a soluble source of both Mg and S for plant nutrition.

Production. Kieserite is primarily obtained from deep underground deposits of minerals in Germany. It is present in the remnants of ancient oceans that were evaporated and are now buried beneath the earth's surface. These mineral resources contain a variety of valuable plant nutrients. The ore is brought to the surface where the magnesium salts are separated from potassium and sodium salts using a unique, dry electrostatic (ESTA) process.

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.

Chemical Properties

Chemical formula:	$MgSO_4{\cdot}H_2O$
Mg content:	16% (kieserite fine); 15% (kieserite granular)
S content:	22% (kieserite fine); 20% (kieserite granular)
Solubility:	417 g/L (20°C)
Solution pH:	9

Fine kieserite

Granulated kieserite

Agricultural Use. Kieserite provides a highly concentrated form of two essential plant nutrients—Mg and S. Since kieserite applications have no major effect on soil pH, it can be supplied to all kinds of soil, irrespective of soil pH. It is commonly used prior to or during the growing season to meet the nutrient requirement of crops. Due to its high solubility it can be used to supply both Mg and S during peak periods of crop demand. Since kieserite is an earth mineral mined from naturally occurring deposits, it is permitted as an organic nutrient source by some organic certifying agencies.

Mining operation to recover kieserite

Kieserite itself is not used as foliar fertilizer or in fertigation systems, but it serves as raw material for the production of Epsom salt ($MgSO_4{\cdot}7\ H_2O$), which is totally soluble and suitable for both fertigation and foliar application.

Management Practices. Many soils are low in Mg and require supplemental nutrients to support crop yield and quality. Sandy-textured soils and soils with a low pH (such as highly weathered tropical soils) are frequently characterized by a low Mg supply for plants. Under these conditions, it is a prerequisite to raise the Mg content in the soil by adequate fertilization.

Splitting Mg applications into two or more doses is recommended in areas with high precipitation in order to avoid leaching losses. Soils in temperate climates with higher clay content may have higher Mg contents and are often less prone to leaching losses.

Fertilizer Mg application rates vary depending on factors such as the specific crop requirement, the quantity removed during harvest, and the ability of soil minerals to release adequate Mg in a timely manner to support crop yield and quality. Kieserite application rates are typically in the range of 200 to 300 kg/ha for many crops. Additional Mg and S demands during peak growth periods demand can be met by foliar application of materials such as Epsom salt or a variety of soluble nutrient sources.

Source: http://www.ipni.net/specifics

M

Sulfur

Module 3.3-18 Sulfur is widely distributed throughout the world in many forms. In some soils, there is insufficient S to meet crop needs. There are many excellent S-containing fertilizer products that can be used to address deficiencies where they occur.

Production. Sulfur is a relatively abundant element in the earth's crust. It has been extracted as pure elemental S from volcanic deposits and salt domes. It is now more commonly obtained as a co-product from processing fossil fuels. Coal, crude oil, and natural gas typically contain between 0.1% and 4% S which is removed during refining or scrubbing of combustion gases. A variety of common earth minerals are used as S sources for agriculture.

Elemental S has a fairly low melting temperature (115 °C), so it is often transported and handled in a hot liquid state until it is transformed into final products. The majority of global S production is converted to sulfuric acid (H_2SO_4) for further processing. A major use of sulfuric acid is in production of phosphate fertilizer.

Common Sulfur Sources

Non-Soluble	Elemental S
Semi-Soluble	Gypsum (15 to 17% S)
Soluble	Ammonium sulfate (24% S); Epsom salt (13% S); Kieserite (23% S); Langbeinite (22% S); Potassium sulfate (18% S); Thiosulfate (10 to 26% S)

Elemental sulfur

Sulfur pastilles, containing small amounts of clay to enhance dispersion and oxidation

Agricultural Use. Elemental S is not water soluble and must be oxidized by soil bacteria (such as Thiobacillus) to sulfate (SO_4^{2-}) before it can be taken up by plant roots. The general reaction in soil is: $2S + 3O_2 + 2H_2O \rightarrow 2H_2SO_4$. The speed of this microbial process is governed by environmental factors such as soil temperature and moisture, as well as the physical properties of the S.

Plants almost exclusively use sulfate as their primary source of nutrition, where it is converted to many essential constituents, such as proteins and enzymes. Various approaches have been used to enhance the conversion of elemental S to plant-available sulfate. The speed of elemental S oxidation is directly related to the particle size, where smaller particles have a greater surface area for the soil bacteria to act on. Therefore, large particles of S may require months or years of biological action before oxidizing significant amounts of sulfate. Fine, dust-sized particles are oxidized quickly, but are not easy to apply.

One approach to enhance the rate of S oxidation is to add a small amount of clay to the molten S prior to cooling and forming small pellets (pastilles). When added to soil, the clay swells with water and the pastille disintegrates into fine particles that are rapidly oxidized.

Very thin layers of elemental S can be incorporated during fertilizer granule manufacturing. This S is quick to oxidize and become available for plant uptake. This reaction can have a positive impact on the plant availability of some micronutrients, such as zinc (Zn) and iron (Fe), that become more soluble as the pH declines. Finely ground elemental S is sometimes added to fertilizer suspensions. Elemental S is widely used as a fungicide for crop protection, where toxic hydrogen sulfide is evolved from the interaction of elemental S and the living fungal tissue.

Elemental S and sulfuric acid are commonly used in the reclamation of soils that contain excessive sodium and in the treatment of some irrigation water.

Management Practices. Sulfur is available in many forms to meet specific cropping requirements. Elemental S is generally applied well in advance of crop demand, since a lag period of bacterial oxidation and conversion to sulfate is involved. Since sulfate is an anion, it may be subject to leaching loss, similar to nitrate. However, there are no adverse environmental impacts associated with typical concentrations of sulfate in water.

Non Agricultural Uses. Sulfur is widely used in many consumer products and industrial applications. It is commonly converted to sulfate prior to use in textiles, rubber, detergents, and paper, as examples.

Source: http://www.ipni.net/specifics

Thiosulfate

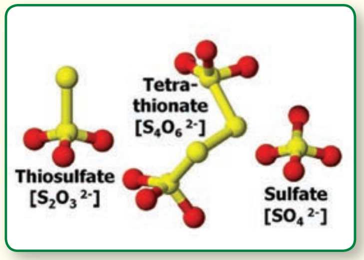
Module 3.3-19 Thiosulfate ($S_2O_3^{2-}$) fertilizers are clear liquids that provide a source of sulfur and can be used in a variety of situations. They also contain other nutrients including N as ammonium (ATS), potassium (KTS), calcium (CaTS), or magnesium (MgTS).

Production. ATS is the most commonly used S-containing fluid fertilizer. It is made by reaction of sulfur dioxide, elemental S, and aqueous ammonia. Other common fluid thiosulfate fertilizers are similarly produced.

Thiosulfates are highly soluble in water and are compatible with many other fluid fertilizers. ATS is commonly mixed with urea ammonium nitrate (UAN) to produce a widely used fertilizer with the analysis 28-0-0-5 (5% S).

Chemical Properties

Formula	Common name	Nutrient content	Density, kg/L	pH
$(NH_4)_2S_2O_3$	ATS	12% N; 26% S	1.34	7 to 8.5
$K_2S_2O_3$	KTS	25% K_2O; 17% S	1.46	7.5 to 8
CaS_2O_3	CaTS	6% Ca; 10% S	1.25	6.5 to 8
MgS_2O_3	MgTS	4% Mg; 10% S	1.23	6.5 to 7.5



Agricultural Use. After application to soil, most of the thiosulfate quickly reacts to form tetrathionate, which is subsequently converted to sulfate. Thiosulfate is not generally available for plant uptake until it is converted to sulfate. In warm soils, this process is largely complete within one to two weeks.

Thiosulfate is a chemical reducing agent and it also produces acidity after oxidation of the S. Due to these properties, thiosulfate molecules have unique effects on soil chemistry and biology. For example, a band application of ATS has been shown to improve the solubility of some micronutrients. Local guidelines should be followed for maximum rates for placement in the seed row.

Thiosulfate can slow the rate of urea hydrolysis, the conversion of urea to ammonium (NH_4^+), and reduce losses of ammonia (NH_3) gas when sufficient amounts of ATS are mixed with UAN. This inhibiting effect is likely due to the formation and presence of the intermediate tetrathionate, rather than the thiosulfate itself. Nitrification...the conversion of NH_4^+ to nitrate...is also slowed in the presence of ATS. Although the initial pH of thiosulfate fertilizers is near neutral, thiosulfate oxidizes to form sulfuric acid and the NH_4^+ in ATS will form nitric acid, thus resulting in slight soil acidification in the application zone.

Thiosulfates may be applied through surface and overhead irrigation systems, sprinklers, and drip irrigation. Many of them are used in foliar sprays to provide a rapid source of plant nutrition (not recommended with ATS).

Management Practices. Sulfur deficiencies are noted in crops throughout the world. Thiosulfates are valuable fertilizer materials because they are easy to handle and apply, require minimal safety precautions, and are compatible with many other common fertilizers. However, these fertilizers should not be mixed with highly acidic solutions since this will cause the decomposition of the thiosulfate molecule and subsequent release of harmful sulfur dioxide gas.

Non-Agricultural Use. Thiosulfate materials are used in a variety of industrial applications. In photographic processing, they are used to bind silver atoms present in film or paper. Sodium thiosulfate is used in water treatment systems to remove chlorine. It is also used for gold extraction, since it forms a strong complex with this metal in a non-toxic process.

Source: http://www.ipni.net/specifics

M

Compound Fertilizer

Module 3.3-20 Many soils require the addition of several essential nutrients to alleviate plant deficiencies. Farmers may have the option of selecting a combination of single-nutrient fertilizers or using a fertilizer that has several nutrients combined into each particle. These combination (compound or complex) fertilizers can offer advantages of convenience in the field, economic savings, and ease in meeting crop nutritional needs.

Production. Compound fertilizers are made using basic fertilizer materials, such as NH_3, ammonium phosphate, urea, S, and K salts. There are many methods used for making these fertilizers, with the specific manufacturing processes determined by the available basic components and the desired nutrient content of the finished product. Here are four brief examples.

Compaction methods (agglomeration) involve binding small fertilizer particles together using compaction, a cementing agent, or a chemical bond. Various nutrient ratios can be combined using undersized particles that may not be suitable for other applications.

Accretion-based fertilizers are made by repeatedly adding a thin film of nutrient slurry which is continually dried, building up multiple layers until the desired granule size is reached.

Pipe-cross reactors are used to chemically melt NH_3, acids containing S or P, and other nutrients—such as K sources and micronutrients—into a solid fertilizer with the desired nutrient content.

The **nitrophosphate process** involves reacting phosphate rock with nitric acid to form a mixture of compounds containing N and P. If a K source is added during the process, a solid fertilizer with N, P, and K will result.

Agricultural Use. Compound fertilizer contains multiple nutrients in each individual granule. This differs from a blend of fertilizers mixed together to achieve a desired average nutrient composition. This difference allows compound fertilizer to be spread so that each granule delivers a mixture of nutrients as it dissolves in the soil and eliminates the potential for segregation of nutrient sources during transport or application. A uniform distribution of micronutrients throughout the rootzone can be achieved when included in compound fertilizers.

These fertilizers are especially effective for applying an initial nutrient dose in advance of planting. There are certain ratios of nutrients available from a fertilizer dealer for specific soil and crop conditions. This approach offers advantages of simplicity in making complex fertilizer decisions, but does not allow the flexibility to blend fertilizers to meet specific crop requirements. Turf managers and homeowners often find compound fertilizers desirable.

Management Practices. Compound fertilizers are sometimes more expensive than a physical combination or blend of the primary nutrient sources since they require additional processing. However, when a consideration is made of all the factors involved with nutrient handling and use, compound fertilizers may offer considerable advantages.

Nitrogen is the nutrient that most commonly needs to be carefully managed and reapplied during the growing season. It may not be feasible to supply sufficient N in advance of planting to meet the entire demand (using only compound fertilizer) without overapplying some of the other nutrients. It may be advisable to use a compound fertilizer early in the growing season and then later apply only N fertilizer as needed.

Compound fertilizers are usually produced regionally to meet local crop needs. There is a wide range of chemical and physical properties that can be adjusted to meet these needs. For example, a desire to minimize P in urban stormwater runoff has led some communities to restrict the addition of P to compound fertilizers sold for turf and ornamental purposes. Soils of a region that are typically low in a specific nutrient may have this element boosted in the compound fertilizer.

Chemical Properties. Chemical formulas vary widely. Common compound fertilizers include: 10-10-10, 12-12-12, 17-17-17, 21-7-14, and many other formulations.

Source: http://www.ipni.net/specifics

M

Coated Fertilizer

Module 3.3-21 A variety of coatings have been applied to fertilizer particles to control their solubility in soil. Controlling the rate of nutrient release can offer multiple environmental, economic, and yield benefits.

Production. A wide range of materials have been used as coatings on soluble fertilizers. Coatings are most commonly applied to granular or prilled N fertilizer, but multi-nutrient fertilizers are sometimes used. Since urea has the highest N content of common soluble fertilizers, it is the base material for most coated fertilizers.

Elemental sulfur (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.

Other coated fertilizers are made by reacting various resin-based polymers on the surface of the fertilizer granule. Another technique is to use low permeability polyethylene polymers in combination with high permeability coatings. The coating materials and coating processes vary among manufacturers.

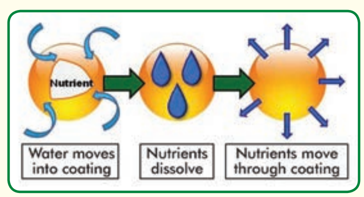
The composition and thickness of the fertilizer coating is carefully adjusted to control the nutrient release rate for specific applications. The duration of nutrient release from specific fertilizers can vary from several weeks to many months, as described on the product label. An additional expense is associated with adding a coating to a fertilizer particle, so coated fertilizers are more costly than the non-coated materials.

Agricultural Use. Coated fertilizers are used in a variety of agricultural and horticultural situations. They provide a prolonged supply of nutrients that may offer many benefits. These include:

- Sustained nutrient release that may decrease leaching and gaseous losses.
- Labor and application costs may be reduced by eliminating the need for multiple fertilizer applications.
- Greater tolerance of seedlings to closely placed fertilizer.
- Prolonged nutrient release may provide more uniform plant nutrition, better growth, and improved plant performance.

The maximum benefit from coated fertilizer is only achieved when the duration of nutrient release is synchronized with the periods of plant nutrient uptake.

Management Practices. Predicting the pattern of nutrient release from coated fertilizers in wide-ranging soil and cropping conditions is complex, since the release is controlled by a variety of environmental factors. For example, many coated fertilizers release more rapidly with increased moisture and soil temperature. Some products depend on soil microbial activity for nutrient release. An understanding of the mechanism of nutrient release is helpful for getting the maximum value from coated fertilizers.



Some coating materials are relatively brittle and are subject to abrasion and breaking under harsh environments. Excessive handling should be avoided when possible.

Non Agricultural Uses. Controlled-release technology is important for many applications. Perhaps their most well known use is for sustained release of pharmaceuticals that can be taken less frequently and maintain a steady concentration in the bloodstream. Coated materials are also used for veterinary and pest-control purposes.

Source: http://www.ipni.net/specifics

M

Gypsum

Module 3.3-22 Gypsum is a common mineral obtained from surface and underground deposits. It can be a valuable source of both Ca and S for plants and may provide benefits for soil properties in specific conditions.

Production. Gypsum is found in both crystal and rock forms. It generally results from the evaporation of saline water and is one of the more common minerals in sedimentary conditions. The white or gray-colored rocks are mined from open-pit or underground deposits, then crushed, screened, and used for a variety of purposes without further processing. Agricultural gypsum generally consists of $CaSO_4 \cdot 2H_2O$ (dihydrate). Under geological conditions of high temperature and pressure, gypsum is converted to anhydrite ($CaSO_4$ with no water).

By-product gypsum comes from fossil-fuel power stations where S is scrubbed from exhaust gas. Gypsum is also a byproduct from processing phosphate rock into phosphoric acid. Gypsum from recycled wall board is finely ground and used for soil application.

Chemical Properties

Type of Calcium sulfate	Formula & Composition	Solubility
Dihydrate (Gypsum)	$CaSO_4 \cdot 2H_2O$ [23% Ca, 18% S, 21% water]	2.05 g/L
Anhydrite	$CaSO_4$ [29% Ca, 23% S]	2.05 g/L
Hemi-hydrate (plaster of Paris)	$CaSO_4 \cdot {}^1/_2H_2O$	[Reverts to gypsum when water is added]

Agricultural Use. Gypsum (sometimes called landplaster) is generally added to soils either as a source of nutrients or to modify and improve soil properties. Gypsum is somewhat soluble in water, but more than 100 times more soluble than limestone in neutral pH soils. When applied to soil, its solubility depends on several factors, including particle size, soil moisture, and soil properties. Gypsum dissolves in water to release Ca^{2+} and SO_4^{2-}, with no significant direct impact on soil pH. In contrast, limestone will neutralize acidity in low pH soils. In regions with acid subsoils, gypsum is sometimes used as a relatively soluble source of Ca for alleviation of aluminum toxicity.

Some soils benefit from application of gypsum as a source of Ca. In soils with excess sodium (Na), the Ca released from gypsum will tend to bind with greater affinity than Na on soil exchange sites, thus releasing the Na to be leached from the rootzone. Where gypsum is used in the remediation of high Na soils, it generally results in the enhancement of soil physical properties—such as reducing bulk density, increasing permeability and water infiltration, and decreasing soil crusting. In most conditions, adding gypsum by itself will not loosen compacted or heavy clay soils.

Management Practices. A well-known use of gypsum is to supply Ca for peanuts, which have a unique growth pattern. Gypsum is most commonly spread on the soil surface and mixed in the rootzone. Equipment exists that allows finely ground gypsum to be distributed through an irrigation system. Gypsum is sometimes prilled to make application more convenient for home and turf use.

Non Agricultural Uses. The primary use of gypsum is for building materials (such as plaster and wallboard). For construction purposes, gypsum is ground and heated (calcined) to remove most of the bound water, resulting in hemi-hydrate plaster (plaster of Paris). When water is later added, the powder reverts to gypsum and dries in a rock-hard state. Gypsum is extensively used in many other applications, such as for water conditioning, in the food and pharmaceutical industries, and as a setting retardant in cement.

Source: http://www.ipni.net/specifics

M

Limestone

Module 3.3-23 Calcium carbonate, the chief component of limestone, is a widely used amendment to neutralize soil acidity and to supply calcium for plant nutrition. The term "lime" can refer to several products, but for agricultural use it generally refers to ground limestone.

Production. Limestone is a common sedimentary rock found in widespread geologic deposits. It has been used throughout much of recorded history as a building material, a cementing agent, and in agriculture to improve acid soils. An agricultural liming material (ag lime) is broadly defined as any substance containing Ca or Mg and capable of neutralizing acidity. Many materials can be classified as ag lime.

Ag lime is extracted from quarries or mines and usually requires mechanical crushing. The fineness of the ag lime is important in determining how quickly it reacts with soil acidity. Limestone of a smaller particle size reacts quickly since there is more exposed surface area for chemical reaction. Larger particles are slower to react, but provide a sustained, longer term source of acid neutralization. A measurement of particle size is typically reported on the product label.

Other materials in the ag lime, such as clay, will reduce its purity and diminish the acid-neutralizing capacity. Ag lime effectiveness is rated based on its comparison with pure calcium carbonate ($CaCO_3$), a value that is expressed as the percent calcium carbonate equivalent (CCE). Ag lime is more soluble in acid soils than in neutral or alkaline soils. The presence of $CaCO_3$ in soil is detected by the effervescence or 'fizz' when a drop of strong acid is applied.

Chemical Properties

Limestone/Calcite – calcium carbonate [$CaCO_3$] Mostly insoluble in water, but solubility increases in acid conditions (contains a maximum of 40% Ca).
Dolomite – calcium magnesium carbonate [$Ca{\cdot}Mg(CO_3)_2$] Mostly insoluble in water, but solubility increases in acid conditions (contains between 2 to 13% Mg).
Hydrated/Slaked lime – calcium hydroxide [$Ca(OH)_2$] Relatively insoluble in water; forms a solution of pH >12.
Burned lime/Quick lime – calcium oxide [CaO] Reacts with water to form hydrated lime.

Agricultural Use. The primary use of ag lime is to raise the pH of acid soils and reduce the concentration of aluminum (Al) in soil solution. Poor crop growth in acid soils is largely due to soluble Al, which is toxic to the root system of many plants. Lime will reduce soluble Al by two reactions:

1) $CaCO_3 + H_2O \rightarrow Ca^{2+} + 2OH^- + CO_2$
2) Al^{3+} [soluble] + $3OH^- \rightarrow Al(OH)_3$ [insoluble]

Additions of ag lime also supply valuable Ca (and possibly Mg) for plant nutrition. Some secondary benefits of neutralizing soil acidity with ag lime include:

- Increased P availability
- Improved N fixation by legumes
- Enhanced N mineralization and nitrification
- Better water use, nutrient recovery, and plant performance with a healthier root system

Management Practices. The quantity of ag lime needed to bring a soil to a desirable pH range can be easily determined in the laboratory. Ag lime is most commonly spread uniformly on the soil and then mixed through the root zone. Neutralizing soil acidity is not a one-time process, but must be repeated periodically depending on the soil and environmental conditions. Typical application rates are measured in tonnes per hectare.

Non Agricultural Uses. Limestone is one of the most widely utilized of all earth materials. In addition to its use in building and construction, limestone is used in diverse applications such as air pollution control, treatment systems for drinking water and waste water, soil stabilization, medicines, antacids, and cosmetics.

Source: http://www.ipni.net/specifics

M

Sodium Nitrate

Module 3.3-24 Sodium nitrate was one of the first commercially available inorganic nitrogen fertilizers. It was very important in plant nutrition before the discovery of ammonia synthesis by the Haber-Bosch process in the early 1900's. Sodium nitrate is a naturally occurring mined product, and as such is used to provide a portion of N nutrition in some organic cropping systems.

Production. Sodium nitrate ore is mined from surface deposits in the Atacama Desert of northern Chile. The ore body occurs within the top two meters in a zone nearly 500 miles (800 km) long and 10 miles (16 km) wide. Sodium nitrate accumulates in this remote region due to very low rainfall and unique geologic conditions.

The nitrate ore, called caliche, is crushed and washed with hot water to dissolve the sodium nitrate. The solution is then filtered and chilled to recover the final product. It is ultimately sold as crystalline or prilled products.

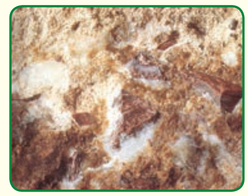
Small deposits of sodium nitrate are reported in other countries, but the Republic of Chile is the only commercial source of this product, so it is frequently referred to as Chilean nitrate.

Chemical Properties

Chemical formula:	$NaNO_3$
Nitrogen content:	16% (present as nitrate)
Sodium (Na) content:	26%
Water Solubility:	880 g/L (20° C)


COURTESY OF SQM

Sodium nitrate prills


COURTESY OF SQM

Caliche Ore

Agricultural Use. Sodium nitrate provides an immediately available source of N nutrition to plants since it is highly soluble. It has been used as a source of N nutrition since the mid 19th century and has a distinguished history as a valuable fertilizer material. It has been a preferred source of plant nutrition for many crops, notably for tobacco, which is typically fertilized with a nitrate form of fertilizer.

Sodium nitrate is approved by the U.S. National Organic Program for use as a supplemental source of N nutrition. The permitted use recognizes that mineralization of carbon-based organic N sources is not always rapid enough to meet the N demand of the growing crop. This deficit between N release and plant demand can be overcome with appropriate applications of sodium nitrate. Organic farmers are urged to check with their local certifying agency to determine the appropriate use of sodium nitrate.

Management Practices. Appropriate management is needed to achieve maximum advantage of any fertilizer, including sodium nitrate. Since nitrate is highly mobile in soils, careful consideration of placement, timing, and rate will minimize undesirable losses. Sodium nitrate can be broadcast onto the soil surface or applied in a concentrated band on top, or beneath the soil surface. This source of N is not susceptible to volatile losses, so it can provide added flexibility compared to ammonium and urea-containing N fertilizers.

Concern is sometimes expressed over Na in the fertilizer. Excessive Na in soils can have damaging effects on soil structure, but this risk is minimal at typical application rates of sodium nitrate. When used in organic production, Na inputs are quite low. For example, application of 30 lb N would supply only 50 lb Na to the soil. Sodium is held less strongly on soil cation exchange sites than other common cations, so it can be leached during typical rainfall or irrigation events.

Sodium nitrate ore is a naturally occurring product. Therefore, it may contain traces of various elements and compounds such as iodate, borate, perchlorate, magnesium, chloride, and sulfate.

Non Agricultural Uses. Sodium nitrate is a strong oxidizer and is used in a variety of industrial and food processes. For example, it is commonly added to charcoal briquettes to make them easier to light, and is used for making glass and in wastewater treatment. It is used as a food additive in meats and poultry (not to be confused with sodium nitrite which is used as a preservative in deli meats).

Sodium nitrate is combined with other nitrate materials to store heat from solar thermal projects. Solar thermal plants store energy in molten nitrate salts instead of storage in electrical batteries.

Source: http://www.ipni.net/specifics

M

Calcium Nitrate

Module 3.3-25. Calcium nitrate is a highly soluble source of two plant nutrients. Its high solubility makes it popular for supplying an immediately available source of nitrate and calcium directly to soil, through irrigation water, or with foliar applications.

Production. Phosphate rock is acidified with nitric acid to form a mixture of phosphoric acid and calcium nitrate during the nitrophosphate fertilizer manufacturing process. Ammonia is then added to neutralize excess acidity. Calcium nitrate crystals precipitate via a temperature gradient and are separated as the mixture is cooled. With the ammonia addition and crystallization, a double salt is formed [5 $Ca(NO_3)_2 \bullet NH_4NO_3 \bullet 10\ H_2O$, referred to as 5:1:10 double salt] and is considered the commercial grade of calcium nitrate. Hence, small amounts of ammonical N may also be present in this grade of calcium nitrate. Calcium nitrate is also manufactured by reacting nitric acid with crushed limestone forming either the 5:1:10 double salt or calcium nitrate tetrahydrate ($Ca(NO_3)_2 \bullet 4\ H_2O$). The latter product is often produced as a wet crystal or a mesh and is subject to specific regulation with respect to handling and safety. Prilling and granulating are the most common methods of making particles ready for field use.

Calcium nitrate is very hygroscopic (absorbs water from the air), so when intended for soil application, proprietary coatings are applied to minimize moisture uptake. Calcium nitrate intended for hydroponics or fertigation does not contain a conditioner, or it may be sold as a clear fluid fertilizer ready for use.

Chemical Properties

Chemical formula:	**Solid** 5 $Ca(NO_3)_2 \bullet NH_4NO_3 \bullet 10\ H_2O$
Nutrient content:	15.5% N, 19% to 22 Ca, <1.5% NH_4
pH (10% Solution):	6.0
Water solubility (20°C)	1200 g/L
Chemical formula:	**Liquid** $Ca(NO_3)_2 \bullet 4(H_2O)$
Nutrient content:	8 to 9% N, 11 to 12% Ca, <1% NH_4
pH:	5 to 7
Density (20°C):	1.47 to 1.48 kg/L, 12.2 to 12.3 lb/gal

Granular form of calcium nitrate

Liquid form of calcium nitrate

Agricultural Use. Calcium nitrate is popular in agronomic situations where a readily soluble source of nitrate or calcium is needed. Nitrate moves freely with soil moisture and can be immediately taken up by plant roots. Unlike many other common N fertilizers, $Ca(NO_3)_2$ application does not acidify soils since there is no acidity producing nitrification of ammonium occurring. Broadcast applications of $Ca(NO_3)_2$ are desirable in some circumstances because the risk of ammonia volatilization is eliminated with its use. In addition, some crops prefer nitrate sources of N.

Applications of $Ca(NO_3)_2$ are also used to provide supplemental Ca for plant nutrition. Some soils may contain considerable amounts of Ca, but it may not be sufficiently soluble to meet plant demands. Since Ca is not mobile in the plant it is important to apply Ca just-in-time in critical growth stages. Solutions of $Ca(NO_3)_2$ are commonly added to irrigation water and to foliar and fruit sprays to overcome such shortcomings that can affect yield and/or quality (such as apple bitter pit), or to meet peak Ca demands during critical growth periods. Part of the popularity of $Ca(NO_3)_2$ also arises from its chloride-free nature and $Ca(NO_3)_2$ can have an ameliorating effect under saline growing conditions, combating the negative effects of Na and Cl^-. Research has shown that a healthy plant with adequate Ca alleviates biotic and abiotic stresses such as fungal disease, and stresses due to drought, heat, or cold. Hence $Ca(NO_3)_2$ is widely used in intensive cropping systems that have a high focus on crop quality.

Management Practices. There are no special practices required for the use of $Ca(NO_3)_2$ beyond the need to keep nitrate from moving below the root zone.

To avoid precipitating insoluble fertilizer salts, $Ca(NO_3)_2$ should not be mixed with soluble phosphate or sulfate fertilizers in nutrient solutions or while fertigating. The extreme hygroscopic nature of solid $Ca(NO_3)_2$ makes it important to store it in a cool and dry environment.

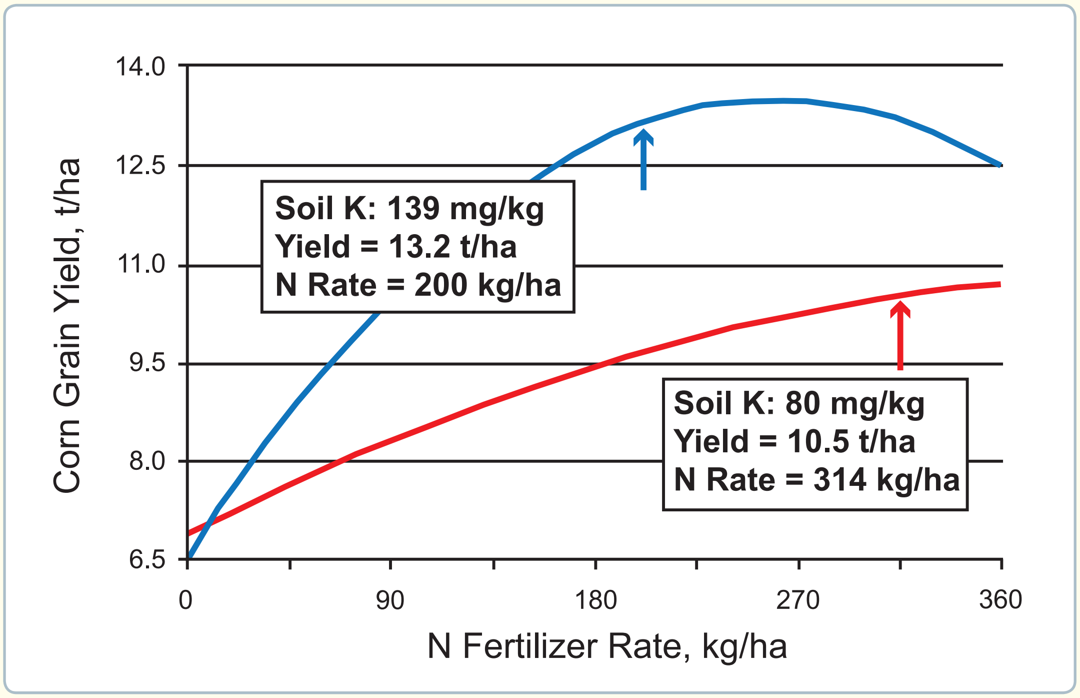
Calcium nitrate (double salt) is not classified as an oxidizer by government agencies, so there are no special restrictions on transport and handling as there may be for ammonium nitrate. However calcium nitrate tetrahydrate is classified as a 5.1 oxidizing agent that can, in conjunction with oxygen, cause or increase the combustion of other materials and may require special attention depending on local regulations.

Non Agricultural Uses. Calcium nitrate is used for waste water treatment to minimize the production of hydrogen sulfide. It is also added to concrete to accelerate setting and reduce corrosion of concrete reinforcements.

Source: http://www.ipni.net/specifics

M

Module 3.5-1 Balancing nitrogen and potassium nutrition is key to improving yield and nitrogen use efficiency. The maximum benefit from applied N fertilizer was obtained in this Ohio, USA example only when the secondary deficiency of K was corrected. **Source:** Murrell and Munson. 1999. Better Crops with Plant Food 83(3):28-31.



Submitted by T.S. Murrell, IPNI, USA, December 2011.

NOTES

Chapter 4

SCIENTIFIC PRINCIPLES SUPPORTING RIGHT RATE

The core scientific principles that define right rate for a specific set of conditions are the following.

- **Consider source, time, and place of application.**
- **Assess plant nutrient demand.** Yield is directly related to the quantity of nutrients taken up by the crop until maturity. The selection of a meaningful yield target attainable with optimal crop and nutrient management and its variability within fields and season to season thus provides important guidance on the estimation of total crop nutrient demand.
- **Use adequate methods to assess soil nutrient supply.** Practices used may include soil and plant analysis, response experiments, omission plots, etc.
- **Assess all available nutrient sources.** For most farms, this assessment includes quantity and plant availability of nutrients in manure, composts, biosolids, crop residues, atmospheric deposition, and irrigation water, as well as commercial fertilizers.
- **Predict fertilizer use efficiency.** Some loss is unavoidable, so to meet plant demand, the amount must be considered.
- **Consider soil resource impacts.** If the output of nutrients from a cropping system exceeds inputs, soil fertility declines in the long term.
- **Consider rate-specific economics.** For nutrients unlikely to be retained in the soil, the most economic rate of application is where the last unit of nutrient applied is equal in value to the increase in crop yield it generates (law of diminishing returns). For nutrients retained in the soil, their value to future crops should be considered. Assess probabilities of predicting economically optimum rates and the effect on net returns arising from error in prediction.

Under- or over-application of a particular nutrient may have crop production, economic, and/or environmental consequences. When fertilizer and other nutrient sources are relatively inexpensive compared to the value of the crop being produced, the incentive to make a precise nutrient recommendation is small unless the crop responds negatively to excessive nutrient levels (e.g. too much N causing lodging of small grains, reduced sugar content of beet, or rank cotton) or a perceived environmental consequence of the nutrient is acknowledged and valued (e.g. P contamination of surface water bodies). However, in times of higher nutrient costs and/or lower crop prices, grower interest in developing efficient fertilization programs increases considerably.

Liebig's Law of the Minimum states that the yield of a crop will be determined by the element present in the most limiting quantity. In other words, the deficiency of one nutrient cannot be overcome by the excess of another. Thus, all of the 17 essential elements must be present in quantities sufficient to meet the requirements of the growing crop. The right rate is conditional on source, time, and place. The nutrient source needs to release the right amount of available forms at the right time and in the right place to meet the needs of the growing plants.

4.1 Assess Plant Nutrient Demand

A key scientific principle to selecting the right fertilizer rate is matching nutrient supply with plant nutrient demand. Nutrient demand refers to the total amount of nutrients that will need to be taken up by the crop during the growing season. Some of these nutrients will be removed from the field in the harvested portion of the crop, while the remainder will be recycled back into the system as crop residue. In some cases, nutrient uptake and nutrient removal values will be similar as in harvesting forage for hay where most of the aboveground biomass is removed. In other situations, such as cereal grain production, only a portion of the total nutrients taken up by the plant is removed from the field.

Plants require nutrients in differing amounts. In general, the macronutrients are needed in the greatest amounts. In soils of temperate climates, macronutrients termed primary (N, P, and K) more frequently limit crop yields than those termed secondary (Ca, Mg, and S). This distinction between primary

Table 4.1 Total nutrient uptake* by selected crops.

Crop***	Region	---- kg uptake/t** ----			
		N	P_2O_5	K_2O	S
Alfalfa (DM)	Argentina	27	5.7	25	3.5
Barley	Argentina	26	9.2	24	4.2
Bermudagrass	USA	23	6.0	25	
Canola	China	43	27	87	
Chickpea	India	46	8.4	50	
Corn	USA	18	9.6	25	
Grape	China	5.6	5.2	8.5	
Mustard	India	33	15	11	14
Oranges	China	2.6	0.80	3.6	
Peach	China	4.5	1.5	5.0	
Peanut	India	63	12	37	3.9
Pear	China	5.0	2.0	5.0	
Peas, green	India	42	15	31	4.3
Potato	Australia	4.9	2.1	12	
Rice	USA	16	8.4	24	
Safflower	India	39	8.4	22	13
Sorghum	India	22	13	34	
Soybean	USA	82	18	38	
Sugar beet	China	4.8	1.4	9.3	
Sugarcane	China	1.8	0.36	2.1	
Sunflower	Argentina	40	25	35	5.0
Tobacco	China	39	12	71	
Tomato	India	2.8	1.3	3.8	
Wheat, spring	USA	37	13	26	
Wheat, winter	USA	32	11	33	

* Total nutrient uptake refers to the quantity of nutrient accumulated in the above ground portion, and harvested portions, of the plant by the time of sampling, usually physiological maturity or when uptake is at its maximum.
**Reported nutrient uptake coefficients may vary regionally depending on growing conditions. Use locally available data whenever possible.
***DM = dry matter basis; otherwise moisture content is standard marketing convention or at the stated moisture content.
Last modified May, 2014. IPNI provides the latest updates to data on nutrient uptake and removal at http://info.ipni.net/IPNI-3296

and secondary may not apply in many tropical soils.The total nutrient demand of a specific crop can be estimated by multiplying the attainable yield (yield goal) for that crop by the appropriate coefficient shown in **Table 4.1**.The micronutrients are typically needed in smaller quantities.

The higher the yield, the greater the nutrient requirement will be. The challenge lies in determining the yield goal for fertilization. Some useful guidelines:

- A yield goal should be both realistic and challenging.
- A common approach to setting realistic yield goals is targeting 80% of the potential yield (with water and nutrients non-limiting) of a crop in a particular climatic condition. Crop simulation models can help determine potential yield.
- A value somewhere between an above average yield and a maximum yield that has been achieved recently on that specific field, or one of similar production and management history, could be set as the target yield.
- Setting a target of 10% above the 3 to 5-year average of crops not suffering a severe yield loss due to drought, excessive rainfall, or pests is also a commonly suggested method. This method requires that individual field records be maintained, and that only those fields of similar production potential be considered in making estimates.
- The yield goal being fertilized for does not necessarily limit yield in any given year to that level. Unusually favorable weather resulting in exceptional yields also often results in exceptional nutrient release from the soil or unusually high nutrient use efficiency.

One of the major challenges in using a yield-based approach for determining fertilizer rates is that yield levels are known to vary widely in a given environment from year to year, as well as among growing seasons within a year where multiple cropping is practiced. Crop responsiveness to fertilizer also fluctuates as a result of the environment, independent of crop yield potential. Both yield potential and crop responsiveness affect the annual fertilizer rate requirement. Other factors that are often considered along with yield potential to estimate plant nutrient demand are cropping system, soil productivity, and fertilizer to crop price ratios. Equations and models that predict crop yield and nutrient uptake are also being utilized to fine-tune N rate recommendations.

4.2 Assess Soil Nutrient Supply

A portion of the plant nutrient demand is met by the soil. The soil's capacity to supply nutrients to a growing crop depends on several mechanisms. These include:

- mineralization and immobilization of nutrients out of and into soil organic matter;
- adsorption and desorption of nutrients to and from the soil;
- precipitation and dissolution reactions that regulate nutrient amounts in soil solution;
- reduction/oxidation reactions that change the speciation and solubility of multivalent nutrients;
- root interception, mass flow, and diffusion of nutrients in solution to absorbing plant roots.

