Plant Nutrient Use in North American Agriculture

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Preface

Meeting the world's demands for food, fiber, and fuel has never been more critical…and has never been more closely scrutinized by an ever-watching public. People want safe, wholesome, and affordable food that has been produced in an environmentally friendly manner. The public understands that nutrients are needed for food production, but are confused about the role, the source, and the management of plant nutrients. Misunderstanding about the differences and similarities of organic and inorganic nutrients is the source of much of the confusion.

This bulletin was written to help dispel the myths and clarify the misunderstandings regarding plant nutrients and to look at their use in today's agriculture. It reviews current information on their sources, their transformations, their availability, their management, their economics, and their effect on food quality and the environment. Nutrient budgets for North America are also discussed. Our hope, in reviewing the recent science, is to shed additional light on a complex subject and provide a comprehensive assessment of essential plant nutrients and their management in North American agriculture.

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President
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Plant Nutrient Use in North American Agriculture

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The 10 chapters which follow in this publication discuss numerous aspects of nutrient management in reference to inorganic and organic sources. Several myths or perceptions, some of which are incorrect, are addressed. Nutrient cycles, nutrient status in North America, and crop nutrient requirements are covered, along with historical nutrient use and the long-range availability of ore bodies used to produce inorganic fertilizer sources. Economics of nutrient use, nutrients and environmental quality, and nutrients and product quality are highlighted. There are chapters dedicated to inorganic and organic nutrient sources. In this executive summary, we do a broad-brush overview of the information contained in the other chapters, concentrating on key issues that affect inorganic and organic nutrients and their use in North America.

- Organic substances are found to some extent in all agricultural soils and are continuously in some state of decomposition, or transition, back to the inorganic form.
- Organic sources of nitrogen (N), phosphorus (P), sulfur (S), and other nutrients are generally converted to inorganic forms before crop plants can use them.
- A 2001 PPI/PPIC/FAR survey of 2.5 million soil samples showed that 47 percent tested medium or below in P; 43 percent tested medium or below in potassium (K).
- Understanding site-specific nutrient requirements and optimum rate, time, and method of nutrient application is essential for improving crop yield, quality, and profitability while protecting the environment.
- Inorganic N fertilizer use has leveled off, and P and K use has dropped in recent years while crop yields continue to climb, resulting in an apparent increase in fertilizer use efficiency. At least a part of the apparent improvement in efficiency for P and K is the result of mining (depletion) of organic and inorganic soil nutrients.
- The amount of farm-level manure will continue to increase as confined livestock numbers rise. Also, the percentage of recoverable nutrients will likely increase as handling and processing facilities improve.
- In enterprise budgeting, when manure is used, it should be sold or charged as an expense to the crop on which it is applied and treated as an income for the farm livestock enterprise where it was produced.
- The growing challenge in agriculture is to find ways to increase crop yields and improve nutrient use efficiency while stabilizing nutrients (not removed in harvested crops and forages) in crop residues and in the soil.
- Scientists have concluded that organic foods are neither healthier nor safer than conventionally produced products.
- Manufactured mineral fertilizers are the primary nutrient sources in North America, although significant amounts are provided through N fixation by legumes and the application of manure.

The paragraphs which follow provide capsule summaries of each chapter.

Introduction to Nutrient Use—Chapter One

Both inorganic and organic nutrient sources are available for use in crop production in North America and, indeed, throughout the world. Of the 17 essential nutrients, N, P, and S are present in both inorganic and organic forms in soils (see **Table 1.3**).

Organic substances are found to some extent in all agricultural soils and are continuously in some stage of decomposition, or transition, back to the inorganic form. As they decompose (mineralize), organic materials contribute to the total inorganic nutrient pool that supports the production of the world's food needs. Attempting to separate them from inorganic elements is difficult and of limited value because nature's processes are constantly cycling them from one form to another. Further, in the context of geologic time, elements exist only momentarily in the organic form, soon returning to their natural, inorganic state.

The most critical aspect of nutrition, plant and animal, is not the balance between inorganic and organic intake, but poor growth or health because of deficiencies of essential nutrients. In plants, deficiencies can be overcome by providing essential nutrients in balanced, adequate amounts by supplementing soil levels with fertilizers, both inorganic and organic.

Transformations of Nutrients in Soils—Chapter Two

Atmospheric N is the primary source of all soil N forms, inorganic and organic. Organic N, however, must be converted to ammonium (NH_4^+) or nitrate (NO_3^-) before crop plants can take it up for metabolic use, as shown in the N cycle (**Figure 2.1**).

Once N enters the soil, it is subject to many **transformations**, the number and type being the same, regardless of the input source, even though source does determine which transformations dominate. For example, N from organic sources becomes a part of soil organic matter, a portion of which will be converted to inorganic N through the process of **mineralization**. In a similar manner, inorganic N can be converted to organic N through **immobilization**.

The NH_4^+ ion is less mobile in the soil because it is attracted to and held (adsorbed) by the negatively charged surfaces and edges of soil particles. The NO_3^- ion is not attracted to the soil, so is easily leached through the soil profile. Nitrate can be converted to gaseous forms through the process of **denitrification** under certain soil conditions. These gases then return to the atmosphere. Ammonium can also be converted to ammonia (NH_3) gas and lost from the soil to the atmosphere through **volatilization**.

Because of the above transformations, managing N so that it is used most efficiently by the crop being fertilized is critical to environmental protection and potential farmer profits. Since the N in organic sources must be converted to an inorganic form before crop plants can use it, proper management is required to minimize volatilization losses, surface runoff, and leaching. In this regard, it is much easier to work with inorganic N sources.

Similar to N, mineralization converts organic P to inorganic forms, and immobilization transforms inorganic P to organic forms. Plants absorb only inorganic P sources, as shown in the soil P cycle (**Figure 2.2**). The two primary species of inorganic P in the soil solution are monohydrogen orthophosphate (HPO_4^{2+}) and dihydrogen orthophosphate ($H_2PO_4^-$).

The soil K cycle is shown in **Figure 2.3**. Unlike N and P, K exists in organic sources as inorganic K, not as a structural component of organic compounds. It is taken up by plants as the inorganic K^+ ion.

Status of Soil Nutrients in North America—Chapter Three

According to a 2001 PPI/PPIC/FAR soil test survey of about 2.5 million samples, there is significant potential for North American farmers to improve nutrient management. Survey results showed that 47 percent of the soil samples collected for the 2001 crop year tested medium or below in P (**Figure 3.4**). The Northern Great Plains had the lowest regional P levels; the Northeast the highest.

Similar results were found for soil test K, with 43 percent of the samples testing medium or below (**Figure 3.8**). Highest soil K levels were found in the Great Plains and West while the Northeast and Southeast were the lowest.

Generally, in regions where manure production is high relative to crop nutrient removal, lower percentages of soil samples tested medium and below. Comparing the results of the 2001 survey (the eighth completed by the Institute) to earlier surveys, the percentages are trending even lower. At the same time, P soil fertility appears to be decreasing in the heart of the Corn Belt while K levels seem to be in decline in the eastern states of the Corn Belt. These data are supported by nutrient budget estimates for the region that show crop removal exceeding P and K application.

Survey results emphasize the importance of routine soil testing to monitor soil fertility of individual fields and develop and implement nutrient management programs that will maintain soil fertility at optimum levels. This will require efficient use of both inorganic and organic nutrient sources and is essential to sustain high yield crop production.

Crop Nutritional Needs—Chapter Four

Agriculture's greatest challenge is to continue to increase crop yields per unit of land farmed to meet the food requirements of a growing world population. It is no secret that proper nutrient management has been and continues to be critical to advances in crop production. Understanding site-specific nutrient requirements and optimum rate, time, and method of nutrient application is essential for improving crop yield, quality, and profitability while protecting the environment.

Yields have increased significantly in North America during the past 40 years (**Tables 4.1a and 4.1b**). As they do, so do nutrient requirements. Soils must be fertile to meet the growing-season demands of a high yielding crop. Research has shown that under the best growing and response conditions the optimum recovery of applied nutrients is 70 percent for N, 20 for P, and 30 for K. Much of the unused nutrients will be available for subsequent crops, but the fact remains that soils must be high in fertility to keep nutrient supply from being a limiting yield factor.

Inorganic Nutrient Use—Chapter Five

Commercial fertilizers were introduced to North American agriculture in the form of Peruvian guano (seabird droppings) in the 1840s. Production of inorganic superphosphate and mixed fertilizers began in the U.S. soon after the process for acidulating phosphate rock with sulfuric acid was patented in England in 1842. The development of the K industry was accelerated following the outbreak of World War I. Major K deposits were discovered in New Mexico in 1925, and high grade reserves were discovered in Saskatchewan in 1943.

The development of the N fertilizer industry lagged behind P and K until after World War II. The first successful synthetic NH_3 plant was built in the U.S. in 1921. Within the next 10 years, several plants were operational. The first NH_3 plants in Canada came into production during the 1940s.

The use of commercial NPK fertilizers in the U.S. and Canada increased rapidly after the middle of the last century, tripling between 1961 and 1980 (**Figures 5.1**, **5.2**, and **5.3** and **Appendix 5.1**). Higher fertilizer consumption during this period corresponded to increases in average crop yields. This relationship should not be surprising since it has been estimated that nutrient inputs are responsible for up to 50 percent of total crop yield. While there are serious challenges to documenting such estimates, they are generally supported by research. For example, data from long-term studies representing 157 years of crop production (reported in Chapter Five), with significant variability in crop response to nutrient applications because of crop species, climate, and other factors, indicate that fertilizer's contribution to total crop yield is in the 30 to 50 percent range.

Since the late 1970s, P and K removal/use ratios in the U.S. have been steadily increasing. They have also been increasing in Canada, but at a much slower rate. In fact, both the U.S. and Canada have been **depleting** soil P and K for several years if organic nutrient use is not taken into account. However, only a small percentage of cropland actually receives nutrients from manure…17 percent of the corn acres and 6 percent of the soybean acres…in the U.S.

Even though inorganic fertilizer N use has leveled off and P and K use has dropped in recent years, crop yields continue to climb. As a result, apparent fertilizer use efficiency has increased. While we should continue to strive to improve nutrient use efficiency, we should also keep in mind that at least a part of the apparent improvement in efficiency is the result of **mining** (depletion) of soil nutrients.

The world's P- and K-containing ore bodies are finite non-renewable resources, and estimates of reserves and availability of exploitable deposits are difficult to predict. However, at current production levels, North America has sufficient P ore reserves to last about 25 years at today's costs and practices and almost 100 years of reserves if higher cost ore is included. Longevity of K ore reserves should be of no concern, with supplies sufficient to last hundreds of years.

Organic Nutrients—Chapter Six

Organic nutrient sources are economic and agronomic resources that can supplement inorganic fertilizer use. They contain varying concentrations of essential nutrients and provide organic carbon (C) that enhances physical properties of soils. However, they can be potentially damaging to the environment because of excessive NO_3^- leaching to groundwater, P moving to surface waters through runoff and erosion, and NH_3 loss to the atmosphere. Indiscriminate use of animal manure and sewage sludge can also create human health hazards because of the accumulation of heavy metals and pathogens. A further challenge of managing manure as a nutrient source is that of variable composition, as shown in **Table 6.1**.

The dominant source of livestock manure potentially recoverable in North America is from confined animal operations including beef cattle, dairy, swine, and poultry…about 38 million animal units (AU, 1,000 pounds of live animal weight) in the U.S. (**Table 6.3**). The total number of such operations is declining, but average size is increasing.

Nutrients from manure that are available for land application in North America were recently estimated at about 2,865 million pounds of N, 3,691 million pounds of P_2O_5, and 4,318 million pounds of K_2O (**Table 6.5**). Much of this manure is already being used in crop production, so it represents a part of the nutrient pool rather than a potential addition. It is uncertain, however, what proportion of the nutrients from manure is being efficiently utilized as opposed to that being disposed of as a waste.

The amount of collectable farm-level manure will continue to increase as confined livestock numbers rise. Also, the percentage of recoverable nutrients will likely increase as handling and processing facilities improve. There is a wide range in recoverable nutrients, depending on livestock type and other factors (**Table 6.8**). In the U.S., average recoverable nutrients are about 20 percent of the excreted N and 37 percent of excreted P and K.

Historically, manure has been applied based on its N content, but repeated applications on the same areas have resulted in a buildup of soil P. Guidelines are now being developed to evaluate the environmental hazards associated with this excess P and how they can be minimized through controlled application rates.

Economics of Nutrient Systems and Sources—Chapter Seven

The long-term economic viability of crop production depends on sound management decisions such as the selection of nutrient sources. Commercial fertilizers are the most common source used, but can be supplemented or sometimes replaced by crop rotation (primarily N from legumes), livestock manure, and other organic sources. Economic analysis of the nutrient management plan becomes more complex when organic nutrient sources are used.

Nutrient use should be evaluated on the basis of all crops in a rotation as well as the entire farm enterprise. In enterprise budgeting, when manure is used, it should be **sold** or charged as an expense to the crop on which it is applied and treated as an **income** for the farm livestock enterprise where it was produced. If the farm has no livestock, there may still be an opportunity to obtain manure from local concentrated livestock operations. It is important to analyze the value of manure compared to commercial fertilizer as a nutrient source.

Proper nutrient rates and sources as well as most profitable crop rotations can be determined by economic analyses of various cropping system scenarios. Although nutrient management is obviously an important consideration in selecting crop rotations, decisions are based on a variety of agronomic, logistical, and economic factors…including risks, timing of machinery operations, and pest management.

Organic crop production systems that depend entirely on manure and other organic sources face certain limitations, including economic considerations. They tend to be centered around specific markets. Favorable economics depend, to a large extent, on the availability of organic nutrient sources, the ability to produce profitable yields, and the dependability of markets. Organic certification may be useful for marketing, but certification guidelines are quite restrictive. Organic production systems can be an economically sound alternative for those who are willing and able to participate in the limited opportunities to market products.

Nutrients and Environmental Quality—Chapter Eight

Nutrient use in North American agriculture is associated with several issues, including improvements in crop yields and crop quality as well as impact on the environment. It affects surface and groundwater quality and potential pollution, is associated with greenhouse gas evolution and global warming, and impacts heavy metal accumulation in agricultural soils.

The application of nutrients in balance with crop needs helps to maintain and build soil quality, reduces the potential negative environmental effects of N and P, and supports the buildup of soil organic matter. Both inorganic and organic nutrient sources impact mycorrhizal and earthworm activity. Properly applied, crop nutrients enhance soil biology.

Long-term use of P fertilizers can increase the level of heavy metals and other trace elements in the soil. However, loading rates are considerably higher from typical biosolids applications than from typical P fertilizer use.

Excess N and P can lead to algal blooms and eutrophication. It is not unusual to find a prevalence of confined animal feeding operations associated with excessively high soil P levels in mineral soils.

Carbon dioxide emissions from agriculture are due to the burning of fossil fuels and decomposition of organic matter and crop residues. Most methane comes from ruminant animals, livestock manure, wetlands, and rice production; little is emitted as a result of fertilizer use.

The growing challenge in agriculture is to find ways to increase crop yields and improve nutrient use efficiency while stabilizing nutrients (not removed in harvested crops and forages) in crop residues and in the soil.

Nutrients and Product Quality—Chapter Nine

The traditional belief that organic manure promotes **quality** while mineral fertilizers promote **quantity** has been proven by research to be over simplistic. Managing nutrients affects both quality and output of various cropping systems. Nutrient inputs should be chosen to efficiently provide balance for optimum results, specific to each soil and crop.

Crop quality factors such as protein, phytate (phytic acid), and trace mineral bioavailability can be manipulated by properly managing N and P fertilization. Nitrogen, P, and K have been shown to increase sugar content in sweet corn, and increasing K levels boosted Vitamin C levels in several vegetable crops.

Functional foods are defined as foods that contain bio-active ingredients thought to enhance health and fitness. The active ingredients are **phytochemicals** and are often called **nutraceuticals**. Functional foods are associated with the prevention and treatment of diseases such as cancer, diabetes, hypertension, and heart disease.

While few of the phytochemicals with nutraceutical properties contain N, P, or K in their chemical structure, they are formed as a result of photosynthesis and are thus dependent on the availability of essential nutrients. For example, research has shown that K has a positive influence on isoflavone levels in soybeans and lycopene in tomatoes.

Certain plant diseases can be suppressed by application of balanced nutrients. In recent research, chloride (Cl^-) has been shown to reduce the incidence of several diseases in small grains.

Comparing the relative effectiveness of organic versus conventional farming in producing high quality food is difficult. Scientists have concluded, however, that organic foods are neither healthier nor safer than products of conventional farming.

Nutrient Budgets in North America—Chapter Ten

Nutrient budgets are valuable in that they provide insight into the balance between inputs and outputs in crop production. Unlike financial budgets, however, they are only partial budgets because of inaccuracies in determining inputs/outputs. There are many sources of error, including variations in crop removal, estimation of N fixation by legumes, nutrient compositions of various manure sources, etc.

Manufactured mineral fertilizers are the primary nutrient sources (inputs), although significant amounts are provided through N fixation by legumes and the application of manure. In North America, only N fertilizer use increased during the last 20 years of the 20th century, with minor declines in P and K use. The ratio of N to P_2O_5 and K_2O nearly doubled during that time. Also, there was a large increase in the numbers of livestock grown in confined feeding operations (**Table**

6.3), significantly increasing the amounts of recoverable manure nutrients.

Crop nutrient removal (outputs) occurs in the forms of grains, oilseeds, fiber, hay, and forage that are exported from production fields. Other outputs include erosion losses, leaching, dentrification, and volatilization.

Nitrogen budgets show that for North America, the amount of N removed in harvested crops is equivalent to about 77 percent of inputs. Nitrogen recovery in the leading U.S. corn states is about 82 percent, compared to 75 percent for the U.S. as a whole. Recovery in Canada is 94 percent. The partial P budget for North America shows that removal exceeds P applied as fertilizer by 29 percent. When recoverable manure is included in the evaluation, removal represents 95 percent of inputs. The partial K budget shows that crops currently remove twice the amount of K being applied as fertilizer. When all recoverable manure is considered, removal still exceeds input by 44 percent. In the leading U.S. corn states, removal of P and K exceeds fertilizer applied plus recoverable manure by approximately 30 percent.

With increasing numbers of confined livestock and, thus, more recoverable manure, nutrient management is becoming more of a challenge. Because of high costs of transporting manure, over-application on lands near confined animal areas is a potentially serious problem. The dilemma of manure distribution makes the development of realistic nutrient budgets a serious challenge for agriculture.

Appendix

More detailed tables of data relevant to specific chapters are provided in the Appendix section at the back of this publication.

Chapter One

Introduction to Nutrient Use: Inorganic and Organic Nutrients

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Synopsis: While there are differences, inorganic and organic nutrient sources also have similarities. It is important to understand their advantages and disadvantages, as well as their limitations.

The word **nutrient** is a derivation of the word nutrition, which implies food. The term **essential nutrients**, then, is redundant in the sense that essentiality is defined as necessary to sustain life, and food sustains life. In the plant world, an element is considered essential if it is necessary for the plant to complete its life cycle, including vegetative and reproductive phases…and no other element can substitute for it completely.

The periodic table is a chart constructed by scientists to organize all of the known atomic sized structures that make up the physical components of the Earth, its land surface, oceans, atmosphere, and all living organisms, including humans (see **Table 1.1**).

