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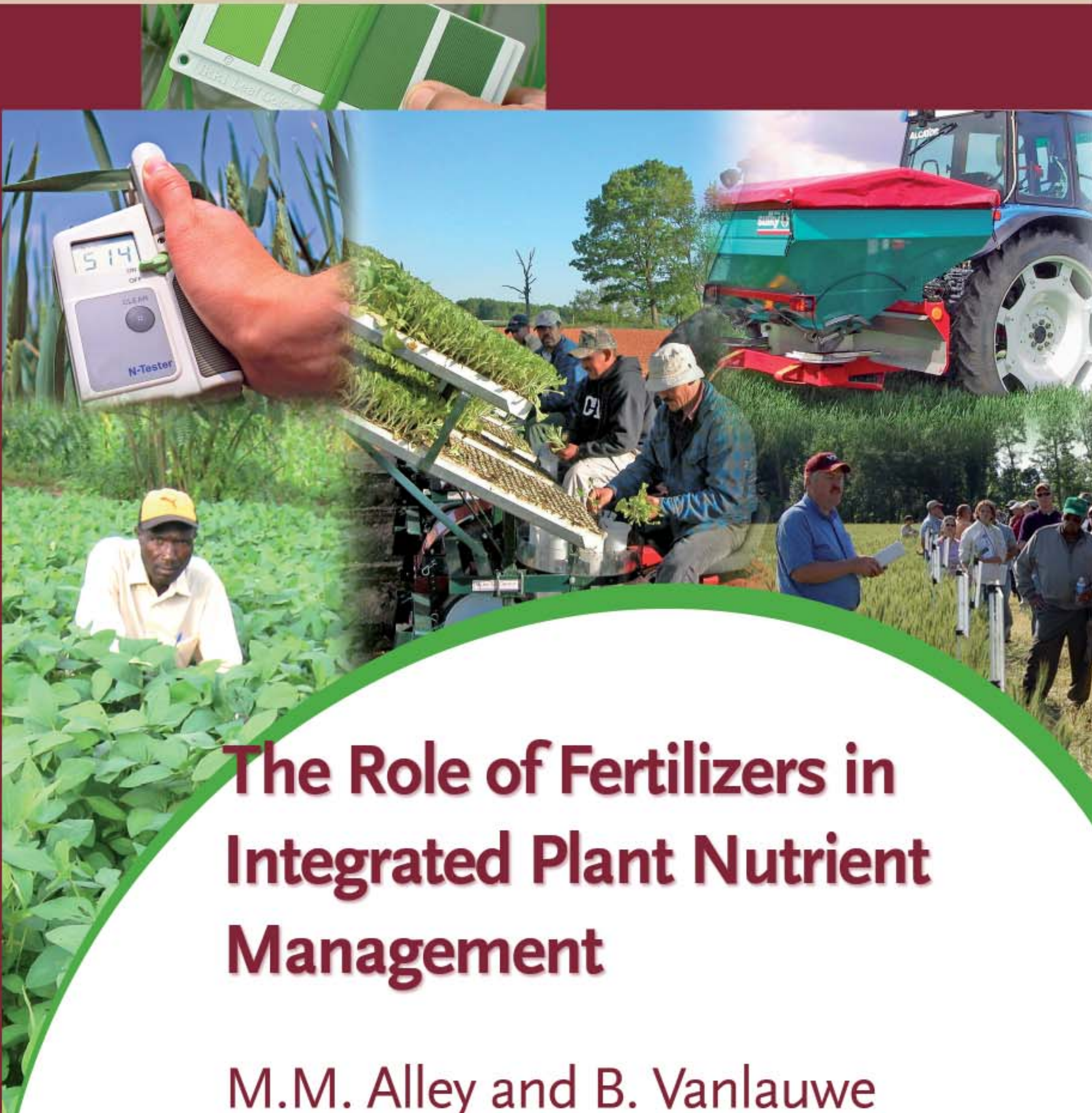

The Role of Fertilizers in Integrated Plant Nutrient Management

M.M. Alley and B. Vanlauwe

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International Fertilizer Industry Association
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Foreword by IFA

There is a common misconception that supporting the use of manufactured fertilizers means opposing the use of organic sources of nutrients. Nothing could be further from the truth. In fact, most agronomists agree that optimal nutrient management entails starting with on-farm sources of nutrients and then supplementing them with manufactured fertilizers. The integration of organic and inorganic sources of nutrients should also be seen in the context of overall crop production, which includes the selection of crop varieties, pest control, efficient use of water and other aspects of integrated farm management. The aim of this document is to put fertilizers in context and to make it clear once and for all that manufactured fertilizers and organic sources of nutrients can, and should, be used in a complementary fashion. This publication is not intended to provide an exhaustive manual for crop production.

Although we expect this report to be most useful for non-experts, we also hope that it will help scientists to explain the concepts outlined here to the general public and to future generations of students. Crop production is very complex, and good farmers are both artists and scientists, who must master a wide range of technical issues. Increasing nutrient use efficiency is just one element, but it lays the foundation for other aspects of good agricultural practices.

Luc M. Maene
Director General
International Fertilizer Industry Association (IFA)

Foreword by TSBF-CIAT

The African Fertilizer Summit, held in 2006 in Abuja, and endorsed by the African Heads of State, resolved to increase fertilizer use in Sub-Saharan Africa from a current average of 8 kg fertilizer nutrients per hectare to 50 kg per hectare. To achieve this goal, Integrated Soil Fertility Management (ISFM) has been adopted as the technical framework for accompanying the African Green Revolution and maximizing the benefits of this increased fertilizer use. Integrated Soil Fertility Management is defined as 'The application of soil fertility management practices, and the knowledge to adapt these to local conditions, which optimize fertilizer and organic resource use efficiency and crop productivity. These practices necessarily include appropriate fertilizer and organic input management in combination with the utilization of improved germplasm'.

From this definition, it is very clear that Integrated Plant Nutrient Management (IPNM) practices play a pivotal role in achieving ISFM. Although this document focuses on how various nutrient sources are used together, it should not be forgotten that this is just one piece of a complex puzzle. For example, organic sources of nutrients also add organic matter to the soil, which helps improve soil moisture retention and resistance to wind erosion, among other benefits. Secondly, germplasm tolerant to adverse soil and/or climatic conditions can increase the demand for nutrients and thus improve the efficiency of IPNM interventions. This booklet serves an important purpose since proper communication tools for dissemination of knowledge and information related to IPNM and ISFM are crucial pieces of the complex puzzle that constitutes the African Green Revolution.

Nteranya Sanginga
Director
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About the book and the authors

This book is written for farmers, students, researchers, extension personnel, agribusiness representatives and policy makers to provide an overview of the concepts of Integrated Plant Nutrient Management (IPNM) and Integrated Soil Fertility Management (ISFM). Integrated Plant Nutrient Management focuses on efficiently utilizing all available sources of essential nutrients for crops. Integrated Soil Fertility Management provides a framework for managing soil fertility to sustain and improving soil quality and production capacity. The combination of these concepts provides a holistic view of providing plant nutrients and maintaining and/or enhancing soil productivity. Specific aspects of IPNM and ISFM are discussed, as well as the use of nutrient budgets for assessing nutrient use on a farm, watershed, regional or national basis. It is hoped that this book will lead to more efficient use of plant nutrients for increasing food production and sustaining and increasing soil productivity in an environmentally sensitive manner.

Mark M. Alley

Mark Alley holds the W.G. Wysor endowed professorship for agriculture in the Crop and Soil Environmental Sciences Department at Virginia Tech University, Blacksburg (VA), USA. He has responsibilities for research, teaching and extension in the areas of soil fertility and crop management. Mark Alley's teaching responsibilities include soil fertility and management courses for BSc students, and a soil-plant relationships course for graduate students.. He has worked extensively to improve plant nutrient use in reduced tillage systems for producing wheat, maize and soybean. Mark Alley is a Fellow of the American Society of Agronomy (ASA) and the Soil Science Society of America (SSSA); and he received the 2002 International Crop Nutrition Award granted by the International Fertilizer Industry Association (IFA). He is currently serving as President of ASA.

Bernard Vanlauwe

Bernard Vanlauwe holds a PhD in tropical agriculture and is senior scientist and leader of the Integrated Soil Fertility Management (ISFM) outcome line of the Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT), based in Nairobi, Kenya. He has joined TSBF-CIAT since 2001 and is currently leading the development, adaptation and dissemination of best ISFM options in various agro-ecological zones in sub-Saharan Africa. Prior to this, Bernard Vanlauwe worked at the International Institute of Tropical Agriculture (IITA) in Nigeria (1991–2000) and the Catholic University of Leuven, Belgium (1989–1991), focusing on unraveling the mechanisms underlying nutrient and soil organic matter dynamics in tropical agro-ecosystems. He has published over 70 papers in scientific journals and over 80 in other forms and has (co-)supervised more than 30 MSc. and 10 PhD. students.

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Symbols, acronyms and abbreviations

(as used in this publication)

Symbols

As	arsenic
B	boron
C	carbon
Ca	calcium
CaO	calcium oxide
Cd	cadmium
Cl	chlorine
Co	cobalt
Cr	chromium
Cu	copper
F	fluorine
Fe	iron
H	hydrogen
Hg	mercury
$H_2PO_4^-$ and HPO_4^{2-}	orthophosphate anions
K	potassium
KCl	potassium chloride
K_2O	potassium oxide
Mg	magnesium
MgO	magnesium oxide
Mn	manganese
Mo	molybdenum
N	nitrogen
N_2	dinitrogen
NH_4^+	ammonium
Ni	nickel
NO_3^-	nitrate
O	oxygen
P	phosphorus
P_2O_5	phosphorus pentoxide
S	sulphur
S^0	elemental sulphur
SO_4^{2-}	sulphate
Zn	zinc

Acronyms

IFA	International Fertilizer Industry Association
IITA	International Institute of Tropical Agriculture
ISO	International Organization for Standardization
NRCS-USDA	Natural Resources Conservation Service of the United States Department of Agriculture
OECD	Organisation for Economic Co-operation and Development
PPI	Potash and Phosphate Institute (now International Plant Nutrition Institute, IPNI)
TSBF-CIAT	Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture
UNEP	United Nations Environment Programme

Abbreviations

BNF	biological nitrogen fixation
g	gram
ha	hectare
IPNM	integrated plant nutrient management
ISFM	integrated soil fertility management
kg	kilogram
m^2	square metre
mg	milligram
Ndfa	nitrogen derived from the atmosphere
t	metric tonne
µg	microgram

Daunting challenges face agriculture

Agriculture must feed, clothe and provide energy to a rapidly increasing world population while minimizing environmental and other unwanted impacts. Land available for agricultural production is limited in most regions of the world, so increasing yields from currently utilized land is the only solution for necessary production increases. Crop yields are limited without adequate plant nutrition. Meeting the production challenge in an environment-friendly way requires a thorough understanding of plant nutrition as a component of crop production programmes, which encompass many critical factors including water management, improved crop varieties and integrated pest management, among others.

Integrated Plant Nutrient Management (IPNM) is an approach aimed at optimizing nutrient use from agronomic, economic and environmental perspectives. Under IPNM, all available nutrient sources are used appropriately within a site-specific total crop production system.

This booklet describes the concept of IPNM and reviews the advantages and disadvantages associated with the use of the main plant nutrient sources. It also presents the use of IPNM and nutrient budgeting in different contexts, and discusses actions required by the different stakeholders to make IPNM a reality.

Integrated Plant Nutrient Management: the concept

Integrated plant nutrient management is a holistic approach to optimizing plant nutrient supply. It includes: (1) assessing residual soil nutrient supplies, as well as acidity and salinity; (2) determining soil productivity potential for various crops through assessment of soil physical properties with specific attention to available water holding capacity and rooting depth; (3) calculating crop nutrient requirements for the specific site and yield objective; (4) quantifying nutrient value of on-farm resources such as manures and crop residues; (5) calculating supplemental nutrient needs (total nutrient requirement minus on-farm available nutrients) that must be met with "off-farm" nutrient sources; (6) developing a programme to optimize nutrient utilization through selection of appropriate nutrient sources, application timings and placement. The overall objective of IPNM is to adequately nourish the crop as efficiently as possible, while minimizing potentially adverse impacts to the environment. A detailed discussion of the IPNM concept can be found in the recent publication *Plant Nutrition for Food Security* (Roy *et al.*, 2006).