Soil organic matter contains most nutrients required for plant growth. Many of these nutrients exist in very small quantities; however, in some cropping systems soil organic matter can be a dominant source of nutrients, particularly N and S. The amount of organic matter mineralized into plant available nutrient forms varies according to amount and type of organic matter and the presence of conditions favorable for microbial decomposition. These factors also make it very difficult to predict the amounts of nutrients that will become plant-available during the growing season.

Questions ?

1. One of the seven core scientific principles that define **right rate** for a specific set of conditions is to
   a. assess all available nutrient sources.
   b. assume high fertilizer use efficiency.
   c. place most of the emphasis on economics.
   d. apply as much as the crop is expected to demand.

2. Primary macronutrients are termed primary because they are
   a. taken up in the largest quantities of all elements.
   b. more frequently limit crop yields than those termed secondary.
   c. the first plant nutrients discovered.
   d. more expensive that those termed secondary.

3. Liebig's Law of the Minimum states that the yield of a crop will be determined by
   a. N, P, and K.
   b. Ca, Mg, and S.
   c. Micronutrients.
   d. the element present in the most limiting quantity.

4. Assessing plant demand involves selecting a realistic yield goal because
   a. nutrient uptake is proportional to yield.
   b. yield cannot exceed the selected yield goal.
   c. the amount to apply should equal nutrient uptake.
   d. weather producing exceptional yields reduces nutrient use efficiency.

Table 4.2 Factors affecting plant availability of various soil nutrients†.

Factor	N	P	K	S	Ca and Mg	Micros
Soil pH	X	X	X	X	X	X
Moisture	X	X	X	X	X	X
Temperature	X	X	X	X	X	X
Aeration	X	X	X	X	X	X
Soil organic matter	X	X		X	X	X
Amount of clay	X	X	X	X	X	X
Type of clay		X	X		X	X
Crop residues	X	X	X	X	X	X
Soil compaction		X	X			
Nutrient status of soil		X	X		X	
Other nutrients		X	X		X	X
Crop type	X	X		X		X
Cation exchange capacity (CEC)			X		X	X
% CEC saturation					X	

† - This table provides a non-exhaustive listing of factors and is only intended to provide an example of predominant factors and commonalities among nutrients

All five mechanisms listed above that influence soil nutrient supply are affected by soil physical characteristics like texture and type and amount of clay, chemical characteristics such as pH, and climatic conditions including temperature, moisture, and aeration. **Table 4.2** lists several factors affecting the plant availability of various soil nutrients.

The best tool for determining soil contributions to plant nutrient supply is a soil test. Detailed information on soil sampling and testing can be found in Chapter 8. As effective as soil testing can be in determining the right fertilizer rate, it is not always available or practical in many regions around the world due to infrastructural constraints. Soil testing is also not always a reliable tool for estimating the availability of some of the more mobile nutrients like N and S in humid and high rainfall areas. Under such scenarios, crop response in omission plot experiments can be used as an indicator of soil nutrient content. The yield of a plot where a particular nutrient was omitted (with ample application of all other limiting nutrients) provides an indirect estimation of the nutrient supplying capacity of the soil, while the difference in yield between a fully fertilized and an omission plot approximates the potential response to additions of the nutrient in question.

4.3 Assess All Available Nutrient Sources

When selecting the right fertilizer rate, the contribution toward meeting crop nutrient requirements coming from all available nutrient sources needs to be considered. Some of these sources include indigenous nutrient supplies (those not applied to the land such as crop residues and green manures), animal manures, composts, biosolids, atmospheric deposition, and irrigation water. The quantity and plant availability of nutrients in these sources can vary widely and can be difficult to estimate; however, efforts should be made to account for them. Average nutrient contents for some selected animal manures are listed in **Table 4.3**; these vary greatly across regions and farms, and generally it is better to use locally appropriate figures or laboratory analysis of the material to be applied.

Table 4.3 Approximate Dry Matter and Nutrient Composition of Selected Animal Manure. (From Havlin et al., 2005).

			Nutrient, kg/tonne			
Type of Livestock	**Waste Handling System**	**Dry Matter, %**	**N**		**P_2O_5**	**K_2O**
			Available*	Total†		
Solid Handling Systems						
Swine	Without bedding	18	3	5	4.5	4
	With bedding	18	2.5	4	3.5	3.5
Beef cattle	Without bedding	15	2	5.5	3.5	5
	With bedding	50	4	10.5	9	13
Dairy cattle	Without bedding	18	2	4.5	2	5
	With bedding	21	2.5	4.5	2	5
Poultry	Without litter	45	13	16.5	23	17
	With litter	75	18	28	22.5	17
	Deep pit (compost)	76	22	34	32	22.5
Liquid Handling Systems						
Swine	Liquid pit	4	10	18	13.5	9.5
	Oxidation ditch	2.5	6	12	13.5	9.5
	Lagoon	1	1.5	2	1	0.2
Beef cattle	Liquid pit	11	12	20	13.5	17
	Oxidation ditch	3	8	14	9	14.5
Dairy cattle	Lagoon	1	1	2	4.5	2.5
	Liquid pit	8	6	12	9	14.5
Poultry	Lagoon	1	1.2	2	2	2.5
	Liquid pit	13	32	40	18	48

*Primarily NH_4^+-N, which is plant available during the growing season. † - NH_4^+-N plus organic N, which is slow releasing.
Source: Sutton et al., 1985, Univ. of Minn. Ext. Bull. AG-FO-2613

Questions ?

5. The best tool for assessing soil nutrient supply is a soil test, because
    a. reliable soil testing is available worldwide.
    b. soil testing can be effective in determining the right fertilizer rate.
    c. reliable soil tests for N are available for high rainfall areas.
    d. soil tests predict plant root interception of nutrients.

6. Indigenous nutrient supplies include
    a. biosolids.
    b. composts.
    c. crop residues.
    d. irrigation water.

7. Symbiotic N fixation is an important indigenous N source in soils because
    a. soil microbes fix N for all crop species.
    b. legumes can fix large amounts of N.
    c. legumes can fix large amounts of P and K.
    d. crops following a legume need more N.

Symbiotic N fixation by legumes is considered to be one of the most important indigenous N sources in soils. Many nutrient management guidelines make N rate adjustments for crops in rotation with a legume. However, N fixation amounts and subsequent N availability to following crops is subject to wide variation due to a number of factors. Estimated ranges of annual N fixation by various legume crops are reported in **Table 4.4.** While the presence of legumes can influence N rate decisions for subsequent crops, the performance of the legume crop, including nodulation, yield, and residual N, is directly tied to proper fertilization with the other nutrients, particularly P and K.

Table 4.4 Estimated ranges of annual N fixation by various legume crops.

Legume	N fixed, kg/ha/yr
Alfalfa	150-250
Clover	100-150
Vetch	50-150
Soybean	50-150
Dry Bean	30-50
Field Pea	3-250
Lentils	3-190
Peanut	35-200

Reported values are averages from multiple sources, local estimates should be used for determining application rates.

Crop residues contain substantial quantities of plant nutrients. Recycling of such residues back to the soil contributes to the indigenous nutrient supply. Alternatively, harvesting crop residues leads to increased removal of nutrients from the field, particularly K, and must be considered as a negative component in the nutrient balance. Recycling of plant residues, besides contributing to inherent nutrient content in the soil, also improves soil organic carbon balances, soil moisture, and temperature regimes, enhances soil structure, and aids in erosion control. Average amounts of nutrients removed with the straw or stover of several crops is shown in **Table 4.5.** The amount of nutrients in crop residues removed from the field can vary depending on the amount of rain and weathering to which they have been exposed, and on other factors like the cutting height of the crop.

Cover crops include a wide variety of plant species (most commonly grasses and legumes) that are planted in the period between cash crops or are sown in the inter-row area in orchards or vineyards. They can help reduce soil erosion, reduce nitrate leaching and contribute organic matter and nutrients to subsequent crops after they decompose. Leguminous cover crops will supply additional N through biological fixation. The amount of N fixed will depend on many factors, but since the duration of growth and biomass accumulated for a cover crop is usually less than for a full season crop, the amounts of N fixed will be lower than those shown in **Table 4.4**.

The nutrient contribution to a crop from indigenous sources is highly variable and local guidelines should be used whenever available to adjust fertilizer rate recommendations accordingly.

4.4 Predict Fertilizer Use Efficiency

Fertilizer use efficiency (FUE) is a major factor in determining the fertilizer rate needed. The general topic of nutrient use efficiency is covered in greater depth in Chapter 9. All rate recommendations either make implicit assumptions about FUE or have it explicitly present in the equations used to calculate recommendations. Even with best management practices based on 4R Nutrient Stewardship, the amount of the applied fertilizer utilized by the crop will be less than 100%. While growers strive to minimize losses and increase efficiencies, some applied nutrients may also be utilized by soil organisms, particularly while soil organic matter levels are being built up. The efficiency of fertilizer nutrient uptake is also often adversely affected by inherent sinks and loss mechanisms that exist in every field. Fertilizer use efficiency will also vary according to site-specific factors, including weather, soil type, and cropping system. That's why adjustments for efficiency should be included when determining fertilizer rate requirements. A major objective of 4R Nutrient Stewardship is to use practices that incorporate right source, time and place within well managed cropping systems to produce high FUE for estimating right rate.

One method of calculating FUE that is useful in determining nutrient rate requirements is agronomic efficiency (AE). Agronomic efficiency is the amount of yield increase per unit of fertilizer applied. When the same units are used for yield increase and fertilizer rate, the expression becomes a unit-less ratio and is calculated as follows:

$$\mathbf{AE = (Y\text{-}Y_0)/F}$$

Where:
1) Y is crop yield with fertilizer nutrient applied;
2) Y_0 is the crop yield with no application of the nutrient in question;
3) F is the amount of fertilizer nutrient applied.

Typical AE range: 10-25; >20 in well managed systems, at low nutrient rates relative to optimum, or at low soil nutrient supply.

Consider a crop with an attainable yield of 9,500 units. Omission plot studies indicate that the AE for N (AE_N) at the site is 20 (20 units of grain increase per unit of N applied) and an expected N omission plot yield is 6,000 units. Yield units and fertilizer units need to be the same (for example, kg/ha of grain and kg/ha of fertilizer N). The N fertilizer rate is calculated as follows:

Fertilizer N = (attainable yield – N omission plot yield)/AE_N
Using the numbers in above example, the N rate recommendation would be:

Fertilizer N = (9,500-6,000)/20 = 175 units

Another method of calculating FUE that is sometimes used in determining nutrient rate requirements is recovery efficiency (RE). Recovery efficiency is the increase in crop uptake of the nutrient in aboveground parts of the plant (for most crops) as a proportion of the applied rate of the nutrient. It is calculated as:

$$\mathbf{RE = (U\text{-}U_0)/F}$$

Where:
1) U is total nutrient uptake in aboveground crop biomass with nutrient applied;
2) U_0 is total nutrient uptake in aboveground crop biomass with no nutrient applied;
3) F is the amount of fertilizer nutrient applied.

This equation can be rearranged to allow calculation of the fertilizer nutrient rate needed as: F = $(U\text{-}U_0)$/RE. As in the previous example using AE, omission plot yields can be used but in this case the yields must be converted to uptake, normally using typical uptake values per unit of crop yield such as those shown in **Table 4.1**. Typical range in field RE values for N applied to cereals is 0.3 to 0.5 (30 to 50%). When best management practices are applied, it can be increased to the 0.5 to 0.8 (50 to 80%) range. Using the yields in the AE example, assuming 0.0215 units of N uptake per unit of yield and an RE of 0.50, the fertilizer rate is calculated as:

Fertilizer N = ((9,500 x 0.0215)-(6,000 x 0.0215))/0.50 = 150 units

4.5 Consider Soil Resource Impacts

Plant nutrition affects the quality of the soil resource in several ways. First, when plant nutrients are present at levels that optimize plant growth, the amount of organic carbon contributed by plants to the soil is greater than when plant growth is limited by nutrients. The greater carbon contribution helps to maintain, build, or slow the depletion of soil organic matter, which is a key factor in maintaining soil structure. In turn, this influences soil water holding capacity and many other properties important to crop growth. Second, many nutrients are retained in soils, and the rate of their addition influences the levels of their available fractions in the soil over time.

Nutrients retained in soils include P and K, and most of the nutrients that are reported on a soil test (see Chapter 8 for more information on soil testing). When soils are very low in these nutrients, amounts considerably greater than the amount removed by the crop may be required to provide optimum crop yields. When soils have very high levels of these nutrients, amounts less than crop removal may suffice. When soils are at a desired or optimum level of these nutrients, it is commonly assumed that these levels will be maintained as long as the total amount of nutrient applied each year equals the amount of nutrient in the harvested crop. **Table 4.5** lists nutrient removal coefficients for selected crops. Though in **Table 4.5** we provide typical values for the crops listed, actual values can vary considerably as illustrated in **Table 4.6**. For that reason, local data should be used whenever possible.

Some soils may require additions that exceed, or are less than, crop removal to maintain desired soil test levels. Examples of the former include soils that fix P or K, either through sorption, chemical precipitation, or entrapment (occlusion) between layers of clay. Other soils may be in a state where net mineralization of P or K from the soil minerals, or the organic fraction, is occurring. For this reason, it is normally recommended to test soils every 3 to 5 years for retained nutrients like P and K to determine whether soil test levels are indeed being held at the desired level. Soil testing helps determine whether the rates of applied nutrients should exceed, equal, or be less than the amounts of nutrients removed by crop harvest.

Questions ?

8. If a nutrient omission plot study is conducted, and Y is 9,000 kg/ha, Y_0 is 7,500 kg/ha and AE_N is 15, what rate of N would be recommended for the same crop in similar field conditions, in kg/ha?
   a. 50.
   b. 100.
   c. 150.
   d. 200.

9. Typical recovery efficiency for fertilizer N applied to cereals is
   a. 10 to 25%.
   b. >20% in well-managed systems.
   c. 30 to 50%.
   d. 50 to 80%.

10. In the long term, levels of available nutrients are maintained at optimum levels in most soils when the amount of nutrient applied
    a. exceeds crop uptake.
    b. is less than crop removal.
    c. equals crop removal.
    d. equals crop uptake.

Table 4.5 Nutrient removal* by selected crops.

	Removal, kg/t**			
Crop* **	**N**	**P_2O_5**	**K_2O**	**S**
Alfalfa (DM)	26	6.0	25	2.7
Alsike Clover (DM)	21	5.5	27	1.5
Bahiagrass	22	6.0	18	
Barley grain	21	8.3	6.7	1.9
Barley straw per t of grain	8.3	3.3	25	2.1
Barley straw	6.5	2.6	20	1.5
Beans (dry)	50	13	15	8.7
Bermuda grass	23	6.0	25	
Birdsfoot trefoil (DM)	23	5.5	21	
Bluegrass (DM)	15	6.0	23	2.5
Bromegrass (DM)	16	5.0	23	2.5
Buckwheat	17	5.0	4.4	
Canola grain	32	16	8.0	5.0
Corn grain	12	6.3	4.5	1.4
Corn silage (67% water) per t of grain	29	9.1	21	3.2
Corn silage (67% water)	4.9	1.6	3.7	0.55
Corn stover per t of grain	8.0	2.9	20	1.3
Corn stover	8.0	2.9	20	1.3
Cotton (lint)	64	28	38	
Cotton stover	9.4	3.3	11	
Fescue (DM)	19	6.0	27	2.9
Flax grain	45	13	11	3.4
Flax straw	13	2.9	39	2.7
Millet grain	28	8.0	8.0	1.6
Millet straw	7.7	2.2	20	
Mint oil	1,900	1,100	4,500	
Oat grain	24	8.8	5.9	2.2
Oat straw per t of grain	9.7	5.0	29	3.4
Oat straw	6.0	3.2	19	2.3
Orchardgrass (DM)	18	6.5	27	2.9
Peanut nuts	35	5.5	8.5	
Peanut stover	16	3.4	12	
Potato tuber	3.0	1.5	6.5	0.30
Potato above-ground stems & leaves	1.9	0.60	5.3	0.20
Red clover (DM)	23	6.0	21	1.5
Reed canarygrass (DM)	15	6.6	13	
Rice grain	13	6.7	3.6	
Rice straw	8.3	2.7	21	
Rye grain	25	8.2	5.5	1.8
Rye straw per t of grain	14	3.8	27	2.5
Rye straw	6.0	1.5	11	1.0
Ryegrass (DM)	22	6.0	22	
Sorghum grain	13	7.8	5.4	1.2

	Removal, kg/t**			
Crop* **	**N**	**P_2O_5**	**K_2O**	**S**
Sorghum stover per t of grain	11	3.2	17	2.4
Sorghum stover	14	4.2	21	3.0
Sorghum-sudan (DM)	15	4.8	17	2.9
Soybean grain	55	12	20	3.0
Soybean hay (DM)	23	5.5	13	2.5
Soybean stover per t of grain	18	4.0	17	2.8
Soybean stover	20	4.4	19	3.1
Sugarbeet root	1.9	1.1	3.7	0.23
Sugarbeet top	3.7	2.0	10	0.20
Sugarcane	1.0	0.65	1.8	
Sunflower grain	27	9.7	9.0	2.5
Sunflower stover per t of grain	28	2.4	41	6.0
Sunflower stover	12	1.0	17	2.5
Switchgrass (DM)	11	6.0	29	
Timothy (DM)	13	5.5	21	1.0
Tomatoes	1.3	0.46	2.9	
Tobacco leaves	36	9.0	57	6.0
Vetch (DM)	29	7.5	25	
Wheat straw per t of grain	12	2.7	20	2.3
Wheat straw	7.6	1.9	15	2.7
Wheat (spring) grain	25	9.5	5.5	1.7
Wheat (winter) grain	19	8.0	4.8	1.7

* Nutrient removal refers to the quantity of nutrient removed from the field at crop harvest.
**Reported nutrient removal coefficients may vary regionally depending on growing conditions. Use locally available data whenever possible.
***DM = dry matter basis; otherwise moisture content is standard marketing convention or at the stated moisture content.
Last modified May, 2014. IPNI provides the latest updates to data on nutrient uptake and removal at http://info.ipni.net/IPNI-3296

Example: Using **Table 4.5**, an example of nutrient balancing would be a 10 t/ha corn crop removes 63 kg P_2O_5 from the soil (10 x 6.3=63). So, the maintenance P_2O_5 application will be 63 kg/ha.

Table 4.6 Variability in nutrient removal in the harvested portion of corn, soybeans and wheat in Missouri, USA (Nathan, 2011).

	Removal, kg/t								
	Corn			**Soybean**			**Wheat**		
	N	**P_2O_5**	**K_2O**	**N**	**P_2O_5**	**K_2O**	**N**	**P_2O_5**	**K_2O**
Average	12	6.2	4.5	46.8	11.5	18.5	18.5	8.0	5.2
Median	12	6.1	4.3	45.7	11.7	18.7	18.7	8.2	5.0
Minimum	7.0	4.1	2.1	32.8	7.0	12.3	12.2	5.0	3.3
Maximum	17.3	10.4	7.7	61.8	14.8	22.3	25.2	11.0	7.8
CV, %	13.0	17.1	23.4	11.8	14.1	10.6	14.4	13.3	17.5
Number	511	509	512	269	270	267	177	179	174

Grain samples collected from all counties in the state across 3 years. Two-thirds of the samples lie between plus and minus one CV from the average.

4.6 Consider Rate-Specific Economics

The economic optimum nutrient rate (EONR) defines the nutrient rate that will result in the greatest monetary return to the applied nutrient from the current crop. This rate will usually be less than the agronomic optimum nutrient rate (AONR), which is the minimum rate that results in maximum crop yield, and will decline if input costs increase and crop price remains stable. Conversely, if commodity price rises and input costs remain stable, the EONR will approach the AONR. Often fluctuations in crop and fertilizer prices occur simultaneously, the ratio between inputs and outputs remains the same, and the EONR is not significantly affected.

Aiming to achieve EONR is the approach typically used for nutrients like N and S which are mobile in the soil and not retained year to year. For nutrients that are retained in the soil, including P and K, the benefits of nutrient application are long-term in nature; therefore, their costs are usually amortized over several years. Applications at rates to build soil fertility are usually above the EONR for a one-year crop response, but may become economical over a longer time period when the responses in the following years are considered.

Benefits of building soil fertility levels to the optimum range include greater flexibility in choices of source, rate, timing and placement. The increased flexibility allows farmers to take advantage of market conditions and fluctuations in fertilizer prices. Higher price ratios (high input costs relative to crop value) increase the value of using best management practices to determine fertilizer application rates needed to optimize crop yield and profitability. Lower price ratios (low input costs relative to crop value) often result in a lower profitability risk; however, the environmental risk associated with over-application of nutrients is greater. See Section 8.5 for more detail.

Under any economic scenario, risk management is best achieved by following the scientific principles for selecting the right fertilizer rate.

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IPNI. 2005. Nutrients Removed in Harvested Portion of Crop. Norcross, GA. [On-line].

Havlin, J.L. et al. 2005. Soil Fertility and Fertilizers: An Introduction to Nutrient Management. 7th edition. Pearson Prentice Hall. NJ, USA.

Ladha, J.K. et al. 2005. Advances in Agronomy 87: 85-176.

Nathan, M. 2011. Improving accuracy of nutrient removal estimates status report. University of Missouri, Colombia.

Module 4.1-1 Fertilizer nitrogen required by wheat and maize in Argentina is best determined prior to planting. In fact, evaluation of available (inorganic) N at planting time has been a useful tool to determine fertilizer N needs in sub-humid and semi-arid regions throughout the world. In a particular area, the level of available N at planting above which no response to fertilizer N is expected can be estimated. This methodology has been calibrated with success in several areas of the Pampas region of Argentina for wheat and corn. Nitrogen fertilizer rates (Nf) are estimated from the difference between the NREQ level and the amount of NO_3^--N determined before planting: Nf = NREQ – X

Where: Nf is the amount of fertilizer N to be applied,
NREQ is the soil N plus fertilizer N required,
X is the amount of NO_3^--N in the soil at 0-60 cm depth.

In **Figure 1**, if soil testing at planting indicates an availability of 70 kg/ha NO_3^--N, the estimated yield would be 7,700 kg/ha. Thus, if the attainable yield in the specific field is 10,000 kg/ha, a NREQ of 150 kg/ha of available N should be reached, and the recommended N rate would be 80 kg/ha fertilizer N.

Levels of NREQ for wheat and maize, according to the expected yields for areas with different soils and climates are shown in **Table 1**.

Source: Bianchini A., F. Garcia, and R. Melchiori. 2008. *In* J. Hatfield and R. Follet (Eds.). Nitrogen in the environment: Sources, problems, and management. Elsevier - Academic Press, San Diego, CA. USA pp 105-124.

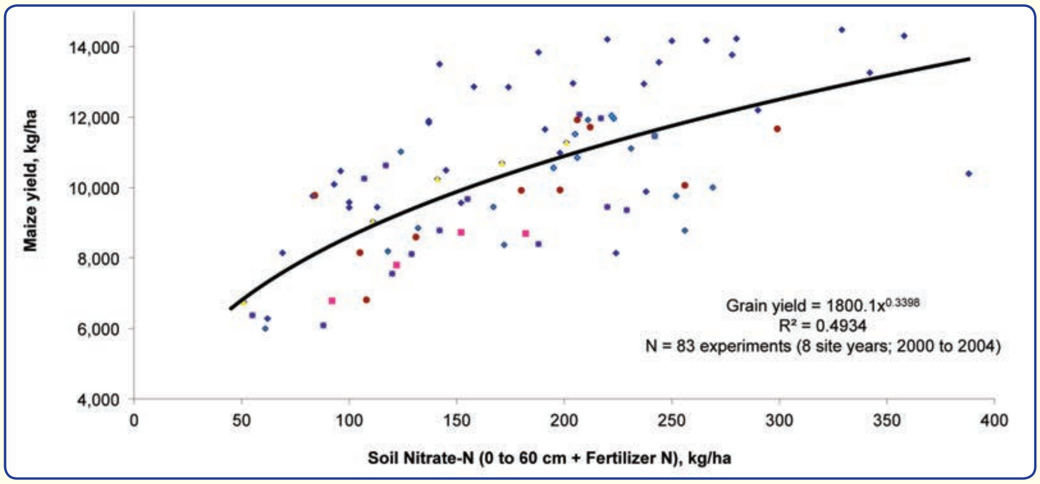

Figure 1. The relationship between soil available N (NO_3^--N) and maize grain yield for 83 field experiments from 8 site years, (2000 to 2004) in the central Pampas.

Table 1. Expected yields correspond to N requirements for different areas.

Area	NREQ level, (NO_3^--N, 0-60 cm)	Expected yield	Reference
	-------- kg/ha --------		
Wheat			
Southeastern Buenos Aires	125	3,500	González Montaner et al., 1991
Southeastern Buenos Aires	175	5,000-5,500	González Montaner et al., 2003
Central and South Santa Fe	92	3,500-4,000	Salvagiotti et al., 2004
Southern Santa Fe and Córdoba	100-150	3,200-4,400	García et al., 2006
Maize			
Northern Buenos Aires	150	9,000	Ruiz et al., 2001
Northern Buenos Aires	150-170	10,000	Alvarez et al., 2003
Central and South Santa Fe	135 162	< 9,500 > 9,500	Salvagiotti et al., 2004
Southern Santa Fe and Córdoba	150-200	10,000-11,000	Nutrition network CREA Southern Santa Fe, 2009

Submitted by F. Garcia, IPNI, Argentina, September 2011.

Module 4.1-2 Calculating fertilizer rates in cereals using omission plot data. The nutrient omission plot approach for calculating fertilizer rates for cereals (rice, wheat, maize) utilizes information on grain yields obtained in plots with the nutrient in question omitted and at ample levels. Other nutrients are applied to ensure they are not limiting yield. The yield of the omission plot is used as an indirect estimate of soil supplying capacity of the omitted nutrient. The grain yield difference between the omission plot and the one fertilized at an ample level can be used to estimate fertilizer rate required for various target yields.

Table 1. Yields from an omission plot experiment in winter wheat from India.

Treatment	Yield, kg/ha
1. Ample rates of N, P, and K	5,556
2. N omitted; ample rates of P and K	1,667

Since the rate of N applied in the "ample" plot in **Table 1** was 150 kg/ha, agronomic efficiency (AE_N) of this plot was (5,556 – 1,667)/150 or 26 kg of grain per kg of N fertilizer.

If one assumes similar soil N supply capacity, and a similar level of efficiency (26 kg/kg), for other fields in the area, **Table 2** shows the resulting rates that would be recommended for different target yields (e.g. fields #1 and #2). If an omission plot in the area with a different preceding crop was conducted and gave a yield as for field #3 below, that information too could be used in the rate calculation.

Table 2. Rate calculation for three example winter wheat fields.

Field #	Yield target, kg/ha	Omission plot yield, kg/ha	Calculated N rate, kg/ha
1	6,500	1,667	(6,500 – 1,667)/26 = 186
2	4,500	1,667	(4,500 – 1,667)/26 = 109
3	6,500	2,500	(6,500 – 2,500)/26 = 154

Compared to values obtained across many trials, the AE_N calculated from the data in **Table 1** is relatively high (see Section 4.4 and **Table 3**). Recommendations are most accurate when site-specific local values for AE_N, omission plot yield, and target yield can be obtained.

Table 3. Observed ranges of AE_N for cereals from selected agronomic experiments in India.

Crop	N applied only[1]	N with ample P and K[1]	Farmers' practice, Punjab[2]	Site-specific nutrient management
Maize	4-7	7-14	–	26-28[3]
Wheat	7-12	17-24	–	20-28[3]
Rice	7-12	14-23	8-10	22-34[4]

[1] Biswas, P.P. and P.D. Sharma. 2008. Indian J. Fert. 4(7):59-62.
[2] Khurana, H.S. et al., 2007. Agron J. 99:1436-1447.
[3] IPNI Unpublished data, 2011.
[4] Singh, B. et al. 2012. Field Crops Research 126:63-69.

The nutrient omission approach can be a sound alternative to a soil test-based approach, in regions of the world where reliable soil analysis services are unavailable. This situation is prevalent in many developing countries.

Submitted by K. Majumdar, IPNI, India, January 2012.

M

Module 4.6-1 Economic optimum nitrogen rates for cotton on a silty clay loam in Alabama change little with changes in prices. In this example, though cotton and N prices varied significantly, they usually varied together, keeping the cost to price ratios relatively constant and the EONR relatively stable. **Adapted from:** Snyder, C.S. and W.M. Stewart. 2005. Using the most profitable nitrogen rate in your cotton production system. [On-line].

	Cotton Price			
N price	**$ 1.15/kg**	**$ 1.37/kg**	**$ 1.58/kg**	**$ 1.81/kg**
($/kg)	Economic optimum N rate, kg/ha			
1.10	91	94	96	99
1.21	88	92	95	97
1.32	87	91	93	96
1.43	85	88	92	95
1.54	83	86	91	94
1.65	81	85	90	93

Submitted by S. Phillips, IPNI, USA, September 2011.

Module 4.6-2 Economically optimum rates of nitrogen for corn varied only slightly with market conditions over a 10-year period. In the west-central and northwest regions of Indiana, the average rate required to remove N limitations for corn following soybeans was estimated to be 192 kg N/ha. The economically optimum rate—defined as the rate at which the last increment of N fertilizer returns a grain yield increase large enough to pay for itself—depends on price ratio and is generally lower. Between 2000 and 2009 the price ratio between N fertilizer and corn grain (expressed as $/t N divided by $/t grain) ranged between 5 and 10 (a higher ratio reflects relatively more expensive fertilizer). Recommended rates (kg/ha) within this range of price ratios varied as shown in the table below. **Adapted from:** Camberato et al. 2011. Nitrogen management guidelines for Indiana. [On-line].

	Grain price, $/tonne					
N cost/tonne	**$110**	**$130**	**$150**	**$170**	**$190**	**$210**
$440	181	183	184	185	185	186
$660	177†	178	180	181	183	183
$880	171	175	177	178	179	180
$1,100	167	170	173	175	177	178
$1,320	162	166	169	171	174	175
$1,540	156	162	166	168	170	172
$1,760	152	158	162	165	168	170
$1,980	148	153	158	162	165	167
$2,200	142	149	155	159	162	165

† Highlighted values represent EONR recommendations (kg/ha) at price ratios (expressed as $/t N divided by $/t grain) between 5 and 10.

Submitted by S. Phillips, IPNI, USA, September 2011.

Chapter 5

SCIENTIFIC PRINCIPLES SUPPORTING RIGHT TIME

The core scientific principles that define right time for a specific set of conditions are the following.

- **Consider source, rate, and place of application.**
- **Assess timing of plant uptake.** Nutrients should be applied to match the seasonal crop nutrient demand, which depends on planting date, plant growth characteristics, sensitivity to deficiencies at particular growth stages, etc.
- **Assess dynamics of soil nutrient supply.** Mineralization of soil organic matter supplies a large quantity of some nutrients, but if the crop's uptake need precedes its release, deficiencies may limit productivity.
- **Recognize dynamics of soil nutrient loss.** For example, in temperate regions, leaching losses tend to be more frequent in the spring and fall.
- **Evaluate logistics of field operations.** For example, multiple applications of nutrients may or may not combine with those of crop protection products. Nutrient applications should not delay time-sensitive operations such as planting.

5.1 Assessing timing of plant uptake

Assessing crop uptake dynamics and patterns can be an important component in determining appropriate timing of nutrient application. The uptake of major nutrients and dry matter accumulation patterns are similar for most crops and usually follow a sigmoid or "S" shaped curve **(Figure 5.1)**. This is characterized by rather slow early uptake, increase to a maximum during the rapid growth phase, and decline as the crop matures. Rate of plant nutrient uptake is thus not consistent throughout the season. Applications timed and

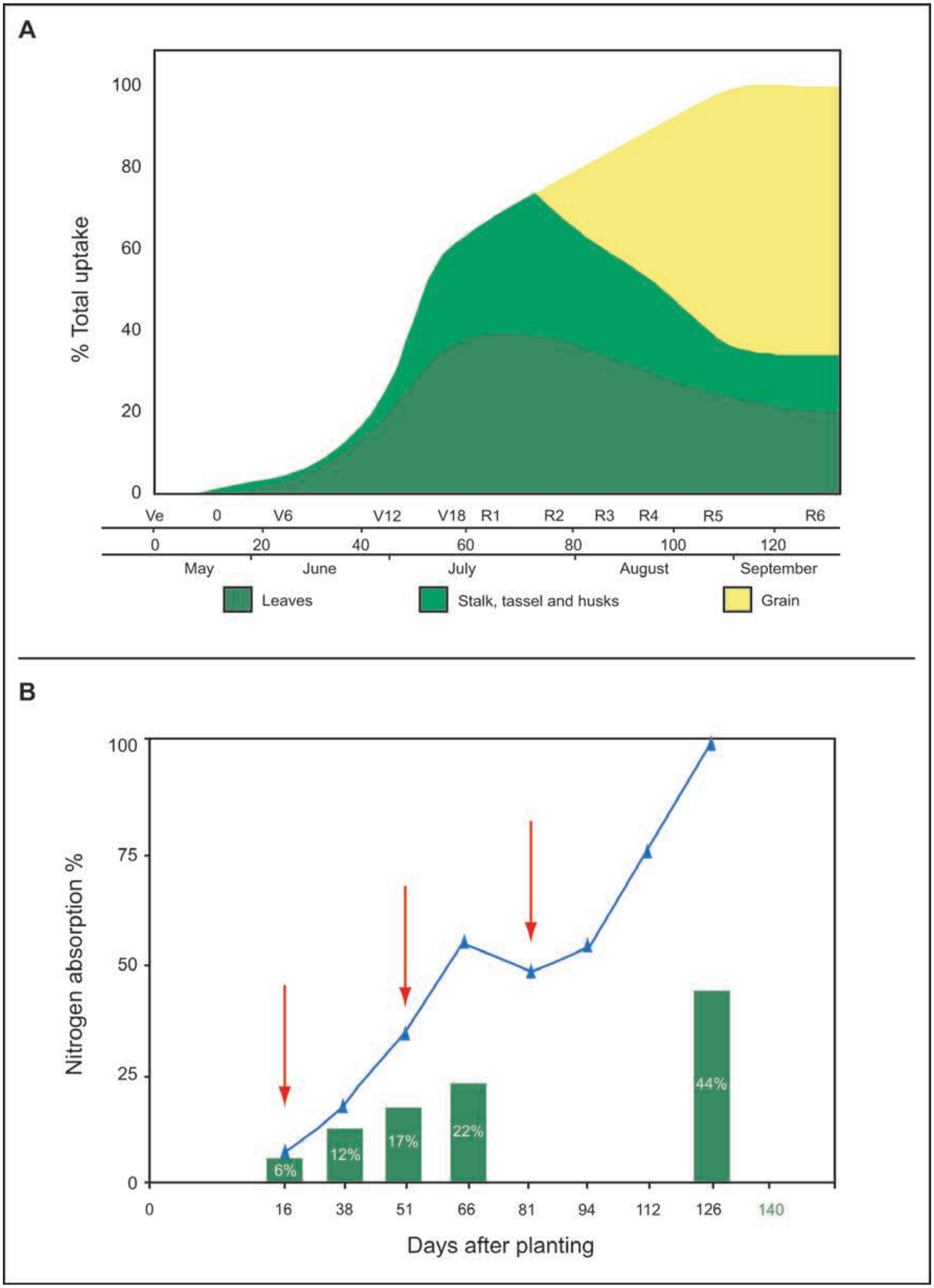

Figure 5.1 Cumulative corn N uptake divided by plant organ (A), and cumulative N uptake with times of peak demand (green columns) and recommended time of application (red arrows) for rice (B). **Sources: A) Adapted from:** How a Corn Plant Develops, Iowa State University Special Report No. 48, November 2008; **B) Adapted from:** Bertsch F. Estudios de absorción de nutrientes como apoyo a las recomendaciones de fertilización. Informaciones Agronómicas 57:1-10. 2005).

targeted at specific growth stages may be beneficial to crop yield and/or quality in some production systems for some nutrients, most notably N. Timed and targeted applications may also be beneficial to reduce environmental impacts of nutrient loss from soil.

Many examples of timing fertilizer applications based on stage of crop growth can be given, but only a few will be offered here.

- **N and K application to cotton.** The majority of both N and K in cotton production are taken up after the appearance of first flower, or the onset of the reproductive phase. It is important to make sure that adequate amounts of these nutrients are available when demand is highest. In some circumstances foliar application of N and even K starting at first flower can improve cotton yield and/or quality.

- **N application to small grains such as wheat.** Most wheat recommendations call for some N applied at planting, with the majority topdress applied by (before) jointing. By the time wheat begins heading later in the season the majority of N has been taken up, and if good N management practices were not previously used, then yield will suffer. Although yield has been determined by the heading stage, late season application of N during this stage in some wheat production systems can increase grain protein. This may be beneficial where a premium is paid for protein. Care should be taken in these late-season applications to avoid damage that might impact grain fill (e.g. flag leaf burn).

- **Fruit trees.** Fruit trees are perennial plants whose characteristics of nutrient uptake and distribution are different from most field crops. A good example is grape plants that have three distinct stages for nutrient uptake: the period between sprouting/early foliage growth and new shoot/fruit development, the period between early fruit development and fruit expansion, and the period after fruit expansion up to fruit maturity.

- **Semi-perennial tropical crops.** For crops such as oil palm or banana that have continuous harvest, the right timing will depend mostly on weather patterns and opportunity for application. It is important nonetheless, to take into account anticipated peaks of productivity, for instance when rains start after a dry period.

- **Ca for peanut.** Peanuts are especially sensitive to Ca deficiency. High levels of available Ca are needed in the soil zone where peanut pods are developing, and thus pre-bloom applications of soluble Ca materials (i.e. calcium sulfate or calcium nitrate) are sometimes made to peanuts.

- **Mn for soybean.** Early season foliar applications of Mn are often made to soybean in areas when deficiency symptoms appear on the plant tissue.

Another consideration for timing is crop sensitivity to specific nutrient deficiencies, often related to soil conditions. Some crops are more prone to certain deficiencies than others, therefore susceptible crops may require specific fertilizer application timing.

Questions ?

1. One of the five core scientific principles that define **right time** for a specific set of conditions is to
   a. apply nutrients just before the grain-filling stage.
   b. evaluate logistics of field operations.
   c. assume slow mineralization of soil nutrients.
   d. apply nutrients just before leaching risks increase.

2. Uptake of major nutrients by most crops usually follows a curve over time whose shape is termed
   a. sigmoid.
   b. rhomboid.
   c. spheroid.
   d. linear.

3. Application of N fertilizer during heading of wheat can increase grain
   a. yield.
   b. fill.
   c. protein.
   d. starch quality.