In **Table 1.1**, the periodic table has been altered to identify those elements that are currently considered to be essential for plants and animals. Plant-essential elements are highlighted with lower triangles, animal-essential with upper triangles. Notice that several elements are essential for both plants and animals. The essential elements make up only a small proportion of the total known elements. They include gases, metals, and non-metals. Essential elements exist naturally, in both **organic** and **inorganic** forms.

Table 1.2. Ten most abundant elements in the Earth's crust.

Element	Chemical symbol	Abundance by weight	
		%	ppm[1]
Oxygen	O	46.10	461,000
Silicon	Si	28.20	282,000
Aluminum	Al	8.23	82,300
Iron	Fe	5.63	56,300
Calcium	Ca	4.15	41,500
Sodium	Na	2.36	23,600
Magnesium	Mg	2.33	23,300
Potassium	K	2.09	20,900
Titanium	Ti	0.56	5,650
Hydrogen	H	0.14	1,400

[1] Parts per million

Source: Weast and Astle, 1982

Scientists have made estimates of the amounts (weights) of each of the elements present in the uppermost part of the Earth's crust. **Table 1.2** lists the 10 most abundant, in percent by weight and in parts per million (ppm) by weight. **Table 1.3** shows the relative

Table 1.1. Periodic table of chemical elements showing those essential for animals and plants.

◥ Animal

◣ Plant

hydrogen 1 **H** ◥◣																	helium 2 **He**
lithium 3 **Li**	beryllium 4 **Be**											boron 5 **B** ◥◣	carbon 6 **C** ◥◣	nitrogen 7 **N** ◥◣	oxygen 8 **O** ◥◣	fluorine 9 **F** ◥	neon 10 **Ne**
sodium 11 **Na** ◥	magnesium 12 **Mg** ◥◣											aluminum 13 **Al**	silicon 14 **Si** ◥	phosphorus 15 **P** ◥◣	sulfur 16 **S** ◥◣	chlorine 17 **Cl** ◥◣	argon 18 **Ar**
potassium 19 **K** ◥◣	calcium 20 **Ca** ◥◣	scandium 21 **Sc**	titanium 22 **Ti**	vanadium 23 **V** ◥	chromium 24 **Cr** ◥	manganese 25 **Mn** ◥◣	iron 26 **Fe** ◥◣	cobalt 27 **Co** ◥	nickel 28 **Ni** ◥◣	copper 29 **Cu** ◥◣	zinc 30 **Zn** ◥◣	gallium 31 **Ga**	germanium 32 **Ge**	arsenic 33 **As** ◥	selenium 34 **Se** ◥	bromide 35 **Br**	krypton 36 **Kr**
rubidium 37 **Rb**	strontium 38 **Sr**	yttrium 39 **Y**	zirconium 40 **Zr**	niobium 41 **Nb**	molybdenum 42 **Mo** ◥◣	technetium 43 **Tc**	ruthenium 44 **Ru**	rhodium 45 **Rh**	palladium 46 **Pd**	silver 47 **Ag**	cadmium 48 **Cd**	indium 49 **In**	tin 50 **Sn**	antimony 51 **Sb**	tellurium 52 **Te**	iodine 53 **I** ◥	xenon 54 **Xe**
caesium 55 **Cs**	barium 56 **Ba**	lutetium 71 **Lu**	hafnium 72 **Hf**	tantalum 73 **Ta**	tungsten 74 **W**	rhenium 75 **Re**	osmium 76 **Os**	iridium 77 **Ir**	platinum 78 **Pt**	gold 79 **Au**	mercury 80 **Hg**	thallium 81 **Tl**	lead 82 **Pb** ◥	bismuth 83 **Bi**	polonium 84 **Po**	astatine 85 **At**	radon 86 **Rn**
francium 87 **Fr**	radium 88 **Ra**	lawrencium 103 **Lr**	rutherfordium 104 **Rf**	dubnium 105 **Db**	seaborgium 106 **Sg**	bohrium 107 **Bh**	hassium 108 **Hs**	meitnerium 109 **Mt**									

* lanthanoids	lanthanum 57 **La**	cerium 58 **Ce**	praseodymium 59 **Pr**	neodymium 60 **Nd**	promethium 61 **Pm**	samarium 62 **Sm**	europium 63 **Eu**	gadolinium 64 **Gd**	terbium 65 **Tb**	dysprosium 66 **Dy**	holmium 67 **Ho**	erbium 68 **Er**	thulium 69 **Tm**	ytterbium 70 **Yb**
* * actinoids	actinium 89 **Ac**	thorium 90 **Th**	protactinium 91 **Pa**	uranium 92 **U**	neptunium 93 **Np**	plutonium 94 **Pu**	americium 95 **Am**	curium 96 **Cm**	berkelium 97 **Bk**	californium 98 **Cf**	einsteinium 99 **Es**	fermium 100 **Fm**	mendelevium 101 **Md**	nobelium 102 **No**

amounts of organic matter and various essential plant nutrients present in temperate region soils. Note that three nutrients, nitrogen (N), phosphorus (P), and sulfur (S), are present in both organic and inorganic forms. Since crop plants grow in a thin layer of the Earth's crust, it is important that nutrient levels be maintained by the addition of nutrient sources, both organic (plant residue and animal wastes) and inorganic (manufactured mineral fertilizers).

Table 1.3. Total amounts of organic matter and plant nutrients present in temperate region soils.

Component	Expected range, %
Organic matter	0.40-10.00
Nitrogen[1]	0.02-0.50
Phosphorus[1]	0.01-0.20
Potassium	0.17-3.30
Calcium	0.07-3.60
Magnesium	0.12-1.50
Sulfur[1]	0.01-0.20
Iron	0.500-5.000
Manganese	0.020-1.000
Copper	0.005-0.015
Zinc	0.001-0.025
Molybdenum	0. 00002-0.0005
Boron	0.0005-0.015
Chloride	0.001-0.1

[1] Present in both organic and inorganic forms.

Source: Brady, 1978

Plants absorb carbon (C), hydrogen (H), and oxygen (O) from the carbon dioxide (CO_2) in the air and from water (H_2O) in the soil. Other nutrients must solubilize and become part of the mixture of compounds present in soil water, or soil solution. The chemical forms utilized by plants are shown in **Table 1.4**. Nearly all of these compounds exist in the soil solution as ionic species. The pathways taken to reach this plant-available form can be complex and varied. The processes by which these nutrients are transformed and move within the environment are termed cycles (see Chapter Two). Regardless of the form in which these elements first enter their respective cycles, they must be converted to the inorganic forms listed in **Table 1.4** before plants can utilize them. Thus all the foods we consume, whether plants or the animals that feed upon them, were produced by inorganic nutrients, even though a particular nutrient may have been supplied to the soil in an organic form.

Organic is a term that has become more prominent in recent years, especially in connection with food. Sometimes it is used to imply that food produced from organic nutrient sources may have some special characteristic, special health benefit, or perhaps greater nutritional value. This 'organic' designation, relative to nutrient use, refers to the practice of supplying plant nutrients only from additions of plant residues or animal wastes rather than from 'chemical' nutrient sources, implying that one is 'natural' and the other is 'synthetic'. Actually, any effort to differentiate foods from a nutrient source standpoint is of limited use because whether the source of nutrients is organic or inorganic, all nutrients are 'chemical'…all are 'natural' and exist in nature…and all organically supplied nutrients are absorbed by the plant *only* after they have been converted to their inorganic form. There is some value in realizing that the different sources of nutrients require different management to assure their efficient use.

Table 1.4. Form of the 13 essential elements taken up by plants from the soil solution.

Element	Chemical form taken up by the plant from soil solution
N	NO_3^-, NH_4^+
P	HPO_4^{2-}, $H_2PO_4^-$
K	K^+
Ca	Ca^{2+}
Mg	Mg^{2+}
S	SO_4^{2-}
B	H_3BO_3, $B_4O_7^{2-}$, $H_2BO_3^-$, HBO_3^{2-}, BO_3^{3-}
Cl	Cl^-
Cu	Cu^{2+}
Fe	Fe^{2+}, Fe^{3+}
Mn	Mn^{2+}
Mo	MoO_4^{2-}
Zn	Zn^{2+}

Source: Havlin et al. 1999

Organic, as defined in chemistry, relates to living (or the remains of once living) substances, which contain C. An entire branch of science is devoted to the study of organic chemistry. Organic substances are found to some extent in all agricultural soils, in the form of either dead plant or animal material, in some stage of decomposition (or transition) back to their inorganic form. As the organic materials decompose, they contribute to the total soil inorganic nutrient pool, which is necessary to grow the world's food requirement.

All food, no matter how it is produced, contains C compounds, and thus is organic. The C actually comes from the CO_2 in the atmosphere that surrounds the plants, not from any organic C that may have been placed or existed in the soil, except as it is released by decomposition and returned to the atmospheric pool.

Nature's processes are continually cycling plant nutrients from one form to another. **Figure 2.1** is a simplified depiction of the N cycle. In the figure, atmospheric N is shown as the primary source for all nutrient N This is true whether the N is transferred there through natural or industrial fixation or deposited there from animals that ate the forages and grain grown on the soil.

There are approximately 75 million pounds of N over every acre of land in the Earth's atmosphere. Yet, as shown in **Figure 2.1**, the N must be transformed into NH_4^+ and/or NO_3^- before the plant can take it up and use it. As can be seen from the figure, all of these forms and sources of N are natural, whether they originate from organic or inorganic sources.

The essential elements that are highlighted in the periodic chart exist overwhelmingly in the inorganic form, in their natural state. Only a very small proportion exists in the organic form at any given time. Placed in the perspective of geologic time, elements exist only momentarily in the organic state and soon return to their more abundant, inorganic state…both being natural.

As with N, all other plant nutrients go through natural cycles, following various pathways to their final destination of being absorbed and utilized by plants that grow all the foods for humans and animals. In the process, some nutrients such as N, P, and S, move back and forth between the organic and inorganic pools.

We have learned through years of study that growth of plants, animals, and humans can often be impaired because of inadequate amounts (deficiencies) of the essential elements. In animal and human health, deficiencies are often overcome by changing the diet to include foods richer in these needed elements (organic) or by supplying mineral supplements (inorganic). In plant health, the deficiencies are overcome by providing these supplements as fertilizers, which can be supplied either from the larger inorganic pool or the smaller organic pool, depending on availability, cost, and convenience. Often using both sources together, depending upon their availability, is the most efficient and economic solution.

It is important to remember that when supplied to plants in the organic form, the plant nutrients still must cycle to the inorganic phase (see Chapter Two) before becoming available to the plant. On the other hand, inorganic fertilizers are supplied in soluble or slowly soluble forms, available for the plant to take them up when needed.

This bulletin reviews current information on plant nutrient use in North America. It integrates organic and inorganic sources of nutrients and discusses their differences and similarities; advantages and disadvantages; relative abundance or scarcity; amounts that are required to produce today's food and fiber demands; estimated availability of each source for that purpose; management challenges for each source; and their effect on the environment and how that concern can be managed. Nutrient budgets for North America are also discussed in detail. In reviewing the current science on these topics, we hope to make this complex subject more understandable and dispel many of the myths and explore the mysteries that seem to exist related to organic and inorganic nutrients and their common and complimentary roles in producing the food, fiber, and fuel needed for a growing population.

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Chapter Two

Transformations of Nutrients in Soils

T.S. Murrell

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Synopsis: Management of nutrients in agricultural systems requires a basic understanding of how nutrients cycle in agroecosystems. Issues of scale, ranging from field to farm, watershed and beyond, must also be addressed. This chapter will review the key aspects of nutrient cycles.

To understand potential differences between organic and inorganic nutrients, it is best to begin by examining the **transformations** that both sources undergo in soils. Such transformations are the result of chemical reactions that determine where in the system nutrients may be found. The entire set of reactions for a given nutrient is referred to as its **cycle**. This terminology is chosen because nutrients are not destroyed in the reactions, but are simply relocated from one part of the environment to another.

Cycles include various systems at different scales. In this chapter, we consider the cycling of nutrients in soils. Many other cycles exist, such as those for atmospheric gases, groundwater, surface water, and oceanic systems. Each cycle is comprised of: 1) inputs, 2) outputs, and 3) transformations or cycling components. Inputs are the places in the cycle where nutrients are introduced. Outputs are where nutrients exit the cycle under consideration. Transformations involve reactions that change the chemical form in which a nutrient exists.

We will examine the soil system cycles for the major nutrients nitrogen (N), phosphorus (P), and potassium (K), both organic and inorganic nutrient sources.

The Nitrogen Cycle

Inputs

The N cycle is shown in **Figure 2.1.** Organic N

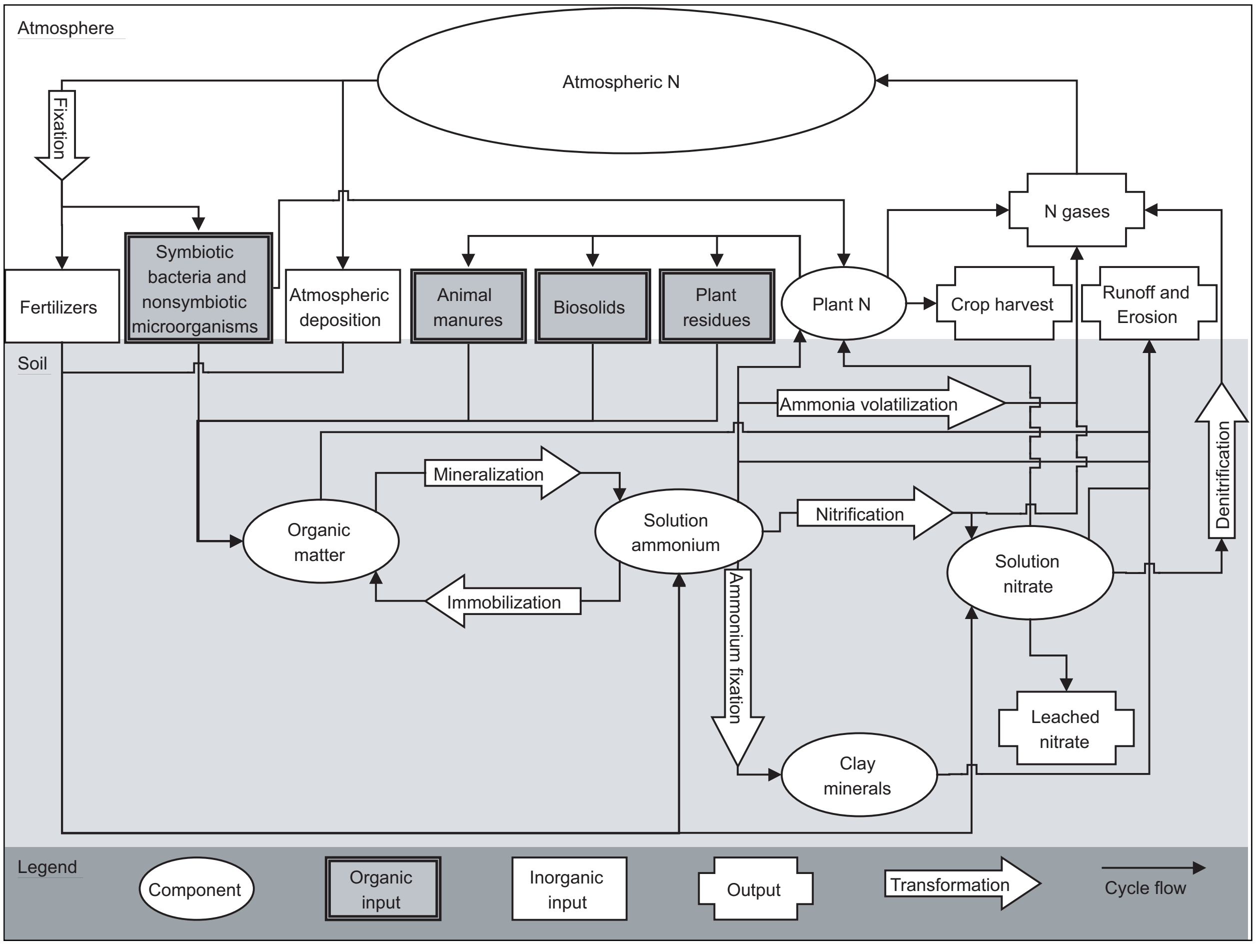

Figure 2.1. The nitrogen cycle.

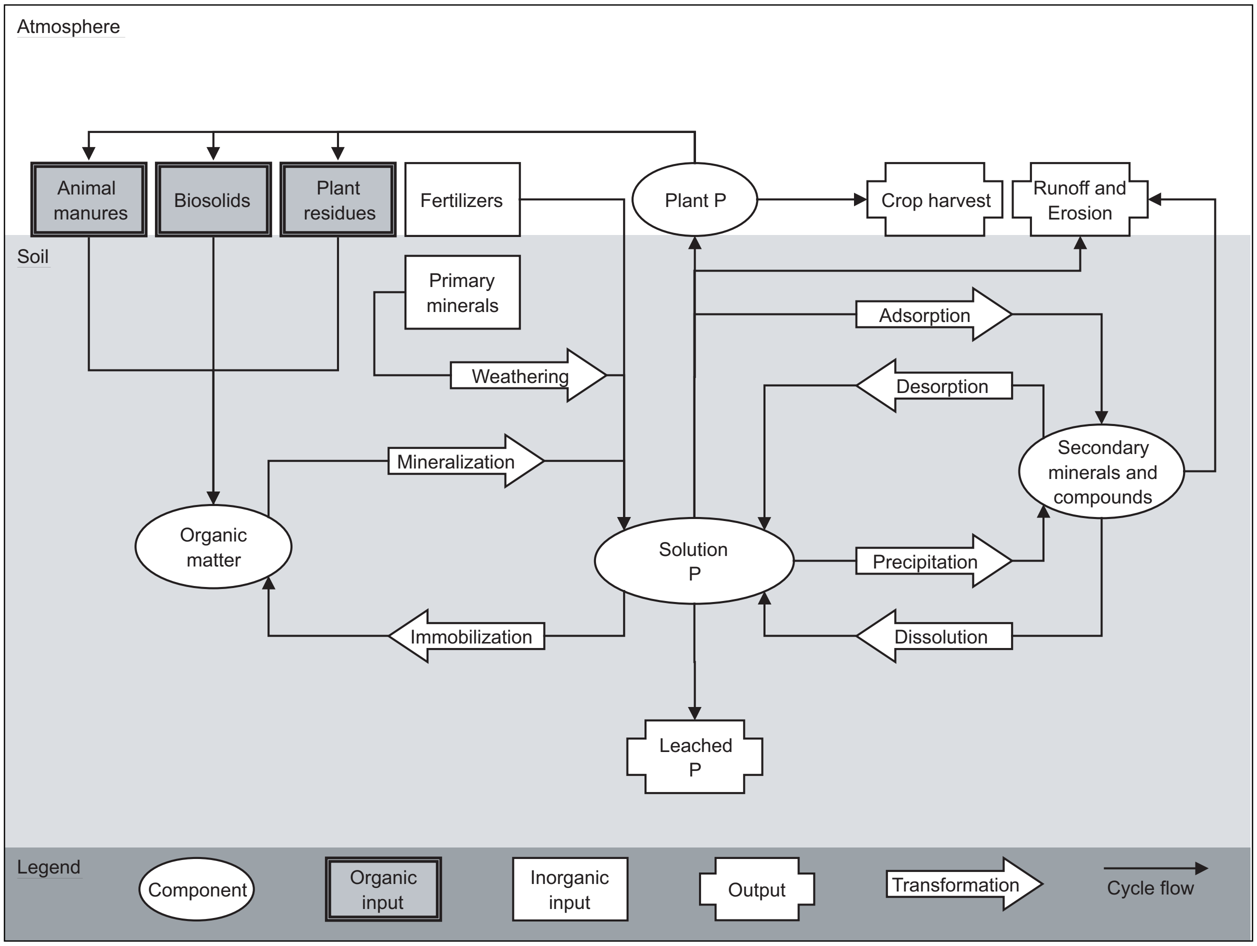

Figure 2.2. The soil phosphorus cycle.

inputs come from animal manures, biosolids, plant residues, and **fixation** by soil organisms. Inorganic inputs originate from application of commercial fertilizers and deposition in rainfall. The production of commercial nitrogenous fertilizers is also a fixation process, involving the conversion of atmospheric N to more concentrated and soluble forms.