Soil fertility ensures robust plant growth

Soil fertility is the capacity of soil to retain, cycle and supply essential nutrients for plant growth over extended periods of time (years). Soil fertility relates not only to the nutrient status of the soil, but also to activities of soil organisms, including earthworms or microbes, clay mineral amounts and types, air exchange rates, and other biological, chemical or physical properties and processes. All of these factors, in combination with the temperature and rainfall regimes, affect the amounts and rates of nutrient supplies for plant growth. A *fertile* soil has the capacity to supply essential plant nutrients in amounts needed to produce high yields of nutritious food or quality fiber for the specific environment. An *infertile* soil does not supply necessary amounts of essential nutrients, and poor yields and/or crop quality result from the lack of adequate plant nutrition. It should be understood that an adequate nutrient supply is an essential, but insufficient factor in plant growth. Overall soil fertility also depends on a number of physical, chemical and biological conditions, as mentioned above, that are beyond the scope of this document. The combination of these conditions and their interactions are the subject of Integrated Soil Fertility Management (ISFM), which includes issues such as soil moisture retention, soil organic matter content and soil pH.

Eighteen elements have been shown to be essential for higher plants: carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), sulphur (S), magnesium (Mg), calcium (Ca), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), chlorine (Cl), nickel (Ni) and cobalt (Co). All elements are not essential for all plants. Carbon, H and O are obtained from the atmosphere and water, and are not considered *mineral* elements. The remaining essential elements can be divided into primary macronutrients (N, P, K), secondary macronutrients (S, Mg, Ca) and micronutrients (Fe, Mn, Zn, Cu, B, Mo, Cl, Ni, Co) based on average concentrations in plants. Primary and secondary macronutrients are found in plants at levels of 0.2 to 5.0% or greater, while plant concentrations of micronutrients range from 0.1 to 100 μg/g.

Plant growth is limited by the essential element that is least available when all other elements are present in adequate quantities (Liebig's Law of the Minimum, Figure 1). Integrated Plant Nutrient Management (IPNM) strives to ensure that plants have adequate but not excessive supplies of all essential elements.

Fortunately, many soils supply the majority of the essential elements in adequate quantities, and only a few elements usually limit plant growth. Nitrogen, P and K are generally the most widely deficient elements, and many fertilizers that are considered to be *complete* contain only N, P and K. However, many agro-ecosystems need nutrients other than N, P and K. For example, Ca fertilization is routinely required for groundnut production on sandy soils in the southeast of the USA; S fertilization is required for optimum forage production in many areas of Australia and New Zealand; and Zn is needed for grain production on alkaline soils in Turkey and Pakistan and in many parts of the Philippines rice-growing areas.

Figure 1. An illustration of Leibig's Law of the Minimum that states that crop yield potential is determined by the most limiting factor in the field
(Adapted from D. Armstrong, IPNI)

Knowing the state of soil fertility is the starting point

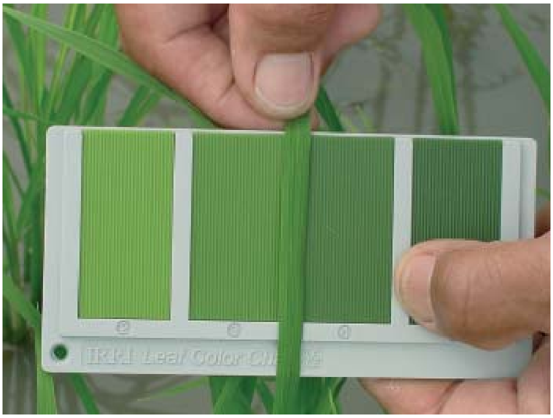
Soil fertility evaluation assesses the capacity of individual fields to supply adequate nutrients for specific crops and associated yield and quality objectives. The initial step in an IPNM programme is soil testing to determine the current soil nutrient status (Picture 1). Soil testing methods developed through research during the past 75 years can provide farmers and advisors in most regions of the world with information on lime, P and K nutrition needs for major crops, and help predict soil salinity problems.

Picture 1. Soil sampling (Credit: INRA - LDAR Laon)

Rapid soil test kits for N, P and K – now being used in some countries – can be made available to others. Nonetheless, many developing regions still do not have access to adequate soil testing services.

Plant tissue analysis and visual observations of nutrient deficiency symptoms (Picture 2) are also used to evaluate soil fertility. Once visual deficiency symptoms are observed, irreversible yield or quality losses may have occurred. One important exception is the comparison of plant leaves to colour charts to determine N needs (Picture 3), and the use of spectral sensors for monitoring N content of crops (Picture 4). These techniques for improving the uptake of fertilizer N by the crop are being extensively researched and implemented in rice (Shukla *et al.*, 2004), wheat (Link *et al.*, 2004) and maize production (Osborne *et al.*, 2004). In addition, frequent plant tissue testing is used to monitor plant nutrient needs in certain intensive crop production systems, such as drip-irrigated vegetables. All of these techniques can increase crop yields, crop quality and nutrient use efficiency.

Picture 2. N sensor (Credit: Yara)



Picture 3. Leaf colour chart (Credit: ©International Rice Research Institute)

Picture 4. Sulphur deficiency in tomato (Credit: The Sulphur Institute)

In absence of access to soil testing or plant tissue analysis, farmers generally know the performance of each of their plots and can relatively easily rank these in terms of general soil fertility status. The most frequent soil property used by farmers to classify their soils, besides color and texture, is productivity history. Earlier work aiming at correlating farmer's classifications with formal assessments has shown high correlations between both approaches.

Fertilizers feed soil and plants

Fertilizers are *substances that supply plant nutrients or amend soil fertility* (IFA, 1992) and are applied to increase crop yield and/or quality, as well as sustain soil capacity for future crop production. According to common dictionaries, fertilizers can include both manures and plant residues, as well as naturally occurring essential elements that have been mined (e.g. P and K) or, in the case of N, fixed from the atmosphere and incorporated into manufactured fertilizers. However, agronomists use this term differently, and in this publication the word "fertilizer" refers to manufactured nutrient sources unless otherwise specifically noted.

Appropriate nutrient applications depend on many factors

Field- and crop-specific nutrient application programmes are developed as part of IPNM to efficiently utilize applied nutrients. Crop, soil conditions, fertilizer characteristics and climatic effects must all be considered. For example, in humid climates, nitrate-based N fertilizers (see Table 1) must be applied close to the time of plant nutrient need in order to prevent nitrate leaching losses, especially on sandy-textured soils, while organic N sources must decompose prior to nutrient release and, therefore, must be applied further in advance of the crop's need. In addition, crop characteristics, such as root distribution and growth pattern, dictate the optimum placement of fertilizers.

Each crop has specific needs

Crop characteristics influence total nutrient needs and their timing, as well as the volume of soil from which nutrients can be extracted. All of these factors are taken into account in IPNM.

Total nutrient uptake is a function of biomass produced (top growth and roots) per hectare and is directly calculated: Total nutrient uptake (kg/ha) = (kg dry matter/ha) x (nutrient content (kg)/ kg dry matter)

Values for nutrient uptake and removal in harvested portions of crops are available in the *IFA World Fertilizer Use Manual* (IFA, 1992) and from the Potash and Phosphate Institute (PPI, 2001). Yields are determined from local field-specific yield measurements.

The crop's growth pattern determines when the plant needs each nutrient. Figure 2 shows an average curve for plant growth or nutrient uptake for an annual crop.

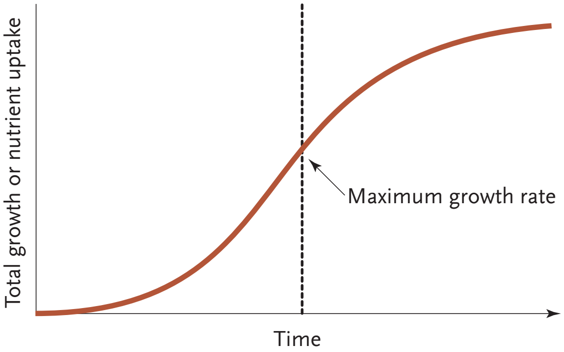


Figure 2. Generalized total growth and nutrient uptake with time for an annual crop.

While adequate nutrient availability is essential in all stages of plant growth, the largest amounts of all nutrients must be available during the period of maximum growth. Integrated Plant Nutrient Management considers plant growth pattern and nutrient needs for individual crops, climates and soils. A specific example of this principle is shown in Figure 3 where the N uptake pattern of winter wheat is related to growth stage. The resulting fertilizer application programme for winter wheat grown in the humid climatic region of Virginia (USA) comprises: (i) a small amount of N applied at planting (mid-October); (ii) another small application made during early tillering (late-January, early February) and (iii) the final application (40 to 50% of total N requirement) made just prior to stem extension. This application programme maximizes N uptake and reduces potential N losses through leaching. Less or non-mobile nutrients in the soil, e.g. P and K, can be applied prior to planting.

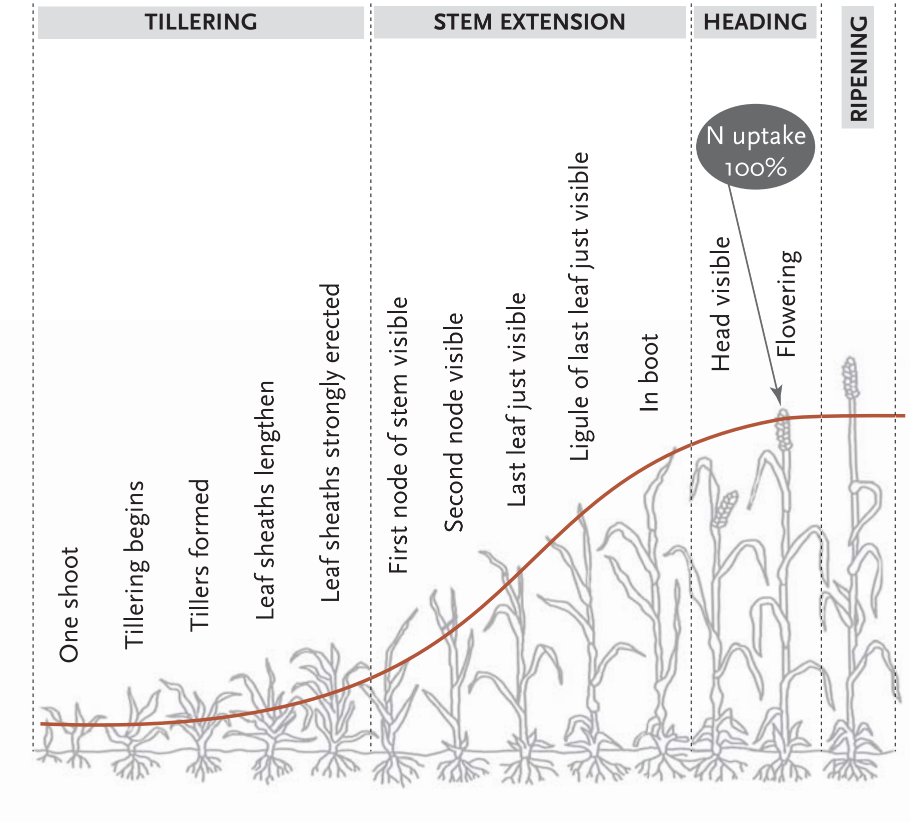


Figure 3. Nitrogen uptake as related to winter wheat plant growth stage in the mid-Atlantic USA (Adapted from Alley *et al.*, 1993).

Soil conditions influence how nutrients are taken up

Soil chemical properties including acidity, salinity and nutrient concentration, combined with soil texture (sand, silt and clay content) and bulk-density (grams of soil per cm^3) influence root development and nutrient uptake. Soil texture and structure determine soil water holding capacity as, for instance, silt loam and clay soils hold more plant available water than sandy soils. Bulk density is related to mechanical impedance of soil to root growth and the movement of oxygen to roots because higher bulk density values mean that the soil has less pore space. Soil management practices that maximize root growth will increase nutrient and water recovery by plants and maximize yield potentials. Large root systems not only increase total nutrient uptake but also increase nutrient uptake rates (kg nutrient per day), a key factor for high crop yields.

Acid soils may contain toxic concentrations of aluminum and/or manganese in the soil solution. Both root and overall plant growth are restricted in these soils. Plant nutrients such as P are rendered less available in acid soils due to precipitation with aluminium and iron. The most direct method to increase plant nutrient availability and growth in acid soils is to neutralize acidity by adding lime (calcium carbonate or calcium-magnesium carbonate). In some regions where lime is unavailable or cost prohibitive, plant breeders have developed acid-tolerant crop varieties. While these varieties will tolerate acidity, adequate amounts of plant nutrients must be available to achieve high yields.

Nutrients are transported to the roots through the soil solution. The soil solution is the water in soil that surrounds soil particles and roots, through which essential nutrients are transported from the soil to the plant root surface for uptake. Plant nutrient concentrations in the soil solution influence nutrient uptake rate by roots. Higher concentrations generally result in higher uptake rates. Root systems of many plants proliferate in soil zones containing higher concentrations of nutrient elements. Barley root growth in sand culture research in the United Kingdom revealed greater growth in zones with increased concentrations of N and P, but not of K (Figure 4). Plant nutrients placed in localized concentrations (bands) reduce exposure to adverse soil chemical reactions and increase nutrient availability.