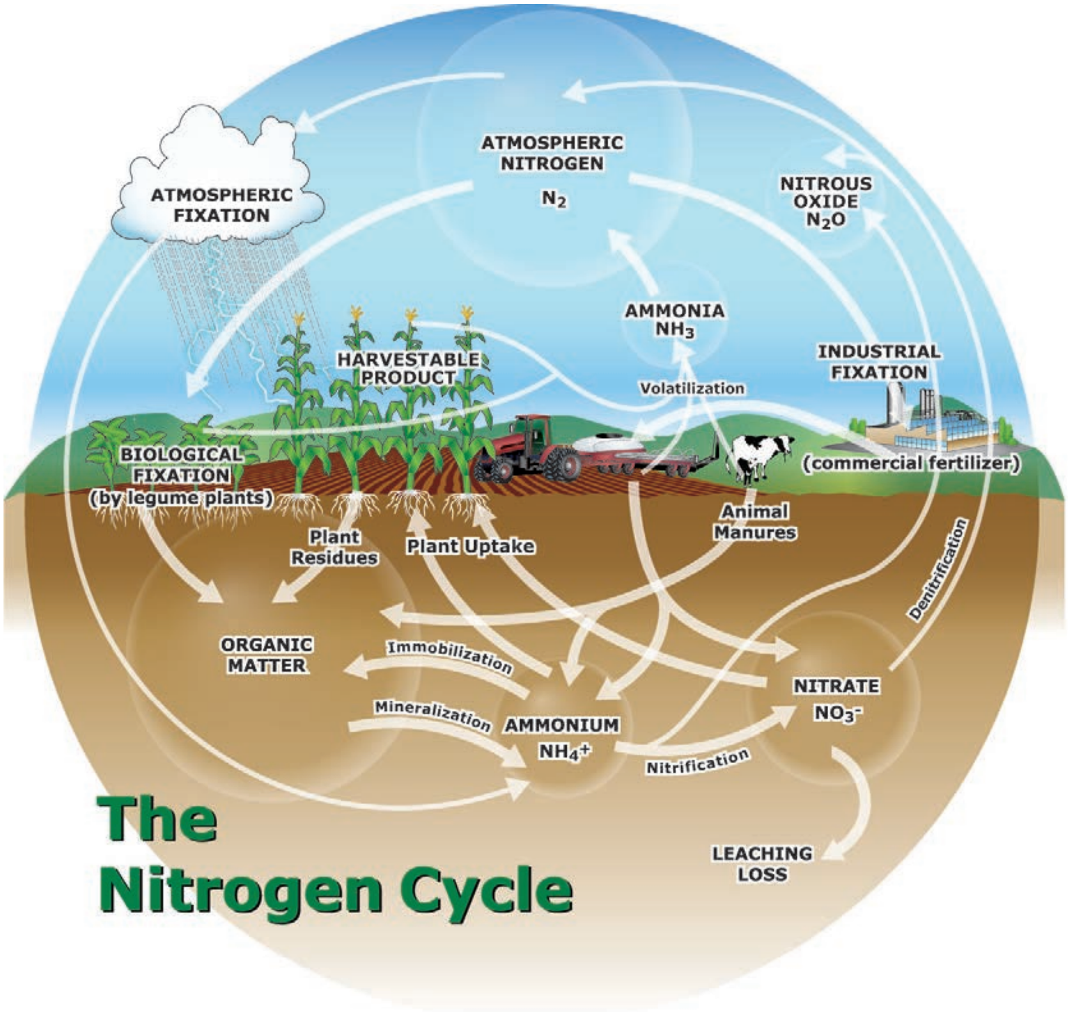

Figure 5.2 Abbreviated general N cycle. Because the N cycle is more complex and dynamic than other nutrients, timing discussions are most commonly centered on N fertilizer.

5.2 Assessing Dynamics of Soil Nutrient Supply

Most soils have the capacity to supply at least some of the nutrient requirements of a crop. Generally, the more sandy or weathered the soil, the lower the nutrient supplying capacity. Soil nutrient supplying capability is relevant to the rate component of the 4Rs, but it can impact timing options and requirements as well. In general terms, the greater the soil's capacity to retain and supply a crop available nutrient and provide it throughout the growing season, the less need there will be for a critical timing emphasis for that nutrient. Two contrasting examples:

- For many agricultural soils, P and K fertilizers can be applied once to supply the needs for one or multiple crops. The applied P and K are held by the soil, but remain crop available over time.
- Some highly alkaline soils, or acid soils quite common in tropical regions, have very high P fixation capacity. Phosphorus fertilizer applied to these soils can be readily converted to sparingly soluble and unavailable forms of P. Therefore, in these environments it is common to annually apply specific P fertilizer products in a concentrated band at planting to enhance crop supply.

A sound understanding of the transformations of N and other nutrients in the soil is fundamental to assessing the dynamics of soil nutrient supply. Nitrogen is taken up as either nitrate (NO_3^-) or ammonium (NH_4^+). Other forms of N must be converted to nitrate or ammonium before the plant can utilize the N. **Figure 5.2** shows a depiction of the N cycle and how N is moved and transformed. Within a given soil, plant available N is supplied by either mineralization of soil organic matter or by residual nitrate and ammonium. In arid climates, nitrate can accumulate in soils and be carried over across multiple seasons. Where rainfall is higher, nitrate is more readily removed from soils by leaching and/or denitrification. Nitrogen may enter the soil from the atmosphere via various paths or it may be added as fertilizer, crop residue, or manure. The N cycle is the most complex among the nutrient elements, as it is subject to more transformations and losses than others.

Another important factor in assessment of the dynamics of soil nutrient supply is soil test level. Soil testing is not an exact science in that it does not provide an absolute answer to whether a response to fertilizer application at a given time will be seen. There are simply too many other factors that affect the system for a single measure such as soil test level to consistently predict an outcome. It does provide, or at least gives an idea of, the probability of response to fertilizer application of a specific nutrient. Generally, the higher the soil test level, the lesser will be the need for fertilizer application and the greater will be the flexibility in timing of the application. See Section 8.5 for more detail.

When assessing the dynamics of soil nutrient supply the practitioner should consider the cycle of the particular nutrient. Key questions include:

- Are there issues with immobilization or other processes that might disrupt nutrient supply?
- Does the soil have the potential to compromise the availability of added nutrients over time (such as P in highly acid or alkaline soils)?

These and other questions will to some degree affect decisions on fertilizer timing, rate, placement, and source.

5.3 Assessing Dynamics of Soil Nutrient Loss

Nitrogen and P loss from cropping systems are generally of the greatest concern since the loss of each not only has negative economic impacts, but can create specific environmental problems as well. Nitrogen can be lost though several pathways including leaching of nitrate, surface runoff from fields, and gaseous loss. Nitrogen in soils tends to be converted to the nitrate form. Because of its negative charge, nitrate is not attracted to negatively charged particles of clay and organic matter. Thus it is free to leach as water moves through the soil profile. Phosphorus is much less susceptible to leaching, but small losses of P can have large impacts on water quality. Losses of P from fields occur mainly in surface runoff. In some soils losses through tile drainage can be substantial, and where soils have accumulated extremely high levels of P, leaching to shallow water tables can lead to losses from the field. Placement of P fertilizer below the surface can greatly diminish the risk of loss.

In soil and climatic environments where there is significant potential for loss of nutrients, application timing will need to be more targeted and specific. For example, fall application of N for spring planted crops such as corn should only be practiced in geographic areas where the risk of loss is low in late fall after soil temperature is below 10 ºC and is expected to continue cooling. Spring preplant and/or sidedress applications typically provide lower risk of loss and greater profitability, and are preferable to fall application despite logistical challenges. In contrast, some irrigated corn systems enable growers to apply multiple in-season N applications through fertigation, further optimizing timing to more closely match crop demand. Thus, through timing, nutrient use efficiency can be improved and potential for loss reduced.

5.4 Evaluating Logistics of Field Operations

The logistics of fertilizer distribution, field operations, and application equipment are important factors affecting timing decisions. As farm size in many regions has increased, the demand is greater than ever for growers to fine tune logistics of planting and input timing. Early application of fertilizer, such as fall application for spring planted crops, can reduce the pressure on planting operations and may enable more timely planting. Early application of P and K fertilizer is generally considered a reasonable practice where the risk of runoff is small in the time between application and the growing season; however, as previously mentioned caution should be exercised in applying N too early, especially where there is elevated risk of loss through leaching and/or denitrification.

In tropical areas it is important to be prepared for the right weather conditions. Soil and plant analysis should be carried out well in advance of nutrient need so as to orientate and ensure the purchase and stocking of proper fertilizers. Fertilizer materials should be ready weeks before the expected time of application. Poor management in this regard may lead to serious problems in some tropical systems. For instance, if N and K are not applied together nutrient imbalances may result that predispose plants to pest attacks, as is well documented with oil palm leaf eaters that benefit from high-N, low-K foliage.

Slow-release and other enhanced-efficiency fertilizer technologies may be useful tools where logistics demand a single application at what might normally be an inopportune time. The price of these technologies has traditionally limited their use in commercial production agriculture; however, with increases in the price of nutrients and heightened environmental concerns, changes in logistics and/or product usage have become more economically viable as with intensive tropical crops like banana, where the total number of applications could be reduced significantly saving money and hand labor.

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Schepers, J.S. and W.R. Raun (eds). 2008. Agronomy Monograph 49. American Society of Agronomy, Inc. Madison, WI, USA.

Questions ?

4. Nitrate can accumulate in soils and be carried over across multiple seasons in
   a. humid climates.
   b. arid climates.
   c. organic soils.
   d. highly alkaline soils.

5. Timing of nutrient application is most important for
   a. N.
   b. P.
   c. K.
   d. Mo.

6. Nitrification involves the conversion of:
   a. nitrate to nitrogen dioxide (NO_2).
   b. nitrate to nitrous oxide (N_2O).
   c. ammonium to nitrogen (N_2).
   d. ammonium to nitrate (NO_3^-).

7. In climates with high rainfall, nitrate is readily removed from soils by
   a. leaching.
   b. nitrification.
   c. immobilization.
   d. volatilization of NH_3.

8. In soils with very high P fixation capacity, an appropriate timing of P application is
   a. annually after crop emergence.
   b. annually at planting.
   c. once every two years.
   d. once every three years.

9. For crops planted in the spring, advantages of applying N in the spring rather than the previous fall include
   a. warmer soil temperatures.
   b. less interference with other field operations.
   c. lower risk of loss and greater profitability.
   d. more timely planting.

10. Enhanced-efficiency fertilizer technologies that control the timing of nutrient release can be appropriate
   a. for improving logistics of field operations.
   b. but only for high-value crops like bananas.
   c. for more rapid nutrient release to crops.
   d. for any nutrient application.

M

Module 5.1-1 Wheat yield response to a late application of additional nitrogen was predicted by leaf color. The conventionally recommended practice for N fertilization of wheat in northwest India is for a basal application (at sowing) of 50% of the N needed with the remaining 50% applied at the crown root initiation (CRI) stage (Zadoks growth stage 13). As shown in the Table below, an application of N at maximum tillering stage (MT; Zadoks growth stage 22) increased yields in each of 3 years when the basal and CRI rates summed to 80 kg/ha or less, and in 2 of the 3 years at higher rates. Yield responses to the late-applied additional N increased as chlorophyll (SPAD) meter values at the MT stage declined below 44. **Adapted from:** Bijay-Singh, et al. 2002. Agron. J. 94:821–829.

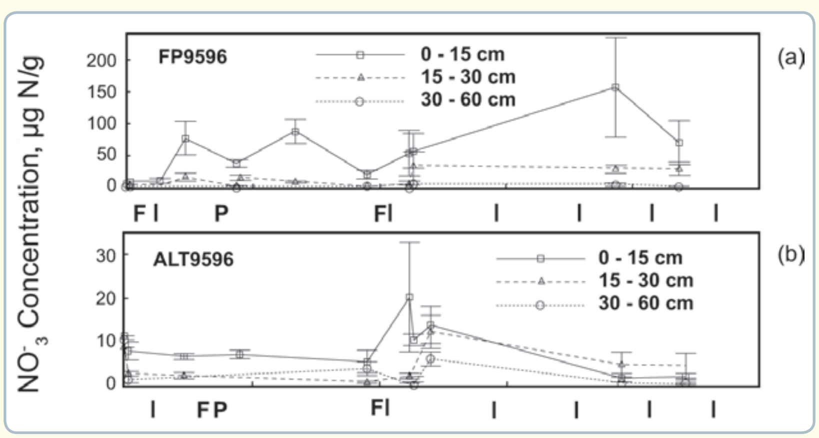
N fertilizer application treatment, kg N/ha				Wheat grain yield, t/ha		
Basal	CRI	MT	Total	1996–1997	1997–1998	1998–1999
0	0	0	0	–	1.7a†	1.8a
0	0	30	30	–	3.1b	2.7b
30	30	0	60	3.3a	3.7c	2.9c
30	30	30	90	4.1b	4.5d	3.7d
40	40	0	80	3.9b	4.2d	3.6d
40	40	30	110	4.5c	5.0e	4.2e
50	50	0	100	4.1b	5.1e	4.4f
50	50	30	130	4.5c	5.2e	4.7g
60	60	0	120	4.6c	5.1e	4.8g
60	60	30	150	4.8c	5.1e	5.1h

† Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by Duncan's Multiple Range Test .

Submitted by H.S. Khurana, IPNI, India, December 2011.

Module 5.1-2 Applying nitrogen in synchrony with crop demand lowered soil nitrate. The highest demand for N by the wheat crop occurs around the onset of stem elongation (Zadoks growth stage 31). Matching N application to crop needs can help improve its utilization efficiency and result in higher profits for the farmer and less adverse effects to the environment.

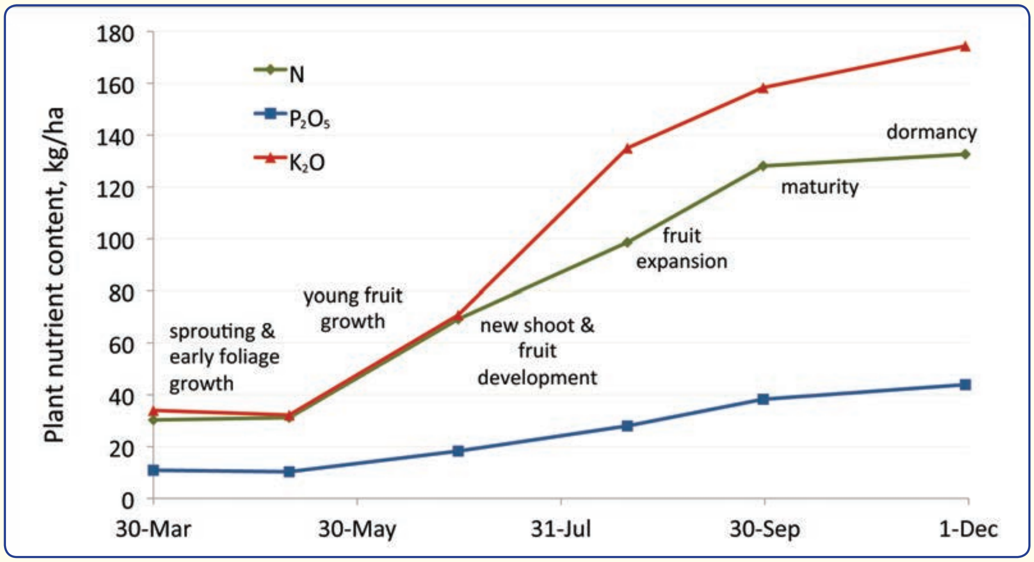
Wheat farmers in northwest Mexico routinely apply 75% of the recommended N application rate (250 kg/ha) 3 weeks before planting and the remainder 5 weeks following planting. Riley et al. (2001) compared farmers' practice with an alternative that consisted of applying 33% of the N at planting and the remainder 5 weeks following planting. They found the alternative timing improved nutrient uptake and decreased the N leaching loss by about 60% compared to the farmers' practice (see figure) while producing comparable economic returns to the farmer." **Source:** Riley, W. J., I. Ortiz-Monasterio, and P. A. Matson. (2001). Nutrient Cycling in Agroecosystems, 61(3): 223-236.



Mineral N concentrations in soil water measured during the wheat growing season for the typical farmer's practice (FP9596) and alternative practice (ALT9596). F, I, and P refer to fertilization, irrigation, and planting dates, respectively. Mineral N was NO_3^- + NO_2^- measured by lysimeters extracting soil water at 70 cm depth.

Submitted by A. Tasistro, IPNI, USA, September 2011.

Module 5.1-3 Patterns of uptake for nitrogen, phosphorus, and potassium by grape plants in Shaanxi, China affect recommendations for application timing. A study was conducted in Fufeng County, located on the western reaches of the Guanzhong Plain in Shaanxi of China, to identify nutrient uptake by 7-year old grape plants according to plant development stage. The figure below shows the increase in N, P, and K content in grape plants during the growing season. Between March 30 and November 30, grape plants accumulated an average of over 102 kg N/ha, 33 kg P_2O_5/ha, and 140 kg K_2O/ha mainly in three distinct stages: 1) the period between sprouting/early foliage growth and new shoot/fruit development; 2) the period between early fruit development and fruit expansion; and 3) the period after fruit expansion up to fruit maturity. These respective periods saw 38%, 29%, and 29% of the total N accumulation, 22%, 29%, and 31% of P accumulation, and 26%, 46%, and 17% of K accumulation. According to the characteristics of nutrient uptake during the growing season, fertilizer N should be split evenly between the three stages of nutrient demand described above. About 50% of the P recommendation should be supplied prior to fruit expansion and 70% of K recommendation should be applied prior to the flourishing of new shoot growth. **Source:** Tong, Y., et al. 2010, Better Crops with Plant Food, Vol. 94, No. 2, 29-31.



Submitted by S. Li, IPNI, China, December 2011.

Module 5.1-4 Splitting the dose makes calcium more available to peanuts. Calcium uptake by plants is closely related to transpiration. Peanut plants have difficulty redistributing Ca from roots, stems and leaves to the developing pods, and thus more than 90% of the Ca required by the pod is taken up directly from the soil by the pod. Thus, adequate levels of available Ca after flowering are needed in the soil zone where peanut pods are developing. A pot experiment was conducted to determine the effect of time of Ca fertilizer application on peanut yield and Ca uptake. The table below shows that a single basal Ca application increased peanut yield by 10 to 24%. Split application of either gypsum or calcium nitrate produced 3 to 7% more yield and 11 to 30% more Ca recovery than basal application alone. Based on this work, pre-bloom applications of soluble Ca are necessary for high yield of peanuts. **Source:** Lin, B. et al. 1997. Chinese Journal of Soil Science, 28(4): 172-174.

Treatments	100% basal		50% basal + 50% topdressing at flowering	
	Yield, g/pot	Ca recovery, %	Yield, g/pot	Ca recovery, %
NPK	26	-	26	-
NPK+$CaSO_4$	29	9	30	10
NPK + $Ca(NO_3)_2$	30	10	32	13

Submitted by S. Li, IPNI, China, December 2011.

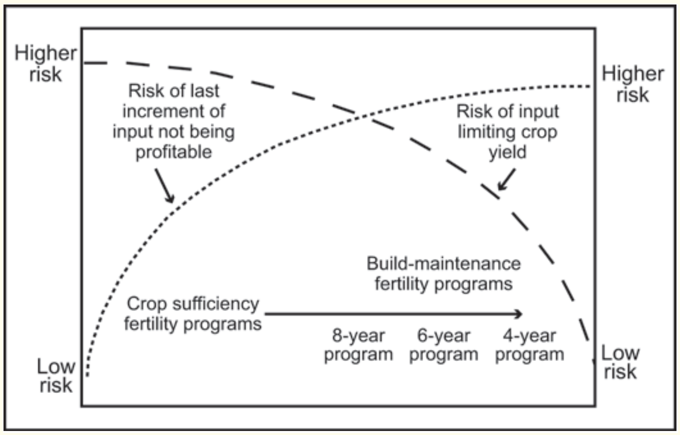
M

Module 5.1-5 Splitting nitrogen application improves grain yield and nitrogen efficiency for winter wheat. Nitrogen is a very important contributor to grain yield of winter wheat in North Central China. A field experiment was conducted to investigate the effect of different basal: topdressing ratios for N application on grain yield, N uptake and efficiency. Basal application was at planting, and the topdress was applied at Zadoks GS30 growth stage (about 150 days after planting) The table below shows that N application increases grain yield by 20 to 35%, and two treatments with N splitting increases 10 to 12% more yield as compared with one application. Nitrogen splitting also increases N uptake by 2 to 7%, and improves N recovery efficiency by 9 to 25%. The best splitting treatment is with 60 kg N/ha applied basally and 180 kg N/ha as topdressing. The result from this study indicates that N application at the right time is important for high yield and efficiency. **Source:** Zhao, S.C. et al. 2011. Plant Nutrition and Fertilizer Science, 17(3): 517-525.

Treatment (split), kg N/ha	Grain yield, t/ha	N uptake, kg/ha	N recovery, %
0 N	5.4	124	-
240 N (0/240)	6.5	170	19
240 N (60/180)	7.3	181	24
240 N (120/120)	7.2	174	21

Submitted by P. He, IPNI, China, March 2013.

Module 5.2-1 High soil test levels allow flexibility in timing of phosphorus and potassium application. The Kansas State University (KSU) soil testing laboratory makes fertilizer recommendations based on the sufficiency approach or the build-maintenance approach to nutrient management. The customer chooses which of these approaches best fits their operation. The goal of the sufficiency approach is to apply just enough P and/or K to maximize profitability in the year of application, but minimize nutrient applications and fertilizer costs. The objective of build-maintenance fertility programs is to manage P and/or K soil test levels as controllable variables. At low soil test values, recommendations are intended to apply enough P and/or K to both meet the nutrient needs of the immediate crop and to build soil test levels to a non-limiting value, above the critical level. KSU faculty generated some classic information and figures on relationships among soil test level, crop yield, and fertilizer recommendations. The generalized relationship in the following graph shows how as soil test level increases flexibility in timing also increases, and the risk of input (fertilizer) limiting crop yield is reduced. **Source:** Leikam, D.F., et al. 2003. Better Crops with Plant Food. Vol. 87, No. 3, p. 6-10. For more information, see Section 8.5.



Submitted by W.M. Stewart, IPNI, USA, December 2011.

Module 5.3-1 Spring applied nitrogen increases nitrogen recovery and profit for corn in southern Minnesota. A long-term U.S. Corn Belt study conducted in Waseca, MN compared fall application of ammonia with and without a nitrification inhibitor (N-Serve, or nitrapyrin) to spring preplant application without the nitrification inhibitor. The table below shows the result of this 15-year study. In short, the data show that applications of N (as ammonia) in the late fall with the nitrification inhibitor and spring preplant were best management practices. However, it should be noted that when spring conditions were wet the spring application resulted in substantially greater yield and profit than fall+N-Serve. Overall, the least risky timing option was spring preplant, followed by fall+N-Serve, with fall (no inhibitor) being the most risky and least efficient. Thus, N application for corn should be avoided in areas with warm/open winters, and where it is appropriate it should be delayed until soil temperature is below 10 °C and expected to continue cooling so as to slow nitrification in the fall and avoid increased nitrate leaching and/or denitrification. Use of a nitrification inhibitor can help further delay nitrification, but even with an inhibitor, fall application, where appropriate, should be delayed until soil temperature cools. **Source:** Randall, G. 2008. *In* Proc. 20th Annual Integrated Crop Manag. Conf., Dec. 10-11, Iowa State Univ., Ames. p. 225-235.

Parameter (mean of 15 years, 1987 to 2001)	Time of N Application		
	Fall	Fall + N-Serve	Spring
Yield (t/ha)	9.03	9.60	9.78
Economic return over fall N ($/ha/yr)[1]	-- --	$69	$119
Flow-weighted NO_3-N (mg/L) in tile drainage water	14.1	12.2	12
Nitrogen recovery in grain (%)[2]	38	46	47

[1] Based on N @ $1.54/kg N; N-Serve = $19.78/ha; Corn = $157.5/t
[2] Nitrogen content of the corn grain as a percent of the amount of fertilizer N applied.

Submitted by W.M. Stewart, IPNI, USA, December 2011.

Module 5.3-2 Timing broadcast phosphorus fertilizer applications can help protect Lake Erie.

Phosphorus (P) is an essential nutrient for growing crops. But excess concentration of P in streams, rivers and lakes can lead to algal blooms. In the Lake Erie watershed in and around the state of Ohio, USA, levels of dissolved P in rivers, and algal blooms in lakes, have been trending upward from 1995 to 2011. Fertilizers applied to the predominant corn-soybean cropping system are not the only cause, but are one of many probable causes, and time of application can have a large effect when P fertilizers are applied by broadcasting.

Broadcast application offers flexibility in timing and often the lowest application cost. In soils with optimum P levels, band and broadcast applications do not differ in terms of availability to the crop and crop response. But they do differ in risk of runoff loss. To minimize P losses from broadcast applications, it is important to apply when the risk of runoff is low. Runoff events are more frequent in late fall, winter and early spring. Ideally all P would be applied at planting, but limited storage capacity and equipment availability often make this impractical.

Even small losses of P in runoff can harm water quality. Producers are advised to pay close attention to the weather forecast, and avoid broadcasting P fertilizer when there is more than 50% chance of intense rain within the next few days. As indicated in **Figures 1 and 2**, levels of dissolved P in runoff decline considerably if the runoff event occurs more than 3 to 5 days after application. Broadcast application of P on frozen or snow-covered soil in the winter is never the right time, because these conditions generally end with spring runoff.

Tillage to incorporate a broadcast application reduces runoff loss of dissolved P, but may increase loss of total P through erosion. Choices for “right time” or “right place” should both be considered for their best fit to the crop production enterprise.

References

Owens, L.B. and M.J. Shipitalo. 2006. J. Environ. Qual. 35:1101–1109.

Smith, D.R., et al. 2007. Environ. Poll. 147:131-137.

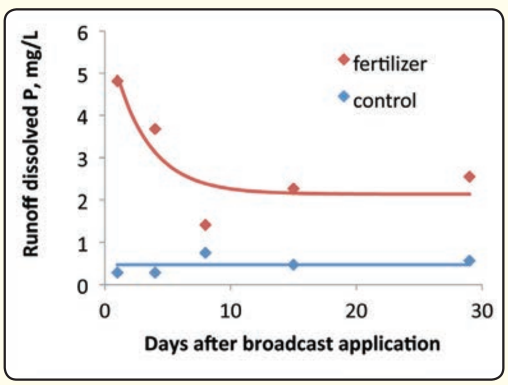


Figure 1. Concentration of dissolved P in surface runoff from plots cropped to tall fescue during rainfall simulations that occurred 1 to 29 days after broadcast application of triple superphosphate fertilizer (Smith et al., 2007). Silt loam soil near Lafayette, Indiana, USA.

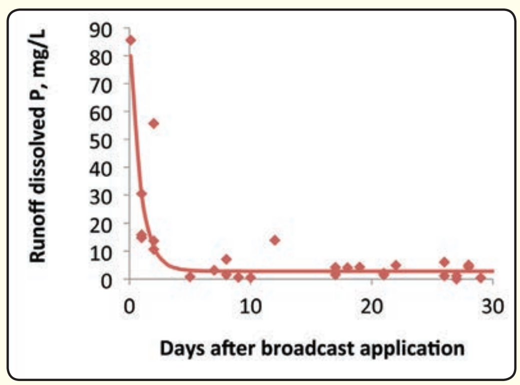


Figure 2. Concentration of dissolved P in surface runoff, sampled during natural rainfall events over a 14-year period, plotted against time after most recent application of superphosphate fertilizer, in grass and legume pastures near Coshocton, Ohio, USA (Owens and Shipitalo, 2006). Well-drained to moderately well-drained silt loam soils.

Submitted by T.W. Bruulsema, IPNI, Canada, May 2013.

NOTES

Chapter 6

SCIENTIFIC PRINCIPLES SUPPORTING RIGHT PLACE

Right place means positioning needed nutrient supplies strategically so that a plant has access to them. Proper placement allows a plant to develop properly and realize its potential yield, given the environmental conditions in which it grows. Right place is, in practice, continually evolving. Plant genetics, placement technologies, tillage practices, plant spacing, crop rotation or intercropping, weather variability, and a host of other factors can all affect which placement is appropriate. Consequently, there is much yet to learn about what constitutes the "right" in right place and how well it can be predicted when management decisions need to be made.

The core scientific principles that define right place for a specific nutrient application are the following:

- **Consider source, rate, and time of application.**
- **Consider where plant roots are growing.** Nutrients need to be placed where they can be taken up by growing roots when needed.
- **Consider soil chemical reactions.** Concentrating soil-retained nutrients like P in bands or smaller soil volumes can improve availability.
- **Suit the goals of the tillage system.** Subsurface placement techniques that maintain crop residue cover on the soil can help conserve nutrients and water.
- **Manage spatial variability.** Assess soil differences within and among fields in crop productivity, soil nutrient supply capacity, and vulnerability to nutrient loss.

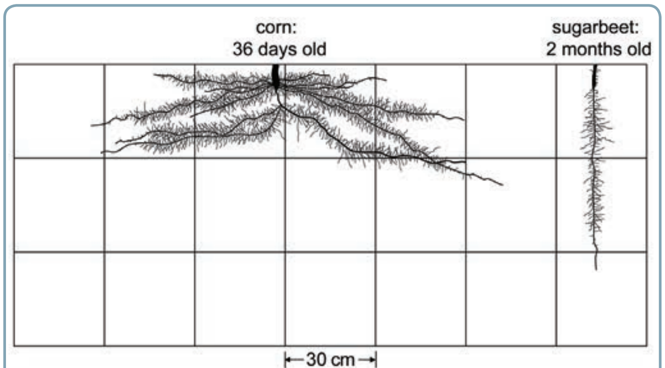


Figure 6.1 Two-dimensional representations of root architecture for corn and sugarbeet (Weaver, 1926).

6.1 Plant Root Growth

Root architecture is the 3-dimensional, spatial configuration of a root system and refers to the geometrical arrangement of plant roots in the soil. Root architecture differs strongly among plant species and interacts strongly with soil conditions.

To demonstrate contrasts in root architecture, **Figure 6.1** provides diagrams of vertical cross sections of corn and sugarbeet. The first diagram is of a root system of corn at

36 days old. The fibrous root system has a distinctly horizontal orientation and is found in shallower soil depths. The second diagram is of a 2 month-old sugarbeet root system under irrigated conditions. The taproot system is oriented vertically and extends deeper in the soil. Different species of plants therefore have different root growth patterns, affecting their individual abilities to access nutrients in various places in the soil. Additionally, within a species, not all of the root system remains active throughout the season, further affecting access to nutrient supplies in any one location.

Root plasticity. A plant's root architecture changes during the season as the plant ages and as the root system responds to its local environment—a characteristic termed "plasticity". Many external conditions can change root architecture; examples include soil moisture content (Sharp et al., 1988), soil temperature (Walker, 1969), nutrient concentration (Zhang and Barber, 1992), and soil bulk density (Kasper et al., 1991).

When plant roots encounter concentrated zones of either N or P, root proliferation occurs. **Figure 6.2** demonstrates how the distribution of barley roots can be changed by a concentrated zone of P. The greater proportion of roots in the zone of high P came from increased root branching. This research example demonstrates that nutrient placement affects more than just the location of nutrient supplies, it also affects how much of the root system will be in those supplies.

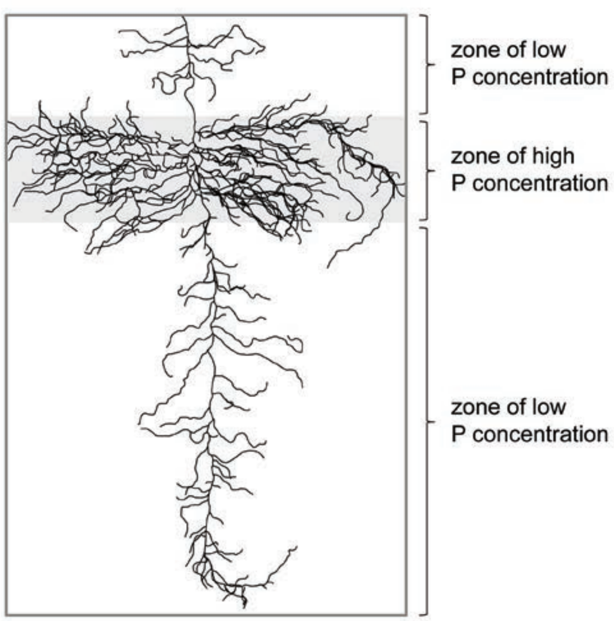


Figure 6.2 The proliferation of barley roots in a zone of higher P concentration (Drew, 1975).

Root nutrient uptake. The absorption of nutrients is one of the primary functions of plant roots. Nutrients enter a root cell from the soil solution by passage through pores in the cell wall.

There is a maximum rate at which a root can take up nutrient (Barber, 1995). This means that as nutrient concentration in the soil solution increases (nutrients are added), the rate at which roots take up nutrients also increases, but eventually approaches a maximum. This means that no single root can supply all of the nutrient needs of the plant throughout its development. Instead, a well developed root system is needed, with each active root contributing to the acquisition of the overall quantity of needed nutrients.

Roots also lose nutrients, a process termed "efflux." Both influx and efflux occur in roots across a range of soil nutrient concentrations. However, as the soil nutrient supply decreases, influx and efflux can become nearly equal. At that point, there is no net nutrient uptake by the root, and thus this concentration is termed C_{min}. Just how low nutrient supplies have to get in soils for uptake to cease varies by plant species and by nutrient.

Plants also have feedback mechanisms that allow them to adjust their nutrient uptake rates (kinetics) to soil conditions. Plants adjust to low nutrient concentrations by altering the transport systems found on root cell membranes, thereby reducing C_{min}. For instance, maize plants grown with P concentrations 10 times lower than normal continued taking up P to a C_{min} level more than 4 times lower than that of normal plants.

Low nutrient concentrations in the soil also cause the maximum rate of nutrient influx to increase. This increase allows each root that does encounter a supply in the soil to provide a greater proportion of nutrients to the total content in the plant. Changes in C_{min} and influx allow a nutrient-stressed plant to partially compensate for a low soil nutrient supply, although total uptake is lower than in a non-stressed plant.

Rates of nutrient uptake by plant roots can change with plant age. For instance the uptake rates of P are several times greater when both corn and soybean plants are younger than when they are older. When uptake rates decline over time, as has been observed for corn and soybean, then a greater amount of root surface area will be needed later in the season, along with a corresponding increase in accessible fertilized soil volume, just to maintain nutrient uptake. However as the above-ground portions of the plant develop, nutrient uptake requirements increase further, requiring more extensive root development.

6.2 Nutrient Placement Practices

There are two primary ways to apply nutrients on or in the soil: 1) broadcasting or 2) banding them. Broadcasting is the process of applying nutrients to the soil surface in a nearly uniform manner **(Figure 6.3).** The objective of broadcasting is to get a fairly even spacing between individual particles of nutrients, whether they are granules of dry fertilizers or droplets of liquid fertilizers. Banding is the process of applying nutrients to areas or volumes of confined widths. Such applications can be made either at the soil surface or at some depth below it.

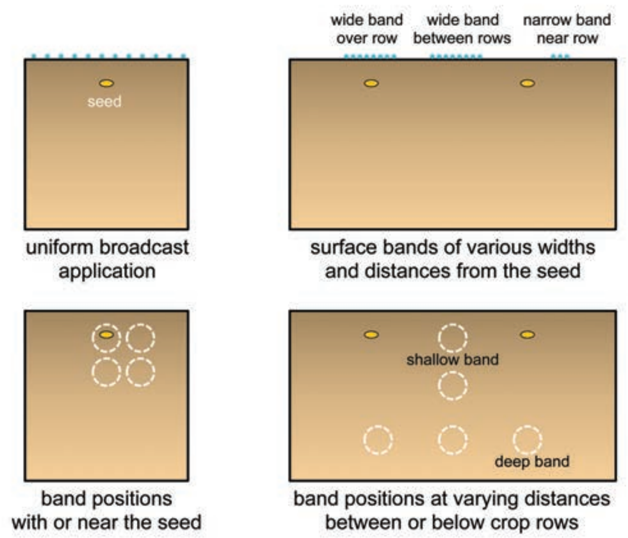


Figure 6.3 Conceptual diagrams of different placement options for nutrients.

As **Figure 6.3** shows, there are a myriad of options available for placing nutrients on or in the soil.

a) Combinations of both broadcast and banded applications are common.

b) The bands themselves can be different widths as well as at different positions relative to rows.

c) The soil can be mixed to various extents by tillage, organisms such as earthworms, or physical processes arising from temporal variations in soil moisture and or temperature.

d) Subsurface applications are most often banded, although regularly spaced point injections, sometimes termed "nests" are also an option.

e) Possible configurations for subsurface bands are many. Bands placed near the seed at the time of planting are often called "starter" bands. Relative to the seed, they can be placed in direct contact with the seed trench (often termed "pop-up"), or to the side, below, or to the side and below (often termed "side band").

f) Multiple bands of any combination can be applied.

g) Bands not placed near the seed can be various distances from crop rows.

h) Depth of placement can also vary greatly, but equipment and power requirements usually confine bands to a depth of 20 cm or less, although deeper placement is possible.

Seed treatment with micronutrients, such as Mo for soybean or Zn for maize, can also be considered as a placement method. However, maximum safe concentrations of such seed treatments may vary among crop species and even among hybrids of maize in different maturity groups. Many crops are sensitive to seed coatings with micronutrients.

Questions ?

1. One of the five core scientific principles that define **right place** for a specific set of conditions is to
   a. bury nutrients deeply in the soil.
   b. consider where plant roots are growing.
   c. mix nutrients throughout the whole soil volume.
   d. incorporate nutrients using primary tillage.

2. Plant roots proliferate in zones of the soil where the fertilizer nutrients placed include
   a. Zn and Mn.
   b. Ca and Mg.
   c. K and Mg.
   d. N and P.

3. When plants adjust to low nutrient concentrations by altering the transport systems found on their root cell membranes, they can
   a. grow more rapidly than at high nutrient concentrations.
   b. take up more of the nutrient than at high nutrient concentrations.
   c. partially compensate for a low soil nutrient supply.
   d. increase the nutrient's C_{min}.

4. The nutrient placement method that most uniformly distributes nutrients throughout the soil volume is
   a. broadcasting.
   b. banding.
   c. seed coating.
   d. pop-up.

6.3 Soil and Root Reactions to Band Placement

Concepts of root development, nutrient uptake, soil chemical reactions, and nutrient movement form the basis of commonly accepted principles of nutrient placement (Barber, 1995). The following processes occur when nutrients are banded:

a) nutrients are concentrated into a smaller soil volume;

b) more of a given nutrient will remain in soil solution, which is particularly important for nutrients that react with soil minerals and with other ions in solution to form compounds that are not readily available to plants;

c) higher soil solution concentrations hasten nutrient diffusion rates as well as provide greater quantities of nutrients moving by mass flow, both of which increase the rate of replenishment of nutrients to plant roots;

d) concentrated supplies of N and P proliferate plant roots, resulting in a greater proportion of total plant uptake coming from the vicinity of the band;

e) uptake rates of individual roots can increase when plants are deficient in nutrients, but they reach a maximum, requiring more roots to be near nutrient supplies as the crop develops.

Mutual consideration of all of these processes has led to the following concepts of band placement:

A) band applications are probably the most efficient placement method when soil fertility levels are low, nutrient application rates are low, and the nutrient applied is one that moves primarily by diffusion (e.g. P or K rather than N);

B) for soils of low fertility, low rates of band-applied nutrients may not meet the total nutritional needs of the crop;

C) for soils of low fertility, a volume of fertilized soil greater than that attained with a single band application is needed for attaining maximum yield.

When fertilizer is applied to soils, each individual granule (dry forms) or droplet (liquid and suspension forms) reacts to form small volumes of fertilized soil in its immediate vicinity. How far these volumes extend from the fertilizer particle varies with the nutrient, environmental conditions, and the chemical and physical properties of the soil. The amount of soil enriched by an individual granule or droplet is small, but the overall fertilized soil volume can be increased in the following ways: 1) utilizing tillage, 2) increasing nutrient rate, 3) increasing nutrient application frequency, and 4) applying nutrients in different positions in the soil.

Tillage provides one means of mixing the fertilized soil volumes around each fertilizer particle with the greater soil volume. While such mixing fertilizes a greater volume of soil, it can also dilute nutrient concentrations within a given volume.