Transformations

Once N enters the soil, it is subject to many transformations. The number and type of reactions are the same, regardless of the input source. However, the source determines which transformations dominate. Nitrogen from organic sources becomes part of the soil organic matter. A portion of this N will be converted to inorganic N through a process termed **mineralization**. Inorganic N may be converted to organic N through **immobilization** processes. Therefore, a portion of the N applied, whether from organic or inorganic sources, will be in the soil organic matter while another portion will exist as inorganic N. The relative proportion of each will depend on the source, soil composition, and environmental conditions.

There are two primary forms of inorganic N in soils: ammonium (NH_4^+) and nitrate (NO_3^-) Since NH_4^+ has a positive charge, it adsorbs to the surfaces and edges of negatively charged soil surfaces through exchange reactions. Conversely, it may also desorb back into solution. A portion of the NH_4^+ is converted to NO_3^- by soil bacteria, a process called **nitrification**. Ammonium can also be chemically bound on the surfaces and between layers of clay minerals (NH_4^+ fixation) where it may or may not go back into the soil solution, depending on soil chemical conditions. Being negatively charged, NO_3^- moves freely with soil water, not attracted to the negative charges on the soil. Ammonium and NO_3^- are the only N species taken up by plants. Once in the plant, they are converted to organic forms, such as proteins.

Outputs

Nitrogen can be lost from the soil in several ways. Crops remove the N accumulated in harvested plant portions. Nitrogen in organic matter as well as adsorbed and fixed NH_4^+ may be lost with soil particles through erosion. Ammonium and NO_3^- in solution may be lost through runoff. Nitrate, because it is not chemically bound to soil surfaces, may be lost to groundwater through leaching, depending on the depth to the water table and the amount of evaporation and transpiration that occurs. Under moist soil conditions, soil NO_3^- may be converted to gaseous forms of N through a process

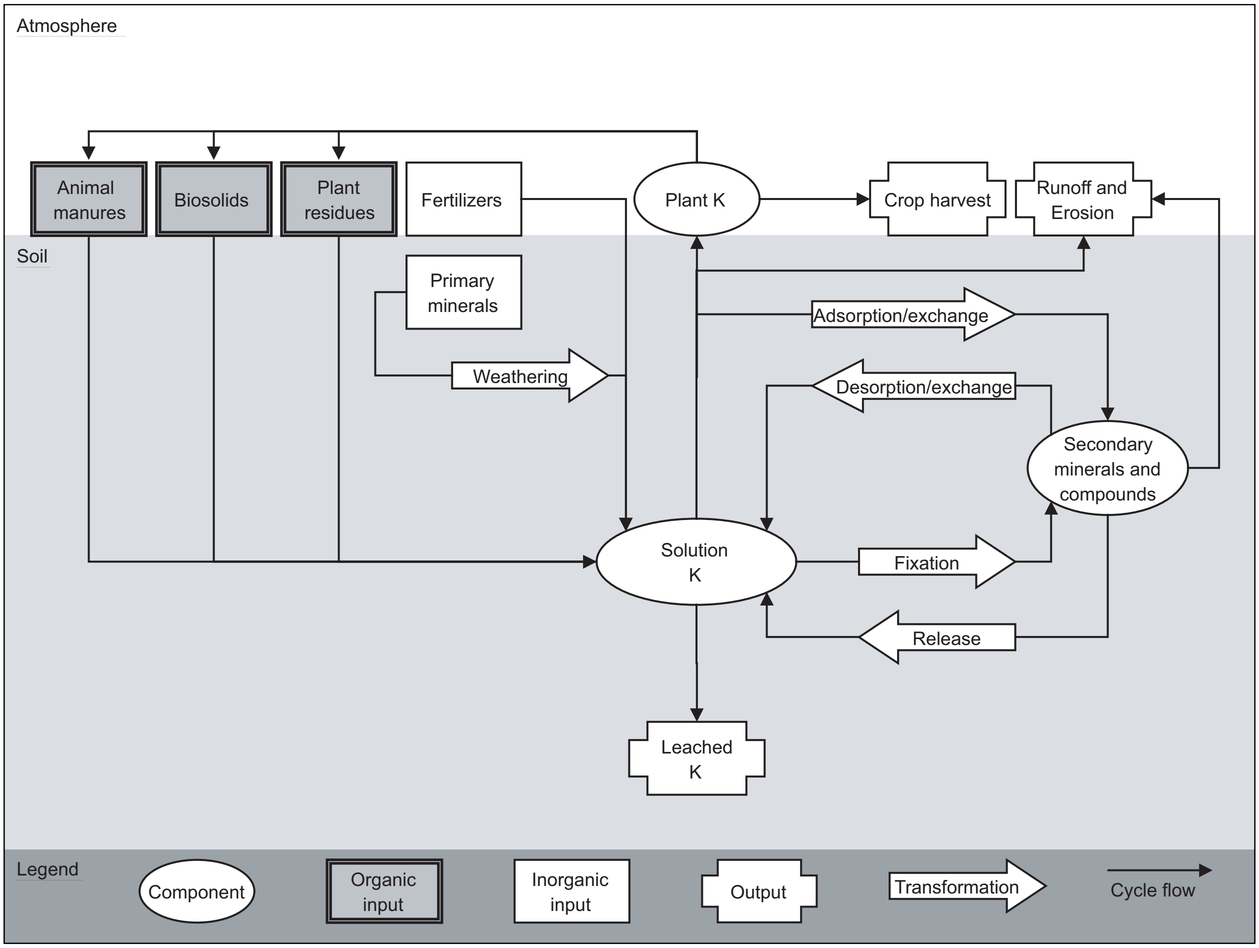

Figure 2.3. The soil potassium cycle.

termed **denitrification**. These gases then return to the atmosphere. One form of gaseous N, nitrous oxide (N_2O), is a greenhouse gas. Finally, NH_4^+ may also convert to ammonia (NH_3) gas and return to the atmosphere, a process termed **volatilization**.

The Soil Phosphorus Cycle

Inputs

The soil P cycle is shown in **Figure 2.2**. Like N, P may be added to the soil in both organic and inorganic forms. Organic inputs are the same as those listed for N: manures, biosolids, and plant residues. Inorganic inputs are those from commercial fertilizers and primary soil minerals. Soil minerals release P through the process of weathering. Unlike N, biological fixation of P does not occur, nor is atmospheric deposition a major input.

Transformations

Soil organic matter is as important for P as it is for N. Like N, mineralization releases inorganic P from organic soil sources. Immobilization is the reverse process, converting inorganic P to organic forms. Regardless of whether P comes from organic or inorganic sources, a portion of the P will exist in organic and inorganic forms in soils.

Inorganic P in the soil solution exists as two primary species: monohydrogen orthophosphate (HPO_4^{2-}) and dihydrogen orthophosphate ($H_2PO_4^-$). The P in solution reacts strongly with surfaces of secondary minerals and other compounds. Two primary reactions are thought to occur: adsorption and precipitation. In adsorption reactions, P is bound strongly to the surfaces of minerals. In precipitation reactions, P may react with surface and solution chemical species to create insoluble compounds. Both types of reactions leave little P in the soil solution. A portion of both the adsorbed and precipitated P may re-solubilize through desorption and dissolution reactions, respectively. Plants can absorb only solution P. Once assimilated by the plant, HPO_4^{2-} and $H_2PO_4^-$ are converted to organic forms, such as adenosine diphosphate (ADP) and adenosine triphosphate (ATP).

Outputs

There are several ways P can be lost from the soil system. Phosphorus losses occur on all soils whenever crops are harvested. Because P is bound so strongly to the solid phase of the soil, it can also be lost through erosion. Solution P can be lost through surface runoff. There is some evidence that the more soluble commercial P inputs are more susceptible to this loss than other, less soluble sources. The final output from the soil system is through leaching in soils with a lesser quantity of reactive surfaces, in higher precipitation areas, where heavy P applications have been made. There is also evidence to suggest that manure P sources result in greater downward movement of P through the soil profile than do inorganic P sources.

The Soil Potassium Cycle

Inputs

The soil K cycle is shown in **Figure 2.3**. The types of K inputs are identical to P: manures, biosolids, plant residues, commercial fertilizers, and through weathering of soil minerals. However, unlike P, K exists in organic sources as inorganic K, rather than as a structural component of organic compounds.

Transformations

Because K is not part of the structure of organic compounds, it is not subject to mineralization and immobilization processes. Inorganic K is soluble and is the only form of K taken up by plants. After the K ion (K^+) is absorbed by plant roots, it remains in the inorganic form.

The dominant reactions of inorganic solution K^+ are exchange reactions, where K^+ adsorbs to the surfaces and edges of soil minerals. This K^+ may also desorb, going back into solution. Like NH_4^+, K^+ may also be fixed between the structural layers of certain clay minerals. A portion of this fixed K^+ may be released back into solution if there is a strong enough chemical potential gradient.

Outputs

Like both N and P, K loss occurs on all soils through removal of harvested crop portions. Adsorbed and fixed K can also be lost through erosion. In soils with low adsorption and fixation potentials in higher rainfall areas, K may also be lost to groundwater through leaching.

Summary

A study of nutrient cycles of N, P, and K reveals that both organic and inorganic nutrient sources are subjected to the same set of reactions and loss pathways. Regardless of the form in which these nutrients are applied, a portion of N and P sources will be transformed into both organic and inorganic forms in the soil. Potassium, however, does not become a structural component of organic compounds. The set of transformations that nutrients undergo is the same regardless of source. However, the one that dominates depends on the source.

Chapter Three

Status of Soil Nutrients in North America

P.E. Fixen and T.L. Roberts

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Synopsis: The goal of nutrient management is to use nutrient-containing amendments to achieve and maintain soil fertility levels that meet crop needs without impairing water or air quality. Therefore, knowledge of soil fertility trends over time and soil fertility status are important indicators of nutrient management challenges and opportunities. In this chapter, a recent summary of soil test results of 2.5 million samples from North American laboratories will be used to develop a picture of these indicators.

"The soil's native ability to supply sufficient nutrients has decreased with the higher plant productivity levels associated with increased human demand for food. One of the greatest challenges of our generation will be to develop and implement soil, crop, and nutrient management technologies that enhance plant productivity and the quality of the soil, water, and air. If we do not improve and/or sustain the productive capacity of our fragile soils, we cannot continue to support the food and fiber demand of our growing population." (Havlin et al., 1999.)

The above paragraph, excerpted from the preface of the leading college text book, *Soil Fertility and Fertilizers*, puts the topic of this chapter in perspective. The current status of soil fertility and trends over time are critical issues for the sustainability of agriculture in North America. They are major factors influencing the short- and long-term consequences of imbalanced nutrient budgets discussed later in this bulletin.

Soil N

Soil testing for plant available nitrogen (N) is not commonly used in much of North America. The exceptions are the more arid regions of the Great Plains and western Corn Belt where nitrate (NO_3^-) present in the soil profile is measured, usually to a depth of 2 feet. In more humid regions, a 1-foot pre-sidedress NO_3^- test is sometimes used. However, adoption has generally been insufficient for evaluation of regional soil N status. Also, the dynamic nature of plant-available soil N over relatively short time periods in more humid areas makes soil test summaries for N less useful than those for phosphorus (P) and potassium (K) soil tests which are highly buffered by the soil.

Nitrogen can carry over from year to year in the soil in more arid regions, as is shown in **Figure 3.1** for the Northern Great Plains. The high levels of the late 1980s were the result of a series of drought years in which crop removal and other N losses were greatly reduced. As the weather improved in the early 1990s, soil NO_3^- levels declined and reached a low point in 1993, a very wet year.

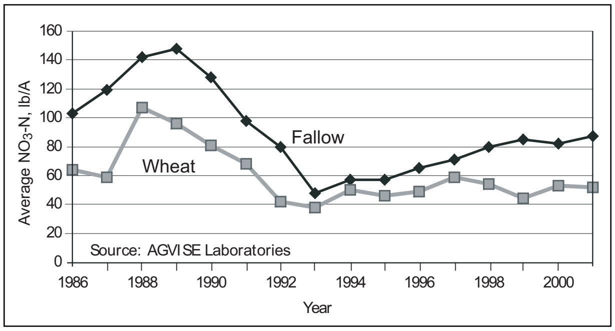

Figure 3.1. Soil NO_3^- levels in the Northern Great Plains.

The impact of fallowing land on soil NO_3^- levels is also apparent in **Figure 3.1**. Nitrate accumulates during the year when no crop is grown due to **mineralization** of soil organic matter. The result is soil NO_3^--N levels following fallow that are 10 to 40 lb/A above those measured following wheat production.

The PPI Soil Test Summary for P and K

The Potash & Phosphate Institute (PPI)/Potash & Phosphate Institute of Canada (PPIC), with the assistance of numerous public and private soil testing laboratories, periodically summarizes soil test levels for P, K, and pH in North America. The most recent summary includes results of tests performed on approximately 2.5 million soil samples collected in the fall of 2000 and spring of 2001 and therefore reflects fertility status prior to the 2001 crop year (Potash & Phosphate Institute, 2001). This summary is probably the most comprehensive evaluation of the status of soil fertility in North America ever conducted. The relative frequency distribution information for P and K for most states and provinces offers a more detailed perspective than has been available in the past. The remainder of this chapter is based on the results of this soil test summary.

The summary includes the percent of samples analyzed that test medium or below. These are soil test categories where most agronomists would predict a significant yield response to P or K in the year of application. The agronomic definition of medium is not numerically consistent among laboratories or regions, but varies due to differences in philosophical approaches and research results. Because of this, Donohue (1987) has advised caution in use of data of this type.

There are many benefits of high P and K soil test levels. High tests are important in providing plants with needed nutrients to take advantage of optimum growing conditions and reduce the negative effects of stressful conditions. They provide protection against deficiencies induced by nutrient stratification in reduced tillage systems, plus offer more options in fertilizer placement, time of application, nutrient application rates, and frequency of soil sampling. High and very high field average soil test levels provide insurance against profit-robbing deficiencies occurring in low testing parts of variable fields. Considering the very high frequency of extreme within-field variability revealed by intensive sampling, this factor alone in many cases justifies building soil test levels to at least the high category.

Because of the factors discussed above, the categories of medium or below generally represent soils where current P and K use is mostly inadequate or just barely adequate, where application rates above current levels will likely increase long-term profitability by building soil fertility to optimum levels. At the same time, it is important to recognize that these nutrients should be protected from loss to avoid environmental degradation (Chapter Eight).

Current Soil P Status

The median soil test P level (Bray P-1 equivalent basis) for North America is 28 parts per million (ppm), but clear regional differences exist **(Figure 3.2).** The lowest median levels are found in the Northern Great Plains (NGP) while the highest occur in the Northeast (NE). Regional cumulative frequency distributions show a marked trend of increasing P levels west to east across North America **(Figure 3.3**). Nearly 80 percent test below 20 ppm in the Northern Great Plains, while only about 10 percent test below 20 ppm in the North-east.

Across all of North America, 47 percent of the soil samples analyzed are medium or below in P. As expected, considerable variation exists among states and provinces **(Figure 3.4**). The Northern Great Plains has the highest frequency of medium or below P tests, with values in the 60 to 90 percent range, while a few states in the Northeast are below 20 percent.

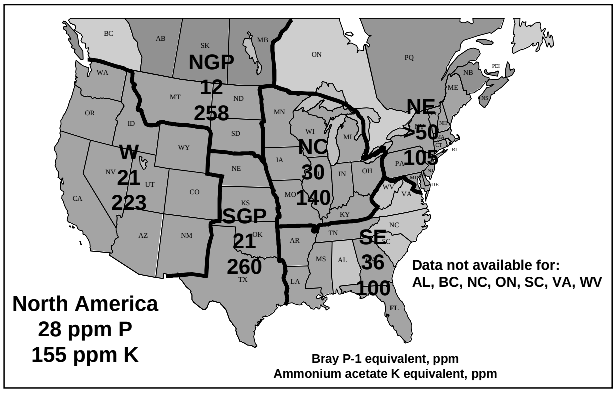

Figure 3.2. **Median soil test P and K levels in 2001. Top number indicates P; bottom number is K.**

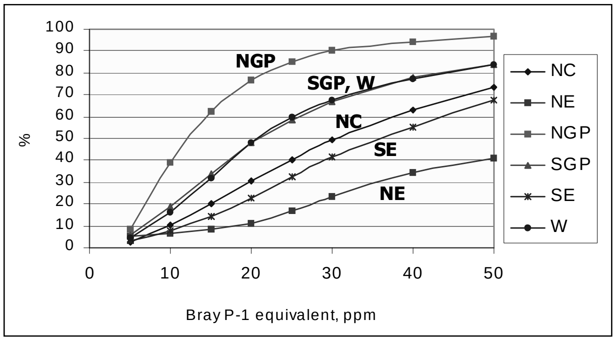

Figure 3.3. **Regional cumulative relative frequencies for soil test P in North America in 2001.**

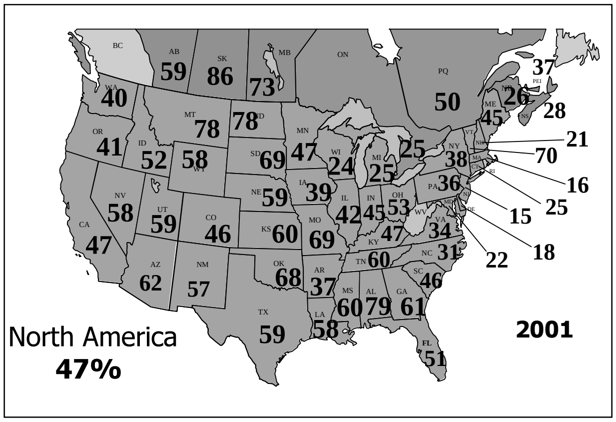

Figure 3.4. **Percent of soils testing medium or below in P in 2001.**

Historical Soil P Trends

The earliest soil test summary data reported by PPI/PPIC were published in the Winter 1979/80 issue of *Better Crops with Plant Food* (Nelson, 1980). The summary period varied somewhat among the 16 states included, but was generally in the late 1960s.