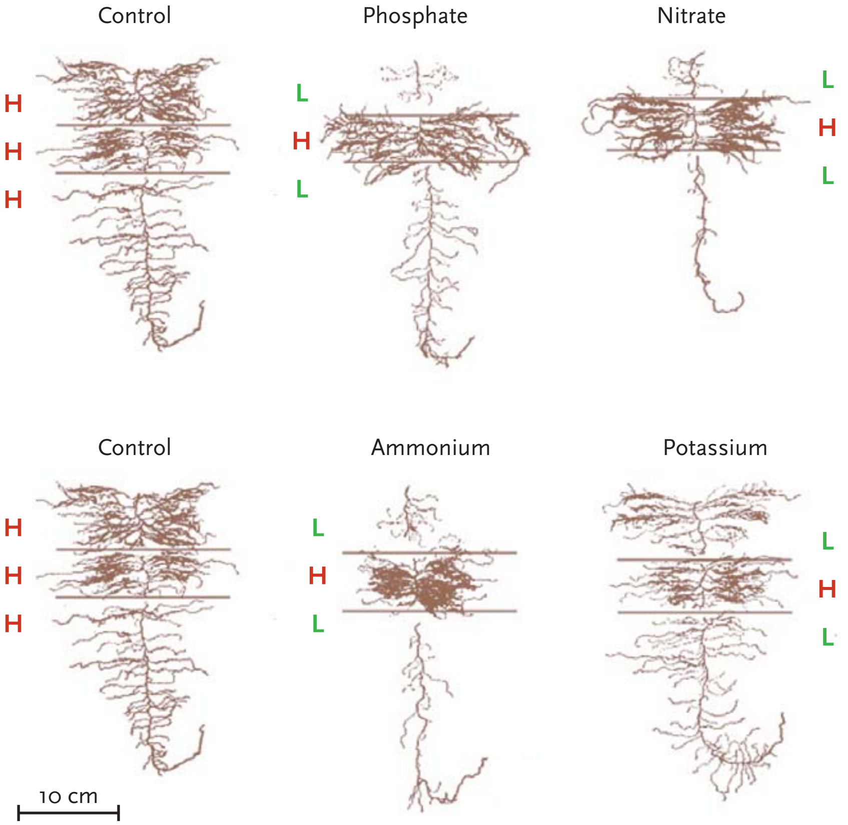


Figure 4. Root growth response to localized zones of low (L) and high (H) N, P and K fertilizer concentration (Adapted from Drew, 1975).

Nutrient characteristics impact their use

General plant nutrient characteristics are presented in Table 1. The influence of individual nutrient characteristics on application timing is direct. For example, positively charged ions such as potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) are held to a greater extent in soils with higher clay contents than in soils with lower clay contents because clay particles are negatively charged. These elements can be applied at higher rates and less frequently on higher clay content soils as compared to soils with low clay content that have a lower capacity to retain nutrients in a plant-available state.

Nitrogen is a special case for several reasons: it is a nutrient needed in great amounts by all crops. It occurs in soil in various forms; and its transformations between the various forms are rapid, with the exception of the dinitrogen (N_2) molecule which is extremely stable. The decomposition (mineralization) of crop residues and manures releases N from organic forms that are unavailable for plant uptake to mineral forms (ammonium and nitrate), as long as temperature and moisture conditions are suitable for microbial activity, and C:N ratios are smaller than 20:1. Organic materials with higher amounts of C relative to N (C:N > 30:1) release N more slowly because soil microorganisms appropriate mineral N to increase their populations. Organic materials with C:N ratios between 20:1 and 30:1 may show a slight delay in mineralization due to immobilization by microorganisms. Mineralized N is first present as ammonium but is rapidly converted to nitrate. Both forms are plant available, but nitrate is subject to leaching.

Table 1. Plant nutrient ionic species and selected properties concerning plant availability and movement in soils.

	Nutrient form	Ionic species	Soil reaction properties
Nitrogen (N) fertilizers	Ammonium	NH_4^+	This positively charged ion is held by negatively charged soil sites such as clay and organic matter. It is converted to nitrate by soil microorganisms under warm moist conditions. It is taken up by plants as ammonium or after conversion to nitrate.
	Nitrate	NO_3^-	This negatively charged ion is not held by soil particles, moves with soil water and can be easily lost through leaching. It is readily taken up by plants.
	Organic N	–	N is part of amino acids, humic acids, and complex protein molecules in manures, plant residues and soil microorganisms. N is transformed to ammonium ions as organic material is mineralized by soil microorganisms. The rate of organic N conversion to ammonium depends on the total carbon content to total N content (C:N) ratio of the organic material as well as on soil temperature and moisture levels.

Phosphate (P) fertilizers	Water-soluble P	$H_2PO_4^-$, HPO_4^{2-} (orthophosphate anions)	These ions are readily taken up by plants but react with iron, aluminum and calcium ions in soil solution to form various compounds, some of which re-dissolve easily while others are highly insoluble. The solubility of soil P-containing compounds is greatest at pH 6.2 to 6.5 and is reduced as soil clay content increases. In addition, highly weathered clays (tropical soils) fix P or reduce its solubility to a greater extent than less weathered soil minerals found in temperate climates.
	Organic P	–	The organic molecules containing P must be mineralized before being available to plants. Mineralization is dependent on soil microbial activity and the C:P ratio of the organic material.
Potassium (K) fertilizers	Water-soluble K	K^+	This positively charged ion is taken up by plants and is held on negatively charged clay and organic matter sites in soil. K^+ held on the soil particles is in equilibrium with K^+ in the soil solution.
	Organic K	–	K content may be low in many manures and biosolids, but can be high in many crop residues. K release from organic residues is generally rapid.
Calcium (Ca) and magnesium (Mg) fertilizers	Water-soluble Ca and Mg	Ca^{2+}, Mg^{2+}	These ions are readily taken up by plants and are held on negative sites on soil clay and organic matter particles. Ca^{2+} and Mg^{2+} held on soil particles are in equilibrium with Ca^{2+} and Mg^{2+} in soil solution. Ca^{2+} is the predominant cation held on soils that are not highly acidic.
	Organic Ca and Mg	–	Ca^{2+} and Mg^{2+} ions become plant available as organic materials are mineralized.
Sulphur (S) fertilizers	Sulphate and elemental S	SO_4^{2-}, S^o	Sulphate ions are readily taken up by plants and move with soil water. However, these ions can be adsorbed on clay sites in acidic subsoil. Elemental S must be converted by soil microorganisms to sulphate before it can be taken-up by plants.
	Organic S	–	Sulphur in organic molecules such as amino acids must be mineralized to sulphate by soil microorganisms prior to plant uptake.

Nutrient releases from organic manures are estimated from local data regarding manure nutrient contents, application methods and climates. For example, in Virginia (USA), the estimates of N availability from different sources shown in Table 2 reveal variations associated with the application method. Varying climatic conditions that affect microbial activities mean that such estimates can differ greatly between regions.

Table 2. Estimated percent organic N availability for different timings of applications in Virginia, USA. Manure samples are analyzed for organic N content prior to application. (Adapted from Virginia Nutrient Management Standards and Criteria, 2005).

Type of manure	Arable crop *spring or early fall applied*	Arable crop *winter top-dress/ spring residual*	Perennial grasses
	Organic N available during first growing season (%)		
Dairy	35	20/15	35
Poultry	60	30/30	60
Swine	50	25/25	50

The practical implications of these estimates are important for IPNM. Organic materials with high C:N ratios and containing little mineral N can result in crop N deficiencies during early season growth if applied at planting. Residues with high C:N ratios should be applied far enough ahead of planting so that mineralization and N release is occurring at the time plants are beginning growth. If cool temperatures prevent significant mineralization prior to planting, manufactured N fertilizers can be applied at planting to satisfy early-season plant growth, with the remainder of the crop N requirement supplied by mineralization from the organic source.

It is essential to analyze the plant nutrient content of organic materials in order to properly determine their contribution to crop nutrient need. Estimating decomposition rates of organic materials under localized conditions is essential to accurately determine the proper time of application. Applying large amounts of organic materials without taking into account the nutrients from these materials can result in an excess of nutrients and potential environmental pollution.

Nutrient use should optimize soil and crop management

Agronomic considerations for IPNM within the context of a total crop management programme include the influence of organic nutrient sources (manures, crop residues, etc.) on soil properties such as soil aggregate stability, soil structure, water infiltration and water retention. Soil aggregate stability improves as soil organic matter increases because organic matter binds mineral particles (sand, silt and clay) together. Soils with high aggregate stability resist rain drop impact and are less susceptible to erosion. Soil structure improves with increased organic matter levels, and allows for higher rates of rainfall infiltration. Organic matter has much higher water holding capacity than mineral soil materials due to greater pore space in organic matter. As a result, an increase in soil organic matter content increases soil water retention and reduces erosion potential. Finally, good soil structure improves air exchange that is needed to promote plant root development.

The recycling of manures and crop residues not only provides organic matter for improving soil physical properties, but also can supply significant amounts of nutrients. For example, stable soil organic matter is approximately 5% N. As soil organic matter levels increase with additions of manures, crop residues and cover crops, the available N supply from the soil increases. However, additional nutrients are generally required to achieve a balanced nutrient supply, as many manures are high in P, have a moderate level of N but may be low in K content, while crop residues may be high in K, have low to moderate P levels and have relatively low N content. An IPNM programme optimizes nutrient availability from organic and inorganic sources to achieve the necessary nutrient supply for that crop production system while sustaining soil productivity levels for the future.

Nutrient use should increase economic value

Sustainable crop production requires that both economic and environmental concerns be considered within an IPNM framework. Yield responses to applied nutrient rates can be graphed as shown in Figure 5, which represents wheat grain yield responses to applied P. Knowing the value of the yield ($/kg wheat) and the cost of P ($/kg P_2O_5)[1] enables the calculation of optimum economic return, which is where the value of the wheat yield increase produced by the fertilizer equals the cost of the fertilizer applied.

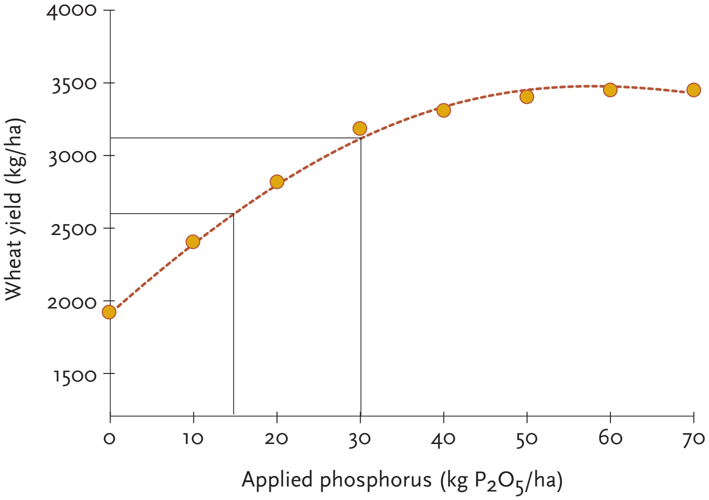


Figure 5. Typical crop yield response to fertilizer application.

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[1] *The P content of fertilizers is expressed as an oxide (P_2O_5) in most countries*

Knowing the amount of crop yield increase to expect per unit of fertilizer applied is especially critical for situations where fertilizer availability is limited. In such situations, the initial part of the response graph (Figure 5) is utilized to calculate the application rate for the largest area that can be treated with the total amount of fertilizer nutrient available. For example, if only 30 kg of P_2O_5 are available for application, should the 30 kg be applied to one hectare, or should the application rate be 15 kg per hectare applied to two hectares? The response in Figure 5 indicates that application of 30 kg P_2O_5 to one hectare would produce approximately 3100 kg for the treated hectare plus 1900 kg for the untreated hectare. Application of 15 kg P_2O_5 to two hectares would produce a total yield of approximately 5200 kg of wheat (2600 kg on each hectare). While 5000 kg/ha of wheat could be achieved the first year by applying 30 kg P_2O_5 to one hectare and not applying any to the second hectare, such an approach leads to the depletion of the residual P fertility in the unfertilized hectare and subsequent soil degradation. Generally, applying smaller amounts of nutrients to all land produces the largest total yield as the yield increase per unit of applied fertilizer is greatest for the initial applications of nutrients, plus it helps maintain soil fertility. Integrated plant nutrient management looks at these questions to optimize the utilization of available nutrients.

Nutrient interactions influence crop yields

Nutrient interactions and their effects on crop yield must also be considered. Figure 6 shows maize grain yield response to fertilizer P applications at various levels of applied N. Although the shapes of the yield response curves to increasing rates of P are similar at different N levels, the yields are much different. This indicates that N is limiting plant response to P. Such data illustrate the need for balanced fertilization. All crop growth limiting plant nutrients must be determined for each specific location. Only then can the proper fertilizer be chosen, and the appropriate rate of application determined.