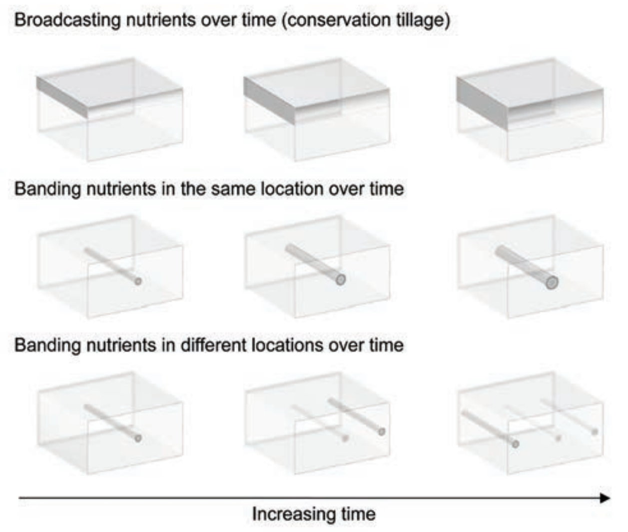


Figure 6.4 Changes in enriched fertility zones over time arising from repeated applications of immobile nutrients like P and K. Darker shading denotes higher concentrations. These tendencies apply to conservation tillage systems where soil mixing is restricted. Other substantial changes (not shown) that are possible include accumulation of nutrients near the surface arising from crop residue deposition, and redistribution of nutrients by soil organisms like earthworms.

Higher application rates affect fertilized soil volume in the following ways:

a) greater quantities of nutrients are moved by mass flow and diffusion, extending the fertilized soil volume;

b) the distance between individual fertilizer granules or droplets is closer, and when rates become high enough, continuous fertilized zones are created—important for promoting uninterrupted root proliferation;

c) fertilized zones have greater longevity.

Greater application frequency can increase fertilized soil volume, but this is dependent upon the rate used. Higher rates are required for keeping fertilized zones enriched for longer periods of time.

There are two primary placement options for repeatedly applying nutrients: 1) apply nutrients in the same location over time or 2) apply them in different locations **(Figure 6.4)**. Applying immobile nutrients like P and K in the same zone over time can increase concentration and lead to greater fertilized soil volume as nutrients diffuse outward; however, the volume of soil not fertilized can become depleted. Fertilizing different zones of soil is the other way to increase fertilized soil volume. Several options exist. For instance, broadcast and band applications can be combined and/or bands can be applied in different locations over time. When bands are applied in different locations, the result is a network of bands in the soil that are of various ages and remaining longevity.

Early season crop needs. Early in the season, young root systems are limited in extent, exploring only a small volume of soil. Additionally, influx rates can be higher at this time than at any other time in the season, leading to more rapid depletion of soil nutrients in the soil surrounding plant roots. Faster depletion of soil nutrients requires faster transport of nutrients to the roots for replenishment, either by mass flow or diffusion. However, environmental conditions early in the season, particularly lower temperatures, can limit shoot growth as well as nutrient transport rates.

A nutrient placement strategy for addressing possible early season nutrient deficiencies is to band nutrients with or near the seed at planting. Such bands: 1) concentrate nutrient supplies; 2) increase rates of nutrient transport to the roots; 3) are strategically positioned for access by a young, limited root system; and 4) proliferate roots if N or P is used.

The proper location of concentrated soil volumes depends in large part upon the root architecture of the young plant. For instance, the most effective placement of P for corn and sugarbeet is consistent with the root distributions in **Figure 6.1**. For corn, studies have demonstrated that placing nutrients to the side and below the seed is a good position for early season root system access and plant nutrition, producing equivalent or higher crop responses than other placement methods. Placement below and to the side of the seed is consistent with the predominately horizontal root architecture of the young corn plant. For sugarbeet, P placement in direct contact with the seed has been shown to be highly effective and efficient (Sims, 2010). Such placement ensures access by the vertically oriented tap root and its associated lateral roots.

Placement of nutrients near the seed must be done with careful consideration of both rate and form, particularly with placement in the seed trench. Seed or seedling damage can result from either ammonia toxicity or salt injury. Factors important to consider for maximum safe rates of seed-placed fertilizer are (Gelderman, 2011):

a) seed sensitivity;
b) fertilizer salt index;
c) width of seed furrow opening;
d) soil texture;
e) soil moisture at planting;
f) amount of stand loss that is tolerable.

Questions ?

5. For a soil deficient in P, if only a low rate of P will be applied to either corn or wheat, it should be
   a. foliar applied.
   b. banded near the seed at planting.
   c. broadcast and left unincorporated.
   d. broadcast and incorporated with tillage.

6. For soils of low fertility, low rates of band-applied nutrients
   a. increase fertilized soil volume as nutrients diffuse outward.
   b. meet the total nutritional needs of the crop.
   c. fertilize a large volume of soil to attain maximum yield.
   d. result in high use efficiency of the applied fertilizer nutrient.

7. A fertilizer placement position that allows early season root access and provides good P nutrition for corn is
   a. 5 cm beside and 5 cm below the seed.
   b. in direct contact with the seed.
   c. directly below the seed.
   d. broadcast and thoroughly incorporated.

Fallow or Flooding. Both a fallow season and extended periods of flooding for a week or more decrease the population of mycorrhizal fungi in soils. When plant-fungus symbiosis is adversely affected, it may not be possible to overcome the lack of mycorrhizal contributions to P nutrition solely from increased P rates. The missing quantity of P may simply be too great. Because the effect is limited to one cropping season, a banded application of a lower P rate is a practical choice for at least partially overcoming reduced quantities of P reaching the plant.

Nutrient losses. Getting nutrients below the soil surface can reduce nutrient losses that potentially harm the environment in several ways. Subsurface placement can:

a) reduce losses through runoff, due to lower surface concentrations of water-soluble nutrients;

b) reduce losses when combined with erosion control, since nutrients are placed below the surface;

c) reduce short-term losses of gaseous forms of N, such as N_2O, depending on rainfall amounts and distribution.

Interactions within bands. When nutrients are confined to the same volume of soil, they can interact in ways not possible when applied in different spaces. Such interactions arise not only from closer proximity but also from higher concentration. Initial reactions of fertilizers in nutrient-concentrated volumes may be little influenced by the surrounding soil. Much of the work on the unique chemical aspects of concentrated volumes of soil comes from studies of subsurface bands. The following interactions have been demonstrated:

a) application of NH_4^+-N with P in the same band can increase P uptake by plants when compared to applying these forms in separate bands;

b) applying urea with either MAP or TSP in a band has been shown to reduce the quantity of NH_3 that is lost, the low initial pH of MAP or TSP explains this effect, but note that it is not likely large enough to allow use of banded urea near seed rows in soils of neutral to alkaline pH);

c) applying KCl in the same band with MCP has been shown to reduce the diffusion of P from the fertilizer band in less weathered soils higher in Ca;

d) applying KCl in the same band with MCP in acid, weathered soils may increase P diffusion rates rather than decrease them.

6.4 Foliar Fertilization

Foliar fertilization is the application of nutrients to plant leaves. Although their primary functions are photosynthesis and respiration, plant leaves do take up nutrients, although the quantities absorbed are usually much less than those absorbed by roots, which are the primary organs for nutrient uptake. Plant leaves can absorb nutrients if they are present as either 1) gases or 2) ions in solution.

Nutrients in a gaseous state enter leaves through stomata. Stomata are pores where most of the gas exchange takes place between the plant and the atmosphere. The majority of stomata are located on the underside of plant leaves. Cells surrounding these pores, called guard cells, expand and contract to regulate the size of the pore opening and therefore the rate of gas exchange. Hydrogen, N, O, and S can enter the plant through the stomata when they are present in the gases ammonia (NH_3), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2). For instance, a recent application of manure can result in significant uptake of N as NH_3. Because stomata are sites of gas exchange, nutrients can also be lost through them as NH_3, SO_2, and other volatile forms of S.

Nutrients in solution enter the leaves through small pores in the cuticle layer of the epidermis of a plant leaf. The cuticle itself is covered by a layer of wax that repels water and protects the leaf from excessive water loss. Pores in the cuticle layer are not the same as stomata, but higher numbers of them tend to exist near stomata than in the leaf surface between stomata. The waxy epidermis and the very small size of the pores in the cuticle greatly limit the amount of soluble nutrients that can be absorbed by plant leaves. (**Figure 6.5**).

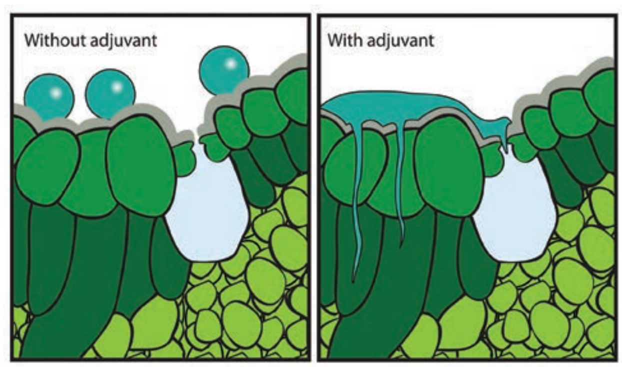


Figure 6.5 The efficiency of foliar fertilization can be enhanced through the use of adjuvants, which help nutrients penetrate the cuticle layer of leaves. **Adapted from:** Noack et al. (2010).

Foliar fertilization occurs with nutrients solubilized in water. Factors that can limit the efficiency and effectiveness of foliar fertilization are (Marschner, 2002):

a) thicker cuticle layers of leaves of plants, such as coffee and citrus;
b) runoff of liquid fertilizer from the plant leaves;
c) washing off of the liquid fertilizer by rain;
d) drying of the liquid fertilizer on the leaf;
e) limited translocation of some nutrients from the leaves being fertilized to other parts of the plant;
f) leaf damage resulting from a localized nutrient imbalance in the leaf, caused by the fertilizer application.

Foliar applications create small, localized supplies of nutrients that have a short duration of effectiveness, typically on the order of a few days to a couple of weeks. For this reason, they must be well timed with plant demand. Depending on the situation, more than one application or a series of applications may be necessary.

Foliar fertilizer can be an effective practice when soil nutrient availability is limited or the plant's ability to acquire or translocate nutrients becomes limited. Foliar fertilization can be used as a rescue treatment for situations where it was not possible to properly manage soil nutrients, obtain varieties or hybrids best suited for soils with specific deficiencies or conditions, or conduct field operations in a timely manner.

6.5 Managing Spatial Variability

In addition to placement within the soil or on the plant, "right place" also considers the larger scale of where to apply nutrients within an area. This area might be a watershed, a farm, a field, or areas within a field. Site-specific management is an approach that breaks a larger area up into smaller ones and manages each one separately in a way that is best suited to it. Site-specific management therefore relies upon measurements that are taken at a higher spatial density than conventional approaches. Higher spatial resolution creates more accurate delineations of problem areas as well as highly productive areas, enabling management to be more targeted.

Variable rate applications (VRA) are a member of the suite of management practices making up site-specific management. Variable rate applications have the objective of applying the right rate of nutrients in the right place within a larger field.

A typical VRA for nutrient recommendations based on soil tests might include the following steps:

a) collect spatially intensive soil samples and record the geo-location (latitude and longitude) of each sampling point, using a global positioning system (GPS) device that records such data from the satellite network;
b) send soil samples to a laboratory for analysis of a comprehensive set of nutrients and other chemical or physical properties that might be important to creating a nutrient recommendation;
c) create a map that mathematically fills in (interpolates) estimates of soil test levels between the actual sampling points. The creation of such a map is done with specialized geographic information system (GIS) software that has capabilities for geostatistical analyses;
d) collect other data required by a particular nutrient recommendation system. Such data might include maps of soil texture, soil electrical conductivity, topography, bare soil satellite imagery, normalized difference vegetation index (NDVI), prior manure application rates and application areas, previous crops, and/or crop yield;
e) use GIS software to integrate all input data into a map of recommended nutrient rates;
f) use a computer mounted in the application equipment to transfer the information in the recommendation map to controllers that vary the amount of each nutrient applied as the applicator is driven across the field. The application equipment may also be able to record how much of each nutrient was actually applied and where, allowing comparisons to be made between what was recommended and what the equipment actually applied.

A typical VRA for a N recommendations based on plant measurements might include the following steps (Raun et al., 2002):

a) in a strip across the field, apply a rate of N that is high enough not to be yield limiting;
b) collect spectral reflectance data at a specific crop growth stage from both the non-limiting N strip and an adjacent strip where a normally used N rate has been applied. Convert the spectral reflectance data from both strips to an average NDVI and then calculate a response index (RI);
c) use recommendation algorithms to convert RI into a map of N rate recommendations;
d) use a computer mounted in the application equipment to transfer the information in the recommendation map to controllers that vary the amount of each nutrient applied as the applicator is driven across the field.

Site-specific nutrient management can also be extended to larger scales to place nutrients in the right place within a watershed to reduce losses of nutrients. For instance, the phosphorus index (PI) can be used to delineate critical source areas (CSAs) within a watershed (Gburek et al., 2000). The CSAs are more vulnerable to P losses and are an important part of the hydrology of the watershed. Targeting management improvements in these areas, such as omitting or reducing P applications or placing P deeper in the soil, can reduce P losses from the entire watershed. For more information on the P Index, see Section 9.8.2.

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Questions ?

8. Applying ammonium forms of N along with P fertilizer in the same band can
   a. increase soil sorption of the applied P.
   b. increase K uptake by plants.
   c. increase P uptake by plants.
   d. reduce N uptake by plants.

9. Dissolved nutrients applied as foliar fertilizers are absorbed by the plant leaf through
   a. stomatal pores.
   b. small pores in the cuticle layer.
   c. leaf damage.
   d. guard cells only.

10. The creation of a map for variable rate application involves interpolating soil test levels measured at specific sampling points within the field. The software used to do this interpolation is called
    a. GIS.
    b. GPS.
    c. NDVI.
    d. VRA.

Module 6.2-1 The placement of nitrogen fertilizer influences weed growth and competition with spring wheat in Alberta, Canada. Adjusting the placement and timing of fertilizer can have a significant impact on crop productivity. In some environments, common agricultural weeds are more responsive to nitrogen (N) fertilizer than crops such as wheat or canola. It is important to manage fertilizer so that the competitive advantage goes to the crop and not to the weeds. A 4-year study was conducted in Alberta, Canada to examine the competition between spring wheat and four common weeds when 50 kg N/ha (as ammonium nitrate) was applied:

Fertilizer Placement: Broadcast on soil surface
Banded 10 cm deep between every wheat row
Banded 10 cm deep between every other wheat row
Point injection of solution at 20-cm intervals and at a 10-cm soil depth (with experimental equipment)

Fertilizer Timing: October or May of each year

Seeds from four weed species were broadcast on the soil surface in the first year (i.e., wild oat, green foxtail, wild mustard, or common lambquarters). Spring wheat was planted in May each year and harvested at maturity.

WEEDS: The N concentration was greater in wild mustard and common lambsquarters than the wild oat and green foxtail. This shows that broadleaf weeds are especially competitive in acquiring soil N in this environment. The placement of N fertilizer was generally more important than the time of application for the weed N concentration. Weed shoot N concentrations were generally greatest with surface fertilizer application and lowest with the point-injected fertilizer.

Weed populations were generally lower with spring-applied N than when the fertilizer was applied in the fall. Weed populations were also generally greatest when the fertilizer was broadcast on the soil surface. Weed growth was always lowest in the unfertilized control treatment.

WHEAT: The N concentration in wheat shoots was positively influenced by fertilizer application method, but not by the time of application. Wheat plant populations were not affected by timing or placement of N fertilizer application.

The method of N application had an impact on wheat yield when weeds were present (**Figure 1**). Grain yields were generally greater with subsurface placement of N fertilizer compared with surface application. Among the subsurface fertilizer placements, the point-injected N always resulted in the highest wheat yield.

The method of N fertilizer application generally had a large effect on weed growth and crop competition. Broadcasting N fertilizer on the soil surface was the least preferred method. Isolating the N fertilizer to a small volume in the soil provided benefits for limiting weed growth while supporting higher grain yield.

More details on this work are available in the publication:

Blackshaw et al. 2004. Nitrogen fertilizer timing and application method affect weed growth and competition with spring wheat. Weed Sci. 52: 614-622.

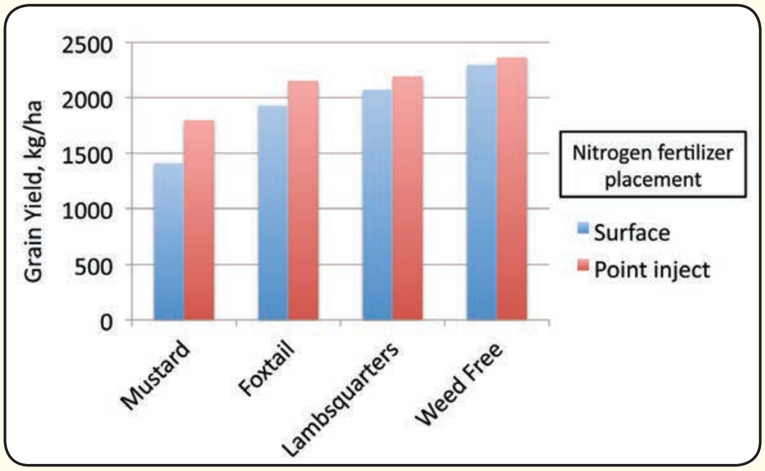

Figure 1. The effect of fertilizer placement and weed species on the 4-year average yield of spring wheat. Data averaged over the fall and spring fertilizer application times.

Submitted by R. Mikkelsen, IPNI, USA, August 2013.

M

Module 6.3-1 Phosphorus placement for soybeans grown on tropical soils.

Tropical soils are generally low in P, which is a condition that can severely limit plant development and yield, especially for crops with high P demand such as soybeans. Due to the high fixation capacity of these soils, P application must be managed in a way to minimize the competition for P between the soil and plant, thereby maximizing P uptake. A sub-surface band application is recommended under such conditions.

As an example, **Figure 1** shows the effect of P fertilizer placement on soybean grain yield under two soil conditions: low P (original soil) and high P (having received a previous broadcast application of 200 kg P_2O_5/ha incorporated into the top 20 cm). For soils low in P, the positive effect of banding over broadcast P application allows for the use of lower rates to obtain the maximum yield. On the other hand, in soils with a previously incorporated broadcast application the method of application (band or broadcast) was not distinguishable since the competition for available P is reduced and more P is available for the growing crop.

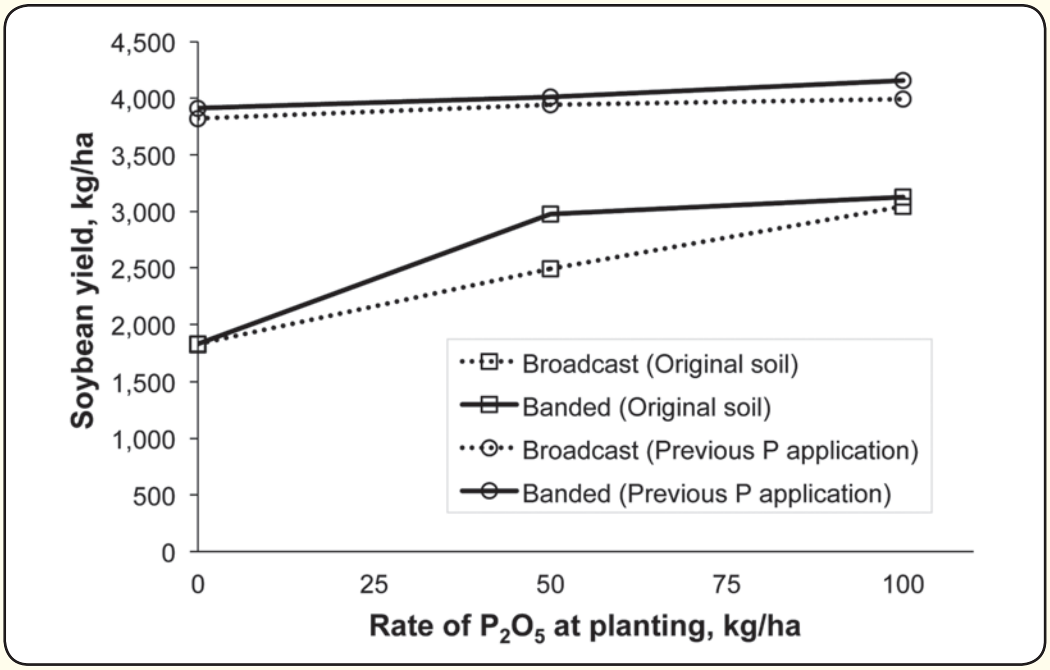

Figure 1. Soybean grain yield in response to rates of P applied broadcast or banded in two different soil condition (original low P soil and soil with previous P application) (Research Foundation MT, 2011 - data not published).

Submitted by E. Francisco, IPNI, Brazil, January 2013.

M

Module 6.3-2 Place phosphorus in the soil to protect water quality in Lake Erie. Phosphorus (P) is an essential nutrient for growing crops. But in excess concentration in streams, rivers and lakes it can lead to algal blooms. In the Lake Erie watershed region in and around the state of Ohio, USA, levels of dissolved P in rivers and algal blooms in lakes have been trending upward from 1995 to 2011. Fertilizers applied to the predominant corn-soybean cropping system are not the only cause, but are one of many probable causes. Wherever practical, growers are encouraged to place fertilizer P in the soil rather than on the soil surface, for two main reasons.

First, placing below the top 2 in. of the soil helps minimize its stratification within the soil profile (**Figure 1**). Stratification of soil P can develop in any soil that is not moldboard plowed. When the soil test P of the top 2 in. increases, so does the concentration of dissolved P in runoff water.

Second, P fertilizer is soluble P. Leaving it on the soil surface dramatically increases the concentration of dissolved P in any runoff that happens to occur soon after application. As shown in **Figure 2**, surface-applied fertilizer resulted in much more dissolved P in runoff than fertilizer incorporated into the soil. Incorporation also minimized levels of total P in runoff when P fertilizer was applied.

Incorporation can increase loss of total P through increased erosion. Using the minimum disturbance possible to place P into the soil is important for managing loss of both dissolved and total P. Innovative growers are coupling conservation tillage practices such as zone tillage with P placement to keep their cropping systems productive while minimizing nutrient losses.

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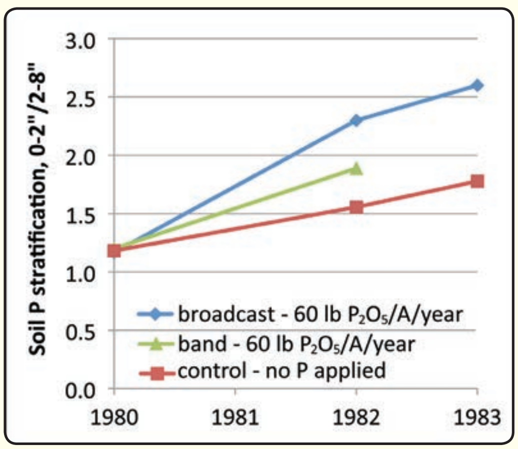

Figure 1. Soil P stratification—defined as the ratio of soil test P in the top 2 in. compared to that in the 2 to 8 in. depth—increased over time more with broadcast than with band application. Silt loam soil near Wooster, Ohio; continuous corn, no-till from spring 1980. Data from Eckert and Johnson (1985).

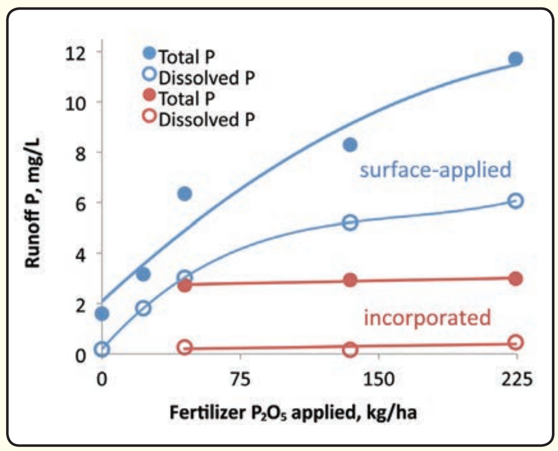

Figure 2. Concentration of dissolved and total P in runoff from a clay loam soil in North Carolina, from artificial rainfall immediately following application of superphosphate fertilizer. Incorporation was to a depth of 5 in. by rotary tillage following application. Data from Tarkalson and Mikkelson (2004).

Submitted by T.W. Bruulsema, IPNI, Canada, May 2013.

Module 6.4-1 Minimizing ammonia loss with 'right place' for sugarcane and corn in Brazil. With some forms of fertilizer, loss of N by volatilization of ammonia (NH_3) can reduce N use efficiency. The amount of N volatilized depends strongly on source, placement, and weather conditions. Sugarcane has been harvested in Brazil by slash-and-burn for decades. Lately, due to economic and environmental issues, more sugarcane has been mechanically harvested and grown with minimum tillage, which over time leads to more crop residues at the soil surface. Measurements of NH_3 losses following surface application of N to such sugarcane soils have revealed high losses when urea is the N source (**Figure 1**). Losses can be reduced, but not eliminated through use of a urease inhibitor. Other research on soils cultivated to corn found large reductions in NH_3 losses when urea-containing fertilizers were incorporated into the soil (**Figure 2**). Thus, urea-containing fertilizers can be used in sugarcane, provided that they are either incorporated or placed into the soil (injection or banded placement is possible in no-till systems). Use of a urease inhibitor can also help reduce losses.

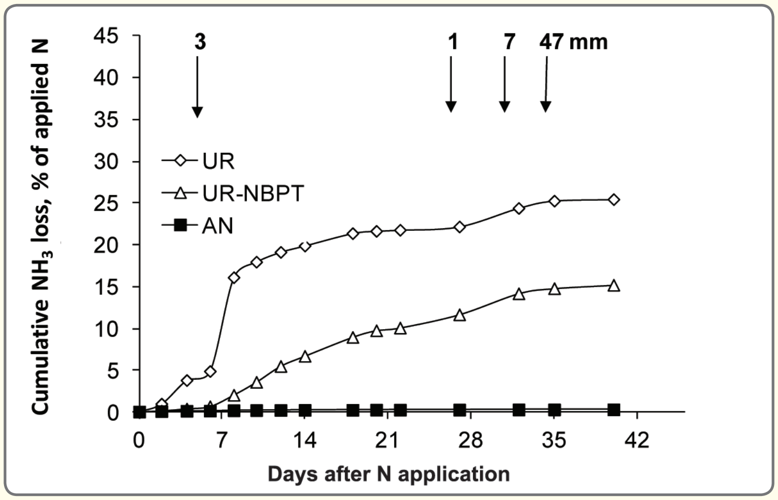

Figure 1. Cumulative ammonia losses from urea (UR), ammonium nitrate (AN) and NBPT-treated urea (UR-NBPT) surface-applied to a trash-covered sugarcane soil. Arrows indicate the amount (mm) and the date of rain events after N application. **Source:** Cantarella et al. (2008).

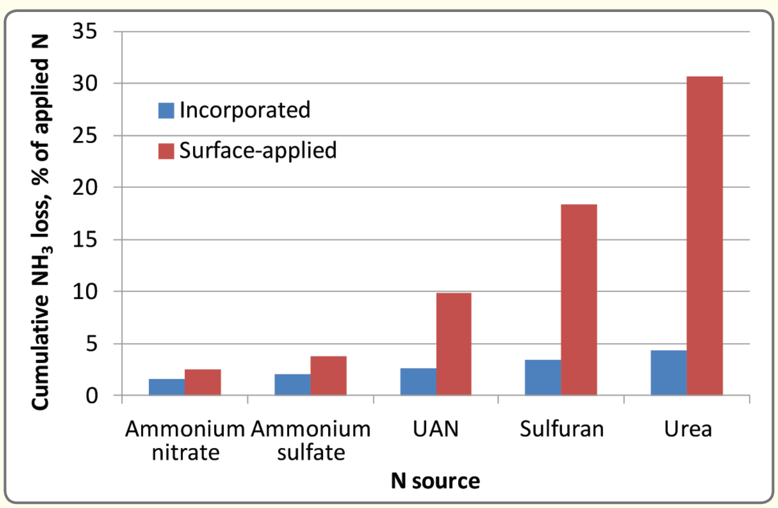

Figure 2. Ammonia volatilization from different N sources in corn crop in conventional tillage. UAN = urea ammonium nitrate; Sulfuran = UAN + ammonium sulfate, a fluid with 40% of its N in the form of urea, 40% as ammonium, and 20% as nitrate. **Source:** Lara-Cabezas et al. (1997).

References:

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Submitted by L. Prochnew, IPNI, Brazil, January 2012.

Chapter 7

ADAPTING PRACTICES TO THE WHOLE FARM

THE UNIVERSAL 4R PRINCIPLES previously discussed are used to select practices with the highest probability of meeting management objectives for the cropping systems of specific sites and more broadly, the economic, social, and environmental goals of sustainable development. Each of the resulting best practices should be consistent with the principles of all four "rights". Local conditions can influence the decision on practice selection, right up to and including the day of implementation.

7.1 Cropping Systems

Nutrient management practices are always nested in cropping systems within which other management and site factors such as tillage, drainage, cultivar selection, etc. can greatly influence the effectiveness of a specific practice. Factors such as genetic yield potential, weeds, insects, diseases, mycorrhizae, soil texture and structure, pH, drainage, compaction, salinity, temperature, precipitation and solar radiation can all interact with plant nutrition and nutrient management practice effectiveness.

7.2 Adaptive Management

Best practices are dynamic and evolve as science and technology expands our understanding and opportunities, and practical experience teaches the astute observer what does or does not work under specific local conditions. Thorup and Stewart wrote in 1988:

> *"Research performed on university farms and by professional researchers on farmer's fields are extremely valuable. However, they do not necessarily relate directly to every farmer's fields. Soils have tremendous variability from one farm to another. Cultural practices vary markedly from one farmer to another. Even climatic factors can vary significantly over very short distances. All of these factors affect possible responses from fertilizer programs. All of this means that the farm operator who survives in the 1990s and beyond is going to have to experiment a little on his own, keep accurate records, be flexible to government programs, world market price fluctuations and soil and water conservation needs."*

Though the term did not yet exist, these agronomists were describing adaptive nutrient management.

Adaptive management was defined in Chapter 2 as an ongoing process of developing improved practices for efficient production and resource conservation by use of participatory learning through continuous systematic assessment. **Figure 7.1** is a simplified version of **Figure 2.3** that focuses on practice selection at a farm level using the process of adaptive nutrient management. Science-based decision support facilitates the integration of multiple site-specific factors and input from stakeholders into a recommendation for right source, rate, time, and place. That recommendation leads to management decisions about practice selection and associated actions. With time the productivity, profitability and environmental impacts are known and resource use efficiency can be determined. With additional time, the durability of the system utilizing the practices in place becomes evident and that collective experience is fed back into the decision making process, allowing for better future predictions of right source, rate, time, and place and the associated practice selection. In theory, every pass through the cycle has the potential to result in better decisions and more appropriate practices. Ideally the assessment of practice performance would be done on the basis of all indicators considered important to stakeholders. A challenge in this process is not to overreact to seasonal observations and any data that might be collected. The unique circumstances of a specific growing season may result in practice impacts that have a low probability of reoccurring. Therefore, it is always wise to pass observations through the filter of scientific principles before making significant changes in practices.

Many possible site factors can influence what will constitute the best set of practices for a given location and reveals why local flexibility is critically important. For example (Fixen, 2007):

a) crop factors usually include yield potential and crop value and in some cases tissue nutrient concentrations or leaf color as several crop cultural practices can influence nutrient management;

b) soil factors often involve soil nutrient supplying indices or other physical, chemical or biological properties that influence nutrient cycling and crop growth;

c) grower factors might include land tenure, availability of capital, opportunity costs, the experience/education of the farmer and local advisers, or philosophical nutrient management objectives;

d) nutrient input factors incorporate information on sources available such as commercial forms or nutrient-containing wastes, fertilizer costs and application costs;

e) water quality factors might include restrictions on nutrient application in riparian zones or near other water bodies or considerations due to ground water quality;

f) climate factors drive some types of model-based support systems while others respond to near real-time weather information for a specific growing season and short term weather forecasts;

g) what relevant technologies are available at the site in question may certainly influence definition of best practices (e.g. in-season refinement of N application rate and timing may be best accomplished with electronic sensor technology in some cases and leaf color charts in others);

h) economic factors beyond those tied directly to the grower but influencing future markets and risks can impact nutrient decisions.

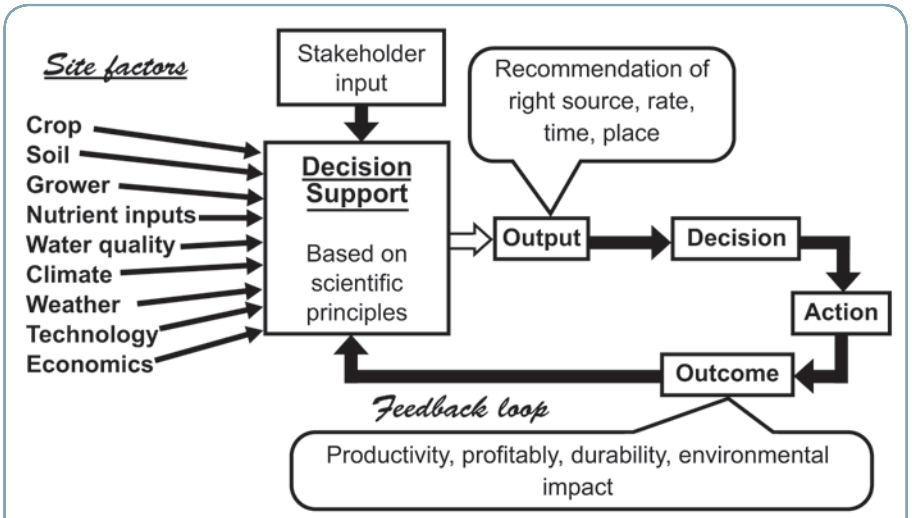

Figure 7.1 The role of adaptive management in practice refinement for 4R Nutrient Stewardship.

7.3 Beyond Cropping Systems

Many managers of plant systems—whether they run farms, ranches, greenhouses, or other operations—are involved in multiple enterprises. A wheat grower may also have a cattle enterprise. A corn producer may also be growing and marketing fresh vegetables from a different section of the farm. A rice farmer may also be employed in the city in a non-related job. These are all common situations and are part of today's real world of agriculture. And, they do influence decisions about practices.

Enterprises may compete with each other for the same equipment. A tractor needed for a fertilizer application to corn may also be needed some distance away for a harvesting operation, possibly influencing fertilizer timing and source selection. Enterprises may also be in competition for time of the manager. A controlled release N fertilizer may be the source selected because a job in the city prevents the farmer from doing split applications of a conventional N source at the optimal time.

Such practice decisions should always be accompanied with a review of the full complement of 4R principles. Often an adjustment in one of the Rs due to an external factor results in a need to adjust one or more of the other Rs to get back to a 4R-consistent set of management practices.

7.4 Decision Support

Many different tools can be employed by growers and their advisers to help integrate the numerous site factors discussed earlier in a systematic approach to making decisions about nutrient management practices. Simultaneous improvement of the numerous potential performance indicators of cropping systems is no small undertaking and tools to support this process can be very beneficial. Support tools may involve minimal on-farm technology and be appropriate for regions of small landholders or be more appropriate for regions with good access to sophisticated technologies. One of the challenges of developing support systems is to consider appropriately both short-term and long-term consequences of nutrient management practices.

The importance of decision support tools and systems for nutrient management will increase with the demand for improved efficiency and productivity. The integration of appropriate decision support devices into support systems to assist with the many interdependent nutrient management decisions has been accomplished for dominant cropping systems in some regions, but is yet to happen in others. Such integration is necessary for existing scientific understanding to be put to use in the field. Open, transparent support systems that facilitate adaptive management through internal feedback promise to improve the quality of nutrient management decision-making. Such open systems are better able to capitalize on local nutrient management expertise and the implementation of site-specific approaches.

Software available varies from tools narrowly focused on one practice or decision to true decision support systems that integrate many aspects of 4R Nutrient Stewardship. Below is a list of example decision support tools and systems:

a) **Nutrient Decision Support System (NuDSS)** – Developed for irrigated rice as part of an initiative by the Irrigated Rice Research Consortium to provide decision support on site-specific nutrient management (SSNM) in the irrigated lowlands. The target audiences are scientists, extension workers and agronomists. [On-line].

b) **Nutrient Expert for Hybrid Corn** – A software tool developed to aid farm advisors in making nutrient recommendations for tropical hybrid corn. The software is currently being adapted to make recommendations for corn and wheat on a wider range of environments. The absence of soil testing information does not limit the use of this software. [On-line].

c) **Fertilizer Chooser** – Software developed as a final step in the recommendation process, Fertilizer Chooser helps the user translate a nutrient recommendation into the correct amount of available fertilizer sources, making cost comparisons to find the least costly combinations of available products. [On-line].

d) **Adapt-N** – A tool developed by Cornell University for estimating corn sidedress N rates. It provides in-season N recommendations for corn production based on simple soils, management and crop inputs and accounts for changes in soil N due to early season weather. [On-line].

e) **Maize-N** – A companion program to the crop simulation program, Hybrid-Maize, developed by the University of Nebraska. Maize-N simulates fertilizer requirement for maize (corn) grown under intensive management based on information on the current and last season crop, tillage and crop residue management, basic soil properties, fertilizer management and manuring, and long-term weather data of the field. It uses this information to simulate yield potential and N released from mineralization of soil organic matter, crop residues, and manures. [On-line].

f) **Seed-Placed Fertilizer Decision Aid** – Developed by South Dakota State University to help determine how much fertilizer can be placed in the seed row in a reasonably condition-specific manner. This decision aid is based on a laboratory emergence study of common fertilizers and crops and verified with published field studies when they existed. [On-line].

g) **Phosphate Rock Decision Support System (PRDSS)** – Developed to help users to decide if a specific Phosphate Rock (PR) is agronomically and economically feasible compared to water soluble P sources as a function mainly of crop, PR properties, soil properties, and other site conditions, such as weather. [On-line].

Many decision support systems and tools are available for specific cropping systems around the world. They have great potential to improve recommendations for source, rate, time, and place of nutrient applications. Developers of these systems need to ensure they address all aspects of 4R Nutrient Stewardship for the crop regions in which they are used.

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Questions ?

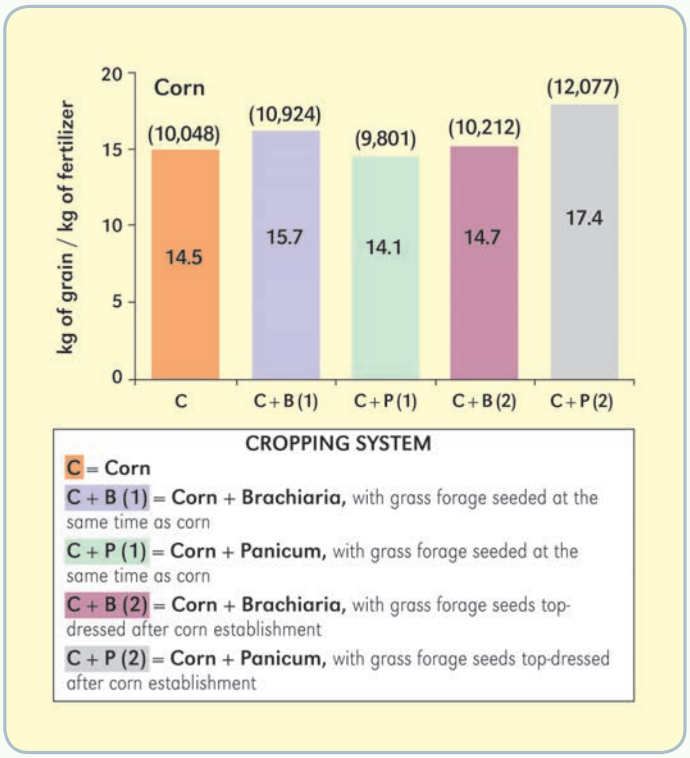
1. Adaptive management is an ongoing process of developing improved practices by use of participatory learning through
   a. crop yield assessment.
   b. site factor assessment.
   c. continuous systematic assessment.
   d. scientific principle assessment.