Soil test P levels in the Great Plains have been quite stable since the summaries were initiated: 70 to 80 percent medium or below in the north [Alberta (AB), Saskatchewan (SK), Manitoba (MB), South Dakota (SD), North Dakota (ND)] and 50 to 65 percent in the south [Kansas (KS), Nebraska (NE), Oklahoma (OK); **Figure 3.5**]. These data indicate that P nutrition remains an important yield-limiting factor in much of the Great Plains.

The lowest curve in **Figure 3.5** shows the soil test P trend for the six leading corn-producing states. In 1975, slightly over 50 percent of samples in the summary were medium or below. As farmers built soil test levels, percent medium or below declined to approximately 40 percent in 1989. Since then, the trend has reversed, and these six states are again approaching 50 percent medium or below, similar to the 1975 level. Nutrient budget estimates discussed later in this bulletin

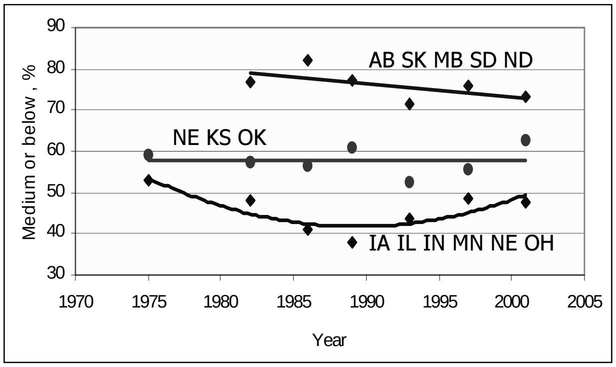

Figure 3.5. Percent of soil samples testing medium or below in P in the Great Plains and Corn Belt.

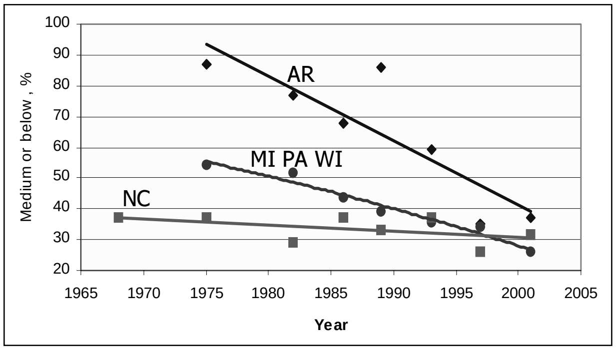

Figure 3.6. Percent of soil samples testing medium or below in P in regions of high manure density.

offer a plausible explanation for declining soil P fertility in the Corn Belt.

In contrast to the stable or currently declining soil test P trends illustrated in **Figure 3.5** are the currently increasing trends depicted in **Figure 3.6** for states with a large manure supply relative to crop P demand. Arkansas has experienced a dramatic increase in P soil test levels with percent medium or below dropping from nearly 90 percent in 1975 to 40 percent today. During the 25-year period of the summaries, poultry and hog numbers in Arkansas have more than doubled (USDA-NASS, 1998). Commercial phosphate use has increased by approximately 40 percent during this period as well. However, 40 percent of Arkansas samples still test medium or below, where first-year response to P is expected. Also, samples for field crops in Arkansas generally have a higher percent medium or below in P value than forage crops, probably due to greater manure application on forages.

Current Soil K Status

The median ammonium acetate equivalent K level for North America is 155 ppm, but as with P, clear regional differences exist (**Figure 3.2).** In contrast to P, the highest median levels occur in the Great Plains and western states while the lowest levels occur in the eastern regions. For example, in the Northern Great Plains less than 20 percent of the samples are below 160 ppm, while in the northeast and southeast more than 70 percent are below 160 ppm **(Figure 3.7)**.

For North America, 43 percent of soil samples analyzed test medium or below in K. Once again, considerable variation exists among states and provinces **(Figure 3.8**). Western states and provinces generally have fewer soils in the medium or below K categories than those in the East. The higher K levels of the West reflect the less weathered status of western soils. However, in states such as California, where 44 percent of soils test medium or below in K, crop removal over several decades with limited nutrient addition has significantly reduced soil K levels.

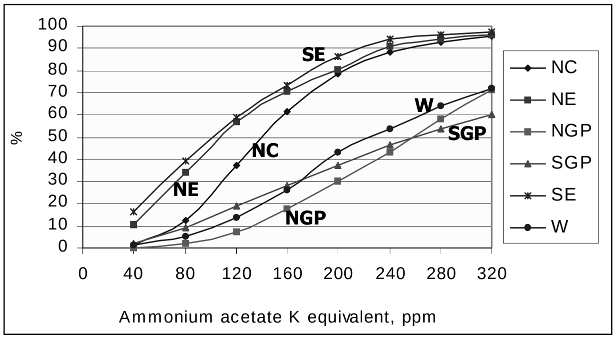

Figure 3.7. Regional cumulative relative frequencies for soil test K in North America in 2001.

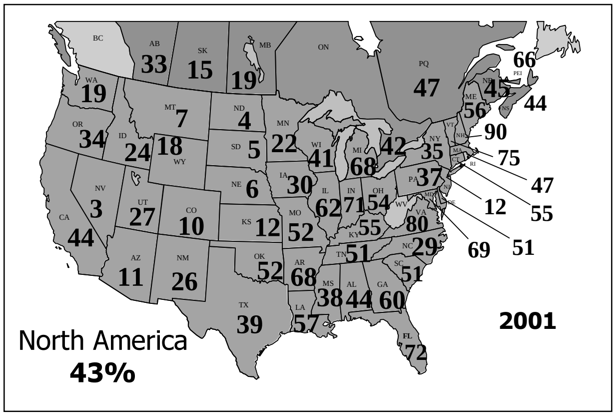

Figure 3.8. Percent of soils testing medium or below in K in 2001.

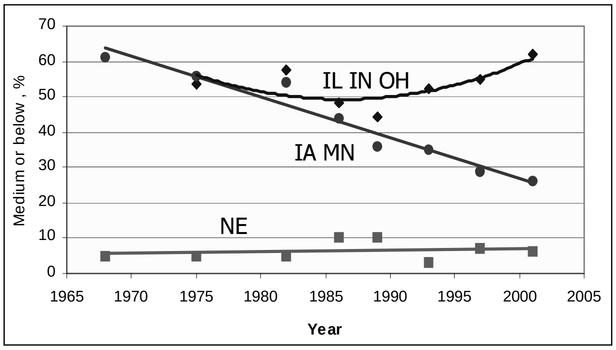

Figure 3.9. Percent of soil samples testing medium or below in K in the Corn Belt.

Historical Soil K Trends

Historical trends in soil test K levels differ markedly among the major corn-producing states **(Figure 3.9**). The trend for the eastern states, Illinois, Indiana and Ohio, is very similar to the P trend observed for these states in **Figure 3.5**. Percent medium and below in K reached a low point in 1989 and has been consistently increasing ever since. Currently, over 60 percent of samples test medium or below in K. This is in striking contrast to Iowa and Minnesota, where percent medium and below has been steadily declining in linear fashion from 1968 to 2001, suggesting a steady buildup of low and medium testing soils into the high or very high categories. In 2001, only 26 percent of the samples from these two states tested medium or below in K, which in this case means below 120 ppm. In some respects, this observation appears in conflict with recent field observations from this region of an increase in frequency of K deficiency symptoms in corn and soybeans. However, many soils from the region test between 120 ppm and 200 ppm where K availability problems have been observed (**Figure 3.7).** For Minnesota and Iowa, 53 percent of samples test below 160 ppm, and 78 percent test below 200 ppm (data not shown). Percent medium or below in Nebraska has been stable throughout the summary period at 5 to 10 percent.

Percent of soils testing medium or below in K may be trending upwards slightly in the Northern Great Plains (AB, SK, MB, SD, ND) and downwards slightly in Idaho, Oregon and Washington. Very little change in any direction has occurred in these two regions for the last several summaries **(Figure 3.10).** Although variable, the upward trend in percent medium or below in California seems quite apparent, increasing from 20 percent in 1986 to approximately 45 percent in 2001. A slow decline in soil test K levels would be expected in much of the West as crops continue to remove K that is not replaced by fertilization.

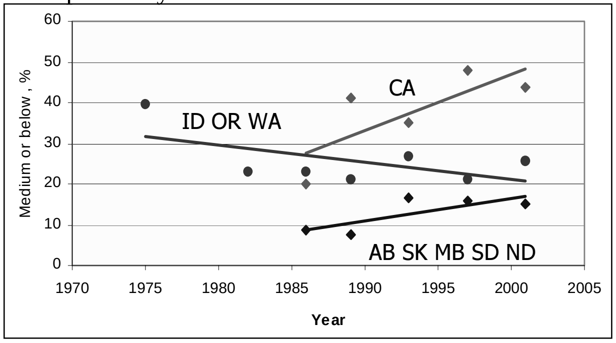

Figure 3.10. Percent of soil samples testing medium or below in K in the western U.S.

Summary

The results show that 47 percent of the soil samples collected for the 2001 crop year tested medium or below in P. The Northern Great Plains continues to be the region with the lowest P levels in North America while the Northeast has the highest.

The results also show that 43 percent of the samples tested medium or below in K. The Great Plains and West contain the highest soil K levels while the Northeast and Southeast contain the lowest.

Both the P and the K results illustrate the importance of regular soil testing because a large number of soils test near agronomically critical levels where nutrient recommendations can vary markedly. These data also amplify the need for representative soil sampling.

Phosphorus soil fertility appears to be decreasing in the heart of the Corn Belt, and K levels appear to be in decline in the eastern states of the Corn Belt. These data are generally supported by nutrient budget estimates for the Corn Belt that show crop removal exceeding P and K application. This trend is another clear call for routine soil testing to monitor soil fertility of individual fields in the years ahead. It should also be of concern since future crop production increases cannot be sustained with deficit nutrient budgets that reduce soil fertility below optimum levels.

The impact of manure production on regional soil test levels is apparent in North America. Generally, in regions where manure production is high relative to crop nutrient removal, a lower percentage of soils currently test medium or below in P, and percentages are trending even lower.

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Chapter Four

Crop Nutritional Needs

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Synopsis: Science-based facts on crop nutritional needs have contributed to improved crop yields throughout the world. With improved yields, the removal of nutrients such as nitrogen (N), phosphorus (P), and potassium (K) has also increased. Effective and efficient resupply of nutrients for optimum crop production requires access to reliable information about crop yield levels, crop nutrient uptake patterns, and nutrient removal from production fields.

Each plant in a field of corn, soybeans, wheat, or other crop is an individual factory requiring specific raw materials to grow effectively and optimize yield based on its genetic potential. Its basic raw materials include water, sunlight, carbon dioxide, and 17 essential nutrients. With these inputs, the plant can generate most of its remaining needs. However, few plants ever express their full genetic production potential. The reasons are many, and some may be site-specific. Growth limitations might be due to: 1) one or more of the raw materials being limiting, 2) stress induced by insects, disease, adverse temperature, drought, or inadequate nutrition, or 3) management restrictions such as the timing of vital production practices. Of the many factors regulating growth, plant nutrition tends to interact in a positive manner with other essential components.

The nutritional requirements for one plant can be quite different from those of another because of differences in genetics, the ability to forage for sustenance, and response to production practices such as balanced nutrition. Thus, it is not surprising that with advances in crop production technology, improved genetics, and greater attention to plant nutrition, crop yields have improved over time.

Meeting the challenge of increasing crop productivity is paramount if agriculture is to provide the quantity and quality of food needed for the 8 billion people projected to inhabit the Earth by the year 2025. The Food and Agricultural Organization (FAO) of the United Nations (UN) has reported many times that proper fertilization is the single most important cropping input for improving the world's food supply.

Access to science-based information on crop nutrient needs is an important first step in making decisions on nutrient management. Understanding site-specific crop nutrient requirements and the optimum rate, time, and method of nutrient application is essential for improving crop yield, quality, profitability, and environmental stewardship.

Crop Yield Trends in North America

Average yields of crops harvested for seed, forage, or fiber in the U.S., 1961 through 2000, are presented in **Table 4.1a**. This 40-year period does not reflect dramatic breakthroughs in yield improvement such as those recorded with hybrid seed in the 1930s or the introduction of fertilizer and crop protection products during the decade of the late 1940s and early 1950s. The 1961 through 2000 period saw the focus on improved management and development of site-specific, best management practices (BMPs) for efficient cropping systems. Certain crops, such as corn and small grain crops (**Figures 4.1, 4.2**), reflect yield improvement anywhere from 50 to 100 percent during the four decades. Even with such improvements, however, today's average yields are less than half of those produced by many top farmers and researchers. The highest recorded yields for selected crops grown in North America are presented in **Table 4.2**. Such yields clearly illustrate that the yield ceiling is high and gaining altitude. Success in attaining such high levels of production results from developing cropping systems characterized by fertile soils and a non-limiting environment for essential growth inputs.

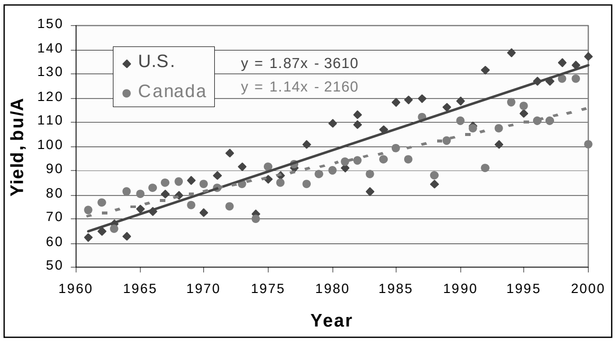

Figure 4.1. Corn yield trends in the U.S. and Canada.

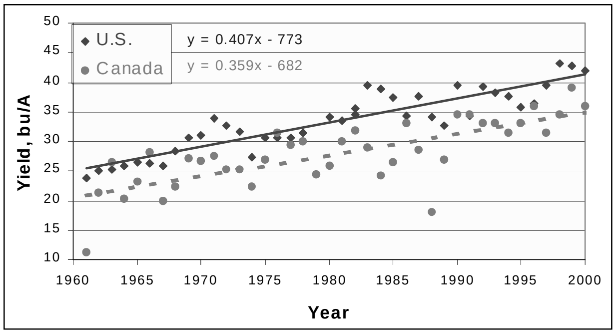

Figure 4.2. Wheat yield trends in the U.S. and Canada.

Table 4.1a. Yields of major crops in the U.S., 1961 through 2000.

Year	Alfalfa, ton/A	Barley, bu/A	Corn, bu/A	Cotton, lb/A	All Hay, ton/A	Peanuts, lb/A	Rice, lb/A	Sorghum, bu/A	Soybeans, bu/A	Sunflower, lb/A	Wheat, bu/A
1961	2.37	30.6	62.4	438	1.74	1,185	3,411	43.7	25.1		23.9
1962	2.54	35.0	64.7	457	1.80	1,185	3,726	44.1	24.2		25.0
1963	2.46	35.0	67.9	517	1.77	1,391	3,968	43.9	24.4		25.2
1964	2.43	37.6	62.9	517	1.76	1,502	4,098	41.7	24.5		25.8
1965	2.52	42.9	74.1	527	1.86	1,661	4,255	51.6	24.5		26.5
1966	2.52	38.3	73.1	480	1.88	1,700	4,322	55.8	25.4		26.3
1967	2.65	40.5	80.1	447	1.98	1,765	4,537	50.4	24.5		25.8
1968	2.73	43.8	79.5	516	2.04	1,770	4,425	52.6	26.7		28.4
1969	2.85	44.7	85.9	434	2.11	1,742	4,318	54.3	27.4		30.6
1970	2.77	42.8	72.4	438	2.07	2,030	4,618	50.4	26.7		31.0
1971	2.80	45.8	88.1	438	2.10	2,066	4,718	53.8	27.5		33.9
1972	2.88	43.7	97.0	507	2.15	2,203	4,700	60.7	27.8		32.7
1973	2.83	40.5	91.3	520	2.17	2,323	4,274	58.8	27.8		31.6
1974	2.77	37.7	71.9	442	2.10	2,491	4,440	45.1	23.7		27.3
1975	2.87	44.0	86.4	453	2.16	2,564	4,558	49.0	28.9	1,109	30.6
1976	2.62	45.2	88.0	465	1.99	2,465	4,663	49.1	26.1	1,058	30.7
1977	2.98	44.0	90.8	520	2.17	2,456	4,412	56.6	30.6	1,365	30.7
1978	3.13	49.2	101.0	420	2.32	2,619	4,484	54.5	29.4	1,365	31.4
1979	3.20	50.9	109.5	547	2.40	2,611	4,599	62.6	32.1	1,349	34.2
1980	3.20	49.7	91.0	404	2.22	1,645	4,413	46.3	26.5	1,016	33.5
1981	3.19	52.4	108.9	542	2.39	2,675	4,819	64.0	30.1	1,177	34.5
1982	3.38	57.2	113.2	590	2.50	2,693	4,710	59.1	31.5	1,129	35.5
1983	3.20	52.3	81.1	508	2.36	2,399	4,598	48.7	26.2	1,044	39.4
1984	3.36	53.3	106.7	600	2.45	2,883	4,954	56.4	28.1	1,014	38.8
1985	3.32	50.9	118.0	630	2.46	2,810	5,414	66.8	34.1	1,109	37.5
1986	3.41	50.8	119.4	552	2.49	2,408	5,651	67.7	33.3	1,369	34.4
1987	3.31	52.4	119.8	706	2.45	2,337	5,555	69.4	33.9	1,469	37.7
1988	2.59	38.0	84.6	619	1.94	2,445	5,514	63.8	27.0	933	34.1
1989	2.99	48.6	116.3	614	2.31	2,426	5,749	55.4	32.3	985	32.7
1990	3.29	56.1	118.5	634	2.40	1,985	5,529	63.1	34.1	1,229	39.5
1991	3.28	55.2	108.6	652	2.46	2,444	5,731	59.3	34.2	1,352	34.3
1992	3.29	62.5	131.5	700	2.49	2,567	5,736	72.6	37.6	1,255	39.3
1993	3.25	58.9	100.7	606	2.46	2,008	5,510	59.9	32.6	1,035	38.2
1994	3.36	56.2	138.6	708	2.55	2,624	5,964	72.7	41.4	1,410	37.6
1995	3.45	57.2	113.5	537	2.58	2,282	5,621	55.6	35.3	1,190	35.8
1996	3.27	58.5	127.1	705	2.45	2,653	6,120	67.3	37.6	1,436	36.3
1997	3.33	58.1	126.7	673	2.50	2,503	5,897	69.2	38.9	1,317	39.5
1998	3.48	60.0	134.4	625	2.53	2,702	5,663	67.3	38.9	1,510	43.2
1999	3.51	59.2	133.8	607	2.53	2,667	5,866	69.7	36.6	1,262	42.7
2000	3.48	61.1	137.1	632	2.54	2,448	6,281	60.9	38.1	1,363	41.9

Source: USDA-NASS, 2001

Table 4.2. Record or near-record crop yields in North America.

Crop	Yield	Location	Year
Alfalfa	24.1 tons/A	Arizona	1982
Barley, spring	190 bu/A	Alberta	1990
Canola, spring	96 bu/A	Alberta	1996
Corn	408 bu/A	Iowa	2001
Cotton	5.4 bales/A	Arizona	1982
Soybean	118 bu/A	New Jersey	1983
Wheat, winter	205 bu/A	British Columbia	1988

Source: PPI, 2000a, 2000b; PPI/PPIC/FAR 2002.