Nutrient use should respect the environment

Integrated plant nutrient management addresses environmental considerations by tailoring nutrient applications to crop needs and soil conditions in order to eliminate both excessive applications that increase potential losses to water or air and insufficient applications that result in soil fertility degradation. Within IPNM, fertilizer applications are timed to optimize nutrient uptake and application methods are designed to minimize possible off-site movement of nutrients by optimizing crop nutrient uptake.

Integrated plant nutrient management programmes meeting these criteria ensure that uptake of N, which is mobile in the soil environment, is maximized; that levels of immobile nutrients such as P do not build-up enough to produce water-quality problems; and that losses to air and water of all mineral and organic nutrient sources are minimized.

Under-application of nutrients, even of a single essential plant nutrient, is also an environmental concern in agro-ecosystems. Nutrient deficiencies limit plant biomass production and associated soil organic matter content, leaving soil exposed to water and

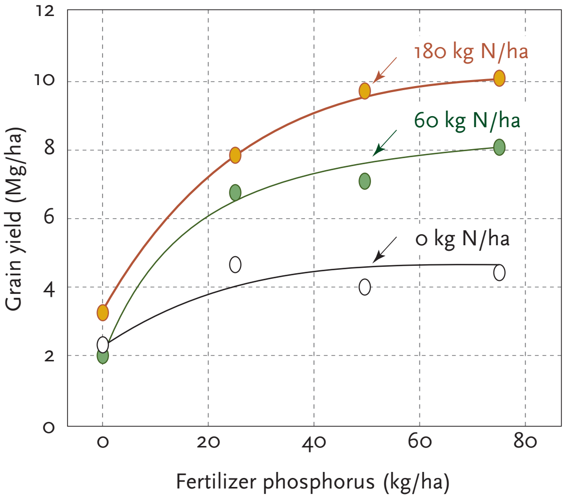


Figure 6. Maize grain yield response to fertilizer P applications for three levels of N fertilization (Adapted from Sumner and Farina, 1986).

wind erosion. Increased water erosion from nutrient-depleted soils causes siltation of rivers and reservoirs and in some cases eutrophication, while wind erosion reduces air quality. Decreased organic matter content also reduces water infiltration and retention, which then reduces yield potential. In addition, organic carbon loss with topsoil erosion may result in additional carbon dioxide emissions to the atmosphere. In extreme cases, induced soil fertility degradation can be a major contributor to desertification.

Integrated Plant Nutrient Managment practices play a pivotal role in achieving Integrated Soil Fertility Management

While IPNM is an approach focusing on the nutrient supply aspects of crop production, Integrated Soil Fertility Management (ISFM) encompasses all dimensions of plant nutrient uptake, including nutrient demand through integration of improved germplasm and the biological and physical dimension of soil fertility that can enhance the uptake of plant nutrients. For instance, under drought stress conditions, a soil covered with organic matter can hold more soil moisture than a soil that does not have mulch, and this extra moisture may result in improved uptake of applied fertilizer nutrients. The objectives of ISFM and IPNM are similar, namely to ensure efficient nutrient uptake and plant growth with minimal adverse impacts on the environment.

Definition and characteristics of Integrated Soil Fertility Management

The goal of ISFM is to maximize the interactions that result from the potent combination of fertilizers, organic inputs, improved germplasm, and farmer knowledge. The ultimate outcome is improved productivity, enhanced soil quality, and a more sustainable system through wiser farm investments and field practices with consequent minimal impacts of increased input use on the environment.

Integrated Soil Fertility Management is defined as *'the application of soil fertility management practices, and the knowledge to adapt these to local conditions, which optimize fertilizer and organic resource use efficiency and crop productivity. These practices necessarily include appropriate fertilizer and organic input management in combination with the utilization of improved germplasm.'* Several intermediary phases are identified in the progression towards 'full ISFM' (Figure 7). 'Full ISFM' comprises the use of improved germplasm, fertilizer, appropriate organic resource management and adaptations to local conditions and seasonal events. These adaptations lead to specific management practices and investment choices, and are iterative in nature leading to better judgments by farmers concerning weed management, targeting of fertilizer in space and time and choice of crop varieties. Farmer resource endowment also influences ISFM, as do market conditions and conducive policies. Local adaptation also adjusts for variability in soil fertility status and recognizes that substantial improvements in agronomic efficiency can be expected on responsive soils (A in Figure 7) while on poor, less-responsive soils, application of fertilizer alone does not result in improved agronomic efficiency (B in Figure 7). Fertilizer is better applied in combination with organic resources (C in Figure 7). Additions of organic matter to the soil provide several mechanisms for

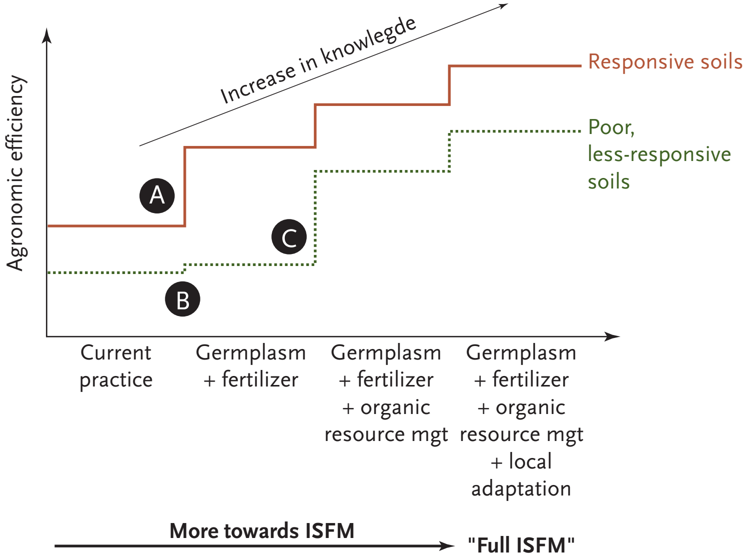


Figure 7. Conceptual relationship between the agronomic efficiency of fertilizers and organic resources as one moves from current practice to 'full ISFM'. At constant fertilizer application rates, yield is linearly related to agronomic efficiency. Note that the figure does not suggest the need to sequence components in the order presented.

improved agronomic efficiency, particularly increased retention of soil nutrients and water and better synchronization of nutrient supply with crop demand, but it also improves soil health through increased soil biodiversity and carbon stocks. Integrated Soil Fertility Management is effective over a wide range of fertilizer application rates and can greatly improve the economic returns from achieving the African Fertilizer Summit's target. Integrated Soil Fertility Management also deters land managers from applying fertilizers at excessive rates that result in reduced agronomic efficiency and environmental pollution.

The advantage of combining fertilizer and organic resources

Based upon agricultural research findings across numerous countries and diverse agro-ecological zones of Sub-Saharan Africa, a consensus has emerged that the highest and most sustainable gains in crop productivity per unit nutrient are achieved from mixtures of fertilizer and organic inputs (FAO, 1989; Pieri, 1989; Giller *et al.*, 1998; Vanlauwe *et al.*, 2001). The ISFM paradigm results from lengthy investigation into the management of crop nutrition (Table 3).

Table 3. Changes in tropical soil fertility management paradigms over the past five decades

Period	Paradigm	Role of fertilizer	Role of organic inputs	Experiences
1960s and 1970s	External input paradigm ‘1st paradigm’	Use of fertilizer alone will improve and sustain yields.	Organic resources play a minimal role.	Limited success due to shortfalls in infrastructure, policy, farming systems, etc.
1980s	Organic input paradigm	Fertilizer plays a minimal role.	Organic resources are the main source of nutrients.	Limited adoption; organic matter production requires excessive land and labor.
1990s	Sanchez’ ‘second paradigm’	Fertilizer use is essential to alleviate the main nutrient constraints.	Organic resources are the entry point; these serve other functions besides nutrient release.	Difficulties to access organic resources hampered adoption (e.g. improved fallows).
2000s	Integrated Soil Fertility Management	Fertilizer is a major entry point to increase yields and supply needed organic resources.	Access to organic resources has social and economic dimensions.	On-going; several success stories (see below).

Integrated Soil Fertility Management was derived from Sanchez’s earlier ‘Second Paradigm’ that relies ‘*more on biological processes by adapting germplasm to adverse soil conditions, enhancing soil biological activity and optimizing nutrient cycling to minimize external inputs and maximize the efficiency of their use*’. Thus, Sanchez recognized the need to combine essential organic inputs with fertilizers but farmer-available organic resources are viewed as the main entry point (Sanchez, 1994). Indeed, combining mineral and organic inputs results in greater benefits than either input alone through positive interactions on soil biological, chemical and physical properties. However, adoption of the ‘Second Paradigm’ by farmers was limited by the excessive requirement for land and labor to produce and process organic resources. Farmers proved reluctant to commit land solely to organic resource production at the expense of crops and income.

The ISFM paradigm, as previously defined, offers an alternative to the ‘Second Paradigm’ by using fertilizer as the entry point for improving productivity of cropping systems. It asserts that substantial and extremely useful organic resources may be derived as by-products of food crops and livestock enterprise. Integrated Soil Fertility Management also recognizes the importance of an enabling environment that permits farmer investment in soil fertility management, and the critical importance of farm input suppliers and fair produce markets, favorable policies, and properly functioning institutions, particularly agricultural extension.

Fertilizer as an entry point for Integrated Soil Fertility Management

The recommendation of the Fertilizer Summit, *'to increase the fertilizer use from the current 8 to 50 kg/ha nutrients by 2015'* reinforces the role of fertilizer as a key entry point for increasing crop productivity and attain food security and rural well-being in Sub-Saharan Africa. The impact of this target will, however, vary depending upon the agronomic efficiency of fertilizer, defined as *'the amount of output (e.g. crop yield) obtained per unit of fertilizer applied'*. This rate varies across regions, countries, farms and fields within farms, and it greatly affects the returns to the recommended 50 kg/ha (Prudencio, 1993). Generally, on responsive soils, where the applied fertilizer nutrients overcome crop nutrient limitations, substantial responses to fertilizer can be expected (Vanlauwe *et al.*, 2006). On soils where other constraints are limiting crop growth (less-responsive soils), fertilizers alone in absence of other corrective measures results in relatively low agronomic efficiencies and small improvement in crop yield (Carsky *et al.*, 1998; Zingore *et al.*, 2007). Also important is the heterogeneity that exists between households within a community, translated in differing production objectives and resource endowments (Tittonell *et al.*, 2005; Giller *et al.*, 2006). The above factors co-determine the range of soil fertility management options available to the household. Ojiem *et al.* (2006) derived the concept of the 'socio-ecological niche' for targeting ISFM technologies, which must be embedded into local social, economic and agro-ecological conditions.

Fertilizer not only improves crop yields but it also increases the quantity of available crop residues useful as livestock feed or organic inputs to the soil (Bationo *et al.*, 2004). Targeting P application to legumes doubles crop biomass and increases the fertilizer agronomic efficiency of the following cereal crop (Vanlauwe *et al.*, 2003; Giller *et al.*, 1998). Similarly, strategic application of N fertilizer improves the performance of most cropping systems, even N-fixing legumes. For example, application of small amounts of starter N to legumes stimulates root growth leading to better nodulation and increased the N contribution to a succeeding cereal crop (Giller, 2001; Sanginga *et al.*, 2001). More accurate timing and placement of top-dressed N during peak demand of maize greatly improves crop yield and agronomic efficiency (Woomer *et al.*, 2004, 2005).

Farmers can draw on many sources of plant nutrients

Sources of plant nutrients include residual soil nutrients, crop residues, green manures, animal manures and biosolids, biologically-fixed N and manufactured fertilizers. Crops utilize plant nutrients from all sources but the nutrient elements must be transformed into the ionic forms (Table 1) before being taken up by plants. The amount of nutrients provided by different sources varies between and within agro-ecosystems. Integrated Plant Nutrient Management identifies and utilizes all available sources of plant nutrients.

Organic nutrient sources require conversion to plant-available forms

Soil organic matter

Soil organic matter contains significant amounts of N, P and S, as well as various micronutrients, but the release of these nutrients depends on the stability of the organic matter. A portion of fresh organic matter readily decomposes, e.g. in one growing season, while more stable organic matter may require decades to decompose.

Without proper nutrient additions and crop residue management, agricultural soils lose organic matter content and productivity. Data from a long-term cropping system experiment at the University of Illinois (USA) showed that the organic carbon content declined rapidly with initial cultivation, from 3.75% to 2.1% C in 20 years, and further declined to 1.25% in the next 90 years, which appears to be a new equilibrium value (Fenton, *et al.*, 1999). Similar trends have been observed in Australia (Dalal and Mayer, 1986) and England (Johnston and Poulton, 2005). This new equilibrium corresponds to organic materials that are very resistant to decomposition and provide few nutrients for annual crop plants. Thus, as soil organic matter declines, the availability of nutrients from this source also declines. Maintaining and/or increasing soil organic matter requires organic inputs from crop residues and/or manures. Practices that hasten organic matter decomposition, such as tillage, should be used sparingly.