2. One of the site factors which influences decisions on the right source, rate, time and place for application of nutrients is
   a. the feedback loop.
   b. stakeholder input.
   c. the outcome.
   d. weather.

3. Decision support systems apply scientific understanding to integrate information on numerous site factors to make decisions on
   a. right source, rate, time and place.
   b. computer software.
   c. stakeholder input.
   d. philosophical nutrient management objectives.

CS

Case Study 7.1-1 Influence of cropping system on nutrient efficiency and crop yields in Brazil. Dry winter seasons prevent farmers in Brazil from successful adoption of sustainable no-till systems. Consequently, these soils generally have low input of crop residues. The intercropping of cereals with tropical forages (most especially Brachiaria or Panicum) has been successfully adopted in several regions of Brazil as a means to protect the soil and obtain higher nutrient use efficiency, higher yields, and also higher economic return. The Figure shows 3-year average corn yields confirming such improvements. Corn yield increased from 10,048 kg/ha, when corn was the only crop, to 12,077 kg/ha when Panicum grass was intercropped with corn. The choice of the right grass intercrop species and seeding time increased nutrient use efficiency (amount of grain produced per unit of fertilizer applied) by 20%. As an example of economic feasibility, in one of the farms of Peeters' agro company in Brazil, there was a 100% increase in profit due to the adoption of a cropping system alternating soybean, corn second crop, and Brachiaria grass in one year with cotton in the other year, as opposed to cotton every year. In such systems, the forage grasses are cultivated either alone or intercropped with grain crops. Such information constitutes a clear example of how the adequate adaptation of practices in terms of correct crop rotation and intercropping can lead to more success for the farm. It is believed that similar cropping systems can be expanded to other areas of the world. **Source:** Crusciol, C.A.C., et al. 2010. Better Crops with Plant Food. 94:2, pp.14-16.



Submitted by L. Prochow, IPNI, Brazil, December 2011.

CS

Case Study 7.1-2 Adapting nitrogen management for potato to irrigation regime in China. China's northwest belongs to an arid and semiarid region with an annual rainfall of 200 to 400 mm or less. Lack of moisture in the soil makes it a challenge to support adequate seedling growth in most spring seasons, and generally restricts agricultural production. To improve crop yield farmers try to irrigate with limited water resources. Potato is the main crop and is often planted in level fields for flood irrigation. Recently, more and more farmers have shifted to planting potatoes on ridges and using drip irrigation. However, nutrient management, especially N application, has been both a challenge and an opportunity under these conditions.

Experiments were conducted on N management under flood and drip irrigation methods in irrigated potatoes grown on Chestnut soils in Wuchuan county, Inner Mongolia. The results in **Table 1** below show that when all of the recommended N was applied before planting under drip irrigation, it produced higher tuber yield, N recovery efficiency (RE_N), and water use efficiency (WUE) than under flood irrigation. Applying only 50% of the recommended N under drip irrigation produced potato tuber yield similar to the yield obtained with 100% recommended N under flood irrigation. The reduced rate also led to higher N recovery efficiency when compared with the flood irrigation method, but lower WUE relative to the full rate of N with drip irrigation. Drip irrigation saved water (630 m^3/ha) and N fertilizer (105 to 120 kg/ha) compared to flood irrigation, while maintaining crop yields. Under flood irrigation, split N application and 100% basal N application produced similar potato tuber yields, but higher N efficiency was obtained with split N application. Thus, great potential exists to use both limited water supplies and fertilizer nutrients to optimize crop production and nutrient use efficiency, under both irrigated regimes. **Source:** Li, S., et al. 2011, Better Crops with Plant Food, Vol. 95, No. 3, 20-23.

Table 1. Potato responses to N management and irrigation regime in Inner Mongolia. Mean of two years, 2009-2010.

N management		Irrigation	Average tuber yield, t/ha	Mean RE_N, %	Mean WUE, kg/ha/mm
Basal	At flowering				
100%		Drip	37.3 a	34	431 a
50%			33.1 b	46	383 b
30%	70%	Flood	34.2 b	27	228 c
100%			33.0 b	22	220 c

Note: $N\text{-}P_2O_5\text{-}K_2O$=210-90-165 kg/ha in 2009, $N\text{-}P_2O_5\text{-}K_2O$=240-90-165 kg/ha in 2010.
Numbers followed by the same letter within a column are not significantly different at $P<0.05$.

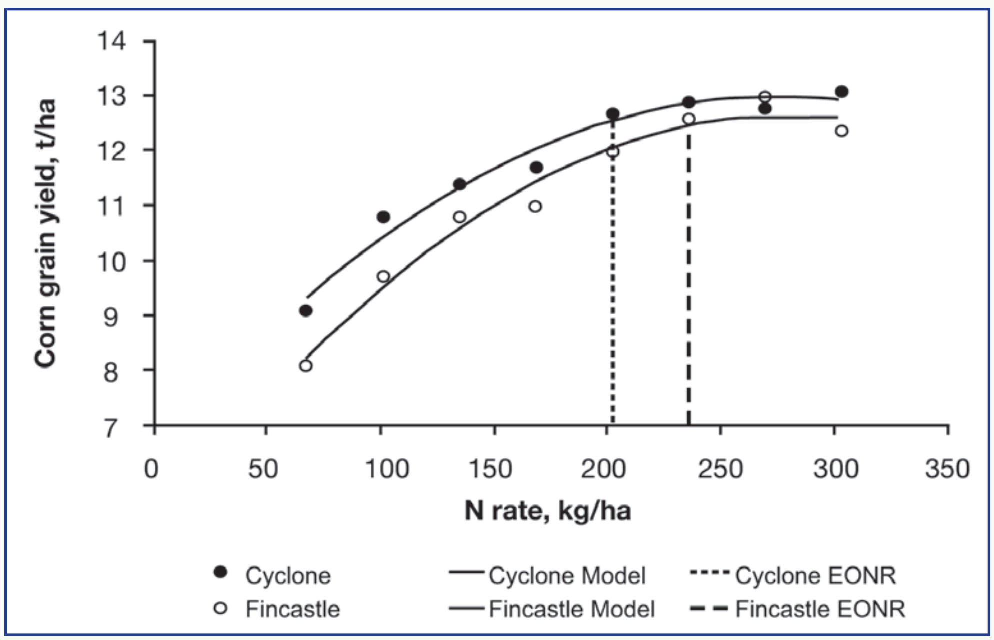
Submitted by S. Li, IPNI, China, December 2011.

CS

Case Study 7.2-1 Adaptive nitrogen management to soils using local data for U.S. Midwest corn. In this example of adaptive N management (Murrell, 2004), an agronomist sought to make improvements upon the N rates recommended by the university in his state. The agronomist had already established a site-specific management program in which soil types were used as the basis for creating management zones within fields. Phosphorus, K, and lime were varied across these zones as their individual needs dictated. However, N was still being applied at one uniform rate across the field, and the university did not provide guidance for site-specific applications.

To determine what differences, if any, should be made to the recommended N rates for the two predominant soils in his area, the agronomist conducted a 5-yr. study that examined corn response to various N rates for the two soils: a Fincastle silt loam and a Cyclone silt loam. Nitrogen rates were selected to encompass local farmer management practices as well as university recommendations. The study was designed so that corn always followed soybean, reflecting local cropping practices.

The Figure shows the 4-year average results (a drought year excluded), indicated that the Cyclone silt loam, which was higher in organic matter, had an economically optimum N rate (EONR) 35 kg/ha lower than that recommended by the university. The Fincastle silt loam, which was lower in organic matter, still needed the fully recommended rate (235 kg N/ha). These results were counter to the opinion held by the farmers in the area that the Cyclone soil, because it was more productive, should receive more, not less, N. Results from this experiment were used to create new recommendations for the Cyclone soil and created the scientific basis for the agronomist to begin a new site-specific N program that varied N rate according to soils within the field. **Source:** Murrell, T.S. 2004. *In* A.R. Mosier et al. (eds.) Agriculture and the nitrogen cycle: Assessing the impacts of fertilizer use on feed production and the environment. Scope 65. Island Press, Washington, DC. p.155-165.

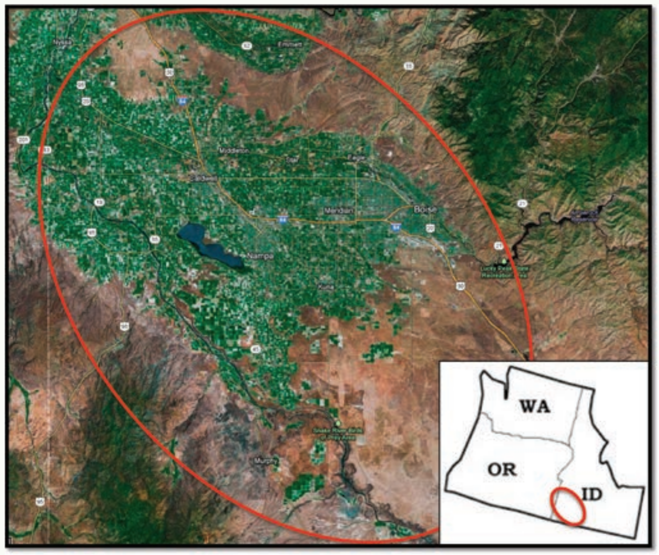


Submitted by T.S. Murrell, IPNI, USA, December 2011.

CS

Case Study 7.2-2 Improving nitrogen management and irrigation practices results in efficiency and yield.

Irrigated agriculture in southeastern Oregon and southwestern Idaho (Treasure Valley) produces high yields of onion, corn, wheat, sugar beet, potato, bean, relying on significant inputs of water and N fertilizer. Prior to the development of irrigation, agriculture in this region was impossible due to low rainfall during the growing season. Irrigated agriculture became possible with the construction of dams and reservoirs in the early 1900s. Until the 1980s, it was common for farms to routinely apply 170 to 225 kg N/ha in the fall, followed with another 170 to 335 kg N/ha in the spring and summer. Furrow irrigation was the dominant method for water delivery.



Outcomes

An intensive education program was launched to help farmers account for all the N fertilizer applied and removed in harvested crops, expand soil nitrate testing, and include deep-rooted crops in rotation with shallow-rooted crops. Growing crops such as sugar beets and wheat after onions and potatoes allows recovery of residual soil nitrate that the previous crops did not use. Demonstrations on the correct N fertilizer timing, placement, and rate of application have resulted in greater crop quality and productivity with fewer nutrient inputs.

Accounting for all N inputs allowed a better match between nutrient applications and the amount required by the growing crop. To do this, growers are now using soil testing results to guide fertilizer applications. Plant petiole samples are routinely analyzed from potato and sugar beet plants, root samples are measured from onion, and flag leaf samples are tested as needed for wheat.

Fall applications of N are now largely eliminated since it is susceptible to leaching with winter rainfall. In dry winters, the fertilizer salts in the planting beds can interfere with crop seedling establishment. Nitrogen applications now typically start in the spring, with split applications starting in March and ending in July. After the plants reach a prescribed maturity, tissue samples are taken to see if more nutrients are needed for the plants through full crop maturity.

Nitrogen management and irrigation management are closely linked, and trying to manage one without the other is futile. Improving N management also requires improved irrigation practices to avoid nitrate leaching. For example, the first irrigation through furrows has increased potential to leach nitrate below the root zone because of the loose surface soil and dry subsoil, which has a high infiltration rate. Applying N fertilizer after the first irrigation reduces the loss of nitrate and has allowed onion growers to reduce N fertilizer applications by 25% while maintaining yield and quality.

Improvements in irrigation practices have also led to benefits in nutrient management. These include:

- Laser leveling of fields to achieve more uniform water application
- Use of mechanical straw mulching to reduce soil movement and sediment loss
- Gated pipe allows more uniform water distribution and decreased water use by 35%
- Weed screens remove obstructions and allows more uniform water flow
- Addition of polyacrylamide binds soil particles and reduces irrigation-induced erosion
- Sediment basins collect soil leaving the field so it can be recovered and returned to the field
- Adoption of sprinkler irrigation may allow water to be applied more uniformly than furrow irrigation
- Switching to drip irrigation allows more precise water and nutrient management. For example, onions grown with drip irrigation require only 60% as much water as when grown with furrow irrigation with gated pipe
- Soil moisture monitoring devices have been adopted by growers to assist with irrigation scheduling

CS

Trends in groundwater nitrate for the past 20 years show that nitrate concentrations are slowly declining at a rate of slightly less than 1 ppm/year. A significant decline in the concentration of other agri-chemicals is also occurring.

With the integrated adoption of 4R principles, significant progress has been achieved in improving nutrient use efficiency, boosting productivity, and achieving environmental gains.

Table 1. Improvements in onion yield and N fertilizer use in Malheur County, Oregon from 1980 to 2008.

	Furrow-irrigated			Drip-2007 irrigated
	1980	**1987**	**2008**	**2008**
Yield, t/ha	27	30	44	46
Total N applied, kg N/ha	448	318	288	196

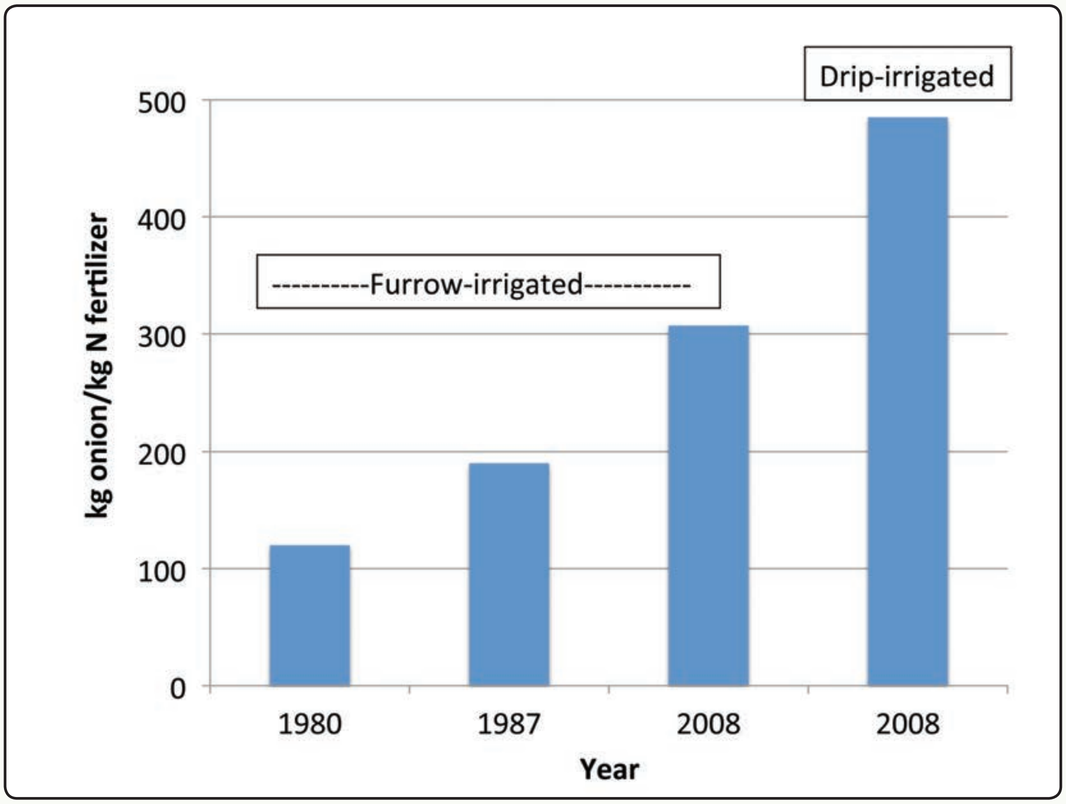


Figure 1. Improvements in nitrogen use efficiency (partial factor productivity) in onion production in Malheur County, Oregon as nutrient and irrigation programs improve nutrient stewardship.

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Submitted by R. Mikkelsen, IPNI, USA, January 2013.

CS

Case Study 7.3-1 Selecting phosphorus practices for wheat based on grower circumstances. The outcome of a workshop on soil test interpretation that was part of the International Symposium on Soil Testing and Plant Analysis in Olympia, Washington, illustrates the importance of grower circumstances on P management practice selection (Fixen, 1994). Workshop participants were soil-testing professionals from 11 countries and were divided into two classes of 20 each. Each class was divided into four groups of five participants with each group having information on a specific farmer. The four farmers, all with wheat as their primary cash crop, were described as follows:

- Young renter. This young farmer carries a high debt load, is very short on capital, and cannot negotiate more than a two-year lease. The farmer grows lower yields than most others in the area due partly to capital constraints.
- Well established farmer. This individual has no debt, invests surplus capital in mutual funds and has excellent yields for the area. Land in question was recently purchased.
- Expanding farmer. This farmer recently made a large land purchase and is short on capital.
- Part-time farmer. This farmer has adequate capital, but also has a nine month teaching job and faces serious time conflicts during planting. This person doesn't feel there is time to band fertilizer with the drill and prefers that the fertilizer dealer take care of fertilizer spreading.

All groups were given the same calibration data, uptake data, and soil test level and asked to develop short term and long term P management plans for their farmer (one of the four described above). After each group had completed their plans, they were discussed and compared to the plans printed by a spreadsheet program called PKMAN developed by the Institute to facilitate personalization of soil test interpretation. The program estimates the soil test level at which the last dollar spent on P or K gives a return equal to the minimum acceptable return on investment input by the user. This level is referred to as the target soil test level. The rate printed out at the target soil test level is equal to the amount of P or K removed in the harvested crop. If the suggested rate Table is followed, soil tests over time should increase or decrease to the target level.

Workshop groups were asked for the amount of P to apply during the first year and for long-term target soil test levels. Their recommendations are reported in the Table along with the output from PKMAN. The recommendations from the two classes were quite similar to each other and in most cases to the PKMAN output. The exception was the first year rate for the part-time farmer. This discrepancy was due primarily to too low a first year rate compared to the target soil test level suggested by the classes. When this was discussed with the classes, the groups agreed that the first-year rate would need to be increased to eventually build to the target soil test level. Thus the computer program generated recommendations similar to those developed intuitively by soil testing professionals. This exercise illustrates how grower circumstances can influence decisions about fertilizer rate, placement and timing. It also shows that computer tools can facilitate the personalization of soil test interpretation by agronomic practitioners and can be a valuable component of 4R Nutrient Stewardship programs. **Source:** Fixen, P. 1994. *In* L.S. Murphy (ed.) Proceedings Intensive Wheat Management Conf., Denver, Co., Potash and Phosphate Institute (now IPNI). p49-79.

	First year rate			Target soil test		
	Class			Class		
Farmer type	**1**	**2**	**PKMAN**	**1**	**2**	**PKMAN**
	kg P_2O_5/ha			mg/kg		
Young renter	17	0	12	NA	NA	5
Well established	56	45	55	26	25	22
Expanding	28	0	37	14	10	14
Part-time	22	39	94	22	20	20

NA = Not appropriate; Initial soil test = 10 mg/kg.

Submitted by P.E. Fixen, IPNI, USA, December 2011.

CS

Case Study 7.3-2 Optimizing N fertilizer management under multiple time demands. Small holder farmers in many parts of the world are continuously searching for new ways to add to their limited household income. In recent years in China, this has meant most available labor has left the farm to work in construction of the country's updated infrastructure. Existing technology suggested that farmers growing high yielding irrigated crops should split N application for highest grain yields and to optimize N use efficiency. However, the value of off farm employment to these workers means that there is no labor left at home to apply the N split at appropriate growth stages.

Controlled-release fertilizer technology provides the farmer with an additional "source" of fertilizer N which allows all N to be applied at planting, but subsequently released at various times over the growing season. Often these controlled-release N products are mixed with untreated N fertilizer to allow for immediate N supply, as well as the deferred N at a later date. The added cost of these products to the farmer is often more than compensated for by the income from off farm labor, and the efficiency of the controlled-release product allowing the farmer to apply his normal rate, or in many cases a reduced rate. **Source:** IPNI China, unpublished data.

Treatment	Sichuan	Chongqing	Hubei	Jiangxi
	--------------- Rice yield, kg/ha ---------------			
Check (no N)	4,167	5,635	6,243	5,623
Urea split*	6,996	7,495	7,004	7,667
Urea/CRU**	7,120	8,352	7,524	8,134

* Urea split is 40% urea N prior to transplanting, 60% urea N at 7 to 10 days after transplanting.
**Urea/CRU is 40% urea N prior to transplanting, 60% CRU also prior to transplanting.

Submitted by A.M. Johnston, IPNI, Canada, December 2011.

CS

Case Study 7.3-3 Improving nutrient balances on dairy farms through forage management. In the northeastern United States, dairy farming is a large part of agriculture. Dairy farms typically grow their own forage crops (i.e. hay, haylage, and corn silage) for feed, but purchase grain supplements to provide the required levels of digestible energy and protein. Manures are usually spread on the land where the forages and corn silage are grown, recycling a large proportion of mineral nutrients back to the soil.

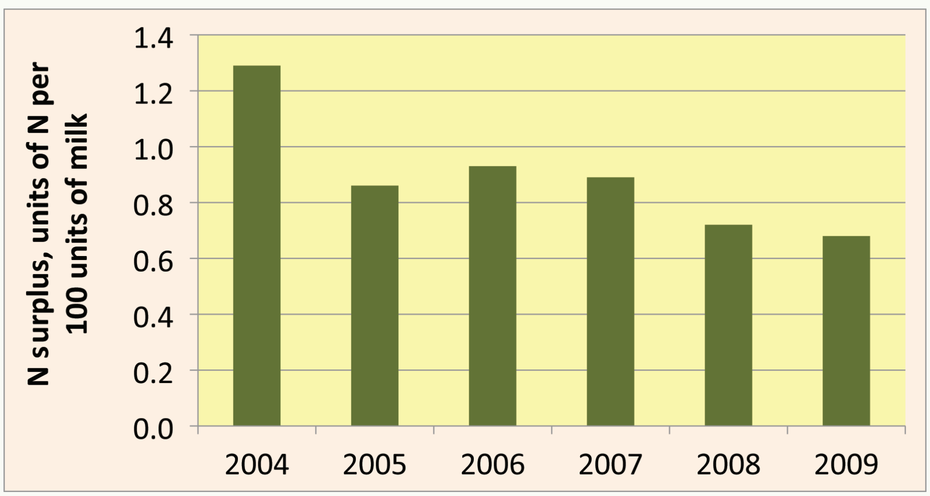
On many dairy farms, the amount of nutrients imported in the form of purchased grains and mineral supplements exceeds the amount of the nutrients exported in the form of milk and animals sold. On these farms, surpluses of nutrients returned to the soil in the form of manure can slowly build up soil reserves of P and K to levels higher than necessary for crop production, and these higher levels can result in higher risk of nutrient runoff harming water quality.

The nutrient surplus issue can be addressed by managing forages for optimum quality. When higher quality forages are fed, fewer supplements in the form of purchased grains and minerals are needed in the diet.

Charles C. Stallings, Extension Dairy Scientist with Virginia Tech, states:

> "Maximizing the amount of forage in the ration not only can improve cow health, but reduces the need for supplemental feeds that are typically high in P. For instance, soybean meal contains 0.7% P (dry basis) compared to 0.3% for alfalfa. Simply supplying more protein with alfalfa will reduce the need for more soybean meal and result in lower ration P. Also, many by-product feeds contain high concentrations of P. Feeds such as whole cottonseeds (0.6%), brewer's grains (0.67%), and distiller's grains (0.83%) are good examples. Using more forage in the ration can reduce the need for these feeds."

As shown in the figure, on an 1,100-cow dairy farm in New York, as the diet was shifted from 52% forage to 60% between 2004 to 2009, the farm's N surplus was cut nearly in half (Fields, 2011). The farm's crop manager notes "The high forage diet is achieved by having top quality homegrown forages, so we need to fully utilize the nutrient value of the manure that's produced. We've shifted to direct injection at the time of spreading ...with the injection, N losses through volatilization are greatly reduced so we're capturing a higher level of N for the corn." Similarly, another 650-cow dairy farm in central New York reduced the N and P content of its manures by 17% and 28%, respectively, as the proportion of feed produced on-farm increased from 43% to 59% over the course of 5 years (Tylutki et al., 2004).



Improvement in the N and P nutrient balance is a result of combined effects of:

- Minimizing nutrient losses from manure in storage;
- Applying manures and fertilizers at the right rate, time, and place;
- Selecting forage species, crop rotations and harvest timings to meet quality targets for protein and neutral detergent fiber;
- Minimizing losses from feed storage;
- Feeding as precisely as possible to animal requirements for protein and P.

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Submitted by T.N. Bruulsema, IPNI, Canada, November 2011.

CS

Case Study 7.4-1 Use of decision support tool increased profitability of maize production in Indonesia. In the Indonesian maize growing regions of Central Lampung and North Sumatra, on-farm trials were conducted to validate Nutrient Expert. Within each region, results were drawn for each practice from five fields in close vicinity to one another.

The Nutrient Expert tool uses information about the field's nutrient supply that is derived either in omission plots or from site and management characteristics that serve as proxies for nutrient supply. The tool recommends rates and timings for application of N, P, and K that differ from the farmers' fertilization practices, which are based on generalized one-size-fits-all regional recommendations, or are estimates that usually do not consider precise site-specific indigenous nutrient supply.

In this case, nutrient supply was estimated from proxy information including soil texture, depth and color, as well as cropping and fertilization history. The attainable maize yield in these two favorable environments was estimated at 9 t/ha, and was used as the yield target for the season. Seed, fertilizer, and grain prices are actual values recorded when the trials were conducted.

On average, use of Nutrient Expert recommendations in Indonesia achieved higher yields with less fertilizer. The higher efficiency and profitability was attained by more closely matching the rate of each nutrient applied to the site's nutrient need, and through the use of improved timing, generally by increasing the number of split applications.

Table 1. Yield and profitability of maize production comparing the farmers' fertilization practice (FFP) based on traditional recommendations and the Nutrient Expert (NE) decision support tool. **Source:** IPNI Southeast Asia (unpublished data).

Maize management parameters Values per hectare	Central Lampung		North Sumatra	
	FFP	NE	FFP	NE
Yield (15.5% moisture, t)	**7.60**	**8.99**	**8.20**	**9.03**
Revenue (USD)	**2,085**	**2,480**	**2,258**	**2,490**
Inorganic fertilizer cost (USD)	130	124	173	163
N (kg)	218	195	175	168
P_2O_5 (kg)	40	34	59	23
K_2O (kg)	23	34	42	53
Organic fertilizer cost (USD)	199	86	-	46
N (kg)	43	20	-	4
P_2O_5 (kg)	24	11	-	4
K_2O (kg)	41	18	-	4
Seed and fertilizer costs (USD)	444	322	286	321
Expected benefit (USD)	**1,640**	**2,158**	**1,972**	**2,169**

References

Pampolino, M. et al. 2011. IPNI, Penang, Malaysia. [On-line].

Witt, C. et al. 2009. IPNI, Penang, Malaysia. [On-line].

Submitted by M. Pampolino, IPNI, Malaysia, December 2011.

NOTES

Chapter 8

SUPPORTING PRACTICES

Some practices play an important role in supplying information for effective decisions for managing the application of the right nutrient source at the right rate, time and place, but do not fit within those four categories. The first of these supporting practices is the visual observation or crop scouting that is fundamental to managing crops. This practice is often associated with a second supporting practice, the sampling and analysis of soils and plants. Effective sampling is critical to ensure the samples are representative of the field. The following step is accurate analysis of the soil and plant samples by a reliable laboratory.

After the analysis results are received it is important to properly interpret the results in order to make an effective nutrient recommendation. The use of computer assisted GPS and GIS, along with development of variable rate application equipment is allowing farmers to divide fields into smaller management units thus making use of natural field variability to more effectively apply the right rate appropriate for different portions of a field. In combination with other spatial information from yield monitors and sensors, these technologies enable more accurate interpretation of soil and plant analysis.

8.1 Crop Scouting and Nutrient Deficiency Symptoms

The practice of field scouting is important for observing potential problems in the crop that can be corrected, or prevented. Scouting is done to monitor potential pest infestations (insect, plant disease, or weed), nutrient shortages or deficiencies, and soil management problems that might be corrected. This section will discuss nutrient shortages and deficiencies but it is important to mention that when field scouting is performed the person doing the field observations should make observations without any bias towards any one crop management discipline, (e.g. pest infestations, nutrient shortages, or soil management problems.) If a person only looks for problems in one discipline they may miss other potential problems that could drastically affect yield potential of a crop.

Identifying nutrient shortages or deficiencies is basic to profitable crop production. There are many aids available for use in developing the skill of nutrient deficiency identification. They include bulletins, charts, and books that show color images of or describe various deficiency symptoms. **Figure 8.1** shows where symptoms typically appear. Also, small in-field strips with a planned gradation of rates of the nutrient in question can help train an observer to see potential nutrient deficiencies. Some crops may not exhibit deficiency symptoms because the nutrient availability may be low, but not deficient until later in the season. This is why there are alternative methods for assessing nutrient availability other than visual observation. However, a working knowledge of the more common visual nutrient deficiency symptoms can be a valuable skill. Some nutrient deficiencies if observed in an early growth stage of a crop can be corrected by applying supplemental fertilization. But some nutrient deficiencies are not effectively corrected by supplemental in-crop applications and corrective nutrient applications are more effective for future crops.

The following simple key describes general deficiency symptoms for most crops, but an individual crop species may have a more specific deficiency symptom for a lacking nutrient.

Remember: Deficiency symptoms are not often clearly observable. Masking effects from other nutrient deficiencies, disease or insect infestations, or weather stresses (drought, flooding, or temperature) can prevent accurate visual diagnosis of nutrient deficiencies.

Remember: Deficiency symptoms often indicate severe deficiency and may not be at all observable if there is only a shortage or minor lack of a specific nutrient. In some instances, however, symptoms can occur without economic yield loss; examples can include late-season symptoms of N and K deficiency on lower leaves of cereals.

Table 8.1 Key to nutrient deficiency symptoms in crops.

Nutrient	Color Change in Lower Leaves (Translocated Nutrients)
N	Plants small with light green or light yellow color ...older leaves yellow (chlorosis) first...yellowing begins at leaf tip and extends along midribs in corn and sorghum.
P	Plants dark green with purple cast...leaves and plants small.
K	Yellow/brown discoloration and scorching along outer margin of older leaves...begins at leaf tip in corn and sorghum.
Mg	A pale green discoloration near the leaf tip ...becomes bright yellow between veins, finally reddish-purple from edge inward.
Nutrient	Color Change in Upper Leaves (Nutrients Not Translocated) Terminal Bud Dies
Ca	Emergence of primary leaves delayed...terminal buds deteriorate. Leaf tips may be stuck together in corn.
B	Leaves near growing point yellowed... growth buds appear as white or light brown dead tissue.
Nutrient	Color Change in Upper Leaves (Nutrients Not Translocated) Terminal Bud Remains Alive
S	Leaves, including veins, turn pale green to yellow... young leaves first.
Zn	Pronounced interveinal chlorosis on citrus and bronzing of leaves. On corn, broad white to yellow bands appear on the leaves on each side of the midrib. Plants stunted, shortened internodes. New growth may die in some bean species.
Fe	Chlorosis first appears in young leaves at the tips of the shoots, the leaf color changes uniformly to yellow, with the exception of the veins, brown spot or dead tissue appears when severely deficient.
Mn	Leaves yellowish-gray or reddish-gray with green veins, marginal and interveinal chlorosis, the chlorotic leaves retain their normal shape.
Cu	Young leaves uniformly pale yellow, or may wilt and wither without chlorosis. In small grain cereal crops there can be clustered growth, twisted younger leaves with necrotic tips, lodging and accompanied by poor seed set in heads.
Cl^-	Wilting of upper leaves followed by chlorosis. In small grain cereal crops there may be chlorotic progressing to necrotic spots on leaves on some varieties.
Mo	Young leaves wilt and turn necrotic along margins. Chlorosis of older leaves due to inability to properly utilize N.
Ni	Curved leaf apices with dark spots.

Note that symptoms similar to this can be confused with symptoms of damage from herbicides, diseases, or insects. Waterlogged or dry soils or wind damage can also create problems that mimic deficiencies. Diagnosis should also consider patterns of symptoms within the field and their relation to soil conditions, or insect and diseases present.

Remember: Many crops start losing yields well before deficiency signs start showing. This costly yield-limiting condition is called HIDDEN HUNGER.

Hidden hunger may greatly reduce yields and quality without the crop ever showing any deficiency symptoms. More and more fields are suffering from sub-optimal nutrient levels but no clear severe deficiency symptom is observed.

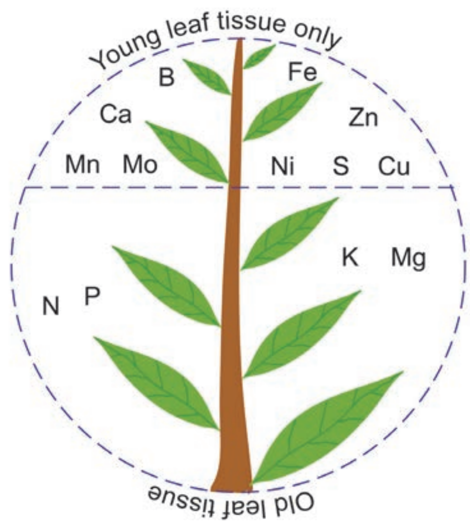


Figure 8.1 Generalized diagram of the portion of the plant where various nutrient deficiency symptoms can be observed.

8.2 Soil Testing

Soil testing is the most often used method of trying to predict nutrient deficiencies. It has become a most effective management tool for farm managers, consultants and researchers, and provides information extending from monitoring soil health to assessing fertilizer requirements and evaluating the potential for adverse environmental impacts. Soil testing can be used to:

a) identify yield-limiting factors, specifically nutrient shortages in the soil;

b) indicate the nutrient supply capacity of the soil being tested, and hence, where to start developing fertilizer and lime recommendations;

c) develop nutrient management plans when combined with production information such as cropping history, soil survey maps or yield maps;

d) monitor soil fertility and trends over time so that nutrient management programs can be adjusted to meet management goals;

e) manage risk, by determining where the largest responses to nutrients are likely to occur.

Sampling of soil is usually done before planting of annual crops or before the active growing season of perennial crops. The greatest potential for error in soil testing is in taking the soil sample.

Accurate soil testing procedures rely on representative samples. The collection of representative samples requires care and skill. In most conditions, the sample represents more than ten million times the amount of soil sent to the lab. So whether the soil sample is taken to represent a small or large field it is important that multiple samples are taken from over the whole field, bulked together and mixed well to yield a truly representative sample for analysis. If a representative sample is collected, the results of the test can provide a reliable estimate of the nutrient status of the soil. Soil testing laboratories often provide sampling instructions that may include these steps:

Questions ?

1. When upper leaves of a soybean plant show a yellowing color between the veins, the nutrient deficiency one might suspect would be
   a. Ca.
   b. N.
   c. Mg.
   d. Mn.

2. When the lower leaves of a young corn plant show a yellow color at the tip and along the margins, the plant may be deficient in
   a. N.
   b. P.
   c. K.
   d. Mg.

3. When a wheat crop in the stem elongation phase appears uniformly dark green in most areas but yellow in low-lying waterlogged areas, the cause is most likely
   a. N deficiency.
   b. insect damage.
   c. poor drainage.
   d. wind damage.

4. A nutrient deficiency that reduces plant growth and crop yield without displaying visible symptoms
   a. is termed hidden hunger.
   b. is caused by pests and diseases.
   c. occurs only with readily translocated nutrient.
   d. can be corrected in-season.

For Field Sampling

a) A separate soil sample should be taken from field areas that have distinct topography, soil types or observable color, or known past management practices. Thus, a large field may be divided into uniform soil areas or past cropping areas depending on the specific site. Assign a permanent identification number. Record the field numbers. Keep a map of sample areas. If a GPS unit is available for use, the location of spots sampled may be recorded and saved for future reference.

b) Use a clean plastic bucket, especially for micronutrient tests. Metal buckets may contaminate the sample.

c) Sample to the depth recommended for the soil test by the laboratory.

d) Additional subsoil samples may be taken down to the rooting depth of the intended crop if there are potential available nutrients that have leached downward. This is more important for mobile nutrients such as N, S, and Cl^-, but less important for less mobile nutrients such as P and K, and many of the other micronutrients.

e) In most cases at least 15 to 20 samples should be taken randomly to make up the composite blended sample from which a subsample is taken for submission to the testing laboratory.

f) The samples may be taken using one of various sampling tools (e.g. soil core probe, shovel, machete etc.). The composite sample may weigh from one to several kg.

g) Thoroughly mix all the cores from a sample area from which to obtain a representative subsample for analysis. This step is extremely important. Clods should be broken while mixing is being done. Improper mixing can result in a non-representative sample. If the soil is too wet to mix well, allow for a partial air-drying first.

h) Several types of containers may be used for sending the sample to the laboratory. Some laboratories provide an inner plastic bag that is placed in a paper box, or a paper bag that has a bonded inner plastic layer adhered to the outer paper layer. If no laboratory container is available, two new and clean, heavy duty plastic bags can be used. The inner plastic bag contains the sample while the outer contains the information sheet and sample identification.

i) To prevent contamination of some micronutrients from your hands wear latex gloves while handling the soil sample.

j) Using hands scoop the mixed soil from the bucket and swing hands back and forth over the open sample container, dropping soil so that a portion falls into the container and the remainder to each side of the container. Repeat this procedure assuring that a portion of the whole sample in the bucket contributes to the subsample, and that the sample container has about 0.5 kg in it.

k) It is advised to keep the soil samples in a cooler or fridge until shipped to the laboratory. If it will take more than a few days from the time of sampling until shipping to the laboratory the soil samples may be air-dried in flat pans where the soil sample can be spread out uniformly. Let the laboratory know if the sample has been air-dried.

l) Fill out the information sheet completely.

m) Most fields should be sampled every 2 to 3 years…more often if desired.

n) Keep a record of results.

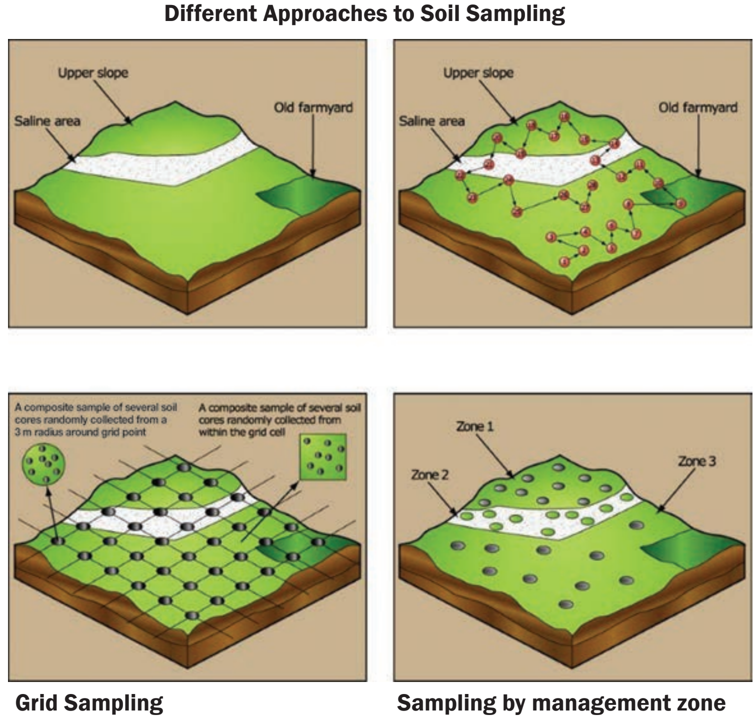


Figure 8.2 Basic soil sampling schemes.