As shown in **Figure 4.3,** U.S. alfalfa and hay crop yields improved for the 1961 through 2000 period, but not to the extent of the grain crops. Alfalfa yields increased less than a ton per acre, hay yields about three-fourths of a ton per acre. Based on some high yield results from specific states, forage crops have massive unrealized yield potential. Top growers have harvested alfalfa at yield levels in excess of 10 tons per acre and hay crops such as bermudagrass at levels of 8 to 10 tons per acre.

The reasons for the difference between current average yields and what can be produced are not secrets. Top yields are the product of attention to detail, to site-specific crop nutrient and protection requirements, and to timeliness in the performance of management operations. For example, forage specialists often point out that the two production practices that can provide substantial yield improvement for many growers are frequent harvest management and fertilization for rapid plant growth and stand longevity.

Yield trends of major crops in Canada during the same period of 1961 through 2000 are presented in **Table 4.1b**. As in the U.S., yields have shown significant improvement during the past 40 years. Yields of canola, wheat, and other small grains have increased by more than 50 percent. Likewise, the yields of corn and soybeans have gone up by nearly 50 percent. Hay yields, as in the U.S., have changed little.

Table 4.1b. Yields of major crops in Canada, 1961 through 2000.

Year	Wheat, bu/A	Oats, bu/A	Barley, bu/A	All rye, bu/A	Corn, bu/A	Field pea, bu/A	Dry bean, lb/A	Soybeans, bu/A	Flax, bu/A	Mustard, bu/A	Canola, bu/A	Sunflower, lb/A	Sugar beet, ton/A	Tame hay, ton/A	Corn silage, ton/A
1961	11.3	32.9	20.8	11.7	73.4	15.8	1,206	31.6	7.0	6.3	15.9	712	13.1	1.71	11.3
1962	21.3	46.1	32.1	19.4	76.6	16.7	1,304	30.2	11.1	11.3	15.9	757	13.2	1.84	12.2
1963	26.5	47.3	36.6	19.8	65.8	19.9	1,299	22.1	12.6	17.2	17.6	943	13.6	1.89	11.4
1964	20.4	43.0	31.4	17.8	81.0	22.9	1,482	30.4	10.3	13.1	16.8	392	12.9	1.73	11.9
1965	23.2	47.5	36.5	22.4	80.2	22.8	1,388	30.6	12.6	15.8	15.9	427	13.6	1.68	11.2
1966	28.1	46.5	40.6	23.8	82.6	18.0	1,491	32.6	11.8	16.6	17.1	619	14.5	2.00	11.6
1967	19.9	40.6	31.8	17.5	85.0	23.9	1,001	28.1	9.2	13.7	15.3	788	13.1	1.98	12.4
1968	22.3	47.6	37.6	19.3	85.2	19.2	1,068	30.9	13.0	17.7	18.6	619	13.9	1.86	12.7
1969	27.2	48.2	40.6	17.9	75.5	17.7	1,299	24.0	12.0	19.5	16.7	708	13.7	2.05	12.5
1970	26.8	50.8	42.2	22.8	84.5	19.0	1,353	31.3	14.6	18.9	18.0	783	13.5	2.09	13.6
1971	27.5	52.8	44.0	23.0	82.6	24.2	1,540	28.3	12.7	18.2	18.0	703	15.1	2.02	14.0
1972	25.2	48.8	42.4	21.5	75.3	23.6	1,442	34.3	13.4	17.0	17.6	783	13.9	1.89	12.7
1973	25.3	48.4	40.2	22.7	84.6	24.2	1,295	31.3	13.4	15.8	17.0	703	14.6	2.02	13.1
1974	22.4	41.3	35.1	22.6	70.2	21.6	1,237	26.9	9.5	15.0	16.4	868	12.4	1.96	11.4
1975	27.0	48.2	40.5	26.4	91.8	24.2	1,228	34.9	12.6	13.7	18.1	1,059	13.2	2.01	13.8
1976	31.4	52.1	45.9	28.1	84.9	26.4	1,206	24.5	13.7	18.1	21.0	1,059	16.2	1.96	13.3
1977	29.5	52.5	47.2	26.0	92.3	24.0	636	39.1	17.4	19.4	24.5	1,059	17.6	1.98	13.3
1978	30.0	51.5	46.3	30.5	84.2	30.5	1,135	27.1	17.4	19.0	22.3	1,170	17.3	2.16	12.8
1979	24.5	50.2	43.2	25.5	88.6	26.7	1,615	35.3	14.0	14.0	18.0	1,202	16.2	2.16	13.6
1980	25.8	52.1	46.2	23.3	90.1	23.1	1,629	37.4	12.7	17.6	21.5	1,081	15.0	1.98	13.1
1981	30.0	53.0	47.7	33.4	93.8	27.9	1,291	32.5	16.2	20.0	23.8	1,264	18.6	2.20	13.8
1982	31.9	58.5	51.5	32.6	94.1	30.0	1,362	35.0	19.0	21.6	22.5	1,086	16.1	2.14	12.7
1983	28.9	51.5	44.8	31.0	88.3	27.2	1,246	30.3	16.5	16.4	20.2	988	17.0	2.13	11.9
1984	24.2	50.2	42.9	28.8	94.4	26.4	1,317	33.9	15.4	14.4	20.0	952	15.4	2.15	13.5
1985	26.6	56.4	49.6	25.8	99.2	34.0	1,433	37.5	19.4	16.4	22.7	1,059	15.0	1.98	13.4
1986	33.0	65.0	57.0	30.4	94.4	27.0	890	37.5	20.8	22.1	25.2	1,273	18.2	2.50	13.0
1987	28.5	62.4	53.2	25.6	112.0	27.0	1,780	42.0	19.2	21.1	25.2	1,362	20.1	2.41	15.6
1988	18.0	57.2	47.5	17.6	88.0	18.0	1,424	33.0	11.2	12.8	19.8	1,086	16.8	2.18	13.0
1989	27.0	54.6	47.5	28.8	102.4	24.0	1,424	34.5	12.8	13.9	19.8	1,139	16.5	2.34	13.4
1990	34.5	59.8	57.0	28.8	110.4	31.5	1,602	39.0	20.8	19.4	23.4	1,513	17.5	2.49	15.5
1991	34.5	54.6	53.2	30.4	107.2	31.5		36.0	20.8	19.3	23.4	1,460	19.6	2.16	12.9
1992	33.0	59.8	55.1	30.4	91.2	28.5	979	34.5	20.8	21.8	23.4	1,131	15.4	1.94	11.7
1993	33.0	67.6	58.9	32.0	107.2	31.5	1,424	39.0	19.2	20.9	23.4	909	15.9	2.07	13.1
1994	31.5	62.4	55.1	33.6	118.4	31.5	1,869	40.5	20.8	17.8	23.4	1,255	19.3	2.07	13.1
1995	33.0	62.4	57.0	30.4	116.8	27.0	1,691	42.0	20.8	16.8	21.6	1,324	18.7	1.85	13.2
1996	36.0	67.6	60.8	30.4	110.4	34.5	1,424	37.5	24.0	17.8	27.0	1,388	19.9	1.98	12.8
1997	31.5	59.8	55.1	32.0	110.4	31.5	1,602	39.0	19.2	15.0	23.4	1,145	20.1	1.49	12.2
1998	34.5	65.0	57.0	32.0	128.0	33.0	1,780	42.0	20.8	15.4	25.2	1,446	21.8	1.58	14.5
1999	39.0	67.6	60.8	36.8	128.0	40.5	1,691	42.0	20.8	20.2	28.8	1,375	19.3	1.76	15.9
2000	36.0	67.6	57.0	36.8	100.8	34.5	1,513	37.5	19.2	17.5	27.0	1,543	22.3	1.53	13.1

Source: Statistics Canada, 2000.

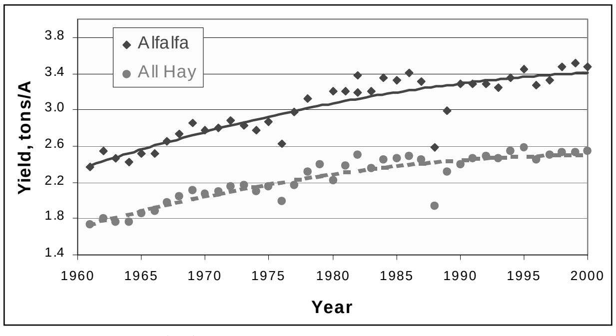

Figure 4.3. Alfalfa and all hay yield trends in the U.S.

Moisture shortages in the semi-arid regions of the Canadian Prairies periodically limit grain yields. Research continues to show that fertilization to achieve balanced crop nutrition also serves to help crops withstand stresses such as those induced by drought, certain diseases, and in some cases adverse temperatures.

Research has established levels of specific nutrients absorbed during the growing season by major crops in North America. These levels are of considerable value when determining the quantity of nutrients removed from a field in the harvested crop and the rates of nutrients required for maintaining the soil's fertility.

Nutrient Requirements for Optimum Crop Production

The absorption and uptake of specific plant nutrients are measures of a crop's requirements for optimum growth. These values vary considerably due to differences in yield level, adequacy of other nutrients for growth, soil characteristics which influence root growth and water availability, and high yield management practices such as plant population and variety selection. Most nutrient uptake values are determined from analysis of the above ground plant parts. Roots of many crops can represent 2 tons or more of dry matter per acre and will contain substantial levels of nutrients. These amounts, however, are seldom measured or listed in total nutrient uptake figures.

Data showing nutrients absorbed by major crops grown in North America for total above ground plant dry matter production are presented in **Table 4.3**. Values are for a single yield level and represent the plant nutrient content at physiological maturity, when plants are no longer building a dry matter base. Adjustments in uptake values can be made when yield is higher or lower than these production levels or for variations in crop type, such as with corn for grain versus sweet corn.

Forage crops such as alfalfa or corn silage remove large quantities of nutrients in proportion to the yield of hay or silage harvested. Nutrient requirements are often in proportion to such crop nutrient removal values. For many crops, where grain and sometimes straw are removed from the field, the total quantity of nutrients removed can easily be underestimated.

In multiple cropping systems, only a part of the nutrients contained in the residue remaining in the field from the first crop will be available for the next crop in rotation. As the residue of the first crop decomposes (mineralizes) nutrient release takes place, but often not in sequence with the next crop’s need for nutrients.

Nitrogen is often credited with being the nutrient that is the major driving force behind plant growth, although total N needs by many plants are only slightly higher than requirements for K. Credit for N carryover from the previous grass or grain crop is seldom provided. Indirectly, however, credit is provided in that residues contribute to the maintenance of soil organic matter, which is considered to provide a part of the total nutrients available from non-fertilizer sources.

Legume crops such as alfalfa, peanuts, or soybeans obtain most of their N needs from the soil atmospheric N through a special symbiotic relationship with *Rhizobium* bacteria. During the first few weeks of seedling development, the legume N generating process is not fully functional, and N must be derived from the seed, soil reserves, and/or applied fertilizer. This is especially important for soybeans following a small grain crop in a double crop system. Some N remains tied up in the residue, and some of that released can be temporarily tied up by soil microorganisms as they decompose the first crop residue. When these conditions exist, the rate of early soybean seedling establishment can be improved with supplemental fertilizer N to stimulate plant growth during the first few weeks. For legumes to fully develop their potential for fixing N, other nutrients such as P and K must not be limiting. These nutrients are vital for fundamental growth processes such as photosynthesis and translocation of growth substances needed for N fixation.

Nutrient Removal by Major Crops

Estimates of nutrient removal per unit of crop yield are reported in **Table 4.4**. The values are the quantity of nutrients removed in the harvested portion of the crop. They should not be confused with nutrient uptake which refers to the total nutrients absorbed by the growing crop. Tabular values are approximations based on the most recent information available to PPI. Actual nutrient removal may vary by 30 percent or more, depending on the specific growing conditions of the crop such as soil fertility level, yield, soil moisture, crop vigor, and limiting nutrients (interactions) as well as the actual crop variety and fertilizer program.

A recent evaluation of the P and K content of corn grain grown in the northeastern U.S. offers a good example of variability in nutrient content (**Table 4.5**; Heckman et al., 2001). Phosphorus content varied from 0.24 to 0.58 lb P_2O_5/bu, while K content varied from 0.18 to 0.35 lb K_2O/bu. Restricting the data to only one hybrid reduced the range only slightly. Additionally, regional differences in typical levels may exist. For example, preliminary evaluations indicate that the P content of corn grain may be lower in the western Corn Belt than in the eastern U.S. When local reliable estimates of nutrient removal per unit of yield are available, they should be used rather than general values such as those in **Table 4.4**.

Table 4.3. Nutrient uptake by major crops in North America.

		N	P_2O_5	K_2O
Crop	Yield	Nutrients absorbed, lb/A		
Field crops				
Canola	60 bu/A	180	79	142
Corn (grain)	180 bu/A	240	100	240
Cotton	2.5 bale (lint+seed)	180	63	126
Peanuts[1]	2 ton/A	240	39	185
Sorghum (grain)	135 bu/A	185	80	258
Soybeans[1]	50 bu/A	257	48	187
Sunflower	3,000 lb/A	151	60	110
Tobacco (flue)	3,000 lb/A	126	26	257
(burley)	4,000 lb/A	307	8	330
Wheat	60 bu/A	125	41	138
Forage crops				
Alfalfa[1]	9 ton/A	495	113	472
Corn (silage)	32 ton/A	266	114	266
Bermudagrsss	8 ton/A	368	96	400
Clover[1]-grass	6 ton/A	300	90	360
Fescue	3.5 ton/A	135	65	185
Vegetable crops				
Cabbage	700 cwt/A	270	63	249
Potatoes	500 cwt/A	269	90	546
Tomatoes	40 ton/A	232	87	463
Fruit and nut crops				
Apples	250 cwt/A	100	46	180
Oranges	540 cwt/A	265	55	330

Source: Potash & Phosphate Institute

[1] Legumes obtain most of their N from the air.

Table 4.4. Nutrient removal per unit of crop yield.

Crop	Unit of yield	N	P_2O_5	K_2O
		------- lb -------		
Field crops				
Barley	bu	1.10	0.40	0.35
Canola	bu	1.88	0.91	0.46
Corn (grain)	bu	0.75	0.44	0.29
Corn (silage, 67% water)	ton	8.30	3.60	8.30
Cotton (lint)	bale	32.00	14.00	19.00
Flax	bu	2.00	1.10	0.65
Lentils	bu	2.00	0.62	1.10
Oats	bu	0.80	0.25	0.20
Peanuts[1]	ton	70.00	11.00	17.00
Field pea	bu	2.40	1.20	0.71
Rice	bu	0.57	0.30	0.16
Safflower	cwt	5.00	1.20	3.80
Sorghum (grain)	cwt	1.50	0.75	0.38
Soybeans[1]	bu	4.00	0.80	1.40
Sugarbeets	ton	4.00	1.50	6.60
Sugarcane	ton	2.00	1.25	3.50
Sunflower	cwt	2.80	1.10	0.60
Tobacco (flue)	cwt	2.80	0.50	5.20
Tobacco (burley)	cwt	4.30	0.43	4.70
Wheat - 10% protein[2]	bu	1.10	0.50	0.35
Wheat - 12% protein[2]	bu	1.30	0.50	0.35
Wheat - 14% protein[2]	bu	1.50	0.50	0.35
Forage crops		Dry matter basis		
Alfalfa[1]	ton	56.00	15.00	60.00
Bahiagrass	ton	43.00	12.00	35.00
Bermudagrass	ton	46.00	12.00	50.00
Bromegrass	ton	36.00	13.00	59.00
Clover[1]-grass	ton	50.00	15.00	60.00
Fescue	ton	38.00	18.00	52.00
Orchardgrass	ton	50.00	17.00	62.00
Sorghum-Sudan	ton	40.00	15.00	58.00
Timothy	ton	38.00	14.00	62.00
Vetch[1]	ton	56.00	15.00	46.00
Vegetable Crops		Fresh weight basis		
Broccoli	cwt	0.44	0.17	0.42
Cabbage	cwt	0.39	0.09	0.36
Celery	cwt	0.19	0.11	0.50
Lettuce	cwt	0.24	0.08	0.50
Potatoes	cwt	0.35	0.15	0.56
Squash	cwt	0.42	0.10	0.60
Sweet potatoes	cwt	0.52	0.23	1.00
Tomatoes	ton	2.50	0.92	5.70
Fruit and Nut Crops		Fresh weight basis		
Almonds (in shell)	ton	130.00	50.00	170.00
Apples	ton	6.00	3.60	16.80
Cantaloupe	ton	7.30	2.30	13.00
Grapes-Table	ton	8.30	3.00	13.00
Oranges	ton	8.80	1.80	11.00
Peaches	ton	6.30	2.70	8.00
Pears	ton	5.70	1.70	6.30
Prunes	ton	6.00	2.00	8.70

[1] Legumes obtain most of their N from the air.

[2] At same moisture content as yield measurement.

Source: PPI/PPIC/FAR, 2001.

Removal estimates for specialty crops are in Appendix 4.2.

Table 4.5. Variation in nutrient content of corn grain in 1998 and 1999.

	All hybrids (23 sites)		Pioneer 3394 (6 sites)	
	P_2O_5	K_2O	P_2O_5	K_2O
	----------------- lb/bu -----------------			
Mean	0.43	0.27	0.37	0.24
Minimum	0.24	0.18	0.24	0.18
Maxium	0.58	0.35	0.44	0.28
CV, %[1]	20	14	19	15

[1] CV = coefficient of variation, standard deviation expressed as percentage of the mean.

Nutrient removal per unit of production can change with increases in yield level. Research with alfalfa has found that the K content per ton of hay is about 50 lb of K_2O at 4 or 5 ton/A yield, but increases to about 60 lb per ton at yield levels of 8 to 10 tons. Thus, the K need adjusts due to higher yield and increased nutrient concentration in the higher forage production. Research in the northeastern U.S. has shown that the P content of corn grain increases somewhat with yield level and soil test P levels (Heckman et al., 2001). As presented in **Table 4.4**, increased protein content of harvested wheat will increase N removal.

When soil test levels are high and a maintenance fertilization program is recommended, nutrient removal values presented in **Table 4.4** provide guidelines for the rate of nutrients to be returned to the field. The efficiency of crop use of applied nutrients deserves consideration, especially where one year's application is also required to meet part of the next year's crop needs. Research has reported that under the best growing and response conditions, optimum uptake of fertilizer nutrients applied for the crop would be about 70 percent for N, 20 percent for P, and 30 percent for K. Adjustments in the rate of application of nutrients are sometimes made to compensate for such differences in use efficiencies.

Vegetative growth from certain grain crops can have off farm market value. Straw from wheat and oats, for example, can contribute to net farm income when sold for livestock bedding, landscaping, mushroom production, or other specialty markets. Nutrients contained in the straw should be added to total removal values for the wheat or oat crop. In a similar manner, where corn stalks or peanut residues are removed for livestock fodder, nutrient removals are higher than those in the seed alone.