Crop residues

Crop residues vary greatly in nutrient content, and the amount of plant available nutrients that are released in a specific time period can only be determined from local data. Table 4 shows a range of nutrient content values of typical crop residues. For tropical agro-ecosystems, Palm *et.al.* (2001) have developed an organic resource database for almost 300 plant species. The database addresses not only ranges in nutrient contents for various plant species but also selected plant parts, i.e. leaves, stems, litter and roots. In addition, the database contains information on carbon quality and nutrient release rates for the various plant materials. Coupling these data with site-specific conditions should improve organic crop residue nutrient management.

Table 4. General nutrient content values of crop residues and poultry and livestock manures (Adapted from Barker *et al.*, 2000).

Nutrient	Crop residues	Poultry manure	Livestock manure
		g/kg	
N	10-15	25-30	20-30
P	1-2	20-25	4-10
K	10-15	11-20	15-20
Ca	2-5	40-45	5-20
Mg	1-3	6-8	3-4
S	1-2	5-15	4-50

Nutrients in crop residues are released through microbial decomposition of the residues, which is directly related to their C content relative to N, P and S. Plant residues (or manures) of moderately low ratios of C:N (<20:1), C:P (<200:1) or C:S (<400:1) are associated with a pattern of initial net release of nutrients from the organic material during decomposition, while residues with high ratios tend to result in immobilization of nutrients. Nutrient immobilization occurs when essential nutrients are utilized by soil microorganisms during decomposition of residues and are unavailable for plant uptake.

Animal manures

Animal manures are widely recognized as valuable nutrient sources. Nutrient management plans – legally mandated for intensive livestock production in North America (NRCS-USDA, 2005) and Europe (Oenema, 2004) – require that animal manures be analyzed for nutrient content on a regular basis. Typical ranges of nutrient contents for various manures are shown in Table 4, although it is widely recognized that the nutrient content of manures varies widely and that poor quality feed for livestock results in manure with low nutrient contents. In Africa, where livestock receives poor quality feed, the N content in manure is often below 2% (Harris, 2002). Since much of the nutrient content of manures is in organic forms, localized nutrient "availability coefficients", especially for N, have been developed for specific manures under varying climate and soil conditions. These coefficients enable farmers to better estimate appropriate manure application rates. An example of how to calculate manure application rates for use in crop production is found in the *Manure Management Planner* software programme developed at Purdue University (Joern and Hess, 2005). The software helps interpret IPNM for farming systems where manure is a major source of plant nutrients. Some caution has to be taken in the use of animal manures due to the possible presence of substances such as heavy metals that accumulate in the food chain.

Green manures

Green manures are fresh plant materials applied directly to the soil to increase soil fertility and/or soil organic matter content. Both legume and grass crops can be used as green manures. Green manure crops can be considered as a type of plants that are used for accumulating nutrients from the soil profile in the case of non-legumes, and for increasing N availability when legume crops are used. Green manures are not composted nor have they been digested by animals. Nutrients supplied to crops following green manures are a direct function of green manure crop biomass, nutrient content and decomposition rate. Determining total biomass and nutrient content is an easy measurement; estimating the amounts of nutrients that will be available to a crop from the green manure is more difficult. Organic matter in green manures must be mineralized, and the rate of mineralization is controlled by the C:N ratio of the green manure, the degree of soil incorporation, and soil temperature and moisture levels.

Cherr *et al.* (2006) summarized data for plants used for green manure and reported that N accumulation for 23 topical plant species -both legumes and non-legumes-ranged from 5 to 306 kg N/ha. Nitrogen accumulation by temperate plants can even range from 2 to 592 kg N/ha. Contents in nutrients other than N are rarely reported, but these vary widely depending on the fertility levels of the soils where the crops are grown. Accumulation of nitrogen and other nutrients by green manure crops are obviously greater for soil environments with balanced nutrient availability. The release of N and other nutrients in green manures is associated with specific crop quality and specific environmental conditions (Vanlauwe *et al.* 2005). Localized experimental data are needed to develop specific estimates of nutrients supplied from green manure crops but, in their absence, general rules can be used to determine the approximate nutrient release on the basis of organic resource quality.

Promiscuous, dual purpose legumes, such as soybean, which can simultaneously improve soil fertility and supply all essential nutrients to humans and livestock is a particular case of green manure, which should be paid more attention in Sub-Saharan Africa. During the last two decades, the International Institute of Tropical Agriculture (IITA) and its partners developed and implemented sustainable cereal-grain legume rotations. The promiscuous soybean lines that resulted from this effort produce about 2.5 t grain/ha and are now available in many countries. Nitrogen fixation contributes about 50 kg N/ha (Sanginga *et al.*, 1997). Maize following soybean had 75% greater yield than maize following maize. Furthermore, fertilizer use efficiency of maize was improved by 100% because applying soybean residues and 45 kg N/ha resulted in maize yields equal to those obtained from applying the 90 kg fertilizer N/ha without soybean.

Biosolids

Biosolids are the residual solids from treatment of municipal wastewater that can be recycled and provide significant quantities of plant nutrients as well as organic matter. Representative values for the nutrient contents of biosolids are shown in Table 5. Nutrients in biosolids vary in forms, depending on the source, treatment, storage and handling processes. Nutrient availability depends on the particular biosolid and the local environment, just as with manures. Generally, biosolids are analyzed for their

Table 5. Representative concentrations of macro- and micronutrients and other trace elements in biosolids (Adapted from Kashmanian *et al.*, 2000).

Element	Mean or median concentration
Macronutrients	(g/kg)
N	33
P	23
K	3
Ca	39
Mg	4
S	11
Micronutrients	(mg/kg)
B	13 (median)
Cu	741
Fe	12,000 (median)
Mn	276 (median)
Mo	9
Zn	1,202
Ni	43
Other trace elements	(mg/kg)
Arsenic (As)	10
Cadmium (Cd)	7
Chromium (Cr)	119
Mercury (Hg)	5
Fluorine (F)	49 (median)

content of organic and inorganic N, total P, trace elements and toxic metals. Plant-available N values for biosolids are derived from the N analysis, method of application, time of application and local climatic situation (which influences mineralization). Phosphorus release from organic P forms is difficult to predict, but application rates to supply adequate N for crop growth generally supply more P than most crops need and, thus, P release is not considered an issue in most biosolid applications. Application of biosolids at rates to supply all crop N needs can increase soil P concentrations to levels that may produce environmental concerns for P runoff to surface waters.

Biosolids must be analyzed for potentially toxic metals such as mercury and arsenic prior to land application. The agricultural use of biosolids is supported by the United Nations Environmental Programme (UNEP) (2000). However, UNEP identifies the following steps for proper use of this resource:

1. The composition of biosolids must be carefully evaluated and closely monitored in order to assure acceptable quality and to calculate proper application rates;
2. Chemical and biological properties must be monitored regularly, including trace elements, pathogens and odours to ensure protection of crops, land and the individuals producing and utilizing the crops;
3. Knowledge and understanding of physical, chemical and biological conditions of soils and crops are needed to determine appropriate rates, methods and timing of applications;
4. Laboratories and research programmes supporting the utilization and monitoring must consistently do high-quality work in order to ensure the integrity of the biosolids utilization plan. Specifically, laboratories should have well-established quality assurance procedures and meet ISO standards.

Resources for successful biosolids utilization that meet these requirements are widely available in developed countries. Many developing countries still need to build laboratories and train individuals in order to safely and efficiently utilize biosolids for crop production.

Fertilizer equivalency

Fertilizer equivalency values directly relate the value of an organic material to a manufactured fertilizer that is readily plant-available. These values are important for successful IPNM because organic materials can vary greatly in nutrient content

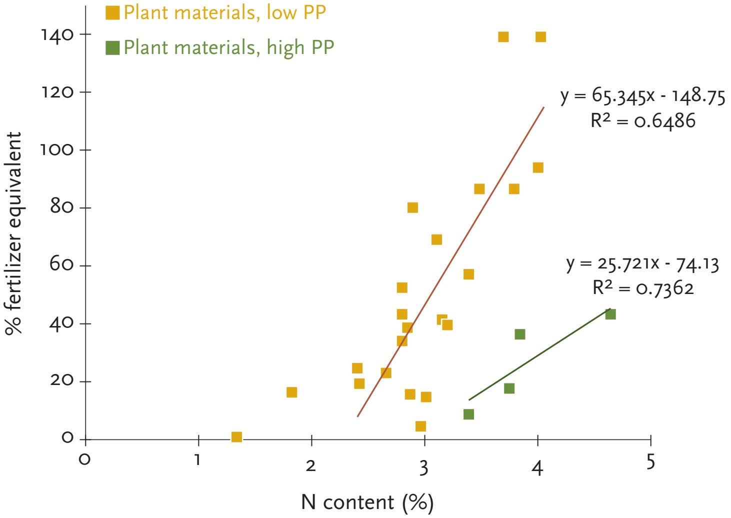


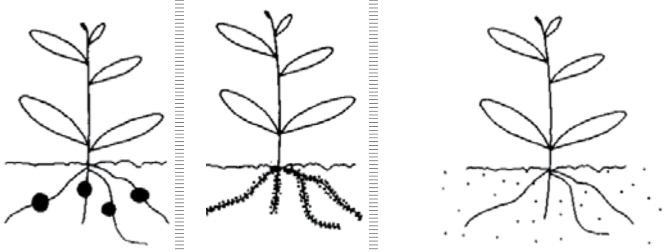
Figure 8. Relationship between the N fertilizer equivalent and the N content of plant residues and manure for a series of sites in Africa. The linear regression equations were calculated separately for the plant materials with low and high polyphenol (PP) content (Adapted from Vanlauwe *et al.*, 2002).

depending on the fertility of the soil on which a green manure crop or a crop residue is produced, the diet of the animal producing manure, or the storage and application methods used in handling the organic material. For example, the capacity of crop residues to substitute for N fertilizer applications is directly related to the N content, as well as to the percentage of carbon and lignin contained in the residues, which must decompose before becoming available for plant use. Figure 8 illustrates that concept for plant residues with different polyphenol contents.

Knowledge of fertilizer equivalency values reduces the risk of insufficient or excessive plant nutrition while maximizing crop nutritional benefits from organic residues.

Biological nitrogen fixation captures nitrogen from the air

Biological nitrogen fixation (BNF) is the conversion of inert atmospheric dinitrogen molecules (N_2) into forms of N that can be utilized by plants. Biological N fixation can be grouped into the three systems shown in Figure 9. Nitrogen fixation is greatest in the symbiotic system and least with the "free living" microorganisms, with values ranging from 20 to 400 kg N/ha/year. Furthermore, although "green manure legumes" generally fix more N than dual-purpose grain legumes, the latter are often more attractive because they provide other immediate benefits to farmers. Biological N fixation can be a major source of N for agro-ecosystems.



System of N_2 fixation ($N_2 \longrightarrow NH_3$) and microorganisms involved	**Symbiosis** (e.g. *Rhizobium*, *Actinomycetes*)	**Associations** (e.g. *Azospirillum*, *Azotobacter*)	**Free living** (e.g. *Azotobacter*, *Klebsiella*, *Rhodospirillum*)	
Energy source (organic carbon)	Sucrose and its metabolites (from the host plant)	Root exudades from the host plant	Heterotroph: Plant residues	Autotroph: photosynthesis
Estimates of amounts fixed (kg N/ha/yr)	Legumes: 50-400 Nodulated non-legumes: 20-300	10-200	1-2	10-80

Figure 9. Biological N fixation systems (Adapted from Marschner, 1995).

Symbiotic BNF occurs in leguminous plants by host-specific rhizobium species that obtain energy from their hosts. Nodulated legumes such as alfalfa and soybean are the most prominent symbiotic N_2-fixing systems in temperate agricultural systems, and 90% of the fixed N is directly transferred from the bacteria to the plant. The N fixed by these plants fully meets the legume's N requirements, and residues from the legumes provide N for non-legume crops following in the crop rotation. Integrated Plant Nutrient Management accounts for legume-fixed N in the cropping system. For example, in the US States of Indiana, Ohio and Michigan, maize N fertilizer recommendations are reduced by 70 kg N/ha when maize follows an average (32 plants/m^2) established forage legume, and by 100 kg N/ha when following an excellent (50 plants/m^2) established forage legume (Vitosh *et al.*, 2004). In addition, research in Argentina has shown that soil organic carbon, microbial biomass N and other soil quality parameters could be maintained by including a minimum of three years of grass-legume pasture with four years of cereal and oilseed production in a seven-year cropping system (Studdert *et al.*, 1997).