For Diagnosing Poor Growth or Problem Areas

a) Collect separate samples using the techniques described above, from good and poor areas.

b) Take both surface and subsoil samples.

c) Include description of the observed poor growth symptoms and send the description with the samples.

d) If a digital camera is available an image may be taken of crop plants from both the poor growth and good growth areas, and used to help diagnose the problem.

Table 8.2 Comparison of the extractants used, the time for extraction and the ratio of soil to extractant specified by nine calibrated soil P tests.

Test Name	Extractants	Reference	Soil pH conditions to be considered
Olsen P	0.5 M sodium bicarbonate (pH 8.5) 0.5 h extraction in 1:20 soil:solution	Olsen et al. 1954. USDA Circular No. 939	Used in slightly acidic, neutral and slightly to very alkaline, and alkaline and calcareous soils (i.e. soil pH 6.0 to >7.2)
Colwell P	0.5 M sodium bicarbonate (pH 8.5) 16 h extraction in 1:100 soil:solution	Colwell 1963. Aust. J. Exp. Agric. Anim. Husb. 3, 190-198	
Lactate P	0.02 M calcium lactate 1.5 h extraction in 1:50 soil:solution	Colwell 1970. Aust. J. Exp. Agric. Anim. Husb. 10, 774-782	
Bray P1	0.03 M ammonium fluoride in 0.025 M HCl 1 min. extraction in 1:7 soil:solution	Bray and Kurtz 1945. Soil Sci. 59, 39-45	Acidic to slightly alkaline (i.e. soil pH <7.2). Not well suited to alkaline soils with high levels of calcium carbonates
Bray P2	0.03 M ammonium fluoride in 0.1 M HCl 40 sec. extraction in 1:7 soil:solution OR 1 min. 1:10 soil:solution	Bray and Kurtz 1945. Soil Sci. 59, 39-45; Chu, P. 1997. A&L Labs, Richmond, VA	Acidic to slightly alkaline (i.e. soil pH < 7.2) The Bray 2 method uses 0.1 M HCl as compared to 0.025 M HCl for Bray 1. It will dissolve extra P compounds in alkaline soils. Not suited to alkaline soils with high levels of calcium carbonates.
Mehlich-1 P	0.05 M HCl in 0.0125 M H_2SO_4 5 min. 1:4 soil:solution	Mehlich 1953. North Carolina Soil Test Div. Publ. 1-53	Acidic to slightly alkaline (i.e. soil pH <6.0 to 7.2)
Mehlich-3 P	0.2 M acetic Acid, 0.25 M NH_4-NO_3, 0.015 M NH_4F, and 0.13 M HNO_3 in 0.001 M EDTA 5 min. extraction in 1:10 soil:solution	Mehlich 1984. Comun. Soil Sci. Plant Anal. 15, 1409-1416	Acidic to slightly alkaline (i.e. soil pH <7.2). Capable to extract and analyze multi-elements compared to Mehlich 1 P. Not well suited to alkaline soils with high levels of calcium carbonates.
Dilute $CaCl_2$ P	0.005 M calcium chloride for 18 h extraction in 1:5 soil:solution	Moody et al. 1988. Aust. J. Exp. Agric. 23, 38-42	
Acid extractable P	0.005 M sulfuric acid for 16 h extraction in 1:200 soil:solution	Kerr and von Steiglitz 1938. BSES Tech. Comm. No 9	
Ion exchange resin	Mixture of anionic and cationic resins	Van Raij et al. 1986. Comm. Soil Sci. Plant Anal. 17(5)	
Morgan	0.54 M CH_3COOH + 0.72 M $NaCH_2COOH$ – pH 4.8 for 0.25 h extraction in 1:5 soil:solution	Morgan, 1941. Connecticut Ag. Exp. Sta. Bull. 450	
Modified Morgan	0.62 M NH_4OH + 1.25 M CH_3COOH – pH 4.8 for 0.25 h extraction – 1:5 soil:solution	McIntosh, 1969. Agron J. 61:259-265	

Soil Sampling When Using Banded Fertilizers

Because some elements, such as soil P, are relatively immobile, where banding of fertilizers is practiced such as with precision placement, soil sampling requires special consideration. In such cases, random sampling may give a high test result if only a few bands were included in the sample. Where the locations of the bands or drill rows are known, research conducted in Australia has suggested that a ratio of 1:20, 1:16 and 1:8 in-the-band cores to between-the-band cores should be considered for 75 cm, 60 cm, or 30 cm band spacings, respectively. An alternative is to take a slice of soil across the rows to include banded and non-banded soil. The reliability of this method, however, has not been evaluated for predicting fertilizer responses relative to other sampling methods.

8.3 Soil Analysis

There are a large number of soil analyses available, and selection of the appropriate analysis is critical in collecting good information. It can be useful to discuss this with the soil-test laboratory agronomist or manager. Most laboratories routinely use a specific extraction and analysis procedure for each nutrient or group of nutrients, but may be able to use another procedure if specific soil conditions are encountered. How are extractants calibrated?

A specific analysis is developed by taking soils and then using various analytic procedures to extract a proportion of the nutrient of interest and this is related back to the weight of the soil analyzed. Ideally the level of nutrient measured is calibrated with a series of regional field experiments that evaluate the response to the specific nutrient of interest. These calibration experiments involve application of an available form of the nutrient over a range of increasing rates, for example, from zero application up to an excessive level using even intervals of increasing rate.

The selection of a particular soil test will usually mean the selection of a particular extraction process that best indicates what a plant root can access from soil solution and often some proportion of the less available forms of the nutrient in the soil that can become available over the course of the growing season. In different environments and different soil types, certain procedures give a better assessment of the nutrient availability, especially the amount that can be accessed from less available pools during the crop growing season that will replenish the soil solution pools. Phosphorus, for example, is present in a range of organic and inorganic forms in the soil. There is no single extracting reagent that can predict the amount of plant available P under all conditions. As a result a range of extractants have been developed for use in particular situations and some examples of these extractants are shown in **Table 8.2.** Each set of extraction procedures has its own critical values so whenever a test result is provided; it must be interpreted against critical values derived from field tests for the crops grown. So make sure you know what test is being used to best interpret the results presented.

While soil tests give useful information, there are some assumptions implicit in their interpretations. Firstly, soil tests are usually from the topsoil, where generally most of the less mobile nutrients (e.g. P) are present. However, mobile nutrients like N and S can move below the sampling depth so that the soil tested indicates a lower nutrient availability than is found in the field. A topsoil test makes the assumption that the proportion of nutrient in the soil tested is proportional to the total amount available to the plant down to the effective rooting depth of the crop.

Secondly, a soil test can give a reasonable estimate of the potential to supply nutrient, but it does not give an estimate of the demand imposed by the crop or pasture. In variable environments, the demand can vary three or four fold for nutrients, and soil tests are usually calibrated to supply nutrients in an "average" season with average fertilizer and grain prices.

When response curves are developed, it is usually assumed that other nutrients or soil conditions are not limiting and that the response seen is a consequence of the addition of the most limiting nutrient. Furthermore, a soil test result should be interpreted in terms of soil texture and soil pH, as often these two particular features are critical in defining potential responses.

Finally, the "number" provided in a soil test report has errors around it that relate to all previously mentioned factors, as well as the uncertainty about future supply rates from less available nutrient forms in the soil. It should be interpreted within ranges—often termed very low, low, medium, high, or very high, but more accurately labeled according to the size and probability of expected response (**Table 8.3**). The best results will be obtained when test results are taken over a number of years to show trends in fertility under existing management, rather than expecting a single value to give a precise prediction of required rate of nutrient application.

Table 8.3 An example of soil test classes and response probability.

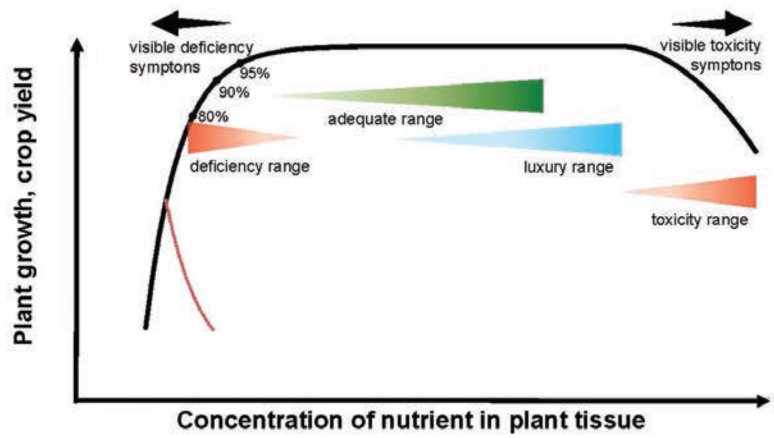
Soil test class	Probability of response
Very low	Profitable response in all but rare cases
Low	Profitable response in most seasons
Medium	Average response over years is profitable
High	Occasional profitable responses
Very High	Profitable response during the season of application unlikely

Questions ?

5. The number of sample cores recommended to represent a field area is
   a. 5 to 10.
   b. 15 to 20.
   c. 30 to 40.
   d. as many as required to fill the sample box.

6. Sampling to a consistent and recommended depth is important for
   a. N and S.
   b. P and K.
   c. micronutrients.
   d. all nutrients.

7. Compared to less mobile nutrients such as P and K, sampling for mobile nutrients like nitrate, sulfate, and chloride should be
   a. shallower.
   b. same depth.
   c. deeper.
   d. done less frequently.



	deficient	low	adequate	high	toxic
P, %	< 0.16	0.16 - 0.25	0.26 - 0.50	0.51 - 0.80	> 0.80
K, %	< 1.26	1.26 - 1.70	1.71 - 2.50	2.51 - 2.75	> 2.75
Mn, mg/kg	< 15	15 - 20	21 - 100	101 - 250	> 250

Figure 8.3 Relationship between nutrient concentration in plant tissue and growth or yield, with example data from Jones, (1967) for P, K, and Mn concentration in the dry matter of soybean leaves in various nutrient supply ranges (**Adapted from:** Marschner, 1995).

8.4 Plant Analysis

The term "plant analysis" refers to the total or quantitative analysis for nutrients in plant tissue. Soil testing and plant analysis go hand in hand. One is not a substitute for the other. Both are useful tools in diagnosis, and many producers use both. Plant analysis has been used for crops including coffee, oranges, peaches, apples, pecans, and other nuts and fruits. Because of the perennial nature of these crops and their extensive root systems, plant analysis is especially useful for determining their nutrient status.

Scientists have newer analytical methods and equipment such as atomic absorption, and especially the emission spectrograph, which can simultaneously analyze for 10 or more elements in a matter of seconds. So, considerable numbers of laboratories in different countries now have the capability to run plant analyses. Demand for this service will continue to increase as research emphasizes opportunities to manage nutrient availability during the growing season.

Plant analysis is used to:

a) Confirm a diagnosis made from visible symptoms;
b) Identify hidden hunger where no symptoms appear;
c) Determine whether applied nutrients have been taken up by the plant;
d) Study the internal functioning of nutrients in plants;
e) Suggest additional tests or studies in identifying a crop production problem.

As with soil testing, an important phase of plant analysis is sample collection. Plant composition varies with age, the portion of the plant sampled, the condition of the plant, the variety, the weather and other factors. Therefore, it is necessary to follow proven sampling instructions.

Most laboratories provide instruction sheets for sampling various crops, plus information sheets and directions for sending in samples. They usually suggest sending a sample from both good and problem areas for comparison if possible. Because experience and knowledge are vital in sampling plants correctly, the job is often carried out by agricultural advisers or consultants.

Plant analysis is the subject of rather extensive research programs among plant nutritionists today. A great deal remains to be discovered about this diagnostic tool. On-going research is constantly uncovering new facts and establishing revised and updated standards. Plant analysis data should be interpreted by scientists who are trained in this field and who understand the factors involved. It is a valuable addition to available diagnostic tools.

Deficiency and Sufficiency Ranges

Usually, a plant analysis is interpreted by comparison of the elemental concentrations with a standard sufficiency range for the plant part, crop species, and stage of growth established by research. Where standardized research values for a given situation are not available, plant analysis can still be useful in identifying nutrient stress problems if paired plant samples can be taken from areas of both poor and good growth within the field or among nearby fields.

Specific critical values for deficiency, sufficiency, and toxicity are best obtained in local or regional crop production guides. The critical level for deficiency is usually defined as that which results in 90% of the yield or growth with the nutrient non-limiting. **Figure 8.3** provides an example of the relationship between the concentration of a nutrient and the relative growth or yield of a crop, with specific values for P, K, and Mn in soybeans (Marschner, 1995).

With some nutrients, it is possible that concentration increases rather than decreases with extreme deficiency, if the deficiency stunts growth to such an extent that the normal dilution of minerals by growth of the plant does not occur. Alternately, in very good growing conditions growth dilution can cause some nutrients to appear deficient when they are not. For this reason, diagnosis of problem areas is sometimes more accurate if a partially affected, rather than the worst-affected area is compared to a nearby normal area.

Nutrient levels in the luxury range reduce the risk that these nutrients will become deficient under conditions unfavorable for root uptake (e.g. drought) or when internal demand is high (e.g. during fruit expansion or kernel filling).

Diagnosis and Recommendation Integrated System (DRIS)

The results of plant analysis can be difficult to interpret, because the critical concentration of a nutrient in plant tissue varies with changes in the concentrations of other nutrients. Diagnoses made using the Diagnosis and Recommendation Integrated System (DRIS) are based on relative ratios of nutrient element concentrations rather than on absolute concentrations per unit of dry matter in plant tissue. Norms for these ratios are established by comparing the complete analyses of crops in high and low yield situations. Because ratios are used, dry matter dilution as the crop grows has less effect on the interpretation, and time of sampling can be more flexible (Sumner, 1977).

Initially, it was suggested that DRIS norms established at one geographic location should apply well to other regions. Results of numerous studies on corn, wheat, soybean, alfalfa and potatoes, however, have indicated that norms developed locally or regionally produced more accuracy in diagnosing deficiencies (Munson and Nelson, 1990; Jones, 1993).

In some countries, including USA, Brazil, Canada, China, and India, public and private crop advisers have adopted DRIS as part of their diagnostic technique in selected areas.

It is now also possible to use DRIS in combination with GIS to delineate productivity zones for a particular crop grown in a region. This delineation helps in identifying potential sites for the purposes of land use planning and monitoring trends in crop productivity.

Though several workers have shown that DRIS often produces more accurate diagnoses of nutrient element deficiency than conventional approaches, the complexity of the DRIS methodology has limited its use. Various modifications in the DRIS methodology which can simplify its use and interpretation have been proposed. Some of these modifications include simplified calculation of intermediate functions, modified parameter selection, and modified criteria for predicting response to additional fertilizer. In addition, computer programs have been developed to make DRIS calculations "just a click away."

Refinements of DRIS include the Compositional Nutrient Diagnostic (CND) which has been applied in the province of Quebec in Canada (Parent, et al. 2009).

Quick Tests

A field tissue test is the determination of the amount of plant nutrient in the sap of the plant, a semi-quantitative measurement of the unassimilated, soluble content.

A large amount of an unassimilated nutrient in the plant sap indicates that the plant is getting enough of the nutrient being tested for good growth. If the amount is low, there is a good chance that the nutrient is either deficient in the soil or is not being absorbed by the plant because of lack of soil moisture or some other factors.

Tissue tests can be run easily and rapidly in the field. Green plant tissue can be tested for several nutrients like NO_3^--N, P, K, and sometimes Mg, Mn, and Fe. However, it takes a lot of practice and experience to interpret the results, especially those for Mg and the micronutrients.

Tissue tests are used to identify one nutrient (N, P, or K) that may be limiting crop yields. If one nutrient is very low, others might accumulate in the sap because plant growth has been restricted, resulting in an improper interpretation. If the crop grows vigorously after the deficiency has been corrected, one might find that other nutrients are not present in amounts to produce high yields. What is identified, or tested for, is the most limiting nutrient at a particular growth stage.

These on-the-spot tissue tests can be very helpful in the hands of an expert. Without leaving the field, N deficiencies can be detected and corrective measures suggested. This savings of time could be valuable. As with total analysis of plants, it pays to compare healthy plants with poor ones wherever possible.

Kits containing instructions and supplies for running tissue tests are available. Many of them include test instructions and supplies for determining soil pH, and even soil P, K, and Zn. Before using these tests, one should seek qualified training to develop diagnostic skills.

8.5 Interpreting Soil Test and Plant Analysis Results

Farmers who regularly have soil and plant samples taken and analyzed do so because they are interested in ensuring their crop yields are not constrained by low availability of nutrients. They also want to ensure that the fertilizer nutrients they purchase generate an economic return, and that the fertility and productivity of their soils are maintained while protecting the environment. Soil tests when properly used can provide an excellent guide for determining fertilizer and lime requirements and for developing nutrient management plans.

A sound recommendation should address all four Rs—source, rate, time, and place—and take farm sustainability goals into consideration. Such recommendations require considerably more information in addition to the soil test result, including the availability of equipment and on-farm nutrient sources, the tillage and cropping systems, the physical properties of the soil, and crop yield and quality goals.

Recommendations may address the following situations:

a) ensuring that all nutrients will be maintained at non-limiting levels from crop planting until harvest;
b) balance among nutrients to ensure efficient use of each nutrient;
c) amounts required to build low soil test levels to the optimum range over a specified number of years;
d) opportunity to draw down nutrients in soils that have accumulated excessive or very high levels of the soil-immobile nutrients such as P or K.

Crop response to nutrients such as P and K is influenced by many factors in addition to soil test level. Responses may be larger or smaller, or may require more or less nutrient addition, depending on crop yield potential, planting date, previous crop, tillage practice, soil compaction, temperature, soil moisture levels, soil pH and levels of other nutrients in the soil. Because of these factors, the soil test behaves more like an accurate predictor of the probability of crop response, rather than a precise predictor of the actual size of the crop response and the amount of nutrient to be applied to achieve it. It is therefore critical that soil tests results are interpreted carefully by a well trained and experienced agronomist.

Farmers also differ in their goals for crop production. Some have more time, interest and capability for managing for yields very close to the maximum attainable. Some have more competing demands for their time than others. Some have more or less access to a wide range of crop inputs, and their ability to purchase such inputs also varies. These differences can have a large influence on their management of plant nutrition.

These factors have led to the development of two distinct and widely recognized approaches to managing soil fertility—the nutrient sufficiency approach and the build-maintenance approach. The choice of approach influences the recommended source, rate, time and place of nutrient application. The following two sections, adapted from Leikam et al. (2003), explain the approaches.

Sufficiency Approach

The goal of a nutrient sufficiency approach is to apply just enough of a given nutrient to maximize profitability in the year of application, but minimize nutrient or fertilizer costs. While inherent variability in nutrient response among and within fields and over time may result in more or less nutrient actually being required for maximum profitability than is recommended, near optimum rates will be recommended over the longer term. Unless initial soil test levels are high and the soil can supply all the nutrient needs of the crop when this approach is adopted, little year-to-year flexibility in nutrient application exists since applications are required every year in order to eliminate profit-robbing nutrient shortages. Choices for placement are also more limited, since at lower soil test levels it becomes more important to place nutrients in a band near the seed.

Nutrient sufficiency recommendations are based on soil test calibration field data collected over many years and sites. To address the complicated and constantly changing issue of marginal return application, these recommendations are typically developed to provide 90 to 95% of maximum yield, or the yield level typically obtained at the economically optimum nutrient rate. Crop response and recommended nutrient application rates are highest at very low soil test levels, while recommended nutrient application rates decrease to zero as the soil test level increases to a critical soil test value. The critical level is the soil test value at which the soil is normally capable of supplying sufficient amounts of P and/or K to achieve 90 to 95% of maximum yield. For nutrient sufficiency recommendations, soil test values are not viewed as a managed variable and there is little consideration of future soil test values.

The sufficiency approach is often used in situations where funds for investment are unavailable or have high interest costs, or when land tenure for the future is not assured (e.g. when land is rented with one- or two-year lease agreements).

Build-maintenance

The objective of build-maintenance fertility programs is to manage P and/or K soil test levels as controllable variables. At low soil test values, build-maintenance recommendations are intended to apply enough P and/or K to both meet the nutrient needs of the immediate crop and to build soil test levels to a non-limiting value, above the critical level. The critical level is the same as that used in the sufficiency approach, and its determination requires a similar amount of soil test calibration field data. The build-maintenance approach tends to be less economically sensitive to uncertainties in recommendations, due to the reduced risk of yield loss at higher soil test levels. Typically, the buildup of soil test values occurs over a planned period of time (usually 4 to 8 years). Once the soil test value exceeds the critical value, nutrient recommendations are made to maintain the soil test levels in a target, or management range.

The soil test target range is typically a range at and slightly above the critical soil test value, where the soil can generally provide adequate nutrients to meet the nutritional needs of growing crops ('medium' to 'high' levels). Once the soil test for a nutrient has been built up to the target range, farmers have greater flexibility as to when and how fertilizer is applied. Above the critical level, the soil is largely capable of supplying the nutrients needed in a given year. Farmers can thus choose to apply fertilizer annually, or to combine applications and apply the fertilizer only every two or three years. This provides flexibility to manage time, cash flow, and fluctuations in market prices for fertilizers and crops.

Build-maintenance fertility programs are not intended to provide optimum economic returns in any given year, but rather attempt to minimize the possibility of P and/or K limiting crop growth while providing near maximum yield, high levels of grower flexibility, and good economic returns

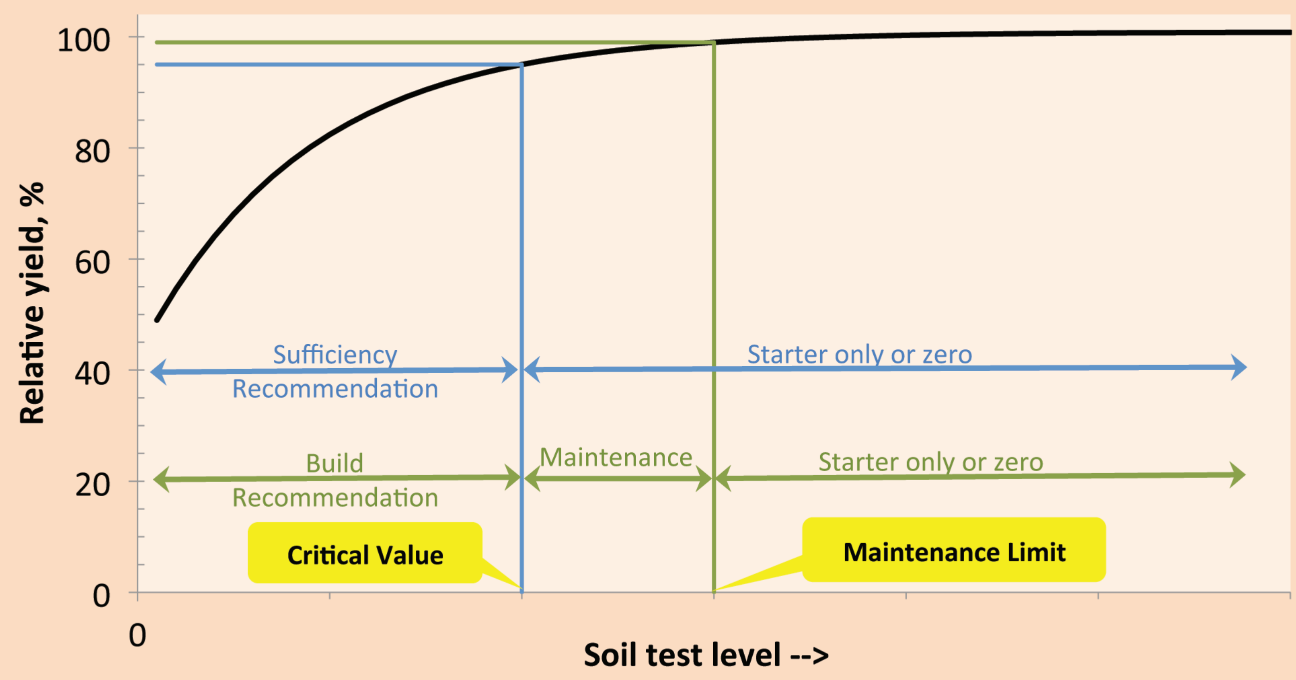


Figure 8.4 As soil test level for a nutrient increases, so does relative yield (the yield of the crop without the nutrient applied as a proportion of the yield when the nutrient is non-limiting). The size and probability of crop response diminish with increasing soil test level. Sufficiency recommendations aim to provide economic return in the year of application, and decrease to zero (or an amount smaller than crop removal, usually placed near the seed, and called a starter) at the critical level. A build-maintain approach recommends amounts greater than crop removal below the critical value, amounts equal to crop removal in the maintenance range, and amounts less than crop removal and declining to zero above the maintenance limit. (**Adapted from:** Leikam et al., 2003)

over the long-run. The disadvantage of soil build-maintenance programs is that required application rates are normally higher than those recommended for nutrient sufficiency programs.

Choosing the Right Approach

Over an extended period of time, the two approaches provide growers the choice between a system which recommends lower nutrient application rates at low soil test levels, but requires annual fertilizer application (nutrient sufficiency programs), versus investing in higher rates for 4 to 8 years in order to gain the flexibility and potential cost savings of making multi-year applications when it is most convenient and economical (build-maintenance programs). Critical soil test values and their relation to rates applied are shown conceptually in **Figure 8.4**.

While the short-term difference in cost between the two approaches may be sizeable, the benefits from flexibility in the overall fertility program, reduced application costs, improved timeliness, and cash management can make the investment in build-maintenance programs worthwhile. Once growers understand the two approaches, they can decide if the cost of building soil test levels is a reasonable investment. If the farm has manure nutrient sources, the economics of the build and maintain approach are more favorable. Even with manure nutrients, however, it is advisable to discontinue application of rates that increase the soil test beyond an environmental threshold (usually higher than the maintenance limit), to avoid nutrient imbalances and increased risk of harm to the environment (see section 9.8.2 and **Figure 9.2**).

Farmers looking for greater profits often will need more than just a fertilizer recommendation. They need a complete nutrient management plan in addition to information on proper varieties, cultural practices, timing of planting, appropriate crop protection strategies, etc. A soil test is only one part of an overall management plan that will ensure high, profitably and efficiently produced yields while minimizing nutrient losses that could harm the environment. Nutrient management plans are further discussed in Chapter 9.

8.6 Omission Plots

Where laboratory analysis of the soil or plant tissue is not feasible, the supply of nutrients from the soil can be estimated using the omission plot technique. This is done by having small plots where each of the nutrients being evaluated is omitted on a plot, while all the other nutrients are adequately applied. There is one plot that receives all the nutrients and one plot that receives no fertilizer at all. If there is no decrease in yield when a nutrient is omitted compared to the "all nutrient" plot, it is assumed that sufficient amounts of that nutrient are being supplied from the soil.

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Questions ?

8. Different extractants used in the analysis of soils for available P are interpreted using different
   a. depths of sampling.
   b. critical values.
   c. limiting nutrients.
   d. estimates of nutrient demand.

9. In plant analysis, the critical level for deficiency of K usually results in 90% of the crop yield as compared to
   a. maximum yield.
   b. maximum economic yield.
   c. yield with all nutrients non-limiting.
   d. yield in the same conditions with K non-limiting.

10. In a build-maintenance soil fertility program, when soil test P is above the maintenance limit, the amount of P recommended should
    a. be zero or starter only.
    b. replenish crop removal.
    c. continue building soil test P.
    d. prevent declining soil test P.

CS

Case Study 8.1-1 Cropping history influences decisions on soil sampling depth. The importance of knowing the cropping history of a field was shown in a case near Calgary, Alberta in Canada. A new landowner wanted to grow a crop of oats as green feed hay on a 65 ha field. The local agriculture retail facility was contacted to take soil samples on the field and develop a fertilizer recommendation prior to planting the oat crop in mid-May. A retail staff member went to the field and took 15 random soil cores down to a depth of 15 cm, combined these together and took a sub-sample that was sent to a soil test laboratory for analysis. The soil test analysis reported levels of available macro nutrients for N, P, K, and S. Based on those levels, the fertilizer recommendation was 132 kg N, 11 kg P_2O_5, and 17 kg K_2O/ha for a target yield of 9 t/ha. The fertilizer applied in the seed row blend consisted of a blend of ammonium phosphate (11-52-0) and potassium chloride that supplied 2kg/ha N/ha. The balance of N was applied as broadcast urea fertilizer at a rate of 282 kg/ha, supplying 130 kg N/ha. The urea was incorporated by tillage prior to planting. The crop grew well because of early summer rains followed by a hot dry July and August. The hay yield was close to the target yield.

All was well until the farmer had a feed analysis done on a hay sample. The analysis showed nitrate levels of 6,000 mg/kg, far above the generally regarded safe level of 1,500 mg/kg nitrate for hay to be fed to beef cattle (Cash et al. 2007). The farmer complained that the N recommendation from the agricultural retail location was too high and had caused excessive nitrate levels in the hay. Further investigation by a regional agronomist with the agriculture retail company found that the field had been in alfalfa for 5 years, disked under late in the summer of the fifth year, and fallowed for a year before being sold to the new owner. The year of fallow had above average rainfall and therefore the agronomist suspected that N mineralized from the decomposing alfalfa, in the year of fallow, had been leached below the 15 cm soil sampling depth. Soil sampling to a depth of 120 cm by the regional agronomist, late in the summer of the year of the oat hay, showed residual nitrate N in the soil to be 80 kg/ha. The high nitrate in the hay was a result of considerable nitrate in the soil below the original sampling depth, which combined with the added N in the fertilizer excessive N available to the oat crop. The hot dry weather in July and August made the nitrate accumulation in the oats even worse.

In hindsight, had the cropping history of the field been investigated, and that information known, it would have been wise to take soil samples to a depth greater than just 15 cm depth. In this type of situation three depths of soil samples are advised: 0 to 15, 15 to 60, and 60 to 120 cm. The residual N would have been accounted for and a much lower N recommendation for the oat crop would have been given.

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Submitted by T.L. Jensen, IPNI, Canada, February 2012.

Chapter 9

NUTRIENT MANAGEMENT PLANNING AND ACCOUNTABILITY

Managing plant nutrition according to principles of 4R Nutrient Stewardship includes accountability for full impacts on sustainability: economic, environmental and social. This chapter discusses and compares approaches used for nutrient management planning and measuring sustainability performance.

9.1 Nutrient Management Plans

In many regions where the intensity of livestock and poultry production has resulted in nutrient surpluses (where more nutrients are excreted in manure than are taken up by crops in the fields), formal nutrient management plans have been made mandatory. In some regions, good compliance and positive impacts have been achieved. However, the extension of this approach to smaller farms and to operations focused primarily on crop production has been limited. Barriers to participation include the amount of time required to assemble the detailed information, lack of flexibility in making changes to respond to weather and markets, and lack of connection to the farm business plan.

9.2 4R Nutrient Stewardship Plans

A 4R Nutrient Stewardship Plan aims to serve two purposes for all operations using plant nutrients. First, it should track and record all crop management practices applied relevant to plant nutrition as part of the adaptive management cycle. This information is primarily for the benefit of the manager and advisers, for use in making decisions on practices to adopt or revise for the next production cycle, as discussed in Chapters 2 and 7. Second, plans need to track performance, the outcome of implementing a set of practices.

People are increasingly asking for information on performance and its improvement over time. Purchasers of a crop product want to know its environmental footprint based on whole-system performance. For example, large food industry corporations have launched or are preparing to launch global initiatives to promote sustainable agriculture, to help businesses put an economic value on the environmental and social impacts of their supply chains. In a 25 August 2011 article, the media publication Businessgreen.com described one such initiative to include:

> …*"resource management, such as water, energy and emissions, as well as farm productivity, preservation of soil fertility, and biodiversity. It will also cover social impacts, such as the effects on farming communities, human rights, and compliance with local laws, standards and regulations."*

The process of setting sustainability goals should include selecting specific performance targets. Performance is assessed through measures and indicators related to economic, environmental and social outcomes. It relates to all outcomes considered important to stakeholders (including farmers, agribusiness, customers, and consumers).

When 4R Nutrient Stewardship principles are applied to the development of plans for managing crop nutrients, the information gathered and reported is targeted to the most important economic, social, and environmental goals. Going beyond agronomic yields and environmental impacts, long-term sustainability is the fundamental consideration, and the nutrient management plan should become an integral part of the farm business plan. **Focusing the performance information on economic, environmental, and social priorities established by stakeholders distinguishes a 4R Nutrient Stewardship plan from nutrient management plans.**

In Chapter 2 it was noted that the 4R Nutrient Stewardship concept relates management practices—selection of nutrient source, rate, timing and placement—to sustainability goals for the enterprise. So the first step in developing a 4R nutrient stewardship plan is to state the sustainability goals of the enterprise, be it a farm, a golf course, or a park. This requires a high level of commitment from the producer or manager and encourages engagement with stakeholders. While stakeholders can contribute to the process of setting goals, managers select practices. General sustainability goals are established in partnership with those people who have an interest in the impacts of the enterprise on things that are important to them. Enterprise-specific goals need to align with these general goals.

The impacts of fertilizer management are expressed in the performance of the cropping systems or soil–plant–air ecosystems in which they are applied. Performance includes the increase in yield, quality, and profit resulting from a fertilizer application and extends to long-term effects on soil fertility levels and on losses of nutrients to water and air. It also includes impacts on the regional economy and social conditions—for example, affordable food. Not all aspects of performance can be measured on each farm, but all those considered priorities to stakeholders should be assessed. Scientifically accepted indexes and credible computer models may need to be used for these assessments.

9.3 Performance Indicators

Performance indicators measure the actual outcome of the implementation of a particular management practice to a particular cropping system. They can be very expensive and difficult to make. Performance measurements are done primarily by research agronomists and are used to validate management practices, often in a controlled field context designed to extrapolate to a large number of practical farm crop situations. An example may be a field trial on an experiment station in which two or more practices are compared and where measurements include crop yields, nutrient uptake, losses of ammonia and nitrous oxide to the air, losses of nutrients in runoff and drainage water, etc.The 4R concept helps guide research and extension toward validation of practices most relevant to achieving the economic, social, and environmental outcomes that stakeholders consider important.

Who chooses the indicators?

Stakeholder input is required to select performance indicators representing progress on the goals considered important by all. In a nutshell, a 4R Nutrient Stewardship plan involves crop producers and their advisers selecting the right source–rate–time–place combination from practices validated by research conducted by agronomic scientists. Goals for economic, environmental, and social progress of the enterprise—and corresponding performance indicators—are chosen to align with general sustainability goals into which the stakeholders of the crop production system have had input. The plan documents both the practices implemented, and the performance according to those indicators.

Questions ?

1. Appropriate plans for managing crop nutrients include information on
   a. management practices.
   b. performance.
   c. management practices and performance.
   d. onerous details.

2. The first step in developing a 4R Nutrient Stewardship plan is to state the farm's
   a. performance indicators.
   b. sustainability goals.
   c. yield goals.
   d. fertilizer rates.

3. Performance indicators reflect the progress of fertilizer management in helping to improve
   a. water quality.
   b. air quality.
   c. crop yield.
   d. sustainability.

Table 9.1 Descriptions of performance indicators reflecting the social, economic, and environmental dimensions of the performance of the crop-soil-climate system. Their selection and priority depends on stakeholder values.

Performance Indicator	Description of Possible Metrics	Relevance		
		Economic	Environmental	Social
Farmland Productivity	Yield and quality of crops, proportion of production due to nutrient input	✓	✓	
Soil Health	Proportion of soils at optimal levels of soil fertility, soil organic carbon, soil structure	✓	✓	
Nutrient Use Efficiency	Partial nutrient balance, nutrient surplus, recovery efficiency	✓	✓	
Water Quality	Nutrient loss, nutrient load, nutrient concentration in aquatic ecosystems, fraction attributable to crop nutrition		✓	✓
Air Quality	Ambient concentrations of ammonia, nitrogen oxides, ozone, and $PM_{2.5}$		✓	✓
Greenhouse Gas Emissions	Nitrous oxide emissions, carbon footprint		✓	✓
Food and Nutrition Security	% or number of people undernourished, % of children stunted, household perception surveys	✓		✓
Biodiversity (land conservation and habitat)	Number and distribution of species in ecosystems, natural land spared from agriculture		✓	✓
Economic Value	Value added to farm revenue or to global economy through productivity increase or employment opportunities, impact on income equality	✓		✓

* The relative importance among these and other indicators needs to be determined by stakeholder input.

What are some possible indicators?

Since fertilizer applications have multiple impacts, no single indicator provides a complete reflection of performance. Neither can all possible impacts be measured. Stakeholders need to select the performance indicators that relate to their priority issues. The list provided in **Table 9.1** describes indicators related to the management of plant nutrients. Each of these indicators can be related to at least two of the three pillars of sustainability, but no single indicator captures all three. Nor does any single indicator capture all priorities of all stakeholders. For this reason, balanced sets of complementary indicators are recommended to be selected to reflect stakeholder priorities.

None of these indicators are affected by fertilizer management alone. They also depend on sound management of all practices applied to the cropping system or plant ecosystem. For instance, a good fertilizer program for turfgrass will not control nutrient loss if clipping management, or species selection, is inappropriate. As another example, choice of a poorly-adapted cultivar of wheat will show poor N use efficiency, in spite of the best possible choices for source, rate, time and place of N application.

Economic support for environmental and social performance

Farmers and managers recognize environmental and social aspects related to keeping their enterprises viable for future generations. Economic profitability, however, is essential for the sustainability of any enterprise, and may sometimes conflict with goals for environmental and social performance. Motivation for managers to more fully address all three aspects can be provided by programs that include recognition (e.g. an environmental compliance certificate or label) or direct payments for ecological goods and services (e.g. carbon offsets related to greenhouse gas mitigation). Such programs can ensure continued improvements in productivity together with progress on environmental and social issues.

9.4 Nutrient Use Efficiency as a Performance Indicator

Performance indicators often include crop yields and sufficient information to calculate economic returns. In addition, they need to reflect environmental and social performance. The indicators selected vary depending on stakeholder priorities, but often include either nutrient balances or nutrient use efficiencies. 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 N applied, so practices chosen to improve nutrient use efficiency can 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. Many of the nutrient losses impacting the environment are difficult to measure. Nutrient balances and nutrient use efficiencies provide an indirect proxy for some of these losses and are not as difficult to calculate, estimate, or measure.

There are examples of issues where very small losses result in environmental impact. Consider the issues of runoff of soluble P, or emissions of nitrous oxide. In both, the losses often amount to only 1 to 3% of the nutrient applied, and the loss in itself is not large enough to make the nutrient application less effective or available for the crop's nutrition. Improving nutrient use efficiency and reducing nutrient surpluses may partially reduce the environmental impact of these losses, but source, time and placement practices may also need to be considered to reduce the impact on the environment to satisfactory levels.

It is often assumed that nutrient use efficiency is the most important indicator of performance for fertilizer use. This is not the case. Crop nutrients are applied to increase the overall performance of the cropping system. Nutrient use efficiency is only one aspect of that performance, as indicated in **Table 9.1**. Nutrient use efficiency has many definitions, reflecting nutrient recovery, nutrient balance, or yield produced per unit of nutrient applied. Each provides unique indications of potential for improvement of fertilizer management, but none provides a full representation of the impact on overall performance.

Production Efficiencies. The simplest form of crop output efficiency is termed partial factor productivity (PFP). It is calculated in units of crop **yield** per unit of nutrient applied. Another term, agronomic efficiency (AE), is calculated in units of **yield increase** per unit of nutrient applied. It more closely reflects the impact of the applied nutrients. The former is easily calculated for any farm that keeps records of inputs and outputs. The latter requires a plot without nutrient input, so is only known when research plots have been implemented on the farm.