By utilizing uptake values and crop yields, it is possible to calculate and provide an estimate of nutrients removed from the field by the harvested crop. Nutrient removal for selected North American crops are presented in **Table 4.6a** and **Table 4.6b**. Nutrient removal estimates for agronomic and horticultural crops for states and provinces are presented in **Appendix 4.1**. The high level of nutrient removal by forage crops underscores the importance of nutrient replacement to maintain high yields and extend longevity and quality of the forage stand.

Table 4.6a. Nutrient removal by agronomic and horticultural crops in the U.S.

	1998-2000 avg production[1], millions		Nutrient removal			Nutrient removal		
Crop		Units	N	P_2O_5	K_2O	N	P_2O_5	K_2O
			- - Thousand short tons[2] - -			- - - - - % of total - - - - -		
Field Crops						**74.1**	**76.1**	**46.2**
Barley	317	bu	174	63	55	1.1	1.1	0.6
Canola	33	bu	31	15	8	0.2	0.3	0.1
Corn (grain)	9,719	bu	3,645	2,138	1,409	22.7	37.5	14.6
Cotton	16	bale	257	112	153	1.6	2.0	1.6
Dry beans	30	cwt	53	14	23	0.3	0.2	0.2
Oats	154	bu	61	19	15	0.4	0.3	0.2
Peanuts	1.8	ton	65	10	16	0.4	0.2	0.2
Potatoes	490	cwt	86	37	137	0.5	0.6	1.4
Rice	194	cwt	123	65	34	0.8	1.1	0.4
Rye	11	bu	7	3	2	0.0	0.0	0.0
Sorghum (grain)	528	bu	222	111	55	1.4	1.9	0.6
Soybeans	2,722	bu	5,443	1,089	1,905	33.9	19.1	19.8
Sugar beets	33	ton	65	25	108	0.4	0.4	1.1
Sugar cane	35	ton	35	22	62	0.2	0.4	0.6
Sunflower	44	cwt	62	24	13	0.4	0.4	0.1
Sweet potatoes	13	cwt	3	1	6	0.0	0.0	0.1
Tobacco	13	cwt	22	3	33	0.1	0.1	0.3
Wheat	2,356	bu	1,532	589	412	9.6	10.3	4.3
Forage Crops						**23.4**	**21.5**	**48.6**
Alfalfa	82	ton	2,299	616	2,463	14.3	10.8	25.6
Corn (silage)	97	ton	401	174	401	2.5	3.1	4.2
Other Hay	72	ton	1,044	432	1,800	6.5	7.6	18.7
Sorgum (silage)	3.4	ton	14	6	14	0.1	0.1	0.1
Specialty Crops						**2.5**	**2.4**	**5.2**
Almonds (shelled)	0.57	ton	37	14	49	0.2	0.3	0.5
Apples	5.5	ton	16	10	46	0.1	0.2	0.5
Beans (snap)	21	cwt	18	4	22	0.1	0.1	0.2
Carrots (all)	46	cwt	8	3	18	0.0	0.1	0.2
Corn (sweet)	91	cwt	71	24	69	0.4	0.4	0.7
Grapes	6.5	ton	27	10	42	0.2	0.2	0.4
Lettuce (all)	92	cwt	11	4	23	0.1	0.1	0.2
Oranges	12	ton	52	11	64	0.3	0.2	0.7
Tomatoes (all)	13	ton	16	6	37	0.1	0.1	0.4
Wood (soft and hard)	25	cord	55	16	42	0.3	0.3	0.4
Other spec. crops			83	34	95	0.5	0.6	1.0
Total			**16,038**	**5,703**	**9,629**	**100.0**	**100.0**	**100.0**

[1] USDA-NASS, 2001. [2] Calculated utilizing data presented in Table 4.4 and Appendix 4.2.

Nutrient Absorption during Plant Growth

Nutrient absorption by crops has been investigated, and specific nutrient requirements by plant growth stage have been determined. Temperature, as measured by growing degree days (GDDs) is a useful tool in monitoring the progressive development of a plant from the seedling stage through maturity. The calculation of GDDs involves subtracting a base temperature (such as 60°F) from the mean daily temperature and accumulating the positive difference (degree days) as the plant develops from seedling to maturity (Dennis, 1984; Oosterhuis, 1990). Scientists have utilized GDDs and plant growth stage to establish the time and rate of absorption of specific nutrients by crops such as corn, wheat, cotton, soybeans, cabbage, and sweet corn.

Nutrient accumulation by 307 bu/acre corn at various stages of growth is presented in **Figures 4.4a**, **4.4b**, and **4.4c** for N, P_2O_5, and K_2O, respectively (Karlen et al., 1988). At physiologic maturity, total uptake was 345 lb N/A, 143 lb P_2O_5/A, and 376 lb K_2O/A. Of these amounts accumulated by the total above ground portions of the plant, approximately 66 percent, 85 percent, and 20 percent of the N, P_2O_5, and K_2O were in the ear and shank portion. Rates of nutrient accumulation in the leaves, stalk, and tassel were greatest during vegetative (V) stages of growth. Rates of nutrient accumulation in the ear and shank portions were greatest during reproductive (R) phases.

Nutrient accumulation in 80 bu/A soybeans throughout the growing season is shown in **Figure 4.5** (Henderson and Kamprath, 1970). Total accumulations of N, P_2O_5, and K_2O at maturity were 411, 77, and 204 lb/A, respectively. In soybeans, as with corn, higher proportions of N and K are taken up early in the season, when compared to P. The patterns of accumulation for each of these nutrients with time has been shown to be inconsistent (Sadler and Karlen, 1995). Soybeans appear more affected by short-term variations in their environment, making uptake patterns more dependent upon seasonal variability than crops like corn and

Table 4.6b. Nutrient removal by major crops in Canada.

Crop[1]	Year 2000 production, millions	Units of yield	Nutrient removal			Nutrient removal		
			N	P_2O_5	K_2O	N	P_2O_5	K_2O
			-- thousand short tons[2] --			----- % of total -----		
Field Crops						**76.9**	**80.9**	**45.9**
Barley	619	bu	340	124	108	13.6	13.2	8.1
Canola	15,695	lb	298	141	72	11.9	15.1	5.4
Corn (grain)	269	bu	101	59	39	4.0	6.3	2.9
Corn (silage)	6.5	ton	27	12	27	1.1	1.3	2.0
Dry beans	5.7	cwt	10	3	4	0.4	0.3	0.3
Dry peas	105	bu	126	63	37	5.0	6.8	2.8
Flaxseed	27	bu	27	15	9	1.1	1.6	0.7
Lentils	34	bu	34	10	18	1.3	1.1	1.4
Mustard	446	lb	8	4	2	0.3	0.4	0.1
Oats	220	bu	88	28	22	3.5	2.9	1.6
Potatoes	101	cwt	18	8	28	0.7	0.8	2.1
Rye	10	bu	7	2	2	0.3	0.3	0.1
Soybeans	99	bu	198	40	69	7.9	4.2	5.2
Sugar beets	0.90	ton	2	1	3	0.1	0.1	0.2
Sunflower	263	lb	4	1	1	0.1	0.2	0.1
Wheat	985	bu	640	246	172	25.5	26.3	12.9
Forage Crops						**23.1**	**19.1**	**54.1**
Alfalfa	15	ton	423	113	453	16.9	12.1	33.8
Other hay	11	ton	158	65	273	6.3	7.0	20.3
Total			**2,509**	**936**	**1,340**	**100.0**	**100.0**	**100.0**

[1] Source: Statistics Canada, 2000.

[2] Calculated utilizing data presented in Table 4.4.

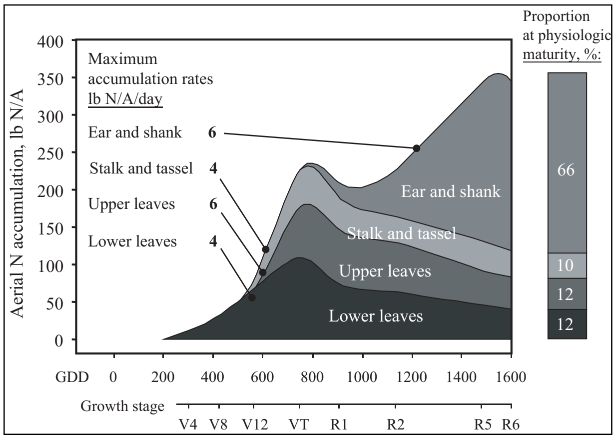

Figure 4.4a. Aerial N accumulation in corn (307 bu/A).

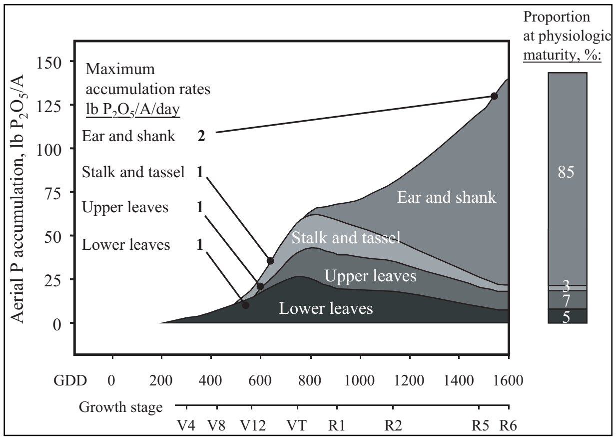

Figure 4.4b. Aerial P accumulation in corn (307 bu/A).

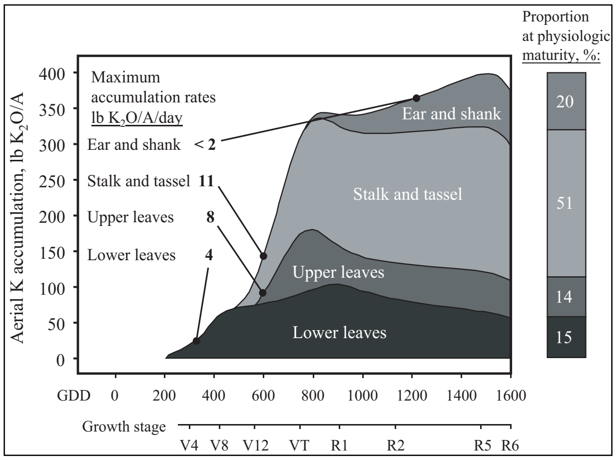

Figure 4.4c. Aerial K accumulation in corn (307 bu/A).

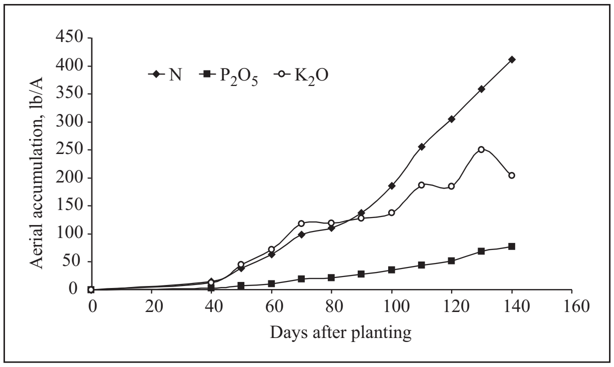

Figure 4.5. Aerial accumulation of N, P, and K by soybeans (80 bu/A).

wheat. Whether a soybean plant is determinate or indeterminate may also be important for discerning uptake patterns (Sadler and Karlen, 1995).

Accumulations of nutrients in 90 bu/A hard red spring wheat are shown in **Figure 4.6** (Miller et al., 1994). Total accumulations at maturity were 104, 63, and 111 lb N, P_2O_5, and K_2O per acre, respectively. The striking feature of this graph is the high accumulation of K prior to anthesis (GDD 1011) and its subsequent decline through mid-grainfill. The losses were attributed to leaching of K from leaves and culms by precipitation, but the mechanisms were not clear. More than 70 percent of the N and P had accumulated prior to GDD 1100 and more than 78 percent of these nutrients accumulated at maturity was in the grain. By contrast, less than 20 percent of the accumulated K was in the grain at maturity. Greater accumulation of K relative to N and P and its subsequent decline has also been demonstrated for soft red winter wheat by Karlen and Sadler (1990).

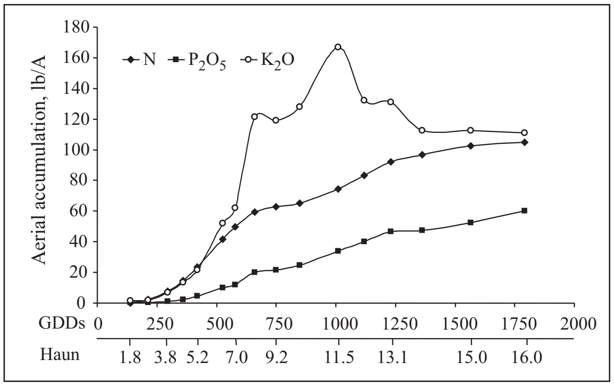

Figure 4.6 Aerial accumulation of N, P, and K by spring wheat (90 bu/A).

Nutrient accumulations for cotton at various growth stages are presented in **Table 4.7**. During the first 60 days after seedling emergence, nutrient absorption is limited. Only about 10 lb N/A, 3 lb P_2O_5/A, and 9 lb K_2O/A are absorbed during the period. However, from 60 days onward, nutrient requirements increase dramatically due to rapid boll and lint development.

Table 4.7. Nutrient accumulation by cotton by plant growth stage.

	Days after planting					
	60	75	90	105	120	135
Nutrient	------------------lb/A------------------					
N	10.3	26.6	54.9	75.4	108.3	119.2
P_2O_5	3	6.4	16	23.2	33.7	39.4
K_2O	8.8	22.2	56	85.6	118.5	134.5

Growth stages:

First square: 35-45 days after planting (DAP)
First white flower: 55 to 65 DAP
Peak bloom: 85 - 90 DAP
First open boll: 115-120 DAP
Mature, defoliation: 135-150 DAP

Source: Hodges et al., 1989.

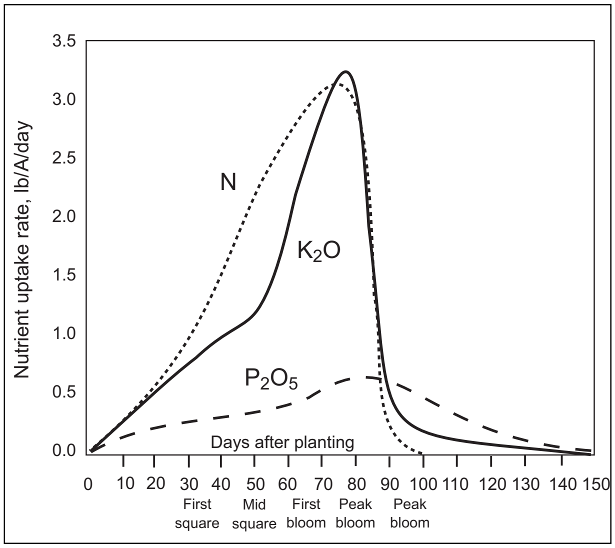

Figure 4.7. Nutrient uptake rates for N, P_2O_5 and K_2O for cotton by growth stage and days following emergence. Source: Hodges et al., 1989.

Research to evaluate late season nutrition for high yield cotton identified the optimum window for foliar application of N, P and boron (B) to be between first flower and the following four or five weeks of fiber and boll development. This sudden increase in nutrient absorption rate is illustrated in **Figure 4.7.**

The absorption of P and K by vegetative plant parts for vegetable crops such as cabbage, sweet corn, snap beans, and beets have been established (Peck, 1975). Like cotton, nutrient needs generally increase dramatically about 60 days after planting. Also, like cotton, availability of both P and K in a balanced nutrition program is important for quality of the harvested product. For example, with inadequate P, vigor of young cabbage plants can be restricted, and the veins in the head can develop a discolored, dark appearance. Potassium fertilization is needed in amounts for optimum marketable yield and firm, high quality heads.

Uptake patterns and the quantity of nutrients in various plant portions can vary with many factors. Precipitation patterns and soil moisture are known to be important (Henderson and Kamprath, 1970; Karlen et al., 1982a; Karlen et al., 1982b; Karlen and Sadler 1990). Soil moisture is known to affect the availability, transport, and absorption of nutrients (Barber, 1984). The level of available nutrients is also important. Marked reductions in P grain concentrations have been demonstrated under similar environmental conditions for one soybean variety planted on a soil low in P compared to the same variety planted on a soil high in P (Hammond et al., 1951). Similar increases in grain P concentration have been demonstrated for corn fertilized with P to supply needed amounts (Mallarino, 1996; Schlegel and Havlin, 1995). The physical condition of the soil and differences among varieties and hybrids in their ability to absorb nutrients have also been shown to impact nutrient uptake (Allan et al., 1996; Peterson and Barber, 1981; Hallmark and Barber, 1981; Silberbush and Barber, 1985). Consequently, much variation in nutrient uptake patterns and resulting crop removal are expected on a variety of temporal and spatial scales.

Summary

The nutritional requirements for growing crops with high yield and optimum quality have been identified and documented through years of field and laboratory research. Balanced crop nutrition is recognized as the foundation of crop production systems necessary to generate the food, feed, fiber, and fuel consumed by a rapidly expanding world population. The use of science-based information on crop nutritional requirements has led to improved yields throughout the world. Greater nutrient removal is closely associated with increases in crop yields. These nutrients must be returned to the soils to maintain and improve long-term productivity.

An efficient nutrient management plan requires access to reliable information about yields, specific crop nutrient requirements and uptake patterns, residual soil nutrients, and preceding crop removal. An understanding of the soil nutrient supply and crop requirements will help in establishing optimum rates, times, and methods for supplying fertilizer nutrients.

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Inorganic Nutrient Use

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Synopsis: This chapter includes an examination of North American and national (U.S. and Canada) trends in nitrogen (N), phosphorus (P), and potassium (K) use, nutrient removal relative to use, apparent nutrient use efficiency of major crops, and yield attributable to fertilizer based on long-term research. Deposits of both phosphate and potash ore in North America are also discussed.

A Brief History of Inorganic Nutrients in North America

Commercial fertilizers were introduced to North America in the 1840s with the importation of Peruvian guano (seabird droppings). This organic material contained 12 to 14 percent N and 10 to 12 percent P_2O_5. Production of inorganic superphosphate and mixed fertilizers began in the U.S. soon after John B. Lawes patented a process by which phosphate rock (PR) was acidulated with sulfuric acid in 1842 in England. Three firms were producing and selling superphosphate in the U.S. by 1853, and many others followed in the 1860s and early 1870s. Early U.S. manufacturers acidulated bones or bone products and phospho-guano.

Although PR was discovered in the U.S. in South Carolina in 1837, its value as a source of P was not recognized until years later when mining began in 1867. Phosphate deposits in Florida were discovered in the 1880s as production in South Carolina was declining. The Florida deposits had a much higher P content and were capable of producing 20 to 40 times more phosphate per acre. Soon after the Florida deposits were identified, PR was discovered in Tennessee. The western deposits (Idaho, Montana, Utah, and Wyoming) were discovered in the late 1890s and were among the largest in the world. Prior to 1920, PR was discovered in 14 other states, but none produced significant amounts except North Carolina, which is still in production.