Tree and shrub species capable of BNF are important nutrient sources in certain regions. At least 650 woody species belonging to nine plant families have the capacity to fix atmospheric N_2, and 515 of these species are legumes (Nair *et al.*, 1998). Several non-leguminous N_2-fixing trees are also important in tropical agroforestry systems with most being used for timber, fuel-wood or fodder and, most importantly, for soil improvement. These trees directly contribute to the soil N pool through transfer of biologically fixed N_2 and cycling of nutrients from deeper depths into biomass that is readily mineralizable.

Trees and shrubs are used in hedgerow intercropping, cropland or parkland systems, improved fallows and shaded perennial-crop systems. Large amounts of N (e.g. 460 kg N/ha) and moderate amounts of P (e.g. 50 kg P/ha) have been observed in standing biomass, but much variation occurs in the recycling of these nutrients (Nair *et al.*, 1998). Predicting the impact on nutrient supplies in specific systems is difficult due to the complexity of the various processes. Research has shown as much as 113 kg N/ha being derived from atmospheric N_2 in a nine-month fallow of *Sesbania sesban* and/or *Crotalaria grahamiana*, or as little as 23 kg N/ha fixed in other similar systems (Cadisch *et al.*, 2002).

The potential for BNF in rice (*Oriza sativa)* production has been studied extensively. Selected N_2-fixing systems, estimated amounts of N_2 fixed and associated increases in rice grain yield are shown in Table 6. While symbiotic N_2-fixing organisms definitely have potential for use in rice production, significant limitations exist with these systems. Most notably, high temperatures can limit growth of the N_2-fixing organisms, as can P deficiency, low pH and high N concentrations in irrigation water, while populations of grazers in the flood water can also reduce N availability for rice.

Biological N fixation can be a significant N source for sugar cane production in regions such as Brazil. The N_2-fixing acid-tolerant bacterium *Acetobacter diazotrophius,* as well as other bacterial species, have been found in roots, stems and leaves of certain sugar cane cultivars (Boddey, 2001). Fixation capacity varies with genotypes and research is being conducted to identify superior genetic resources, especially for soils with low N

Table 6. Selected examples of N_2-fixing systems, increases in rice grain yield with the system and estimated amount of fixed N_2 (Adapted from Choudhury and Kennedy, 2004).

N_2-fixing system	Experiment type	Increase in rice grain yield	(%)	Estimated amount of fixed N_2
Azolla-Anabaena symbiosis	Field	1.5 t/ha	50	48 kg/ha
Cyanobacteria	Field	1.4 t/ha	29	24 kg/ha
Azotobacter sp.	Field	0.4-0.9 t/ha	7-20	11-15 kg/ha
Azospirillum lipoferum	Greenhouse	6.7 g/plant	81	58.9% Ndfa*
Herbaspirillum spp.	Greenhouse	3.7-7.5 g/plant	45-90	28-58% Ndfa*
Burkholderia vietnamiensis	Field	0.5-0.8 t/ha	13-22	Data not available
Rhizobium leguminosarum	Greenhouse	0.6-7.9 g/pot	2-22	23-31 mg/pot

* % Ndfa = N derived from the atmosphere vs. total N

availabilities. These bacteria apparently do not survive well in soil, but fix significant amounts of N and are propagated with the planting of stem pieces. Recent research in Guatemala and Australia has shown that 25 to 60% of the N requirement of certain cane genotypes can be provided by N_2-fixing bacteria (Pérez, *et al.*, 2005; Coelho *et al.*, 2003).

Integrated Plant Nutrient Management programmes should maximize BNF within the constraints of cropping systems and soil and climatic resources.

Mycorrhizae are symbioses that improve nutrient uptake

Mycorrhizae are associations between fungi and plant roots. Mycorrhizae fungi colonize plant roots and depend on the host plant for energy. The beneficial effect of mycorrhizae on plant nutrition is to improve nutrient uptake, especially nutrients of low mobility in soil solution, such as P. Mycorrhizae also improve water uptake, which has a positive interaction with nutrient use efficiency. The mycelia network of mycorrhizae increases nutrient uptake beyond the distance normally influenced by the plant root. For example, P uptake per unit root length in mycorrhizal plants is generally two to three times higher than in non-mycorrhizal plants (Tinker *et al.*, 1992). However, benefits to plant growth decrease as soil P levels increase because plant demand is met by uptake through the roots without need for the mycorrhizae mycelia. Mycorrhizae have also been shown to increase Zn and Cu uptake by both maize (Kothari *et al.*, 1990) and soybean (Lambert and Weidensaul, 1991). Practices that promote the potential of indigenous mycorrhizae, e.g. reduced tillage, should have positive benefits on plant nutrition in soil systems with low plant available nutrient levels.

Manufactured fertilizers compensate for lack of nutrients from other sources

Manufactured fertilizers are materials applied to soils for their ability to supply the nutrients required by crops, and are generally purchased from off-farm sources. In this brochure, the term manufactured fertilizers is restricted to those materials produced from mining of naturally occurring nutrient deposits or from industrial fixation of atmospheric N_2 into plant-available forms.

The most widely utilized manufactured fertilizers, their nutrient content and physical state are shown in Table 7. The nutrients in these fertilizers are all water-soluble and plant-available with the exception of rock phosphates and some superphosphates. Plant availability of the P in rock phosphates depends on the solubility of each rock source. The

Table 7. Most widely utilized manufactured fertilizers, nutrient content and physical state.

Fertilizer	Nutrient content (%)						Physical state
	N	P_2O_5	K_2O	CaO	MgO	S	
Anhydrous ammonia	82						Gas
Urea	45-46						Solid
Ammonia nitrate	33-34.5						Solid
Calcium ammonium nitrate	20.4-28						Solid
Urea ammonium nitrate	28-32						Liquid
Ammonium sulfate	21					24	Solid
Monoammonium phosphate	11	48-55					Solid
Diammonium phosphate	18-21	46-54					Solid
Calcium nitrate	15			34			Solid
Potassium nitrate	13		44	0.5	0.5	0.2	Solid
Rock phosphate		25-40*					Solid
Single superphosphate		16-22				11-12	Solid
Triple superphosphate		44-53				1-1.5	Solid
Potassium chloride			60-62				Solid
Potassium sulfate			50-52			17	Solid
Potassium magnesium sulfate			22		22	11	Solid

*Available P ranges from 14-65% depending on the rock phosphate source.

superphosphate sources are not completely water-soluble, but P availability generally ranges from 97 to 100%. Anhydrous ammonia is the only gaseous fertilizer, and it must be injected below the soil surface to avoid loss through volatilization. Anhydrous ammonia is utilized for maize and wheat production in North America but, worldwide, it mostly serves in the manufacture of other N fertilizers and ammonium phosphates.

Manufactured fertilizers are essential to increasing crop yields and maintaining soil productivity and soil quality wherever crop harvests are moved to off-farm sites for human consumption, livestock consumption or industrial processing. When nutrients in crop yields are transported far from the site of crop production, it usually costs too much in energy and labour to return those nutrients, which are in the form of manures, biosolids or industrial by-products, to crop production sites. The use of manufactured fertilizers in these situations is essential. This need is particularly critical in areas where nutrient export from farms has occurred for many years without replenishment, with resulting decreased yields, increased erosion and reduced soil quality.

Of special note is the importance of the Haber-Bosch N fertilizer synthesis process. On a worldwide basis, Smil (2001) concluded that "for about 40% of humanity it [the Haber-Bosch process] now provides the very means of survival; only half as many people as are alive today could be supplied by pre-fertilizer agriculture with very basic, overwhelmingly vegetarian diets; and pre-fertilizer farming could provide today's average diets to only about 40% of the existing population." Because N is essential for protein production by plants, it is usually seen as the most critical nutrient. However, low levels of the other essential crop nutrients limit crop production in many regions. The use of manufactured P, K, S and micronutrient fertilizers in conjunction with N fertilizers in a balanced fertilization programme is a key part of a total crop production system that enhances crop yields and sustains soil productivity.

Organic matter is critical to maintaining soil productivity. Yet crop residues and/or manures cannot be returned to soils in many crop production systems where yield levels are not adequate to support food needs of the population. Soil degradation and declining production result in these situations as nutrients and organic residues are exported from the fields. Nutrients supplied in manufactured fertilizers can reverse the downward spiral in productivity and soil quality if nutrient applications are combined with management practices that increase yields and retain organic residues in the soil.

Major advantages of manufactured fertilizers are the higher concentration of nutrients compared to organic sources that reduce transportation costs, as well as the immediate plant availability of nutrients in most fertilizer products. Manufactured fertilizers also provide the possibility, through split and timely application, to deliver nutrients to the crop when required for most efficient uptake. In addition, manufactured fertilizers can be a pivotal component to re-establishing productive cropping systems that have been degraded by nutrient depletion although, under most circumstances, restoration of the productivity of degraded soils may be more complex and require a concerted effort combining manufactured fertilizers, organic inputs and adapted germplasm. Understanding the characteristics and proper use of manufactured fertilizers is fundamental to successful IPNM.

Realizing the potential for Integrated Plant Nutrient Management is both simple and complex

Crop production systems are complex; so increasing productivity enough to feed, clothe and provide bioenergy to the world's increasing population while limiting environmental impacts requires knowledgeable and motivated people. Successful implementation of IPNM has implications for both individuals and institutions. On an individual basis, IPNM requires a basic understanding of the following topics: (1) elementary chemistry; (2) essential plant nutrients; (3) organic and inorganic nutrient sources; (4) nutrient cycles in soil systems; (5) soil testing for essential nutrients (although in some places, other ways of assessing soil nutrient levels will be needed for the foreseeable future in absence of adequate infrastructure for large-scale and timely soil analysis); (6) crop nutrient removals; and (7) total crop production programmes. This is a lot of information for individuals managing soil fertility to understand. The right people need to be identified and trained across the world and deployed at the lowest geographical level feasible to address site-specific challenges in nutrient management for agricultural production.

Personnel in universities, research institutes, fertilizer companies, retail dealers, farmer unions, extension/outreach organizations and financial institutions must: (1) understand local or site-specific nutrient needs; (2) establish efficient programmes to provide nutrients using all available sources; (3) strive to increase crop production and nutrient use-efficiency for the overall improvement (food and nutrition[2] security and environmental quality) of society; and (4) develop site-specific IPNM strategies to optimize and sustain crop productivity.

Food and nutrition security coupled with enhanced environmental quality frees up resources to work on resolving other societal issues. Making IPNM a reality opens the door for significantly improving the quality of life for much of the world's population, and deserves a high priority in scientific, government and industry efforts.

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[2] *Nutrition security takes into account whether diets are balanced or not, whereas traditional measures of food security focus on calorie counts but have overlooked important nutrient deficiencies.*

Integrated Plant Nutrient Management must be a joint effort

Policy makers, research, extension, agribusiness, the fertilizer industry and farmers each have key roles for successful implementation of IPNM. These groups must cooperate and coordinate their activities to achieve the most rapid result.

How can policy makers encourage IPNM?

1. Provide funding to build laboratories in research institutions and extension agencies to conduct research and provide advisory services, as well as support the training and employment of individuals to utilize the laboratories, interpret data and provide advisory services;
2. Support a comprehensive effort at the local level to assess and summarize data on nutrient needs to realize crop yield potentials and develop nutrient budgets;
3. Establish and assign primary responsibility to a specific institution for providing farmers and agribusiness with comprehensive IPNM information for specific crops and soils; and
4. Support the development of transportation, banking and marketing infrastructures that ensure appropriate nutrient sources are available to farmers at the proper time so that crop yield potentials are reached with least cost.

Research institutions must improve the understanding of IPNM

The research community plays a vital role in widening knowledge about nutrient management under various conditions and developing tools to improve management. Some specific tasks for researchers include the following:

1. Continually conduct research on crop nutrient needs, nutrient sources, application methods and nutrient budgets to increase understanding of IPNM at local levels, and provide up-to-date information to all stakeholders, with a focus on increasing nutrient use efficiency;
2. Develop tools facilitating the implementation of IPNM by farmers whose access to tools and techniques varies, e.g. software for nutrient budgeting, leaf colour charts, rapid soil test kits and simplified ways to determine manure application rates;
3. Develop relevant courses based on current, local research in the following topics: (a) soil fertility assessment; (b) nutrient cycling in soils, manures and crop residues; (c) crop growth and nutrient needs; (d) fertilizer materials; and (e) fertilizer application methods and timing for specific crops, soils, environmental conditions and nutrient sources;
4. Provide high quality instruction for extensionists and agribusiness personnel; and

5. Produce training materials for extensionists, agribusiness and fertilizer industry personnel that show the application of IPNM in region-specific situations.