The PFP answers the question, "How productive is this cropping system in comparison to its nutrient input?" The AE answers a more direct question: "How much productivity improvement was gained by the use of this nutrient input?"

Recovery Efficiencies. Nutrient recovery efficiency also has at least 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

Table 9.2 Four selected definitions of nutrient use efficiency (NUE).

NUE Term	Calculation	Reported examples
PFP - Partial factor productivity of applied nutrient	Y/F	40 to 80 units of cereal grain per unit of N
AE - Agronomic efficiency of applied nutrient	$(Y-Y_0)/F$	10 to 30 units of cereal grain per unit of N
PNB - Partial nutrient balance (removal to use ratio)	U_H/F	0 to greater than 1.0 - depends on native soil fertility and fertility maintenance objectives <1 in nutrient deficient systems (fertility improvement) >1 in nutrient surplus systems (under-replacement) Slightly less than 1 to 1 (maintains soil fertility)
RE - Apparent crop recovery efficiency of applied nutrient	$(U-U_0)/F$	0.1 to 0.3 – proportion of P input recovered first year 0.5 to 0.9 – proportion of P input recovered by crops in long-term cropping systems 0.3 to 0.5 – N recovery in cereals – typical 0.5 to 0.8 – N recovery in cereals – best management

F – amount of fertilizer nutrient applied
Y – crop yield with applied nutrient
Y_0 – crop yield in control with no applied nutrient
U_H – nutrient content of harvested portion of crop
U – total nutrient uptake in aboveground crop biomass with fertilizer applied
U_0 – total nutrient uptake in aboveground crop biomass with no fertilizer applied

crop producers. It can be reported for any number of growing seasons.

The more complex form—preferred by scientists studying the crop—is termed recovery efficiency (RE), 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 AE, its measurement requires the implementation of research plots without nutrient input. The PNB answers the question, "How much nutrient is being taken out of the system in relation to how much is applied?" The RE, on the other hand, answers the question, "How much of the nutrient applied did the plant take up?"

Usually, AE and RE are calculated to describe short-term results: either for a single nutrient application or for the response during a single cropping season. When calculated over the long-term, however, results can differ substantially, particularly for P, as indicated in **Table 9.2**.

9.5 Steps to Developing a 4R Nutrient Stewardship Plan

The following provides a generalized set of steps to establish and implement a 4R Nutrient Stewardship plan that provides accountability for progress toward higher levels of sustainability. These steps are designed to be consistent with the principles of adaptive management as described in Chapter 7.

1. Set sustainability goals – for the whole farm or enterprise:

a) Consider stakeholders. This may include neighbors, customers, local public interest groups, farm or business associations, or other organizations active in voluntary promotion of sustainability improvement.

b) When farmland is leased, discussions should occur between the land owner and the farmer operator to determine who is responsible for implementing sustainability practices and monitoring their effectiveness.

c) Set economic, environmental and social goals for the enterprise, with performance indicators chosen with consideration of the concerns of the people listed above.

Choose an appropriate nutrient management strategy that will support the farm's sustainability goals. An example of a farm listing goals for environmental sustainability is provided in an article from Cornell University's Whole Farm Evaluation series (see #1 by Karl Czymmek).

2. Gather needed production information – for each field:

a) Crop to be grown.

b) Target yield and quality (e.g. protein, trace element content, color, or other characteristics influenced by nutrient management).

c) Soil characteristics including texture, organic matter, pH, levels of available nutrients.

d) Cropping history, and past nutrient management practices.

e) Expected number of days of suitable soil conditions for field operations (nutrient applications, tillage, planting, crop protection and harvest) based on soils and typical weather.

f) Water drainage, infiltration rates, susceptibility to leaching, proximity to surface water.

g) Location, dimensions and surface area (legal description, GPS coordinates, map).

h) Opportunity and potential for applying variable rates of nutrients at a sub-field scale.

i) Equipment available for applying nutrients.

j) Reliable recommendations and decision support tools for optimum combination of source, rate, time, and place for nutrient application, given the conditions above.

3. Formulate the Plan - for each field:

a) Decide nutrient requirements to reach target yield and quality.

b) Estimate the nutrient supplying capacity of the soil.

c) Consider the supply of all available nutrients and choose the most feasible nutrient source and the appropriate rate, time and place for application.

4. Implement the chosen practices, applying the right nutrient sources at the right rate, time and place to attain the maximum performance. This can be done by the farm manager or in combination with advisers, fertilizer retailers or custom applicators, buyers, and regulatory staff. Recording and tracking precisely what was done is an important part of the adaptive management cycle, and should also include tracking the condition of the crop.

Questions ?

4. The performance indicator most important to managing plant nutrients is
   a. partial factor productivity.
   b. nutrient use efficiency.
   c. agronomic efficiency.
   d. closely related to sustainability goals.

5. The process of developing and implementing a 4R Nutrient Stewardship plan for a farm
   a. is consistent with the principles of adaptive management.
   b increases the burden of government regulations.
   c. is independent of the farm business plan.
   d. allows stakeholder concerns to be dismissed

6. A 4R Nutrient Stewardship plan should contain information for each field on
   a. practices applied and performance in comparison to past years.
   b. sustainability goals and performance indicators.
   c. all possible performance indicators.
   d. alternative sources of nutrients.

5. Monitor the effectiveness of the practices employed. The final step in the cycle of adaptive management assesses performance through the chosen indicators to determine whether the practices selected achieved the intended results. This assessment then influences the next cycle of planning decisions (i.e. step 2). The impact of many practices cannot be easily measured within a single growing season and will need to be assessed over multiple years to document improvements.

Such monitoring can be as simple as determining crop yields and assessing whether or not this was close to targeted yields based on the plan. But often, depending on priority sustainability goals, the monitoring can also include an accounting-like exercise tracking nutrient use as follows:

a) in-season and at-harvest monitoring of crop nutrient concentrations;

b) determining residual nutrients in soil following harvest, and in some cases crop stalk nutrient concentrations (i.e. primarily N);

c) assessing whether the target yield was achieved, taking into consideration the yield potential based on weather experienced (e.g Was precipitation and irrigation adequate and timely? Were there adequate heat units for crop development? Were there other factors that interfered with normal plant development?);

d) calculation of nutrient balances and nutrient use efficiencies;

e) monitoring of water quantity and quality leaving the farm at drainage outlets;

f) measuring or assessing soil quality using appropriate indicators.

9.6 Example 4R Plan Worksheet

Attached below is an example is of a worksheet that could be used by a crop consultant or crop adviser to help a farmer develop a nutrient stewardship plan for a field.

1) Farm information

Enterprise name: (farm or business name)		
Contact information - farmer: (Name, address, phone, email)		
Contact information - adviser: (Name, address, phone, email of Certified Crop Adviser or consulting agronomist)		
Enterprise description: (Number of fields, crops grown, livestock or poultry, nutrient sources available)		
Sustainability Goals and indicators related to nutrients:		
	Goals	**Performance indicator(s)** related to nutrient management for each goal
Economic		
Environmental		
Social		

2) Field information *(for each field):*

Field or management zone name or number	
Legal location and GPS coordinaters	
Map and description	
Area (size)	
Previous crop	
Specific Crop(s) for this planning event	
Realistic Target Yield(s)	
Landscape topography and soil drainage characteristics	

Soil Characteristics		**Soil test levels**			
Organic matter		**N**		**Ca**	
Texture		**P**		**Mg**	
pH		**K**		**Zn**	
CEC		**S**		**Mn**	

Nutrient Applications Planned (recommended)				
Application	**RIGHT SOURCE (analysis)**	**RIGHT RATE**	**RIGHT TIME (date, crop growth stage)**	**RIGHT PLACE (depth, method)**
1				
2				
Nutrient Applied				
Application	**SOURCE**	**RATE**	**TIME**	**PLACE**
1				
2				

Nutrient Balance Summary						
Nutrient Balance Summary						
	N	**P_2O_5**	**K_2O**	**S**		
Applied						
Uptake						
Removal						

Performance Indicators *(may include soil fertility levels, nutrient use efficiencies, balances, crop yield, etc. consistent with sustainability goals. Chart over time to show trends):*

Indicator	**Past year**	**Past year**	**Past year**	**Current year**
Yield				
Net return				
Partial nutrient balance — N				
Partial nutrient balance — P				
Partial nutrient balance — K				

9.7 Comparing Regulatory and Voluntary Standards for Nutrient Management Plans

The proper role of regulation is debated in every country and society. Each culture and political system has a different view regarding the appropriate role of government in controlling the activities of individuals and groups. For environmental regulation, it is recognized that the collective quality of life is affected by numerous human activities that impact natural resources such as air, soil, and water. These impacts are sometimes mitigated by governmental control on the local, regional, or national basis. Some environmental impacts are best addressed at a local basis, while other environmental issues are global in scope and require multi-national agreements.

It is clear that when plant nutrients are not properly managed and inadvertently leave the field, they can contribute to adverse environmental impacts. But it is not always clear whether voluntary or mandatory responses best address these environmental issues. Some arguments for and against manditory and voluntary approaches are listed below.

Mandatory Standards:

a) Mandatory reporting results in standardized approaches that provide credible information to address stakeholder concerns and questions.

b) A standard set of requirements mandates a level of operational transparency that addresses specific environmental issues.

c) There is currently no standard approach for record keeping nor accountability for nutrient decisions-making it difficult to document progress towards environmental goals without uniform standards.

d) It is argued that mandatory regulations may ultimately lead farmers to greater efficiency, higher profits, and more social welfare over the long term. Opinions on this assertion differ.

e) In regions where a wide variety of commercial crops are grown, the ability of regulators to make mandatory rules to accommodate the specific needs of each crop would be severely challenged.

f) Mandatory approaches often lack the flexibility to adjust to new circumstances, environmental conditions, market changes and advancing technology. This can put a burden on farms that operate in a global business environment.

g) Strict regulations undermine innovation and reduce the incentive to go beyond the minimum requirements and record keeping.

h) Many regulations have "winners and losers", making rule-making a political issue rather than a science-based outcome.

i) It is difficult for regulators to monitor compliance with on-farm regulations, which can undermine confidence in the rules and make enforcement appear unpredictable.

Voluntary Standards:

a) Environmental standards are still developing and voluntary measures move farmers along in the proper direction as the science matures.

b) Voluntary approaches allow current industry information to be rapidly deployed in practice. Government regulators are often playing "catch up" to modify policy to reflect changing conditions.

c) Self-regulation provides more flexibility than tight regulation, allowing management practices to be selected that best meet local challenges. This avoids the difficulty in dealing with politically challenging situations that regulators must deal with each time a rule is changed.

d) If participants are involved in selecting the right management practices for a specific field, more appropriate outcomes are likely than a one-size-fits-all approach.

e) Self-regulation may result in a higher level of compliance. When individuals are involved in setting the rules, the more reasonable the rules are likely to appear to them.

f) Voluntary standards may allow everyone to achieve compliance as the group polices individual members to achieve common goals in the interest of the entire industry.

g) Voluntary approaches may not provide sufficient motivation for individual or group participation to achieve desired outcomes.

h) Complying with voluntary standards may involve unwanted disclosure of negative information and not be forthcoming.

i) Self-regulating initiatives are based on a sharing of information, which can pose a conflict of interest.

j) Self-regulating organizations may be reluctant to administer appropriate penalties to serious violators among their peer group.

k) When specific individual interests appear to deviate from overall societal goals, conflicts of interest make self monitoring and enforcement more difficult.

l) Many farmers operate in markets controlled by global conditions. When foreign markets are not constrained with regulations, self-regulation can be a competitive disadvantage (although this applies to mandatory regulation as well).

m) Voluntary approaches may not address some of the broader environmental and social impacts of specific management decisions.

n) Voluntary approaches may not provide sufficient verification of performance to meet the desires of all stakeholders.

9.8 Managing Environmental Impacts

A core goal of 4R Plant Nutrition is to manage and reduce nutrient losses that impact the environment. The future of the global human family depends on the manner in which we use fertilizer N and P and other available nutrient resources to produce an abundant, safe, and nutritious food supply… and the way in which we achieve greater protection and restoration of the quality of the air and water. The N and P cycles are intimately linked with the cycles of other essential nutrients, which sustain all life on Earth. Our present nutrient management actions, based on the 4Rs, will dictate current and future economic, societal, and environmental outcomes. Each fertilizer consumer should make management choices while asking: will my management decisions and actions result in a profitable outcome, a better environment, and a net social benefit?

These questions are difficult to answer, mainly because environmental impacts are difficult to measure at the farm level. For example, it is not realistic to expect every farm producer to measure their emissions of nitrous oxide to the atmosphere, or their losses of P to drainage water. Both these examples involve sporadic losses during very specific soil and weather conditions. In addition, no single practice can be employed across all farming conditions to mitigate these losses—there is no "one-size-fits-all" solution. Science has identified conditions under which specific combinations of fertilizer source, rate, time, and place will achieve lower losses without limiting productivity. These conditions are described in indexes, protocols and other instruments, related to the information contained in nutrient management plans, and described in several of the case studies that accompany this chapter.

The following two sections will focus more specifically on the two nutrients most often associated with environmental impacts, N and P.

9.8.1 Managing Environmental Impacts of N

Implementation of 4R Nutrient Stewardship in a comprehensive site-specific manner can improve recovery of N by plants from the soil. Such improvements in plant N recovery minimize the potential for losses which decrease profitability and which increase risks of damage to the environment. Increased recovery of applied N reduces losses of N that could harm water and air quality. It also reduces the potential transfer of N to pristine non-agricultural areas where it could harm natural biodiversity.

Many paths by which N is lost

Unfortunately, crop recovery of applied N during the growing season for most cereal crops is often far from complete. It can range from 30 to 70% or even more widely. The remaining portion of the applied N may be:

a) stored on soil exchange sites as ammonium;

b) stored in soil organic matter;

c) lost via leaching below the active root zone to risk contamination of groundwater;

d) lost to surface waters via runoff, leaching and/or drainage discharge;

e) lost to the atmosphere as volatilized ammonia, or;

f) lost to the atmosphere as either nitrous oxide (N_2O, a potent greenhouse gas that contributes to global warming and climate change) or as the benign N_2 gas, from which all fertilizer N originates.

Certain soils are prone to larger N losses via some of the principal N loss pathways mentioned above. For example, deep sandy soils may be prone to higher losses of N in the form of nitrate; finer-textured silt loam to clayey soils in low lying areas of the landscape may be subject to higher losses via denitrification and emission to the atmosphere as N_2O and/or N_2.

Managing N loss requires knowledge

Use of the appropriate N source, use of urease and/or nitrification inhibitors, synchronizing N applications to better coincide with crop N uptake patterns and uptake rates, and applying N in the right place using appropriate placement methods requires greater knowledge of:

1) fertilizer N sources;
2) soil characteristics and properties;
3) weather conditions (moisture, temperature);
4) cropping system nutrient demands and balances;
5) the complexity of the N cycle, and;
6) water management and irrigation efficiency.

For example, volatile losses of N as ammonia can be large when urea or urea-containing fertilizer N sources are surface applied and sufficient rainfall or irrigation does not occur within about 48 hours of application. This may also occur when ammonium sulfate is surface-applied to calcareous soils.

For many farmers and growers who spend the majority of their time making purchasing and marketing decisions, the disciplinary skills of a professional agricultural consultant, (e.g. a Certified Crop Adviser) or an experienced extension agent may be essential. These professionals can help farmers and growers plan and implement N management practices that are agronomically sound, resulting in economic, environmental, and societal benefits.

Many paths to improve N use efficiency

Paths to improvements in crop recovery and soil retention of applied N include:

a) improved crop genetics;
b) newer fertilizer technologies;
c) better timing and split application;
d) advances in fertilizer application technologies;
e) greater access to and implementation of GPS and GIS tools;
f) adoption of conservation practices that enhance water use efficiency.

Adaptive management, as described in Chapter 7, can help farmers make choices from among the paths listed above.

9.8.2 Managing Environmental Impacts of P

Phosphorus needs to be periodically added to most soils to maintain an adequate nutrient supply to support crop growth and replace the nutrients removed during harvest. While P is an essential nutrient for plants and animals, elevated concentrations in fresh water rivers and lakes can overstimulate biological productivity. Excessive plant growth in water bodies from nutrient enrichment is called eutrophication. Eutrophication is most often caused by human activities, but it is also a naturally occurring process, especially in lakes. Some government agencies consider eutrophication as the primary cause of surface water degradation.

The total amount of P lost from an agricultural field may be quite small, but even a small enrichment of soluble P in streams, rivers and lakes can accelerate unwanted eutrophication (e.g. in some lakes algal blooms may result at concentrations as low as 0.02 mg P/L). Eutrophication may lead to serious economic, health, and aesthetic impacts.

Paths of P loss start on the surface

Soil P is found in organic matter and also in association with many inorganic components in soil—including surface retention on clays, and oxide minerals, and also precipitated with cations such as Al, Fe, or Ca. Phosphate is not very mobile in most soils and is primarily attached to solid particles rather than dissolved in water. Therefore P loss is most commonly associated with surface soil erosion that carries particulates from the field. **(Figure 9.1)**.

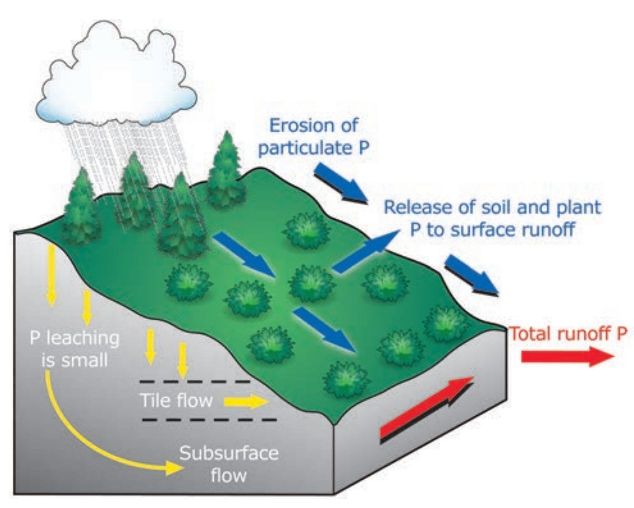

Figure 9.1 The primary path of P loss is surface runoff, but in some soils leaching can carry P to tile drains. **Adapted from:** Sharpley et al. (2003)

When applied manure or P fertilizer is left on the soil surface or incorporated only shallowly into the surface layer, the uppermost soil becomes enriched with P—and the zone most susceptible to loss with flowing water. In these areas, P loss occurs mainly in surface runoff. This can happen during rainfall, snowmelt, or during irrigation. Leaching can also transport P through soil to drainage ditches and subsurface tile lines which discharge into surface water. Such movement through soil can occur with combinations of low soil P-fixing capacities, elevated soil test P levels, and preferential flow through soil macropores. Such preferential flow often originates from the soil surface. Thus, most forms of P loss can be managed and minimized by subsurface band placement of applied nutrients. Water management can also be a component in minimizing P loss.

Manage P rates to control accumulation in soil

There are several potential sources of P that can enrich surface water. When farmers are using commercial fertilizer as their primary P source, there is generally less over application of P occurring since adding fertilizer beyond an economically

Questions ?

7. An advantage of voluntary compared to mandatory standards is that they
   a. allow solutions that are more sensitive to site-specific constraints.
   b. limit decision-making flexibility to respond to changing conditions.
   c. undermine innovation.
   d. administer appropriate penalties to serious violators.

8. The two nutrients most critical to the future of the global human family are
   a. N and P.
   b. cobalt (Co) and selenium (Se).
   c. cellulose and lignin.
   d. cadmium (Cd) and fluoride (F).

9. The above-ground crop recovery (uptake) of applied N by most cereal crops during their growing season is usually:
   a. above 70 to 90%.
   b. less than 30%.
   c. 50 to 60%.
   d. 30 to 70%.

sensible concentration represents a waste of money. Monitoring with periodic soil testing is needed to keep the P concentrations from exceeding the range required for crop production. Long-term application of P fertilizer at rates that greatly exceed crop removal can increase soil P concentrations to undesired levels.

The intensive production of animals can lead to a surplus of manure and nutrients within a localized region. Repeated manure application to farmland frequently results in P accumulation in excess of crop removal and ultimately raises the risk of nutrient loss in water running off of fields. Annual application rates may exceed several times crop removal in some areas. Improved methods of regional manure distribution may be needed to move the surplus nutrients to areas where there is an agronomic need. Continued application of nutrients in excess of crop demand can lead to an unwanted accumulation and a potential environmental concern. The principle of balancing nutrient inputs and outputs is important for all types of forms.

Manage both P and water to minimize loss

Adoption of two on-farm practices will help protect fresh water from eutrophication:

a) Phosphorus in soils should be managed to balance inputs of manure and fertilizer with harvested crops. This can be done by accounting for the nutrients added to each field and the nutrients removed during harvest or in the grazing animals. Periodic soil testing will provide feedback on whether soil P concentrations are increasing or decreasing over time. Adjustments to nutrient application rates can be made based on long-term trends.

b) Most P loss occurs when sediment is leaving the surface of the field in runoff water. Conservation practices that minimize erosion and reduce runoff will also reduce P loss. Some on-farm conservation practices that could be considered for reducing P loss include:

Reduced tillage	Irrigation practices
Wetlands	Riparian zone management
Cover crops	Stream management
Ditch management	Strip cropping
Erosion control	Irrigation tailwater recovery
Grass waterways	Nutrient placement
Spreader calibration	Nutrient application timing

Risk indexes help minimize P loss

Nonpoint source pollution from runoff may be hard to identify and difficult to regulate. Most of the P lost in surface runoff usually comes from a fairly small area in the field. Special attention should be paid to these high-risk zones. Appropriate soil conservation practices should be implemented in these areas to halt particulate transport to surface water.

Various approaches have been used to identify individual fields with a high risk for P loss. Techniques for making these estimates range from simple P-loss assessments to sophisticated computer models. All of these estimates must be calibrated for local soil, weather, and cropping conditions. In general, these approaches look at the contribution of P source and the potential for P transport to water. These factors are listed in **Table 9.3**.

Table 9.3 Factors controlling loss of P from cropland.

Phosphorus Source Factors
Soil P concentration
Fertilizer P application rate, timing, and placement
Manure application rate, timing, and placement
Manure P concentration
Manure physical properties
P source solubility
Phosphorus Transport Factors
Surface water runoff potential
Soil erosion potential
Subsurface drainage
Field-edge vegetative buffers
Proximity and connectivity to water
Soil texture and drainage class

Soil tests guide P management for both economic and environmental objectives

Soil testing has been very useful for predicting the need for P application and its likelihood of producing an economic crop response. These objectives differ from those of predicting the risk of loss to drainage water, but the same form of P—soluble phosphate—required by cultivated crops also supports eutrophication and nourishes algal blooms. The major difference is that runoff P is influenced by a much shallower depth of soil than the topsoil that contributes the bulk of nutrition for plants. This difference matters little in soils where inversion tillage (moldboard plowing) is used, but in conservation tillage systems (such as no-till or systems that leave most of the crop residue on the surface) the vertical mixing of the soil is diminished.

New soil tests under development can improve prediction of both crop response and risk of potential P loss. An examples of such tests is the P/Al ratio of the Mehlich 3 test, used as an estimate of soil P saturation. These new soil tests need to account for factors such as when to sample the soil, the depth of soil sampling, appropriate soil handling methods, and laboratory extraction techniques.

Practical measures can be immediately implemented to reduce the risk of P loss and eutrophication. Soil testing to minimize excessive P accumulation can easily be initiated. Fertilizer and manure applications need to be scheduled for times of the year when the risk for loss is minimized. Decisions on the placement of manure and P fertilizer need to consider how to minimize

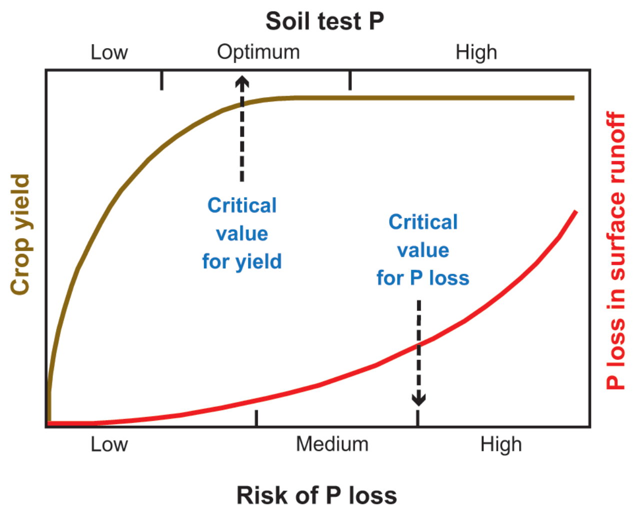

Figure 9.2 As soil test P increases, so does crop yield and the risk of P loss. **Source:** Sharpley et al. (2003)

runoff losses. Field conservation practices to reduce soil erosion should be an important part of all farming operations, regardless of field size, nutrient status, or management capacity.

9.9 Stewardship Synergism

The process relating source, rate, time and place of nutrient applications to sustainability outcomes can be daunting. Sustainability impacts are highly complex, site-specific and varying over time. They involve uncertainty and require further research in support of continuous science-based improvement. Nevertheless, practical common-sense thinking—guided by an appropriately global framework—can change practices and improve outcomes within both short-term and long-term timeframes.

In the short term, it encourages practical ground-level action toward synergistic solutions. For example, once a grower understands that band placement of a starter fertilizer can both boost crop yield and reduce P runoff, the practice change may be put in place almost immediately.

In the long term, it guides scientific research and extension efforts towards the practices most efficacious in addressing priority sustainability issues. Often these are issues that are difficult to solve on-farm, for example, the improvement of N use efficiency of cereal crops.

Guiding practices towards plant nutrition for optimum productivity can help to resolve many of the current issues associated with plant nutrient use.

REFERENCES

Sharpley, A.N. et al. 2003. Agricultural Phosphorus and Eutrophication. 2nd Ed. [On-line].

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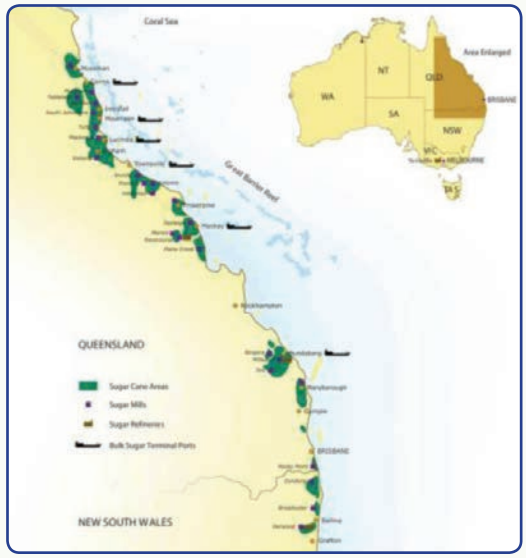
Case Study 9.1-1 Nutrient management plans for sugarcane in Australia's wet tropics. The Australian sugar industry produces around 5 million (M) t of raw sugar from 35 M t of cane and 4,000 farms. Sugarcane is grown in high-rainfall and irrigated districts along coastal plains and rivers on Australia's north-eastern coast from Queensland to New South Wales (see map). Cane growing and sugar production underpins the economy of many coastal communities and is second only to the tourism industry in its regional economic impact.



Government and Industry Partner to Develop the "Six Easy Steps" Program for protecting the Great Barrier Reef

The northern cane regions are in the wet tropics with 2,000 to 4,000 mm annual rainfall and are adjacent to sections of the Great Barrier Reef World Heritage Area.

The Great Barrier Reef is a unique and treasured ecosystem. The Great Barrier Reef is already under stress from fishing, urban growth in its catchments, sewage and mining, as well as climate change impacts such as ocean acidification and warming. Corals and other reef organisms that make up the Great Barrier Reef are affected by water quality variables such as temperature, some pesticides, salinity, nutrients and suspended sediments.

Sugarcane production in Australia is a highly specialized industry that has responded to changing economic and social issues with new and improved agronomic techniques. All cane is mechanically planted and harvested; most is grown under a green trash blanket in lieu of burning the trash before harvest. Minimum tillage is widely practiced and many growers have adopted site specific nutrient management within their fields. Farmers are also developing riparian zones within their farms as nutrient and sediment traps.

Targets have been set to protect the water quality of the reef area by reducing inputs of nutrients and pesticides from nearby sugarcane production areas. Any person who grows sugarcane commercially on more than 70 ha in the wet tropics catchment is required to prepare an Environmental Risk Management Plan (ERMP), whose requirements include:

- Identification of any hazards on the farm that may cause the release of contaminants into water entering the reef.
- Measurable targets and performance indicators for improving the quality of water being discharged from the farm.
- Include a management plan that provides for the management of nutrients applied to the soil, agricultural chemicals, and sediment loss from the farm.
- Application of no more than the optimum amount of fertilizer N and P to the soil, based on soil properties, other sources (e.g. mill byproducts) and sugar cane yield potential.
- Records of soil test results and the application of fertilizers. In some regions, soil tests must be taken before any nutrients are applied to the crop. Soil testing must include a measure of mineralizable N and plant-available P.
- Variances from these recommendations may be done only with the consent of an accredited adviser.

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The ERMP for each farm is then assessed by the Queensland Department of Environment and Resource Management (DERM). Once assessed and agreed to, the plan will have an accreditation term of one to five years. Plans would include maps of the farm, nutrient management plans and Integrated pest and weed management plans.
These plans are registered and audited by DERM, so that a nutrient management plan – usually formed around the *SIX EASY STEPS* approach of BSES Limited (a sugarcane producer organization) becomes a legal statement of the way a cane grower will use fertilizers on their farms.

The *SIX EASY STEPS* program is an integrated nutrient management tool that enables adoption of nutrient best management practices for cane growers, and these tools can be used to develop nutrient management plans required in the ERMP. The six steps are:

- Knowing and understanding your soils
- Understanding and managing nutrient processes and losses
- Regular soil testing
- Adopting soil-specific nutrient management guidelines
- Checking on the adequacy of nutrient inputs (e.g., using leaf analyses)
- Keeping good records to modify nutrient inputs when and where necessary

The program is delivered through a short course developed with growers. The objective is to provide a guide to implementing balanced nutrition on-farm, optimizing productivity and profitability, without causing adverse off-farm effects.

For more information:
The *SIX EASY STEPS* approach. [On-line].
ReefWise Farming. Qld. Government, Australia. [On-line].

Submitted by R. Norton, IPNI, Australia, December 2011.

CS

Case Study 9.1-2 How 4R Nutrient Stewardship reduces greenhouse gas emissions. A 4R Nutrient Stewardship plan forms the basis of the Nitrous Oxide Emission Reduction Protocol (NERP) for farm-level carbon credits in a quantifiable, credible and verifiable way in Alberta, Canada. This protocol was developed by ClimateCHECK and by the Canadian Fertilizer Institute, and was officially approved by Alberta Environment (Government of Alberta) in October 2010.

During NERP's development, one of the first issues raised was the potential trade-off between nitrous oxide (N_2O) emission reductions and crop yield loss. However, the two pronged approach for the quantification of N_2O emissions tries to account for that. The "Tier 2" approach accepted by the Intergovernmental Panel on Climate Change for Canada's greenhouse gas inventory assigns a region-specific emission factor as a function of N rate applied. This emission factor varies across Canada from about 0.2% to 1.7% of applied N emitted as N_2O.

To account for the other three R's of right source, right time and right place a reduction modifier, derived from expert judgement, is applied to each performance level. Three beneficial management practice (BMP) performance levels ranging from Basic to Intermediate and Advanced allow the adoption of varying levels of BMPs and intensity of monitoring data with increasing degree of landscape-directed management. The higher the performance level, the more potential exists for reduced emissions as reflected by the smaller reduction modifier. Examples of BMPs for the prairie soils of Western Canada specified for the Basic performance level include the use of ammonium-based formulation, spring or split fertilizer application and banding. The Intermediate level also requires ammonium-based formulations but must also use slow/controlled release fertilizers or inhibitors. Under the Advanced category the rate of N application is based on quantified field information derived from grid sampling, satellite images or digitized soil maps.

By applying the principles of 4R Nutrient Stewardship, the NERP seeks to:

- "Optimize the crop response per unit of added nitrogen" and,
- "Minimize the opportunity for nitrate-N to accumulate or persist in the soil where it is potentially denitrified, and/or emitted directly or indirectly as N_2O or lost to the system through leaching".

The protocol specifies a role for accredited professional advisors (APAs) in assisting farmers to set up and implement their 4R plans, and in calculating the associated carbon credits. Professional Agrologists (PAgs) and/or Certified Crop Advisers (CCAs) can qualify as APAs by completing specialized training in 4R Nutrient Stewardship and NERP requirements, and by passing an accreditation exam. Only APAs are authorized to sign the plan. Additional requirements may also apply, varying with local laws and regulations.

The quantification approach of the NERP is based on the methods used in Canada's National Greenhouse Gas Inventory Report, which is prepared to meet Canada's reporting requirements under the United Nations Framework Convention on Climate Change. The NERP has been developed according to the ISO 14064-2 standard, which meets the requirements of the Alberta Offsets System, and is compatible with the stated intentions of Canada's Offsets System, of the Climate Action Reserve, and of other voluntary greenhouse gas programs in North America. The Alberta NERP is the first of its kind in the world. NERP is being evaluated for possible implementation in the United States by The Fertilizer Institute.

The NERP was developed through a process of comprehensive and transparent consultation with science experts for approval under the Alberta Offset System. These science experts represent the major agricultural universities in Canada, Agriculture and Agri-Food Canada, the International Plant Nutrition Institute, provincial soils specialists, and industry stakeholders. International experts were also included.

At the initial Consultation Workshop for the NERP held in Calgary in 2008, participating experts approved the general design of the NERP according to the 4Rs. Although consensus was achieved on the main elements of the NERP, the participating experts identified some gaps requiring further development. These gaps were subsequently addressed in a Decision Paper, which was submitted to the science experts in an on-line webinar format to further the consensus-building process. The webinar participants resolved the development of the NERP to allow standardization and submission to the formal review and approval process of the Alberta Offset System. This process is a prime example of how the 4R principles and stakeholder involvement may be applied to address specific societal concerns and nutrient management challenges.

Reference

Alberta Environment. 2010. Quantification Protocol for Agricultural Nitrous Oxide Emissions. [On-line].

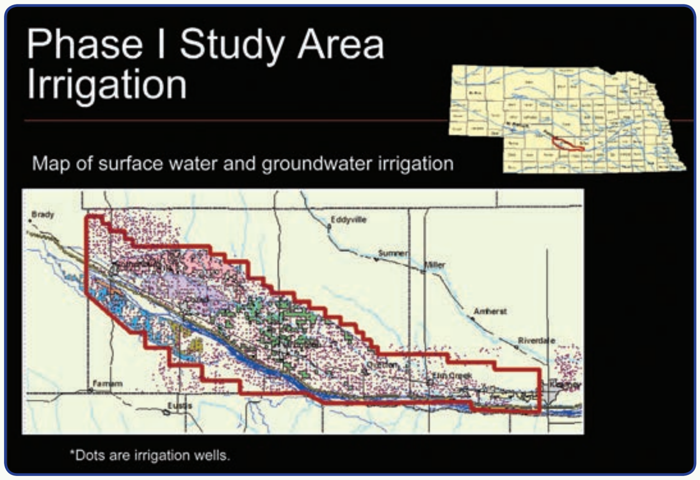
Submitted by C.S. Snyder, IPNI, USA, January 2012.

CS

Case Study 9.1-3 Water and nutrient management practices improve groundwater quality in Nebraska, USA.

Since 1985, across the Lower Platte Natural Resource District (NRD), Nebraska, USA nitrate concentrations in ground- and surface water across the district have been monitored.

The terrace area in the north of the district has silt loam and medium to fine sandy soils with a water table 1.5 to 7.5 m below the surface, and is intensively cropped to irrigated corn. In this terrace area, groundwater nitrate levels have consistently exceeded the drinking water standard of 10 mg nitrate-N/L.



Three tiers (phases) of N management have been implemented, depending on groundwater nitrate-N levels. Areas with irrigation well nitrate concentrations averaging ≤7.5, 7.6 to 15, and ≥15.1 mg/L are designated Phase I, II, and III, respectively. Since 1987, most farmers have been required to meet the Phase I requirements, with fewer required to meet Phases II, III, and IV. All operators using fertilizer must be certified every 4 years, and are encouraged to use practices from the higher phases even where not required. Recommendations for N rate are based on yield goals (set at 105% of past 5 years) with credits for preceding crops, N in irrigation water, and soil nitrate to 90 cm depth. Some of the requirements related to nutrient management are listed below.

Phase I

- Fall application of N fertilizer is prohibited on non-sandy soils before November 1.
- Application of N fertilizer is prohibited on sandy soils until after March 1.

Phase II

- Annual soil and irrigation water tests for nitrate-N.
- Annual fertilizer application reports.
- Nitrogen fertilizer only permitted on non-sandy soils from November 1 to March 1 if approved nitrification inhibitor is used, with records from fertilizer dealer.

Phase III

- Application of N fertilizer prohibited in fall and winter on all soils until after March 1.
- Spring applications of N fertilizer require split application (pre-plant and sidedress) or the use of an approved nitrification inhibitor, with records from fertilizer dealer required if 50% or more of N fertilizer is applied pre-plant.

Phase IV (for areas where groundwater nitrate is not declining at an acceptable rate)

- Crop yield goal set by NRD.
- Fertilizer N rates not to exceed NRD recommendation.
- NRD staff work directly with operators on best management practices.

Results: Groundwater nitrate in the terrace (north) area declined from 1987 to the end of the study in 2005 (see Figure). About 20% of the decline is attributed to increasing N removal with crop harvests, and 50% is attributed to shifts from furrow irrigation to sprinkler irrigation. Perhaps, by difference, one can conclude that the remaining 30% of the decline arose from changes to time of application and source (increased use of nitrification inhibitors). Further reductions in groundwater nitrate may require increased adoption of current BMPs, or adoption of additional technologies such as controlled-release N fertilizers and the use of crop canopy N sensors.

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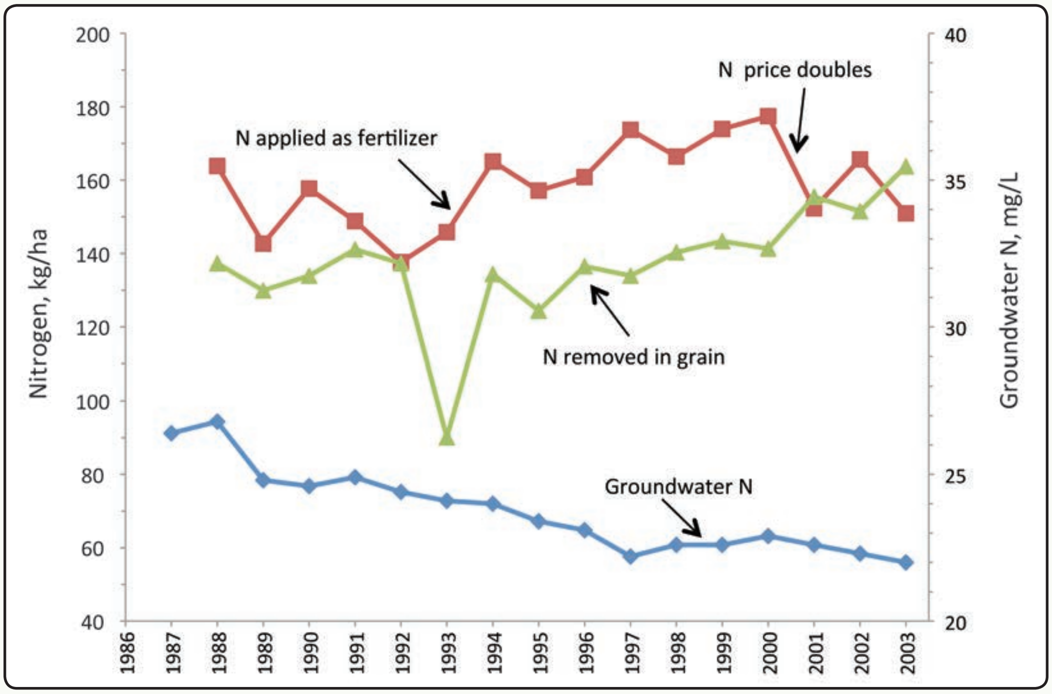

As crop yields and N removal increased over time, groundwater nitrate levels declined.