The U.S. was a major importer of German potash prior to 1910, but problems with pricing and the German potash syndicates resulted in a nationwide effort to find and develop U.S. domestic resources. The outbreak of World War I resulted in even greater shortages. Natural brines from Searles Lake, California; lakes in western Nebraska; and the Great Salt Lake and Salduro Marsh in Utah were the major sources from 1915 to 1920. Other important mineral sources included alunite from Utah, cement dust, and blast furnace dust. Organic sources of importance included kelp, alcohol distillery wastes, sugar beet industry wastes, and wood ashes from the lumber industry. In 1925, while searching for oil, drillers discovered a major world deposit of potash in Eddy County, New Mexico. Exploration for gas and oil intensified during World War II, and that led to the discovery of the world's greatest reserves of high-grade potash in southern Saskatchewan in 1943. Potash was also discovered in New Brunswick in the early 1970s.

Commercial N production lagged behind the P and K industries until after World War II. Chilean nitrates, and to a lesser extent by-product ammonia (NH_3) from coke ovens, were the primary sources of commercial N in North America until the world's fixed-N industry began to be established in the 1930s. The synthesis of NH_3 by reacting hydrogen and atmospheric N is the foundation of today's N industry. German chemists Fritz Haber and Carl Bosch were responsible for the development of the process between 1904 and 1911, with the first full-scale synthetic NH_3 facility coming on stream in Germany in 1913. The first successful synthetic anhydrous NH_3 plant built in the U.S. was at Syracuse, New York in 1921. Within the next 10 years, several other plants were operational in Niagara Falls, New York; Seattle, Washington; Belle, West Virginia; Hopewell, Virginia; Pottsburg, California; and other locations. The first NH_3 plants in Canada came into production around 1940, with two located in British Columbia and one each in Alberta and Ontario. Research on the direct application of anhydrous NH_3 to soil and its effect on crop yield began in the 1940s. **(Information in this section was taken from Nelson, 1990.)**

Inorganic Nutrient Consumption: Past and Present

The use of commercial NPK fertilizer in North America increased by about 200 percent from 1961 to 2000, with most of the increase occurring the first 20 years. **Figures 5.1 to 5.3** and **Appendix 5.1** show N, P, and K consumption for the U.S and Canada during that 40-year period. The significant increase in fertilizer use corresponds to increases in average crop yields and productivity in North America. A readily apparent characteristic in these data is the significantly greater fertilizer consumption in the U.S. compared to Canada. This is due primarily to the greater amount of farmland and crop production in the U.S. For example, in the mid 1990s, the U.S. had over 450 percent more area in farmland than did Canada. The use of NPK in Canada has increased rather steadily since the early 1960s, while U.S. consumption increased until the mid 1980s

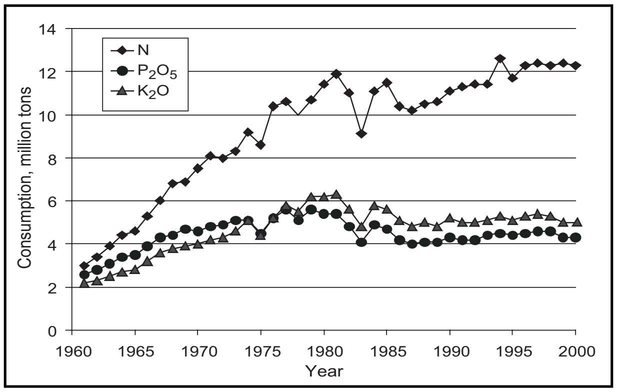

Figure 5.1 **Consumption of N, P_2O_5, and K_2O in the U.S. from 1961 to 2000 (Terry and Kirby, 2001).**

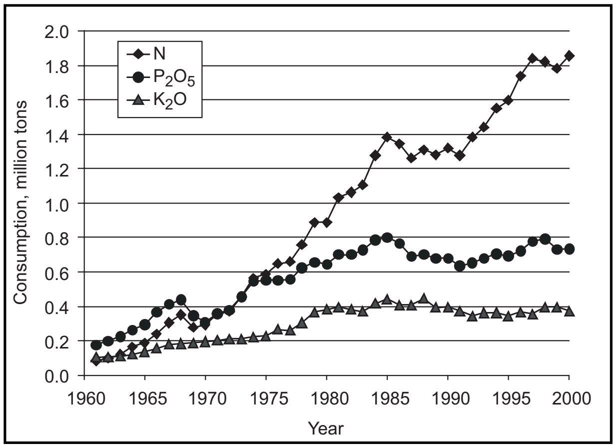

Figure 5.2. **Consumption of N, P_2O_5, and K_2O in Canada from 1961 to 2000 (Korol and Rattray, 2000).**

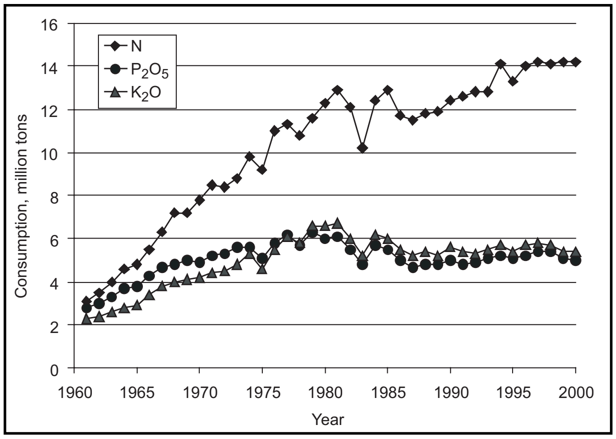

Figure 5.3. **Consumption of N, P_2O_5, and K_2O in North America (U.S. and Canada) from 1961 to 2000.**

and has been relatively stable since.

Fertilizer consumption (N+P+K) in the U.S. from 1961 to 2000 can be separated into three distinct segments. A period of significant growth occurred from 1961 to about 1974. During this time, use increased linearly by about 150 percent, or on average about 11 percent per year. This period was marked by relatively flat fertilizer and crop price indexes and total crop acres. A period of very erratic consumption occurred from the mid 1970s until the mid 1980s, accompanied by dramatic swings in fertilizer and crop prices and total area in production. It started in 1973 with the Arab oil embargo and the deregulation of fertilizer prices, both resulting in sharp increases in fertilizer prices, and ended in 1986 with the Conservation Reserve Program (CRP). Other significant events during this time were the oil embargo in 1979 and the USDA's Payment-in-Kind (PIK) program of 1983. Additionally, starting in the 1970s, increased attention was turned to plant nutrients as a potential contributor to environmental impairment. A period of relatively steady consumption has occurred from the mid 1980s to present, with use ($N+P_2O_5+K_2O$) increasing by about 13 percent from 1987 to 2000.

Inorganic Nutrient Contributions to Crop Production

Some have estimated that nutrient inputs are responsible for between 30 to 50 percent of crop yield. Making these estimates presents significant challenges. Certain assumptions are required regardless of the approach taken. One difficulty that arises is that crops respond differently to different fertilizer nutrients. For example, corn response to N fertilizer is much greater than that of a legume such as soybeans or peanuts. This effort is further confounded by many other factors such as variable soil fertility levels, climatic conditions, and changes in production practices that affect nutrient use efficiency. Nevertheless, meaningful estimates of the contribution of inorganic fertilizer to crop yield can be and have been made.

Smith et al. (1990) investigated the impact of chemical use reduction on yields for eight major crops in the U.S. The authors analyzed the impact of eliminating the use of pesticides (herbicides, insecticides, fungicides) and inorganic N fertilizer on corn, cotton, rice, barley, sorghum, wheat, soybeans, and peanut yields. Other crop nutrients were not taken into account. The estimated effect of eliminating N fertilizer alone (i.e., no pesticide elimination) on U.S. crop yields is shown in **Table 5.1**. Average U.S. corn yield was predicted to decline by 41 percent without N fertilizer. In other words, N fertilizer was responsible for 41 percent of corn yield. The elimination of all pesticides and N fertilizer resulted in an estimated 53 percent decline in corn yield. Therefore, N fertilizer was responsible for the majority of corn yield among the inputs analyzed. The elimination of N in cotton production resulted in an estimated yield reduction of 37 percent, the largest of any single input group analyzed. The average estimated reduction in yield from elimination of N fertilizer of the six non-leguminous crops analyzed was 26 percent.

One approach to estimating the portion of crop yield attributable to fertilizer is to select studies for major crops where zero fertilizer controls have been employed and calculate the portion of yield attributable to fertilization. At Oklahoma State University, scientists have studied wheat fertility since the late 1800s (OSU

Table 5.1 **Estimated effect of eliminating N fertilizer on U.S. crop yields (Smith et al., 1990).**

	Yield[1]		
Crop	Baseline[2]	Without N	Reduction, %
Corn	122	72	41
Cotton	679	427	37
Rice	5,500	4,000	27
Barley	47	38	19
Sorghum	69	56	19
Wheat	32	27	16
Soybeans	34	34	0
Peanuts	2,281	2,281	0

[1] Crop yields are in bu/A for corn, barley, sorghum, wheat, and soybeans; lb/A for cotton, rice, and peanuts.
[2] Baseline yields taken from 1987 USDA/ERS report.

Soil Fertility Research Highlights, 2000). The Magruder Plots were established in 1892 and are the oldest continuous soil fertility wheat research plots in the Great Plains and among the oldest in the world. As one would expect, the fertility treatments have changed since the plots were established, with yearly inorganic fertilizer applications commencing in 1930. The inorganic N source was sodium nitrate from 1930 to 1946, when it was changed to ammonium nitrate. Nitrogen rates have ranged from 33 to 60 lb N/A. The early inorganic P source was ordinary superphosphate [0-20-0-12 sulfur (S)]. It was replaced by triple superphosphate (0-46-0) in 1968. The P rate throughout the study has been constant at 30 lb P_2O_5/A. **Figure 5.4** shows that when averaged over 71 years, N and P fertilizer have been responsible for 40 percent of wheat yield.

Another long-term study is being conducted at the University of Illinois. Various crops, rotations, and fertility treatments have been evaluated in the well-known Morrow Plots since 1876. Early fertility treatments included manure, PR, bone phosphate, and limestone. In 1955 commercial fertilizer treatments were imposed that combined N from urea, P from superphosphate, K from muriate of potash, and lime. An evaluation of grain yields from continuous corn (**Figure 5.5**) from the no fertilizer control and the N+P+K+lime treatment revealed that on average, from 1955 to 2000, 57 percent of yield was attributable to the fertilizer+lime treatment (derived from data provided by Dr. Harold F. Reetz, personal communication).

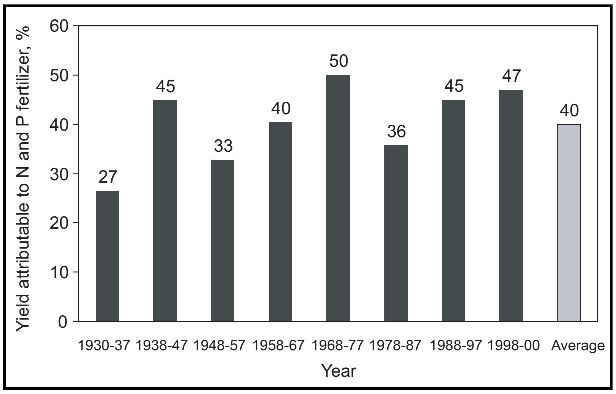

Figure 5.4. **Wheat yield attributable to inorganic N and P fertilizer from 1930 to 2000 in Oklahoma State University Magruder Plots (OSU, 2000).**

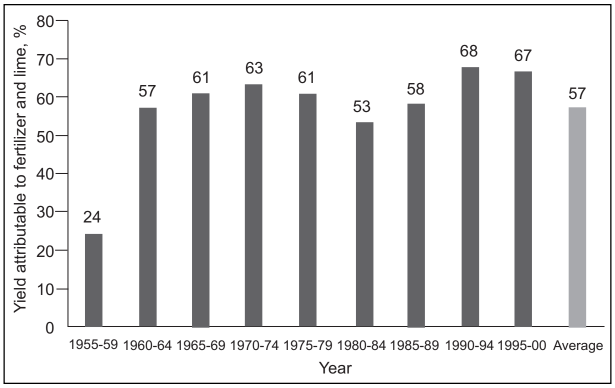

Figure 5.5. **Continuous corn yield from Morrow plots attributable to N, P, and K fertilizer and lime over 46 years (Reetz, 2001, personal communication).**

A long-term irrigated study in western Kansas has examined the effect of various N rates (0 to 200 lb N/A in 40 lb increments) and P fertilization (0 and 40 lb P_2O_5/A) on yields of corn and grain sorghum. Over 40 years (1961 to 2000) of this study, N and P fertilizer on average produced 44 percent of corn yield and 31 percent of sorghum yield (derived from Schlegel, 1990, 1991, and 2000). The data presented in **Table 5.2** summarize 40-year average yields for both crops for each fertility treatment and percent of yield attributable to fertilization. These data clearly illustrate the importance of balanced fertility in crop production. A somewhat more realistic approach to estimating the amount of yield attributable to fertilizer would be to examine the contribution to yield that fertilizer makes at the optimum rates of N and P. The economic optimum N rate for corn in this study was 160 lb/A. In most years for sorghum, it was 80 lb/A (Schlegel, 2000). Phosphorus fertilizer (40 lb P_2O_5/A) was necessary to maximize profit for both crops. The 40-year averages for percentage of yield attributable to fertilizer at the economic optimum rates for N and P for

Table 5.2. **Effect of N and P fertilizer on 40-year average (1961 to 2000) irrigated corn and grain sorghum yields and percent yield attributable to fertilization in western Kansas. (Schlegel, 1990, 1991, and 2000).**

Fertilizer applied, lb/A		Grain yield, bu/A		Yield due to fertilizer, %	
N	P_2O_5	Corn	Sorghum	Corn	Sorghum
0	0	68	70	—	—
0	40	72	72	5	3
40	0	102	90	33	22
40	40	119	106	43	34
80	0	116	102	41	31
80	40	145	113	53	38
120	0	117	98	42	29
120	40	160	118	57	40
160	0	124	102	45	31
160	40	169	120	60	42
200	0	127	105	46	33
200	40	169	121	59	42

corn and grain sorghum were 60 and 38 percent, respectively.

The data from the long-term studies discussed in this section represent 157 years of crop production. Although significant variability in crop response to fertilizer inputs occurs among crop species, soil conditions, climate, and other factors, these data and the results of the chemical use reduction investigation (Smith et al., 1990) support the generalization that somewhere between 30 and 50 percent of crop yield is attributable to nutrient inputs.

Crop Nutrient Removal Relative to Fertilizer Use

One way to evaluate nutrient use is to consider it relative to nutrient removal. Estimates of annual national N, P, and K removal/use ratios were made for both the U.S. and Canada (**Appendix 5.2a and 5.2b**). The estimates use production data from 18 crops in the U.S. and 17 in Canada. These crops represent the majority of acres harvested in each country, accounting for practically all production in North America. From these data, total nutrient removal was estimated, using data from **Table 4.4**, for each of 40 years from 1961 to 2000. The yearly inorganic nutrient use data were taken from **Appendix 5.1**.

Trends in P and K removal/use ratios in the U.S. and Canada are shown in **Figures 5.6 and 5.7**. They agree with trends in yield of major crops relative to total P and K use. Over the entire 40-year period, yields of major crops have increased. Consumption of both P and K was increasing in the U.S. and Canada until the mid to late 1970s. Beginning in the late 1970s to early 1980s, use began to flatten in both countries. Therefore, since the late 1970s, removal/use ratios in the U.S. have been steadily increasing. They have also been increasing in Canada, but at a much slower rate. Considering the 1:1 line in these figures, the U.S. and Canada have been in a depletion mode for soil K over the entire 40 years. The U.S. has been depleting soil P since the early 1980s, and Canada has been depleting soil P for most of the entire 40 years.

These estimated removal/use ratios do not take into account organic nutrient use. However, only a small percentage of cropland actually receives nutrients from manure. For the four major U.S. crops, the average proportion of acres receiving manure from 1990 to 1997 was 17 percent for corn, 6 for soybeans, 4 for cotton, and 3 for wheat (USDA-ERS, 2000). Therefore, the increasing rate of depletion of soil P and K across the nation applies to the majority of acres in production. Evaluations of nutrient budgets that include manure nutrients are included in Chapter Ten.

Crop Production to Fertilizer Use Ratios of Selected Crops

Crop production to fertilizer use ratios are sometimes viewed as indicators of apparent fertilizer use efficiency (AFUE). However, since many other factors, such as native or residual soil fertility and crop genetics, affect units of production per unit of fertilizer applied, using AFUE as an efficiency indicator must be done carefully. For example, short-term increases in production to fertilizer use ratios may be the result of **mining** (depletion) of organic or inorganic soil nutrients either inherent in the soil or residual from past nutrient applications. Increasing fertilizer or nutrient use efficiency has potential economic as well as environmental benefits as long as it does not jeopardize future productivity. With higher use efficiency, more of the fertilizer nutrient is used in producing crop yield and less is left in the environment.

Average rates of application for N, P, and K for each of the four major crops in the U.S. (corn, soybeans, wheat, cotton) and production to fertilizer use ratios have been calculated for each year from 1964 to 2000 (**Figures 5.8 to 5.15 and Appendix 5.3a and 5.3b**). Acreage data used in making these calculations were taken from USDA-NASS (2001b) and total nutrient use by crop data were based on results of annual Agricultural Chemical Usage Surveys obtained via personal communication with Harold Taylor (USDA-ERS, Washington, D.C.). Details on the Usage Surveys can be obtained from USDA-NASS (2001a). Nutrient use data by crop in Canada are not available, so these ratios could not be determined.

Ratios for N, P, and K in corn production have trended upward over the past 20 years or so (**Figure**

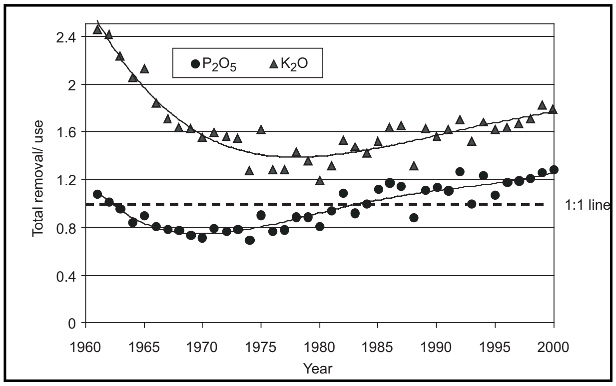

Figure 5.6. Estimated total nutrient removal relative to inorganic nutrient use in the U.S. from 1961 to 2000.

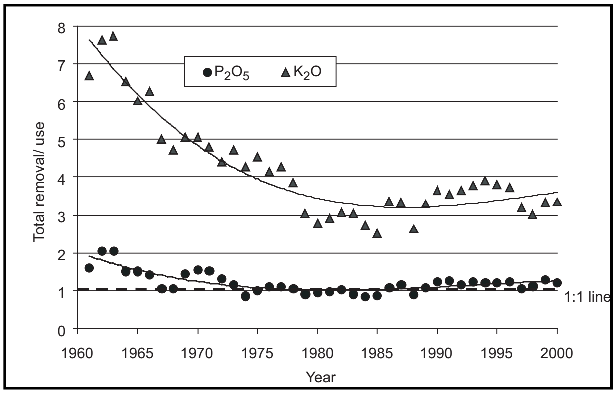

Figure 5.7. Estimated total nutrient removal relative to inorganic nutrient use in Canada from 1961 to 2000.