Extension and agribusiness are key links for optimizing IPNM implementation

Providing links between policy makers and researchers on one hand and farmers on the other, extension agents and agribusinesses both play an important function to help farmers understand their role in meeting wider policy goals, and to help farmers stay at the cutting edge of knowledge about nutrient management. Some of the things they can do include:

1. Develop and deploy relevant communication tools to raise farmers' awareness of the economic, social and environmental benefits of implementing IPNM;
2. Conduct field demonstrations applying locally-adapted IPNM and prepare literature with the results from the local demonstrations;
3. Assist farmers in making the best decisions for managing crop nutrients at the field and farm levels; and
4. Provide farmers with all necessary products, services and information to successfully implement IPNM.

How can the fertilizer industry contribute to IPNM?

Fertilizer manufacturers must also contribute to optimal nutrient use. Some things that the fertilizer industry should be doing include:

1. Developing and supplying the most appropriate fertilizer materials for each major agro-ecological region and crop, as determined by local research;
2. Conducting field demonstrations in cooperation with local extension organizations and agribusiness on the most appropriate use of fertilizers for specific crops, soils and farming systems; and
3. Training agribusiness retailers to consider all other available nutrient sources and then to select the most appropriate fertilizer products, application rates, methods and timings for specific crops and soils.

Key steps to IPNM implementation by farmers

At the end of the day, the most important people for good nutrient management are the farmers themselves. The other actors listed in this section are enablers, but it is farmers who manage the land directly. The steps that they can follow to apply IPNM include:

1. Evaluate all fields for crop yield potential;
2. Determine residual nutrient availability and major yield-limiting factors for each field;

3. Assess availability of on-farm nutrients from animal manures, plant residues, green manures, cover crops, symbiotic N_2 fixation by legumes and nutrients in irrigation water;
4. Calculate and prioritize supplemental nutrient needs for each field and crop (priorities are generally determined by greatest yield increase for money and/or labour spent on supplying nutrients);
5. Establish the most efficient nutrient application programme with respect to crop, nutrient source, application timing, placement method and amount; and
6. Continually assess the results of nutrient applications in terms of crop yield and quality responses, residual soil nutrient levels and changes in soil quality.

Coordinated sustained efforts by the above-mentioned groups will increase the efficiency of nutrient use to the benefit of farmers, the environment, the economy and, most importantly, people in need of nutritious food, quality fibre and energy. Integrated Plant Nutrient Management is a concept that has universal application.

Integrated Plant Nutrient Management meets the need for improved nutrient management

Nutrient budgets and balances illustrate the vast array of nutrient management needs throughout the world. Integrated Plant Nutrient Management can and should be applied in all of these situations. Site-specific programmes should be developed to increase crop yields and food quality, improve nutrient use efficiency and reduce potential adverse environmental impacts that could arise from nutrient misuse, whether either too little or too much. Integrated Plant Nutrient Management is certainly one of the most important methods for meeting the challenge of increased food, feed, fibre and bioenergy production in sustainable agro-ecosystems.

Nutrient budgets and balances in agro-ecosystems provide vital health checks

Plant nutrient budgets are accounting exercises to monitor nutrient inputs and outputs of agro-ecosystems and provide the data for assessing nutrient balances. The major objective of a plant nutrient budget is to prevent nutrients being lost from the agro-ecosystem or accumulating excessively in the system. Agro-ecosystems are considered to be the most sustainable when nutrient inputs are in balance with nutrient outputs at an optimal level of crop production for the specific site.

Nutrient balances are used to do gross evaluations of system sustainability for crop production, soil quality and/or of the potential for nutrient losses to the air and water. The FAO publication entitled *Assessment of Soil Nutrient Balance* asserts that "agricultural intensification without adequate restoration of soil fertility may threaten the sustainability of agriculture" (Roy *et al.*, 2003). Nutrient balances can be calculated on national, provincial, watershed, farm and field scales, but budgets at the farm level serve slightly different purposes. Nutrient flows to and from fields, watersheds, provinces and countries are evaluated to determine if soil nutrient stocks are being depleted or enriched. Farm-level balances can be used as a daily management tool, whereas balances for agglomerations serve as indicators for policy-level management.

Simple evaluations conclude that if outputs equal inputs, then the system is in balance. However, nutrient budgets must be carefully evaluated as national, provincial, watershed and even farm budgets may mask extremely important field-specific imbalances. Moreover, simple evaluations ignore lost yield opportunities in soil systems producing low yields due to nutrient deficiencies, even though nutrient inputs and outputs may be in balance. Yield levels and nutrient balances change as nutrient deficiencies are addressed, and balanced site-specific fertilization is the most efficient crop nutrition programme.

Nutrient budgets for individual farms help manage nutrient sources

Nutrient budgets for individual farms provide information for the farmer to utilize in developing management plans for individual crops and fields. The components used to calculate a nutrient budget for an individual farm are shown in Figure 10. Internal nutrient flows on the farm are analyzed to determine potential areas for improving nutrient use. For example, in larger scale farms with livestock, purchased feed and supplemental fertilizers are usually major sources of nutrient inputs, while manure is the source of recycled nutrients on the farm, and animal products are major sources for nutrient exports. For arable farms, fertilizers are the major source of nutrients into the farm and crop products are the major source of exports.

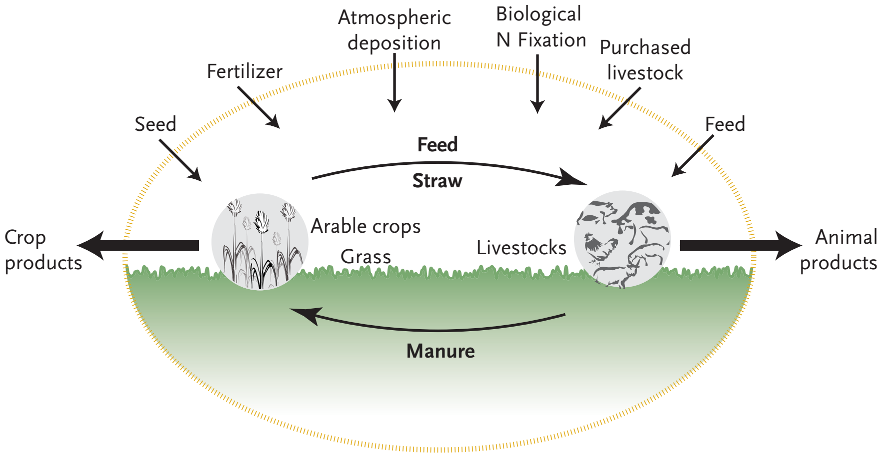


Figure 10. Nutrient budget components for a livestock farm (Adapted from Domburg *et al*., 2000).

The use of budgets to identify areas for improving nutrient use efficiency and decreasing adverse impacts is shown in work by Domberg *et al.* (2000). These researchers calculated nutrient budgets for individual farms in a 68,500 ha watershed in northeast Scotland. The data in Table 8 illustrates that the largest nutrient surplus occurred with the "pigs and poultry" farms, while the lowest surplus occurred with the "cereals" farms. These data enable targeting of education and demonstration programmes for improving nutrient use efficiency on farms with the greatest problems; in this case, farms with large amounts of nutrients in purchased feed and manure but with relatively small nutrient exports in farm products. For the watershed, the budgets clearly show nutrient surpluses, even for "cereals" farms. It must be noted that part of the N surplus can be considered as "virtual" because N inputs are subject to inevitable losses through different pathways.

Table 8. N and P budgets for various farm types in a northeastern Scotland watershed (Adapted from Domberg *et al.* 2000).

	N (kg/ha)			P (kg/ha)		
Farm type	Input	Output	Surplus	Input	Output	Surplus
Cereals	154	84	70	30	16	14
General cropping	212	108	104	56	23	33
Pigs and poultry	1030	510	520	320	119	202
Dairy	239	66	173	44	14	30
Cattle and sheep	192	74	118	17	8	10
Mixed	190	71	119	40	16	24

Nutrient budgets can also be calculated for individual fields for the purpose of comparing management practices and nutrient flows. Figure 11 shows nutrient budgets measured for organic rice fields in Japan (Hasegawa *et al.*, 2005). Nutrients were supplied as manure composts with and without straw removal, and with only straw incorporation. Balances were calculated as inputs minus removals during one season. All balances were positive except for K in the straw removal treatment, and researchers indicated that soil data were showing declining K fertility with straw removal. The major short-term concern in this situation is excess N and P in the compost systems, associated low nutrient use efficiency, and potential adverse impacts of continuing the same management practices.

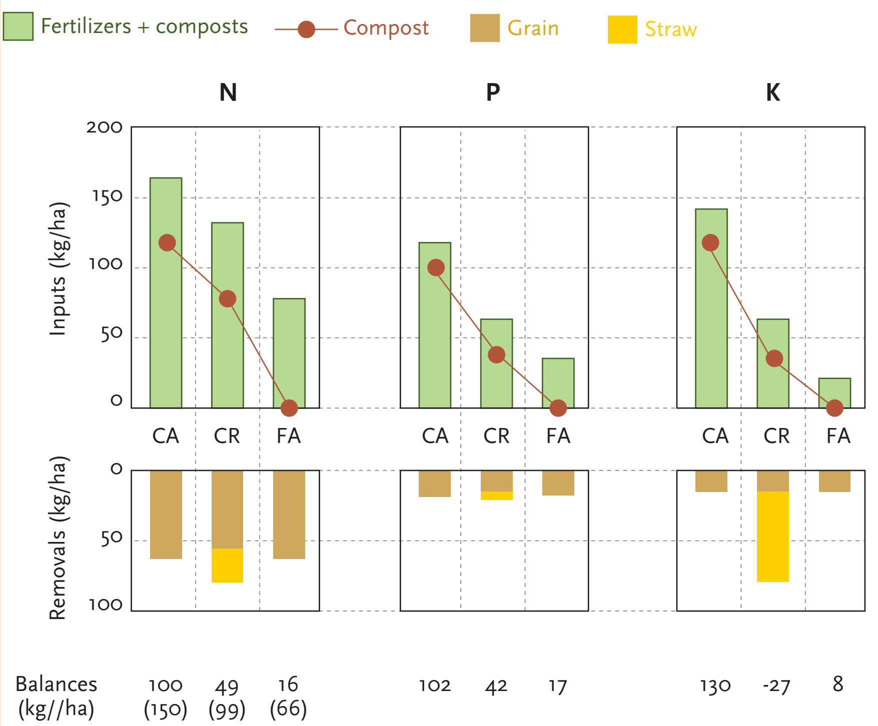


Figure 11. Nutrient budgets in organic paddy rice fields with differing organic amendments (CA = cattle/chicken compost; CR = cattle compost addition with rice straw removal; FA = rice straw incorporation). N values in parenthesis indicate N balances with biological N fixation estimated for the systems. Fertilizers used in this experiment were certified organic materials and included dried blood, plant cake, bone, feather and fish meals and bran (Adapted from Hasegawa *et al.*, 2005).

The farm and field level nutrient budgets discussed previously show that adequate to excessive nutrients were available to the farmers in both cases. Farm-level nutrient budgets must include all sources, and when nutrient supplies are limited, nutrients from the household may be important. Also, nutrient budget calculations on smallholder farms must consider the scale of nutrient cycling as nutrients may be concentrated near the household as livestock are grazed on communal pastures but maintained near the home (Figure 12).

The importance of considering all nutrient flows in systems with limited nutrient inputs, as well as the scale of the nutrient budget, can be seen in the work by de Ridder *et al.* (2004) measuring changes in soil fertility indicators as the distance from the village increased (Table 9).

Inflows

In1: mineral fertilizers

In2: organic inputs from outside the farm

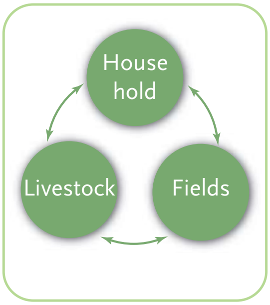
In3: atmospheric deposition

In4: biological nitrogen fixation

In5: sedimentation

In6: perennial crops taking up nutrients from the subsoil

Farm (internal flows)



Outflows

Out1: products leaving the farm

Out2: crop residues and animal wastes leaving the farm

Out3: leaching below the root zone

Out4: gaseous losses

Out5: erosion and runoff

Out6: human excreta disposed of in deep pit latrines

The balance of a given nutrient can be calculated as follows:

Balance = [In1 + In2 + In3 + In4 + In5 + In6] - [Out1 + Out2 + Out3 + Out 4 + Out 5 + Out 6]

Figure 12. Nutrient flow analysis for smallholder farms (Hilhorst and Muchena, 2000).

Table 9. Soil fertility indicators in relation to distance from a village in Mali (Adapted from de Ridder *et al.*, 2004).

Distance to village km	P-Bray mg/kg	N-total g/kg	Carbon-total g/kg	pH-KCl
0	45	1.1	10.0	7.0
1	3	0.6	4.6	6.9
2	2	0.6	4.6	5.8
6	3	0.4	3.3	5.1

Nutrient budgets for individual farms can reveal nutrient needs, inefficient nutrient use and the nutrient flows where changes in management and/or inputs could be of value. However, these budgets must be considered within the context of the farm location and the farming system in order to make wise decisions regarding possible management changes.