Note: These data are for commercial N fertilizer applied and N removed in the grain for irrigated corn land on the terrace of the NE CEAP study area in the Central Platte Natural Resources District and the nitrate concentration in the primary aquifer beneath the terrace. **Adapted from** Exner, M.E., H. Perea-Estrada, and R.F. Spalding. 2010. The Scientific World Journal 10: 286-297. Data for Figure provided by Dr. R. Ferguson and Dr. M. Exner, U. of Nebraska.

About half the decline in groundwater nitrate was attributed to shifts from furrow to sprinkler irrigation.

Submitted by C.S. Snyder, IPNI, USA, January 2012.

CS

Case Study 9.1-4 Managing fertilizer phosphorus by soil test level improves food production and environmental performance in China.

China is a country with a large population and a limited land resource. To ensure food security and sustained increase in crop production, China has paid strong attention over the past 60 years to building up soil fertility.

With a history of several thousand years of reliance on soil organic matter and recycling of crop residues as nutrient sources for maintaining soil fertility, by the early 1950s most arable land in China was low in fertility and had low crop productivity. Since then, use of N fertilizer became a common practice and crop yield increased, removing more P and other nutrients from the soil. Since a large portion of crop-absorbed P is in the harvested part (about 80% for grain crops), soil P was quickly de-pleted, and low soil P became a severe yield-limiting factor for crop production. By the 1980s, based on the results of the second national soil fertility survey, about 48% of the arable land was very low in Olsen P (below 5 mg/kg), and another 30% was considered low (below 10 mg/kg).

Given that soil P condition, and with the national objective to ensure food security and to build up soil fertility, P fertilizers became an important part of the fertilization program throughout China, starting from the south and gradually spreading to the north. It has been estimated that from 1981 to 2000, a total of about 133 million metric t of P_2O_5 has been applied to arable lands in China as chemical fertilizers. Assuming the accumulated utilization rate (recovery efficiency) of that applied P was 50%, about 480 kg/ha P_2O_5 accumulated in the soil, on average. If organic P sources were taken into consideration, the P accumulation in the soil would be even greater (Li, 2003).

The overall soil P balance (i.e. P input – P output) changed quickly after the extended period of large negative balances that continued from the 1950s into the 1960s and 1970s. By the 1980s, the P balance in arable lands became positive and P began to accumulate in soils. It has been estimated that soils in China received a P surplus of about 79 kg P_2O_5/ha in 2005. With this high P balance in soil-crop systems, it was expected that available soil P would build up gradually and that soil P fertility would be improved. Although there is no direct national survey data to verify this, it is now generally believed that the percentage of total arable land with P deficiency (i.e. Olsen P level below 10 mg/kg) has declined to less than 50%. The results of P analyses performed by the CAAS-IPNI Soil and Plant Analysis Laboratory on 43,156 soil samples collected from 1991 to 2007 also showed that 48% of soils tested were deficient in P.

In recent history, the high rate of P fertilization helped China to increase crop production and to build up soil P fertility. However, at the same time, with the increased accumulation of P in the soil, the risk of P losses from crop land and its effect on the environment cannot be ignored. Although there is only limited information available about the contribution of P losses from crop land to surface water pollution, it has been reported that 14% to 68% of the total P in selected lakes came from agricultural lands (Li, 2003).

With these changes in soil P fertility levels in China, for both economic and environment benefits, the following points may be considered when strategy for P fertilization is developed:

1. Application strategy for P should be according to soil test. Apply enough to build soil P levels when the Olsen soil test is below 20 mg/kg for most crops. Replenish crop removal on soils above this level, and apply no P on soils with very high levels of soil test P.
2. For all conditions, attention is needed to control soil P losses through soil erosion.
3. A P fertilizer program should be developed for the entire crop rotation with attention to increasing overall P fertilizer use efficiency. Pay attention to long-term accumulated P recovery efficiency for different cropping systems.
4. Realize that different crops (i.e. vegetables vs. grain crops) have different requirement for soil P levels. Different critical levels of soil test P for different yield levels may also need to be identified.

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Soybean response (right) to P due to an "optimum" (OPT) fertilization treatment applied in Heilongjiang Province, Northeast China.

The change of fertilizer efficiency in China followed the Law of Minimum and other related principles in plant nutrition. Before the 1950s, Chinese farmers mainly used organic manures to maintain the nutrient balance in soil/crop systems with relatively low production capacity. After the 1950s, with increase of crop yield and increased use of N and P, higher crop removal of K resulted in depletion of available K in the soil and negative balances for K in soil/crop systems. Based on the study and nutrient balance estimated by Li Jiakang in 2003, the input-output balance of N and P in the soil/crop system turned from negative to positive in the mid 1980s, but the balance for K was still negative in 2000 (**Table 1**).

Table 1. Nutrient input-output balance in agricultural land in China (in 1,000 tonnes).

		Year	1965	1975	1985	1995	2000
	Organic Manure	**N**	2,930	4,100	5,030	6,110	6,520
		P_2O_5	1,380	1,940	2,560	3,300	3,440
		K_2O	3,060	4,620	6,210	7,600	8,320
	Inorganic Fertilizer	**N**	1,210	3,640	12,590	22,240	25,140
		P_2O_5	550	1,610	4,190	10,350	9,730
		K_2O	3	130	980	3,360	6,590
Output		**N**	5,220	7,490	11,140	13,730	16,620
		P_2O_5	2,370	3,340	4,790	5,770	6,640
		K_2O	5,600	8,130	12,080	14,550	17,390
Balance		**N**	-1,690	-1,570	190	3,500	2,470
		P_2O_5	-600	-280	710	4,890	3,610
		K_2O	-2,540	-3,380	-4,890	-3,550	-2,480

Source: Li Jiakang et al. 2003.

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NOTES

Glossary

Absorption — The process by which a substance is taken into and included within another substance, i.e., intake of gases, water, nutrients, or other substances by plants.

Acid — A substance that releases H^+; a condition in which the activity of H^+ exceeds that of OH^-.

Acid Soil — Soil containing a prevalence of H^+ in the soil solution (active acidity) and on the surface of soil colloids (reserve or potential acidity). Specifically, a soil with a pH value of less than 7.

Acidity, Active — The activity of H^+ in the aqueous phase of a soil. This is measured and expressed as a pH value.

Acidity, Potential or Reserve — The amount of exchangeable H^+ in a soil that can be released into the soil solution by cation exchange, or generated by the hydrolysis of Al^{3+}.

Adhesion — The molecular attraction between surfaces that holds substances together. Water adheres to soil particles.

Adsorption — Adhesion in an extremely thin layer of molecules to the surfaces of solids or liquids with which they are in contact.

Adsorption, Electrostatic — Adsorption caused by the electrical attraction of ions to a charged surface.

Aeration — The process by which air in the soil is replaced by air from the atmosphere. The rate of aeration depends largely on the volume and continuity of pores within the soil.

Aggregate — Individual sand, silt, and clay particles bound together into a larger particle. Aggregates may be spheres, blocks, plates, prisms or columns.

Alkali Soil — A soil with a high degree of alkalinity (pH of 8.5 or greater) or with a high exchangeable Na^+ content (15% or more of the exchange capacity), or both.

Alkaline — Containing or releasing an excess of OH^- over H^+.

Alkaline Soil — Any soil with a pH greater than 7.0.

Amendment, Soil — Substance added to soil to improve its pH or physical properties, for example, aglime, gypsum, peat, compost, etc.

Ammonification — The biochemical process whereby ammoniacal N is released from N containing organic compounds.

Anion Exchange Capacity (AEC) — The sum total of exchangeable anions that a soil can adsorb.

Availability (of nutrients) — A general term, frequently used in describing supply or adequacy of nutrients taken up by plants.

Available Water — The portion of water in a soil that can be readily absorbed by plant roots. Considered by some to be that water held in the soil against a pressure of up to approximately 1.5 M Pa.

Base — Substance that reacts with H^+ ions or releases OH^- ions; a substance that neutralizes acid and raises pH.

Banded Fertilizer — Placement of fertilizer in a concentrated zone either on or below the soil surface.

Banding — A method of fertilizer application. Banding is a general term that implies applications which concentrate fertilizer into narrow zones that are kept intact to provide a concentrated source of nutrients. Applications may be made prior to, during, or after planting.

Base Saturation Percentage — The percentage of total CEC occupied by basic cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+).

Bedrock — The solid rock underlying soils and weathered rock in depths ranging from zero (where exposed by erosion) to several hundred feet.

Biological Nitrogen Fixation — Reduction and assimilation of atmospheric N (N_2), a capability of certain free-living and symbiotic bacteria.

Boron (B) — An essential element which may be involved in carbohydrate transport. Essential for growth of pollen tubes, germination of pollen grains. Probably the most common micronutrient deficient in crop growth.

Broadcast Application — Application of either solid or fluid fertilizer, or other materials, on the soil surface with or without subsequent incorporation by tillage. No specific location
relative to the plant is implied. Nutrients may be applied prior to or after the crop is planted.

Buffering — Processes that constrain or reduce the shift in pH when acids or bases are added. More generally, processes that constrain shifts in the dissolved concentration of any ion when it is added to or removed from the system.

Buffer pH — A measure related to the amount of lime required to neutralize the acidity in a particular soil.

Bulk Density — In soils, the dry mass (weight) of soil per unit of bulk volume.

Bulk Volume — The volume, including the solids and the pores, of an arbitrary soil mass.

Calcareous Soil — Soil containing free lime (carbonates) that effervesces visibly when treated with diluted (1:10) hydrochloric acid.

Calcium (Ca) — An essential nutrient, a constituent of the plant cell wall; required by some enzymes. Calcium acts in metabolic regulation.

Capillary Forces — Forces between water and soil surfaces in the small (capillary) pores.

Carbohydrate — Organic substance with the general formula $(CH_2O)_n$, for example sugars and polysaccharides.

Carbon Cycle — The sequence of transformations whereby carbon dioxide (CO_2) is fixed in living organisms by photosynthesis or by chemosynthesis, liberated by respiration and by the death and decomposition of the fixing organism, used by heterotrophic species, and ultimately returned to its original state.

Carbon: Nitrogen Ratio — The ratio of the weight of organic C to the weight of total N in a soil or in organic material. It is obtained by dividing the percentage of organic C by the percentage of total N.

Carbonate — A sediment formed by the organic or inorganic precipitation from an aqueous solution of carbonates of calcium, magnesium or iron, such as limestone or dolomite.

Cation — An atom, a group of atoms, or compounds that are positively charged electrically as the result of the loss of electrons.

Cation Exchange Capacity (CEC) — The sum total of exchangeable cations that a soil can adsorb.

Cation Exchange — The interchange between a cation in solution and another cation on the surface of a material such as clay colloid or organic colloid.

Cellulose — The carbohydrate most abundant in plants.

Chemigation — Applying fertilizers and/or pesticides in irrigation water to fertilize crops and control pests.

Chloride (Cl)$^-$ — An essential nutrient, required by plants for photosynthetic reactions involved in oxygen evolution. It may act in osmotic regulation.

Chlorophyll — Green pigment; traps light for photosynthesis in plants, algae and some bacteria.

Chlorosis — An abnormal condition of plants in which the green parts lose their color or turn yellow.

Clay — Naturally occurring inorganic crystalline particles in soils and other parts of the Earth's crust. Clay particles are less than 0.002 millimeters (mm) in diameter.

Cobalt (Co) — Cobalt is essential for animals and for N fixation. It may act in enzyme activation for other plants.

Colloid — Organic or inorganic particles less than 0.001 mm in diameter. Colloids have a large surface area, often very reactive.

Conservation Tillage — Any tillage system that maintains a minimum of about 30% crop residue cover after planting compared to clean tillage where all crop residues are incorporated into the soil.

Consumptive Use — The water used by plants in transpiration and growth, plus water vapor loss from adjacent soil or snow or from intercepted precipitation.

Conventional Tillage — Conventional tillage systems vary widely from region to region and crop to crop. The term conventional tillage originally implied use of the moldboard plow, disking, and harrowing to level the soil surface prior to seeding. In actuality, however, conventional tillage systems have now evolved to the use of other tillage implements, including wide-spread use of the chisel plow as a primary tillage implement.

Copper (Cu) — An essential nutrient, a component of several enzymes in plants. Necessary for chlorophyll formation in plants.

Coulter Injection — Use of a narrow disk coulter to place a fluid, dry, or granular fertilizer in a vertical band below the soil surface to the depth of coulter penetration. A variation of banded fertilizer application.

Cultivation — A tillage operation used in preparing land for seeding or transplanting or later for weed control and for loosening the soil.

Deep Banding Fertilization — Deep banding refers to preplant application in a concentrated band of nutrients placed 10 to 20 cm below the soil surface. Some applications are deeper, as much as 40 cm. The applied nutrients may be in solid, fluid or gaseous forms.

Denitrification — The biochemical reduction of nitrate (NO_3^-) or nitrite (NO_2) to gaseous N_2, NO, or N_2O. Occurs under O_2-deficient conditions.

Depletion Zone — Narrow zone next to root where immobile nutrient concentrations in soil become markedly lowered.

Desorption — Release of an ion or molecule from a surface. The opposite of adsorption.

Diffusion — Molecular movement along a gradient. Water diffusion occurs from wet to dry areas. Gas and solute diffusion occurs from zones of high concentration to zones of low concentration.

Disperse — To break up compound particles, such as aggregates, into the individual component particles, or to distribute or suspend fine particles, such as clay, in or throughout a dispersion medium, such as water.

Dolomite — A mineral comprised of Ca and Mg carbonates; term applied to limestone containing some Mg.

Dribble Fertilization — Dribbling or strip banding is a form of band placement that involves application of solid or fluid fertilizers in bands or strips of varying widths on the soil surface or on the surface of crop residues.

Dual Placement — Simultaneous placement of two fertilizer materials in subsurface bands.

Exchangeable Base — A basic cation adsorbed on a soil colloid, but which can be replaced by H^+ or some other cation.

Effective Precipitation — That portion of the total precipitation which becomes available for plant growth.

Electrons — Small, negatively-charged particles that are part of an atom's structure.

Element — Any substance that cannot be further separated except by nuclear disintegration.

Enzymes — Catalysts that direct and control the cell's biochemical reactions.

Equilibrium — The condition of a chemical reaction or an entire ecosystem in which there are only minor changes in conditions over time.

Equivalent — The weight in grams (g) of an ion or compound that combines with or replaces 1 g of H^+. The atomic weight or formula weight divided by its valence.

Erosion — The wearing away of the land surface by running water, wind, ice, or geological agents. Accelerated erosion is wind or water erosion at more rapid than normal or geological rates, usually associated with human activities.

Essential Nutrient — An element necessary for a plant to complete its life cycle. The 17 elements essential to plant growth are: carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium K), calcium (Ca), magnesium (Mg), sulfur (S), copper (Cu), chloride (Cl)$^-$, iron (Fe), boron (B), manganese (Mn), zinc (Zn), nickel (Ni), and molybdenum (Mo).

Eutrophication — Abundant growth of aquatic plants leading to oxygen deficient conditions in lakes or streams, accelerated by nutrient enrichment.

Evaporation — Water vapor loss from soil or free water directly into the atmosphere.

Evapotranspiration — Loss of water from the soil by evaporation plus transpiration loss from plants.

Exchange Complex — All the materials (clay, humus) that contribute to a soil's exchange capacity.

Exchangeable Ions — Ions held by electrical attraction at charged surfaces; can be displaced by exchange with other ions.

Exchangeable Sodium Percentage (ESP) — The degree of saturation of the soil exchange complex with Na^+.

Fertigation — Application of fertilizer in irrigation water.

Fertility, Soil — The status of a soil with respect to the amount and availability to plants of elements (nutrients) necessary for plant growth.

Fertilizer — Any natural or manufactured material added to the soil in order to supply one or more plant nutrients. The term is generally applied to manufactured materials other than aglime or gypsum.

Fertilizer Grade — The guaranteed minimum analysis, in percent, of the major plant nutrients contained in a fertilizer material or in a mixed fertilizer, expressed as total N, available P_2O_5, and soluble K_2O.

Fertilizer Placement — Concentrating fertilizer into a band or strip at a specific location on or below the soil surface. Examples: Seed row starter, dribble fertilization, deep banding.

Fertilizer Use Efficiency — An expression of the units of yield per unit of nutrient provided for the crop.

Fertilizer Requirement — The quantity of certain plant nutrient elements needed, in addition to the amount supplied by the soil, to increase plant growth to a designated optimum.

Field Capacity — The percentage of water remaining in a soil two or three days after having been saturated and after free drainage has practically ceased. Not a precise quantity.

Fine Texture — Consisting of or containing large quantities of small particles, in a soil, referring to a high percentage of silt and clay.

Fixation — Processes by which available plant nutrients are rendered temporarily unavailable by reaction with soil components. Generally, refers to reactions of P, NH_4^+, and K leading to decreased availability.

Flotation Application — A type of fertilizer applicator equipped with large, low pressure tires intended to spread the weight of the vehicle over a larger soil surface area minimizing soil compaction.

Flocculation — Joining of colloidal particles to form clusters.

Foliar Diagnosis — Estimation of the nutrient status of a plant or the nutrient requirements of the soil for producing a crop through chemical analyses or color manifestations of plant leaves, or by both methods.

GIS — Geographic information system. A generic term for systems that store, display, and analyze digital map data.

Glucose — A common sugar (carbohydrate) with six C atoms per molecule. Present in all cells. A constituent of cellulose, starch, and other polysaccharides.

GPS — Global positioning system. A network of satellites that generate continuous signals identifying their positions. Electronic receivers on the ground use this information to locally calculate ground locations.

Green Manure — Plants grown to be incorporated into soil to improve soil fertility.

Gypsum — A mineral or rock composed of calcium sulfate ($CaSO_4 \cdot 2H_2O$).

Horizon, Soil — A soil layer approximately parallel to the land surface.

Humus — The stable, dark-colored fraction of the soil organic matter remaining after most added plant and animal residues have decomposed.

Hydrated — Having water attached or incorporated as part of a chemical structure.

Hydroxyl — OH^- ion or group.

Immobilization — The conversion of elements from inorganic to organic form by their incorporation in microbial or plant tissue, making them less available for plants.

Incorporation — Mechanical mixing of fertilizer materials (or herbicides) with the surface soil.

Injection — Band placement of fluid fertilizer or anhydrous ammonia (NH_3) in the soil, either through use of pressure or non-pressure systems.

Infiltration — Entry of water into the soil.

Ion Exchange — The interchange between an ion in solution and another ion on the surface of any surface - active material such as clay or humus.

Iron (Fe) — An essential metallic micronutrient and is absorbed by plants as the ferrous (Fe^{2+}) ion. Iron is a catalyst in chlorophyll formation and acts as an oxygen carrier. It also helps form certain respiratory enzyme systems in the plant.

Knifed Application — Process where fertilizer materials are banded into the soil with a slender knifing tool.

Leaching — The removal of materials in solution by the passage of water through soil. In agriculture, leaching refers to the downward movement of free water (percolation) out of the plant root zone.

Lime — The term "lime," "agricultural lime," or "aglime" is applied to ground limestone containing calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$), hydrated lime (calcium hydroxide, CaOH) or burned lime (calcium oxide, CaO). Lime is used to reduce soil acidity and provide Ca and Mg as essential plant nutrients.

Lime Requirement — Lime requirement is the amount of good quality agricultural lime required to establish the desired soil pH range for the cropping system being used. Lime requirements are determined in the laboratory using a buffer pH in equilibrium with the soil.

Liming Material — Agricultural liming materialmeans a product whose Ca and Mg compounds are capable of neutralizing soil acidity.

Liquid (Fluid) Fertilizers — This term applies to anhydrous and aqua NH_3, N solutions, and liquid mixed fertilizers including clear liquid and suspensions of solids in liquids.

Macronutrients — The essential plant nutrients required in the largest proportions by plants.

Macropores — Large pores, often formed by roots and small soil animals and worms.

Magnesium (Mg) — An essential nutrient classed as a secondary nutrient along with Ca and S. It is a constituent of chlorophyll and is actively involved in photosynthesis. Magnesium aids in P metabolism, plant utilization of sugars, and the activation of several enzyme systems.

Manganese (Mn) — A metallic micronutrient functioning primarily as a part of enzyme systems in plants. It activates several important metabolic reactions and plays a direct role in photosynthesis by aiding chlorophyll synthesis.

Mass Flow — Movement of fluid in response to pressure. Movement of heat, gases, or solutes together with the flowing fluid in which they are contained. For example, NO_3-N moves by mass flow in the soil.

Micronutrients — Nutrients that plants need in only small or trace amounts. Essential micronutrients are B, Cl, Cu, Fe, Mn, Mo, Ni, and Zn.

Microorganism, Soil — Soil bacteria, fungi and other organisms which recycle nutrients and enhance availability of nutrients. Pathogenic organisms may have negative impacts on plants.

Mineralization — Release of elements from organic to inorganic form during the decay of organic matter containing the elements. Processes are carried out by soil microorganisms.

Minimum Tillage — Tillage system (cultivation) that reduces the number of machinery operations to the fewest required to create the proper soil condition for planting and seed germination.

Mobile Nutrients — Those nutrients that can be translocated from older tissues to younger tissues in the plant.

Molybdenum (Mo) — A metallic micronutrient required in the smallest quantities of all the essential elements. Molybdenum is required for the synthesis and activity of the enzyme nitrate reductase. Molybdenum is also vital for the process of symbiotic nitrogen fixation by Rhizobia bacteria in legume root nodules.

Mulch — Any material spread on the soil surface to protect soil from raindrops, sunshine, freezing or evaporation.

Mycorrhiza — The association, usually symbiotic, of fungi with the roots of plants. Fungal hyphae increase root area and nutrient uptake.

Necrosis — Death of plant tissue.

Neutral Soil — A soil with a high percentage (80% to 90%) of the exchange capacity occupied by Ca and Mg ions and the soil pH near 7.

Nickel (Ni) — An essential plant nutrient classed as a micronutrient. It is taken up by plants as Ni^{2+}. Nickel is the metal component of urease that catalyzes the conversion of urea to ammonia. It also plays a beneficial role in the N metabolism of legume crops.

Nitrification — The formation in soils of nitrite (NO_2) and nitrate (NO_3^-) from ammonium (NH_4^+) ions through the activities of certain soil bacteria; the biochemical oxidation of NH_4 to NO_3.

Nitrification Inhibitor — Compounds such as nitrapyrin (N-serve) and dicyandiamide (DCD) that delay bacterial oxidation of the ammonium ion to nitrite and thus slow production of NO_3. The objective of use of these compounds is to control leaching of NO_3 by keeping N in the NH_4^+ form longer, to prevent denitrification of NO_3-N, and to provide NH_4-N to plants over a longer period of time.

Nitrobacter — A genus of obligate aerobic chemoautotrophic soil bacteria that oxidizes NO_2 ions to NO_3^- in the final stage of the nitrification process.

Nitrogen (N) — An essential primary nutrient, a constituent of every living cell, plant or animal. In plants it is a part of the chlorophyll molecule, amino acids, proteins and many other compounds.

Nitrogen Cycle — The routes taken by N from the atmosphere through soils, plants, animals, and man, back to the atmosphere.

Nitrogen Fixation — The conversion of atmospheric nitrogen (N_2) into organic or inorganic forms. Specifically in soils, fixation refers to the assimilation of N_2 from the soil air by soil organisms in the formation of N compounds that are available to plants. The N fixing process associated with legume root nodules is known as symbiotic N fixation.

Nitrogen Solutions — Solutions of N fertilizers in water. Nitrogen solutions are used in manufacturing liquid or dry mixed fertilizers and/or applied to the soil either with special applicators or in irrigation water. Most commonly, the term refers to urea-ammonium nitrate (UAN) solutions, made from a mixture of urea and ammonium nitrate (NH_4NO_3) containing 28 to 32% N.

Nitrosomonas — A genus of obligate aerobic chemo-autotrophic soil bacteria which oxidize NH_4^+ ions to NO_2 in the first stage of the nitrification process. Nitrification inhibitors such as nitrapyrin specifically inhibit the activities of these organisms.

No-Tillage, No-Till, Zero Tillage — A farming system in which a crop is planted in the residue from a previous crop without soil tillage.

Nutrient — Element that contributes to an organism's growth and health.

Nutrient Management — Applying the right source of nutrients at the right rate, time and place to improve plant productivity while minimizing losses to air and water.

Nutrient Uptake — The process of plant absorption of nutrients, usually through the roots. Small amounts of nutrients may be absorbed through leaves following foliar applications of nutrients.

Organic Fertilizer — Organic material that releases or supplies useful amounts of an organic plant nutrient when added to a soil.

Organic Soil — Soil that contains a high percentage of organic matter throughout.

Orthophosphate — A general class of phosphate compounds manufactured from orthophosphoric acid (H_3PO_4) including primarily NH_4 and Ca salts.

Osmotic Regulation — The movement of electrolytes such as soluble ions and sugars across cell membranes to maintain water potential within plant cells.

Oxidation — A chemical change involving addition of O_2 or its chemical equivalent. It includes the loss of electrons from an atom, ion, or molecule during a chemical reaction. It may increase the positive charge of an element or compound.

Oxygen — A colorless, tasteless, odorless gas (O_2); the most abundant and most widely distributed element in nature. Comprises about 21% by volume of the air.

Parent Material — The unconsolidated material, mineral or organic, from which the soil develops.

Percolation — The downward movement of fluid in soil.

Permanent Wilting Point — The moisture level of a soil at which plants wilt and fail to recover turgidity. Value is not a constant.

Permeability — The ease with which a porous medium transmits fluids.

pH — A numerical designation of acidity and alkalinity. Technically, pH is the common logarithm of the reciprocal of H^+ activity of a solution. A pH of 7 indicates precise neutrality. Values between 7 and 14 indicate increasing alkalinity, and value between 7 and 0 indicates increasing acidity.

Phosphate — A salt of an ester of phosphoric acid. In the fertilizer industry, however, the term phosphate is usually applied to any P-containing material used as a fertilizer. Also used in reference to P_2O_5, an expression of P content of fertilizers.

Phosphate Rock — A natural rock containing one or more calcium phosphate minerals of sufficient purity and quantity as to allow its use, either directly or after concentration, in the manufacturer of commercial products. Most phosphate rock deposits utilized in fertilizer manufacturing in the U.S. and Canada are based on the apatite class of minerals, primarily calcium phosphates.

Phosphorus (P) — One of the essential nutrients required by plants and classified as one of the three primary nutrients. Phosphorus, a mobile plant nutrient, plays key roles in photosynthesis, respiration (utilization of sugars), energy storage and transfer, cell division, cell enlargement, genetic coding and many other plant processes.

Photosynthesis — The process by which green plants capture light energy by combining water and carbon dioxide to form carbohydrates. The pigment chlorophyll is required for the conversion of light energy to chemical energy.

Plant Analysis — A quantitative laboratory analysis to determine total content of a nutrient or nutrients in plant tissue.

Plant Available Moisture — Soil water held loosely enough that plants can extract it for use.

Point Injection — Use of a spoked wheel to inject fluid fertilizer into the rooting zone (10 - 12 cm) at points about 20 cm apart. Spoke injection is synonymous with point injection.

Polyphosphate — A general class of phosphate compounds characterized by molecules containing two or more P atoms. Polyphosphates are comprised of two or more orthophosphate molecules with the loss of a molecule of water between each orthophosphate unit. Derived from superphosphoric acid. Available primarily in fluid fertilizers as ammonium polyphosphates.

Pop-Up Fertilizer — Fertilizer applied at planting in direct seed contact. A form of starter fertilizer.

Pores — The space not occupied by solid particles in the bulk volume of the soil.

Potassium (K) — Potassium is an essential element, one of the three primary nutrients including N and P. It is required by most plants in approximately the same amounts as nitrogen. Potassium has important roles in activation in enzyme systems, is vital to photosynthesis and to the formation and utilization of sugars, has an essential role in protein synthesis and maintenance of protein structure and helps the plant use water more efficiently.

Primary Nutrient — One of the three nutrients...N, P, and K... which are most commonly limiting in crop production.

Preplant Fertilizer — Fertilizer applied to the soil prior to planting.

Reserve (Potential) Acidity — The exchangeable H^+ ions held on the soil colloids and hydrolyzable Al_3^+ are referred to as reserve or potential acidity. Reserve acidity is in dynamic equilibrium with H^+ ions in the soil solution (active acidity). Conservative calculations suggest that reserve acidity may be 1,000 to as much as 100,000 times greater for a clay soil than active acidity.

Residual Acidity — The ultimate acidity that develops from fertilizer use in a particular soil horizon after the residual salts are removed from that horizon by leaching.

Residual Fertility — Available nutrient content of a soil carried over to the next crop after fertilizing the previous crop.

Retention Zone — Soil zone where nutrients are concentrated following a fertilizer application. Usually refers to some sort of banded application.

Rhizobia — Bacteria capable of living symbiotically with higher plants, usually legumes, from which they receive their energy, and capable of using N_2, converting it into forms plants can use.

Runoff — Water that runs off the soil surface instead of infiltrating.

Saline - Alkali Soil — A soil containing a high proportion of soluble salts with either a high degree of alkalinity or high amount of exchangeable Na, or both, so that the growth of most crops is less than normal.

Saline Soil — A non-alkali soil containing soluble salt in such quantities to interfere with the growth of most crop plants; containing an appreciable quantity of soluble salts.

Salt Index — An index used to compare solubilities of chemical compounds used as fertilizers. Most N and K compounds have high indices, while P compounds have low indices. High salt index compounds applied in direct seed contact at rates too high can cause seedling damage because of the compounds' high affinity for water.

Sand — An inorganic particle with a size ranging between 2.00 mm and 0.05 mm in diameter.

Secondary Nutrients — Calcium, Mg and S are called secondary nutrients because they are essential to plant growth, but less frequently deficient than the primary nutrients.

Side-Banded Fertilizer — Placement of fertilizer in bands on one or both sides of the seed row (seedlings).

Side-Dressed Fertilizer — Applications of fertilizer to the side of crop rows after plant emergence.

Silt — An inorganic particle with a size ranging between 0.05 mm and 0.002 mm in diameter.

Site-Specific Management — Management of nutrient inputs, pesticide applications, crop population and other cropping system practices according to changes in soil characteristics and composition.

Sodic Soil — A soil that has been affected by high concentrations of salt and Na. Sodic soils are relatively low in soluble salts but are high in exchangeable Na.

Soil — The upper layer of earth in which plants grow.

Soil Aeration — The process by which air in the soil is replaced by air from the atmosphere.

Soil Amendment — Any material, such as aglime, gypsum, sawdust, or synthetic conditioner, that is worked into the soil to make it more amenable to plant growth. The term commonly refers to added materials other than those used primarily as fertilizer.

Soil Matrix — Like soil fabric, the combination of solids and pores in a soil.

Soil Profile — A vertical section of the soil extending from the surface through all its horizons and into the parent material.

Soil Solution — The liquid phase of the soil and its solutes.

Soil Test — A chemical analysis of soil composition, usually intended to estimate availability of plant nutrients but also including measurements of soil acidity or alkalinity and physical measurements of soil electrical conductivity.

Soil Texture — The relative proportions of various sized particles making up the soil. These particles are frequently referred to as soil separates and include sand, silt, and clay.

Solute — A material dissolved in a solvent to form a solution.

Split Application — Fertilizer applied two or more times during the crop growing season. Preplant and one or more post-plant applications are common.

Starter Fertilizer — Fertilizer applied at planting either in direct seed contact or to the side and below the seed. Exact position is not implied.

Strip Fertilizer — Fertilizer applied in surface bands that may be incorporated by tillage or remain on the soil/residue surface.

Strip Cropping — A technique to reduce soil erosion in which fallow strips or row crop strips are alternated with small grains, grasses or a legume hay crop.

Structure — In soil, the arrangement of primary particles into secondary units or peds with a particular size and shape.

Subsoil — The underlying layers of the soil beneath the topsoil which may contain less organic matter and more characteristics of the soil's parent material

Sulfur (S) — An essential secondary plant nutrient, essential in forming plant protein because it is a part of certain amino acids. As a part of plant protein, it is essential for enzyme activities. Involved in nodule formation and N fixation in legumes. Essential in chlorophyll formation although not a constituent of the chlorophyll molecule.

Superphosphate — Superphosphate is a product obtained when phosphate rock is treated with either sulfuric acid or phosphoric acid or a mixture of these acids. "Normal", "ordinary", or "simple" superphosphate refers to all grades containing up to 22% available P_2O_5 which are commonly made by the acidulation of rock phosphate with sulfuric acid. Contains primarily mono-calcium phosphate plus a significant amount of gypsum.

Surface Band Application — Placement of a liquid or solid fertilizer in either a dribble or forced stream on the soil surface.

Suspension Fertilizer — A fluid containing dissolved and undissolved plant nutrient compounds. Suspension of the undissolved materials is usually produced with the aid of a suspending agent of non-fertilizer properties (clay). Mechanical or air agitation may be necessary to facilitate uniform suspension of undissolved plant nutrients.

Symbiotic Bacteria — In agriculture, the definition usually relates to bacteria in nodules growing on the roots of legumes which have the ability to fix atmospheric N_2 into forms which can be utilized by the host legume plants.

Symbiotic — The relationship between two living organisms in which both benefit, such as N fixation by Rhizobia in nodules on legume roots.

Terrace — In soil conservation, a more or less level or horizontal strip or berm of earth usually constructed on a contour to reduce erosion.

Tilth — The physical condition of soil as related toits ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration.

Tissue Test — A rapid, qualitative colorimetric field test to determine the unassimilated, soluble nutrient content of plant tissue sap.

Top-Dressed Application — Surface application of fertilizer to the soil after the crop has been established.

Topsoil — Topsoil refers to the surface layer of the soil including most of the organic matter content of the soil profile. Technically, this layer is considered as the dark-colored A horizon of the soil profile.

Trace Elements — Elements occuring in low concentrations, including micronutrients.

Transpiration — Evaporation from leaves; the flow of water through plants from soil to atmosphere.

Triple Superphosphate — Refers to all grades containing 40% or more available P_2O_5 which are commonly made by the acidulation of rock phosphate with phosphoric acid. Normal superphosphate contains appreciable S (gypsum), triple superphosphate does not. Phosphorus is present primarily in the form of monocalcium phosphate.

Urease — An enzyme required for the breakdown of urea to NH_3; common to all plant materials.

Variable-Rate Fertilization — A technique which changes nutrient application rates according to changes in available nutrient levels in soil as the applicator moves across the field.

Water Retention Curve — Graph showing the soil moisture content versus energy applied to remove the water (moisture release curve).

Water Table — The upper boundary for ground water or that level below which the soil is saturated with water.

Weed-and-Feed — A term used in the agricultural chemical industry to denote mixing an application of fertilizer and herbicide.

Yield, Sustained — A continual annual, or periodic, yield of plants or plant material from an area; implies management practices which will maintain the productive capacity of the land.

Zinc (Zn) — A metallic micronutrient, one of the first recognized as essential for plants. Zinc aids in synthesis of plant growth substances and enzyme systems and is essential for promoting certain metabolic reactions. It is necessary for production of chlorophyll and carbohydrates.

Review Answers

Chapter 2
1. d, 2. b, 3. c, 4. a, 5. b, 6. c, 7. b, 8. d, 9. d, 10. d

Chapter 3
1. b, 2. c, 3. d, 4. a, 5. c, 6. b, 7. a, 8. a, 9. d, 10. b

Chapter 4
1. a, 2. b, 3. d, 4. a, 5. b, 6. c, 7. b, 8. b, 9. c, 10. c

Chapter 5
1. b, 2. a, 3. c, 4. b, 5. a, 6. d, 7. a, 8. b, 9. c, 10. a

Chapter 6
1. b, 2. d, 3. c, 4. a, 5. b, 6. d, 7. a, 8. c, 9. b, 10. a

Chapter 7
1. c, 2. d, 3. a

Chapter 8
1. d, 2. c, 3. c, 4. a, 5. b, 6. d, 7. c, 8. b, 9. d, 10. a

Chapter 9
1. c, 2. b, 3. d, 4. d, 5. a, 6. a, 7. a, 8. a, 9. d

CONVERSION FACTORS FOR U.S. SYSTEM AND METRIC

Listed here are symbols/abbreviations for nutrients and related terms used frequently throughout this publication.

To convert Col. 1 into Col. 2, multiply by:	Column 1	Column 2	To convert Col. 2 into Col. 1, multiply by:
Length			
0.621	kilometer	mile, mi	1.609
1.094	meter, m	yard, yd	0.914
0.394	centimeter, cm	inch, in.	2.54
Area			
2.471	hectare, ha	acre, A	0.405
Volume			
1.057	liter, L	quart (liquid), qt	0.946
Mass			
1.102	tonne[1] (metric, 1,000 kg)	short ton (U.S. 2,000 lb)	0.9072
0.035	gram, g	ounce	28.35
Yield or Rate			
0.446	tonne/ha	ton/A	2.242
0.891	kg/ha	lb/A	1.12
0.0159	kg/ha	bu/A, corn grain	62.7
0.0149	kg/ha	bu/A, wheat or soybeans	67.2

[1]The spelling as “tonne” indicates metric ton (1,000 kg). Spelling as “ton” indicates the U.S. short ton (2,000 lb). When used as a unit of measure, tonne or ton may be abbreviated, as in 9 t/ha. A metric expression assumes t=tonne; a U.S. expression assumes t=ton.

SYMBOLS AND ABBREVIATIONS

Listed here are symbols/abbreviations for nutrients and related terms used frequently throughout this publication.

Al	Aluminum
B	Boron
C	Carbon
Ca	Calcium
$CaCO_3$	Calcium carbonate
$CaCl_2$	Calcium chloride
$CaSO_4 \bullet 2H_2O$	Calcium sulphate (gypsum)
$Ca(NO_3)_2$	Calcium nitrate
CH_4	Methane
Cl/Cl^-	Chlorine/Chloride
Cu	Copper
$CuSO_4$	Copper sulphate
DAP	Diammonium phosphate
Fe	Iron
$FeSO_4$	Ferrous sulphate
H^+	Proton or hydrogen ion
HCO_3^-	Bicarbonate
K	Potassium
KCl	Potassium chloride (also muriate of potash or MOP)
K_2O	Potash
KNO_3	Potassium nitrate
K_2SO_4	Potassium sulphate (also sulphate of potash of SOP)
MAP	Monoammonium phosphate
MCP	Monocalcium phosphate
Mg	Magnesium
$MgSO_4$	Magnesium sulphate
$MgCl_2$	Magnesium chloride
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
NH_3	Ammonia
NH_4^+	Ammonium
$(NH_4)_2SO_4$	Ammonium sulphate
NO_2^-	Nitrite
NO_3^-	Nitrate
N_2	Dinitrogen
NO_x/N_2O	Nitrogen oxides/Nitrous oxides
P	Phosphorus
ppb	parts per billion
ppm	parts per million
S	Sulphur
SO_4^{2-}	Sulphate
TSP	Triple super phosphate
Zn	Zinc
$ZnSO_4$	Zinc sulphate

NOTES

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