Nutrient balances cannot be used solely to derive crop fertilizer requirements

Soil nutrient mining is an option for farmers as long as they do not see responses in crop growth and yield when fertilizers are applied. If stocks of available nutrients in soils are high, relatively high cereal yields for the specific environment can still be obtained without adding fertilizers. Obviously, sustained nutrient removal means that nutrients will have to be replaced after some time, but the speed with which nutrients are depleted depends on the crop yields and the amounts of nutrients removed in relation to the soil's nutrient stocks. The major conclusion is that, in cases of nutrient-rich soils, nutrient balances cannot be used to indicate sustainability or to indicate fertilizer requirements without consideration of the nutrient stocks in the soil (Vanlauwe and Giller, 2006). Moreover, if a nutrient balance study indicates a deficit (i.e. an overall removal of nutrients), then simply supplying that amount of nutrients in the form of manufactured fertilizers is not sufficient to lead to a balanced nutrient budget since, particularly in the case of N, added fertilizer nutrients are subject to significant unwanted losses.

Plant nutrient budgets to study national and regional nutrient trends can help policy makers set priorities

For example, plant nutrient budgets have been used to quantify soil fertility depletion in Africa, unbalanced fertilization in China, and nutrient exports from intensive crop production regions of North America.

Case study 1: regional nutrient balances illustrate soil nutrient depletion in Sub-Saharan Africa

In Sub-Saharan Africa, soil fertility is severely affected by continuous soil mining. Atmospheric deposition is low, organic sources are often used for other purposes such as construction and fuel, and manufactured fertilizers are not available or affordable in much of the sub-continent. Table 10 gives average nutrient balances calculated for selected sub-Saharan African countries in the years 1982-84 and 2000. Nutrient balances were negative for both evaluation periods and tended to be worse in 2000, which reflects increased cropping intensity, greater erosion and lack of nutrient inputs from either organic or manufactured nutrient sources. While these data do not reveal anything about individual farms, the information shows disturbing national trends. These countries do not have sustainable agricultural systems. Urgent action is needed to reverse the situation and restore soil fertility in order to achieve food and nutrition security. This can be done through IPNM, which utilizes all available nutrient sources: animal manure, crop residues, biosolids, biological N fixation and manufactured fertilizers. Farmers should be encouraged to apply as much organic matter as possible to their land, and to include legumes in their crop mix. Also, appropriate policies must be developed to improve availability and affordability of manufactured fertilizers.

Table 10. Average nutrient balances for selected Sub-Saharan African countries (Adapted from Roy *et al.* , 2003)

Country	N		P		K	
	1982-84	2000	1982-84	2000	1982-84	2000
			kg/ha/year			
Benin	-14	-16	-1	-2	-9	-11
Botswana	0	-2	1	0	0	-2
Cameroon	-20	-21	-2	-2	-12	-13
Ethiopia	-41	-47	-6	-7	-26	-32
Ghana	-30	-35	-3	-4	-17	-20
Kenya	-42	-46	-3	-1	-29	-36
Malawi	-68	-67	-10	-10	-44	-48
Mali	-8	-11	-1	-2	-7	-10
Nigeria	-34	-37	-4	-4	-24	-31
Rwanda	-54	-60	-9	-11	-47	-61
Senegal	-12	-16	-2	-2	-10	-14
Tanzania	-27	-32	-4	-5	-18	-21
Zimbabwe	-31	-27	-2	2	-22	-26

Case study 2: national nutrient budgets influence nutrient use policies in China

Nitrogen inputs and outputs for China from 1961 to 1997 are shown in Figure 13. Nitrogen depletion was great throughout the 1980s, but the use of large amounts of fertilizer N (Table 11) essentially corrected the N depletion situation at the national level during the following decade. Input and output flows for P and K in Table 11

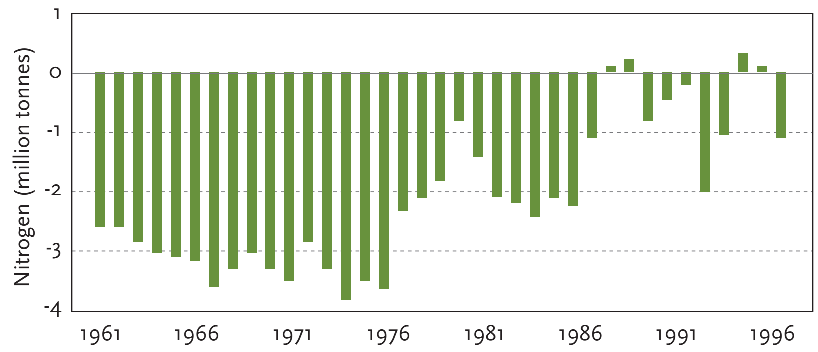


Figure 13. Nitrogen balances for China, 1961-97 (Adapted from Sheldrick *et al.*, 2003).

Table 11. Estimated nutrient input and output flows in arable farming in China in 1997 (Adapted from Sheldrick *et al.*, 2003).

	N million tonnes	%	P million tonnes	%	K million tonnes	%
Input flows						
Fertilizer	23.3	64.7	4.1	56.8	2.8	14.1
Crop residues	2.8	7.8	0.4	5.5	5.2	26.1
Manure	5.2	14.4	1.8	25.1	3.4	17.1
N fixation	1.0	2.8				
N deposition	1.4	3.8				
Sewage	1.2	3.4	0.3	4.3	0.3	1.5
From soil	1.1	3.1	0.6	8.3	8.2	41.2
Output flows						
Arable crops	12.0	33.4	2.3	31.2	4.6	23.0
Crop residues	7.0	19.4	1.0	13.8	12.9	65.0
Residual nutrient level increases and/or losses	17.0	47.1	4.0	55.0	2.4	12.0

includes a “from-soil” category, which represents the percentage of the nutrient supply that must be coming from soil reserves because it is not being supplied by any other source. If this percentage is high, as is the case for K, soils will become depleted over time.

The K data in Table 11 are in agreement with the high negative K balances calculated by Jiyun Jin *et al.* (1999) and shown in Table 12. Evaluation of the partial nutrient balances shows that all nutrient balances for the country were negative through 1975, but only K was still negative in 1995. This type of partial budget provides a rational basis for developing country-wide soil fertility education programmes to address major imbalances. China increased the use of N and P fertilizers greatly during the last two decades of the 20th century, and is now widely promoting balanced fertilization with increased use of K. With respect to the volumes needed, the largest share of this additional K is likely to come from manufactured fertilizers as K inputs from organic sources will probably not be sufficient.

Table 12. Nutrient balance in Chinese farmland, 1945 to 1995 (in 10,000 tonnes) (Adapted from Jiyun Jin *et al.* 1999).

	Input in organic form			Input in inorganic form			Output			Balance		
Year	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
1949	162	79	187	0.6	----	----	291	138	306	-129	-59	-119
1957	249	123	286	31.6	5.2	----	511	236	562	-246	-110	-276
1965	293	138	306	121	55	0.3	522	237	560	-169	-60	-254
1975	410	194	462	364	161	13	749	334	813	-157	-28	-338
1980	416	206	509	943	287	39	867	378	933	21	29	-385
1985	503	256	621	1259	408	109	1114	479	1208	19	63	-478
1990	526	280	693	1740	647	203	1279	559	1375	117	174	-478
1995	611	330	760	2224	995	376	1373	577	1455	350	449	-315

In contrast, emerging environmental problems linked to the mismanagement of N and P nutrient sources in parts of China, such as eutrophication of inland and coastal waters, call for development and adoption of better farming practices. These include site- and time-specific application determined by field-level nutrient budgets. Animal manure and biosolids should be better recycled. Similarly, high atmospheric N deposition rates, which can reach up to 80 kg N/ha/year in the North China Plain (Zhang *et al.*, 2006), must be taken into account in the nutrient balances.

Case study 3: nutrient budgets mask residual soil nutrient supplies in North America

Partial nutrient budgets for North America are shown in Tables 13 and 14. Nitrogen balances are positive in all regions, even for the six major maize-producing states with very large crop production areas. However, P and K budgets for the six leading maize states are slightly negative, indicating the export of nutrients in maize and soybean crops. For North America as a whole, the partial P budgets suggest that removals are slightly less than applications but K budgets are clearly negative. This reflects the high native K supplying capacity of soils in the Great Plains region of North America. More K is being removed than is being applied, but crops are not K deficient because of the high native K supply. However, the inherent K supply is finite, and soil testing should be used regularly to identify declining K availability before deficiencies become widespread.

Table 13. Partial N balance for North America, average of 1998-2000 (Adapted from Fixen and Johnston, 2002).

Region	Crop removal	Biological fixation	Applied fertilizer million tonnes	Manure	Balance*
USA – six major maize states	6.6	3.8	4.0	0.23	1.4
USA	14.6	7.1	11.2	1.2	4.9
Canada	2.3	0.64	1.65	0.13	0.12
North America	16.9	7.74	12.85	1.33	5.02

*Balance = (biological fixation + applied fertilizer + manure) – crop removal

Table 14. Partial P and K balances for North America, average of 1998-2000 (Adapted from Fixen and Johnston, 2002).

Nutrient	Region	Crop removal	Applied fertilizer	Manure	Balance
		million tonnes			
P_2O_5	USA – six leading maize states	2.3	1.4	0.41	-0.59
	USA	5.2	4.0	1.5	0.32
	Canada	0.85	0.69	0.18	0.02
	North America	6.05	4.69	1.68	0.34
K_2O	USA – six leading maize states	3.0	1.86	0.45	-0.68
	USA	8.8	4.59	1.73	-2.45
	Canada	1.2	0.35	0.23	-0.62
	North America	10.0	4.94	1.96	-3.07

Nutrient budgets can be used to assess potential environmental problems

Nutrient budgets have been used in Europe and North America to raise awareness of potential environmental problems associated with nutrient accumulation from high levels of manure application (Goodlass *et al.* 2003). Many of the nutrients contained in imported feed stuffs are eventually exported from the farm in meat and dairy products. Others may be applied to the land in the form of animal manure, which needs to be carefully managed to avoid exceeding crop needs. Graphic representations of nutrient balances such as the one shown in Figure 14 help farmers understand the implications of their nutrient management decisions.

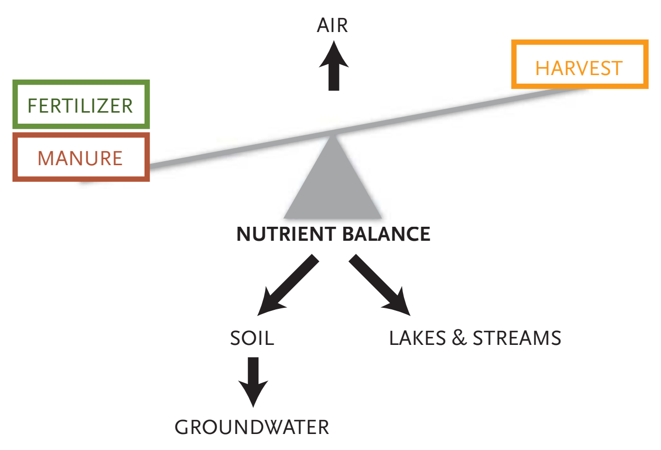


Figure 14. Simplified nutrient balance diagram illustrating potential environmental problems associated with excess nutrient inputs relative to crop removal (Adapted from Parker *et al.*, 2006).

Data on P balances in Rockingham County, Virginia (USA), where intensive dairy and poultry production are coupled with a limited arable crop area, are shown in Table 15. The large P surplus in this county is associated with feed grain imports. Although inexact, these balances are useful in showing that, despite progress in reducing the excess P balance since its peak in 1997, efforts are still needed to transfer manure from this region to other areas with cropland.

Table 15. Phosphorus balances for Rockingham County, Virginia (USA) for 1992, 1997 and 2002 (Parker *et al.*, 2006).

Factor	1992	1997	2002
		tonnes	
P inputs	5187	6012	4878
P outputs	819	775	762
Balance	4368	5237	4116

Environmental concerns about N and P enrichment associated with continued nutrient build-up in soil systems has led to regulations being imposed on livestock farms in both North America and Europe. Nutrient budgets are used to measure overall progress towards more balanced systems. For example, N and P budgets calculated by the Organisation for Economic Co-operation and Development (OECD) for member countries are now used by policy makers as environmental indicators (OECD, 2001). The assumption is that if nutrient inputs to an area are greater than nutrient removals by crop production, especially of N and P, then the excess nutrients have the potential to be lost to ground water, surface waters and the atmosphere. Excessive nutrient imbalances are often concentrated in relatively small areas, but the influence on downstream water quality can be dramatic. Nutrient budgets for whole farms can increase awareness of environmental concerns by individual farm operators and encourage changes in nutrient use practices.

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