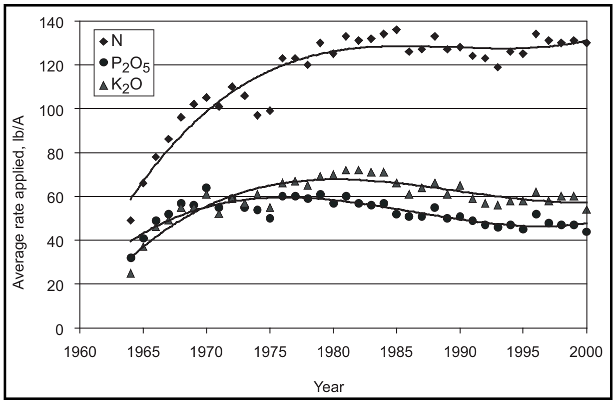

Figure 5.8. Average rates of application of N, P, and K fertilizer on corn in the U.S.

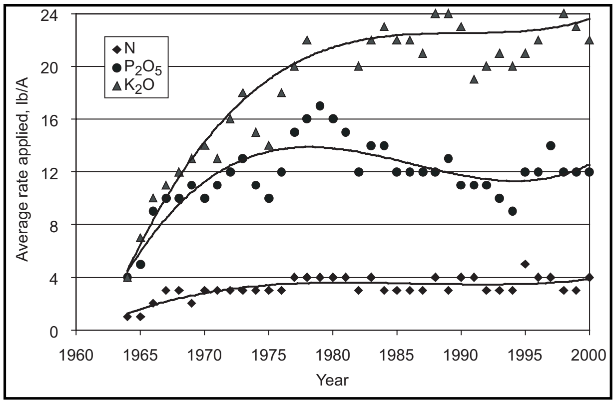

Figure 5.9. Average rates of application of N, P, and K fertilizer on soybeans in the U.S.

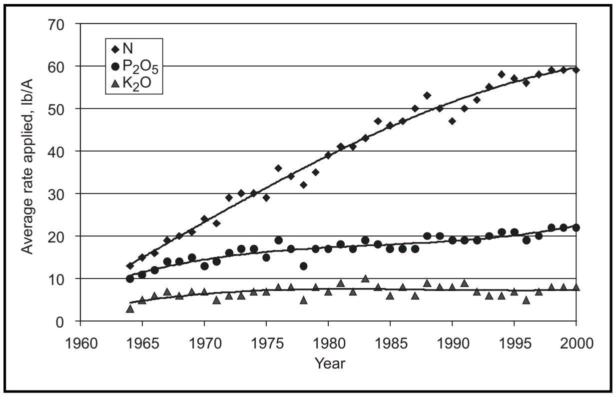

Figure 5.10. Average rates of application of N, P, and K fertilizer on wheat in the U.S.

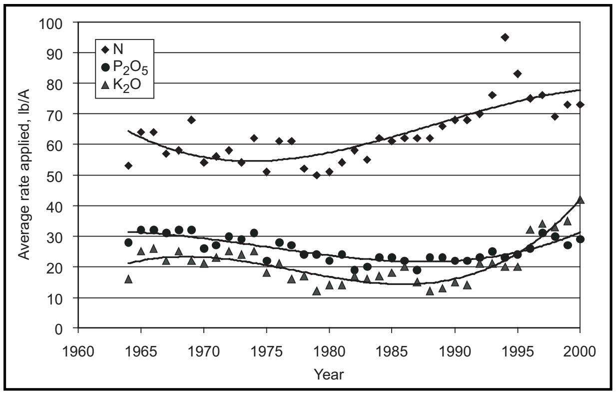

Figure 5.11. Average rates of application of N, P, and K fertilizer on cotton in the U.S.

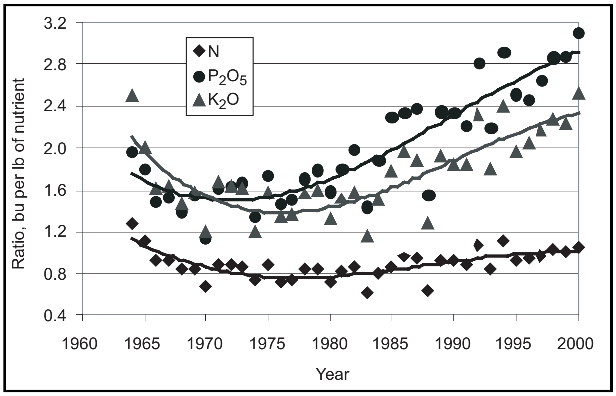

Figure 5.12. Ratio of corn production to estimated N, P, and K fertilizer use on corn in the U.S.

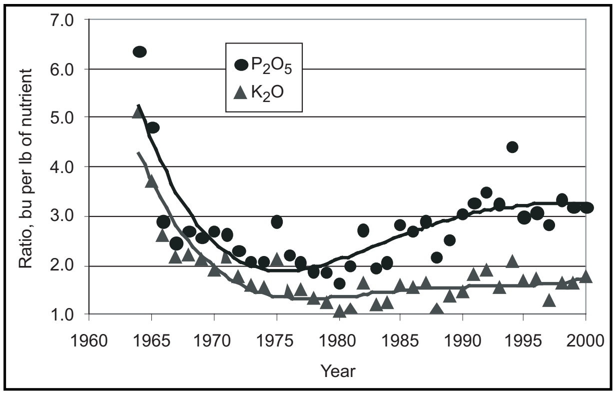

Figure 5.13. Ratio of soybean production to estimated P and K fertilizer use on soybeans in the U.S.

5.12). The increase has been much more dramatic for P and K than for N. This is reasonable since over the same time period total N use on corn has been relatively flat while total P and K use has declined. Still, this increase for N amounts to a 35 percent increase in AFUE during a period when corn yields increased 40 percent.

In soybean production, AFUE for both P and K declined from 1960 to about 1980 as some farmers began directly fertilizing soybeans (**Figure 5.13**). Since 1980, yields have increased more than P and K use, causing AFUE to trend slightly upward.

Nitrogen AFUE in wheat production declined until about the mid 1980s and has remained relatively constant since (**Figure 5.14**). The initially higher AFUE for N was probably due to high levels of residual N in grassland prairie soils that has since been depleted. Increased use of conservation tillage and a reduction in fallowing have contributed to the reversal of long-term soil organic matter declines in much of the Great Plains, a major wheat producing region, but also likely immobilized N, contributing to the apparent reduction in N AFUE. Trends in both P and K AFUE in wheat production have, for the most part, remained relatively flat over the 40-year period.

Trends in AFUE for P and K in cotton production

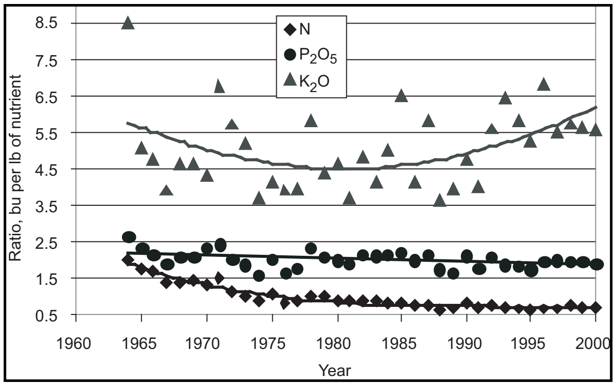

Figure 5.14. Ratio of wheat production to estimated N, P, and K fertilizer use on wheat in the U.S.

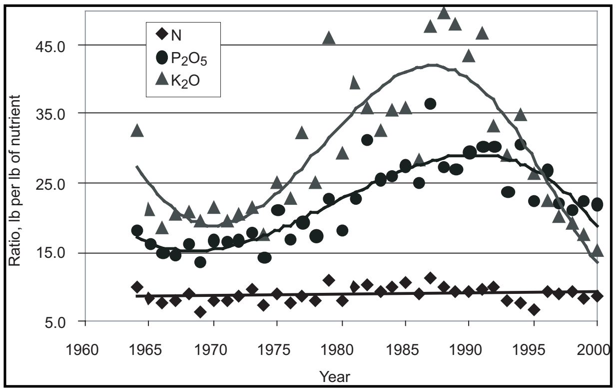

Figure 5.15. Ratio of cotton production to estimated N, P, and K fertilizer use on cotton in the U.S.

have been quite variable, while N has been relatively constant (**Figure 5.15**). The K trend is especially dynamic but is explainable. From about 1975 to 1995, fertilizer K use on cotton was less than estimated removal. A ratio greater than about 25 indicates that K removal exceeds application. Thus, plant-available K in the soil profile was being depleted unless fertilization of other crops in the rotation balanced the removal. In the late 1980s, severe K deficiency symptoms were detected on cotton late in the season in many cotton-growing regions (Oosterhuis, 1994). Recognition of the problem resulted in increases in fertilizer K application rates (**Figure 5.11**) as farmers attempted to correct these deficiencies and restore the fertility mined from their soils during the previous decade. The increase in average K application rate on cotton is reflected in the downward trend in the ratio beginning in the late 1980s (**Figure 5.15**). A similar, but much less dramatic trend, is apparent for P.

Inorganic P and K Production and Reserves

Phosphate

The U.S. is the world's largest producer of PR, accounting for nearly 27 percent of the total world production of 141 million short tons in 2001 (**Table 5.3**). It is also the world's largest consumer and exporter of PR. More than 90 percent of phosphate ore mined in the U.S. is used to make fertilizers and animal feed; the remainder goes to the production of elemental P and other industrial phosphates (Jasinski, 2000).

Domestic production of marketable PR steadily increased from 1970 until the early 1980s where it peaked at about 60 million tons (**Figure 5.16**). Since then annual production has varied from 41 to 55 million tons, with an average of about 45 million tons in the last five years. Trends in consumption have closely followed production.

Table 5.3. World phosphate rock production, reserves, and reserve base (thousand tons).

	Marketable mine production								
	1997	1998	1999	2000	2001	Reserves[1]	Reserve life[1], years	Reserve base[1]	Life reserve base[2], years
United States	50,582	48,708	44,741	42,537	37,688	1,102,000	25	4,408,000	98
Brazil	4,243	4,706	4,518	5,400	5,510	363,660	75	407,740	84
China	22,040	27,550	27,660	21,379	22,040	1,102,000	46	11,020,000	457
Israel	4,463	4,518	4,518	4,529	4,408	198,360	44	881,600	196
Jordan	6,502	6,502	6,612	6,072	6,061	991,800	156	1,873,400	295
Morocco and Western Sahara	25,787	26,448	26,448	23,803	24,244	6,281,400	248	23,142,000	913
Russia	8,265	10,800	12,232	12,232	11,571	220,400	20	1,102,000	100
Senegal	1,697	1,433	1,984	1,984	2,204	55,100	30	176,320	95
South Africa	3,306	3,086	3,196	3,086	3,086	1,653,000	524	2,755,000	874
Syria		2,755	2,314	2,391	2,314	110,200	56	881,600	451
Togo	2,898	2,424	1,873	1,510	882	33,060	17	66,120	34
Tunisia	7,791	8,761	8,816	9,191	8,926	110,200	13	661,200	76
Other countries	14,546	12,122	10,469	12,453	12,232	1,322,400	107	4,408,000	357
World total (rounded)	152,076	159,790	155,382	146,566	141,056	13,224,000	88	51,794,000	343

[1] Reserve and reserve base cost less than $36/ton and $90/ton, respectively. Cost includes capital, operating taxes, royalties (if applicable), miscellaneous costs, and a 15 percent rate of return on investment, FOB mine (based on 1992 costs).
[2] Life based on 1997-2001 five-year average mine production (2001 production numbers are estimated).
Source: U.S. Geological Survey, Mineral Commodities Summaries, 1998-2002.

Fifteen active mines located in Florida, North Carolina, Idaho, and Utah produced almost 38 million tons of PR in 2001 (**Figure 5.17**). Florida and North Carolina accounted for 85 percent of production. There is one mine in Canada located at Kapuskasing, Ontario, with a production capacity of about 1.1 million tons of PR.

Estimates of world phosphate reserves and how long it will take until reserves are exhausted vary greatly. Phosphate rock deposits are found worldwide, and definitions of the availability of these deposits differ. The U.S. Bureau of Mines (USBM) and U.S. Geological Survey (USGS) (1981) define **reserves** as those deposits that can be economically extracted or produced at the time of determination. **Resources** are defined as reserves plus all other mineral deposits that may potentially be feasible at some time in the future. **Reserve base** is that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices.

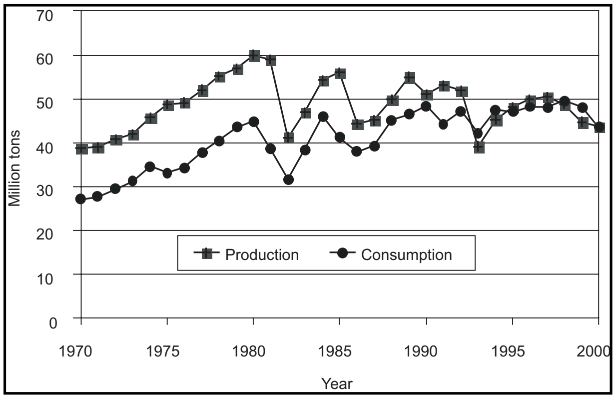

Figure 5.16. U.S. phosphate rock production and consumption (1970-2000).

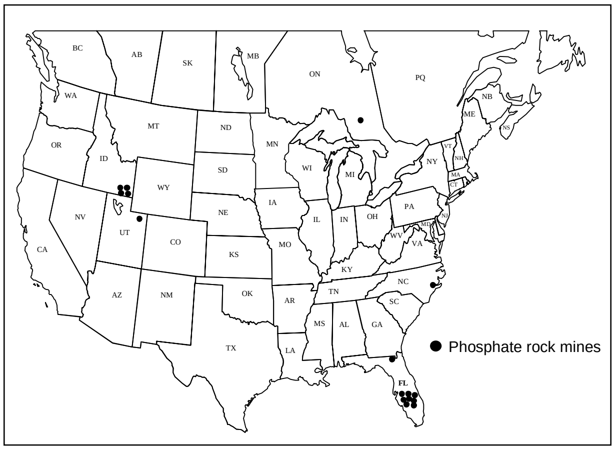

Figure 5.17. Location of North American phosphate mines.

Table 5.3 shows USGS estimates for PR reserves and reserve base for the major producing countries in the world. The U.S. has about 8 percent of world reserves and 8 percent of the global reserve base. Depletion of reserves is difficult to predict. If future consumption equaled production averaged between 1997 and 2001 (i.e. 45 million tons), U.S. phosphate reserves would last another 25 years, while world reserves would last 88 years. Using the same assumptions, the remainder of the U.S. reserve base would be used up in another 73 years, and the world's reserve base would last another 255 years.

Supposing future consumption remains constant may be too simplistic and conservative, although the data in **Figure 5.16** suggest U.S. consumption appears to have stabilized. Herring and Fantel (1993) modeled depletion of world PR deposits by anticipating future demand based on population growth. They considered various scenarios of unconstrained growth in PR based on world historical production, assuming production to be equal to demand and with no future additions to reserves. Their estimates suggested that known world reserves would be depleted within 50 years from 1990 and that the remainder of the reserve base would be exhausted within 100 years.

The above predictions do not mean that the U.S. and other countries will run out of PR at some preset time in the future. **Table 5.4** shows the amount of phosphate reserves available in the U.S. in 1989 in terms of cost per ton. The USGS current reserve figures assume a maximum cost of $36/ton for estimates. If the cost exceeds $36/ton, the U.S. reserve base more than triples. Such detailed cost data are not readily available for most of the other world producers, but it is reasonable to assume that similar costs govern the reserve/reserve base in other countries. Also, the above estimates do not consider world phosphate resources, which are not presently economically recoverable.

Table 5.4. U.S. phosphate rock reserve base (million tons) in terms of cost[1] (1989).

	Cost, $/ton						
Location	<18	18-27	27-36	36-54	54-73	73-91	Total
Florida	247	290	284	1,213	573	191	2,798
North Carolina		432		374			806
Utah					724	77	801
Wyoming					116	118	234
Idaho		79	15	77			172
Tennessee	2	3		9			14
Montana		1					1
Total	249	806	300	1,673	1,413	386	4,826
Cumulative total	249	1,055	1,354	3,027	4,440	4,826	

[1]Costs include capital, operating taxes, royalties (if applicable), miscellaneous costs, and a 15 percent rate of return on investment.
Source: Stowasser 1991

Data for total U.S. phosphate resources are not shown, but estimates are immense. Onshore phosphate resources for the Atlantic Coastal Plain have been estimated at about 24 billion tons (Herring and Fantel, 1993). Using the same assumptions for the reserve life estimates in **Table 5.3**, that resource life would exceed 500 years. Southeastern offshore deposits are believed to extend from peninsular Florida to possibly as far north as the Grand Banks, and as much as 200 billion tons of phosphate resources may be contained in the Miocene sediments of the Continental Shelf offshore Georgia (Manheim, Herring and others as cited by Herring and Fantel, 1993). In the western U.S., resources less than 325 yards below ground and that could be surface mined are estimated at 28 billion tons. Another 550 billion tons of phosphate resources are deeper than 325 yards. However, they are not considered a resource because the depth is too great for mining in the foreseeable future.

The USBM and USGS have reported a total of about 105 billion tons of PR resources in the world (cited in Fantel et al., 1985). Using an average world production of 151 million tons (1997-2000), it would take more than 695 years to deplete world PR resources, assuming they could economically be available at some time in the future.

Potash

The world mined 30.2 million short tons of K_2O in 2001. Canada remained the largest producer at 9.7 million tons, or 32 percent of the world's total production. The U.S. was the sixth largest producer with 4 percent. About 95 percent of the Canadian production was mined in Saskatchewan at eight underground mines and two solution mines, with the remaining production coming from an underground mine in New Brunswick (Pearse, 2000, **Figure 5.18**.). Most of the U.S. production was from three underground mines in southeastern New Mexico (Searles, 2000). The balance of U.S. production was from a deep solution mine in Michigan and a surface brine mine in Utah.

Canada continues to be the world's largest exporter of potash with 43 percent of the world trade in 2000, and the U.S. remained the largest user with about 20 percent of the world's consumption. More than 90 percent of the potash utilized in the U.S. comes from Canada.

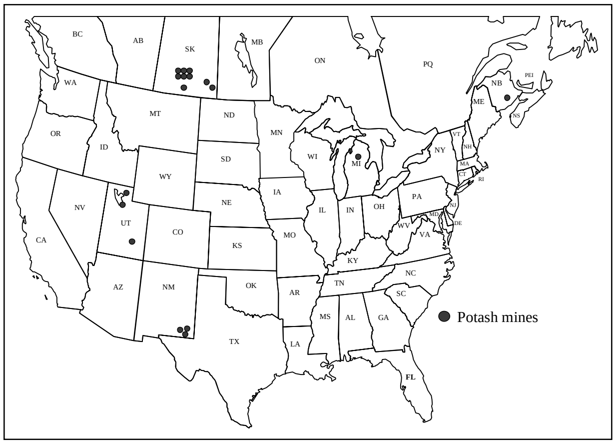

Figure 5.18. Location of North American potash mines.

North American and world reserves and resources of potash are extensive. With 5 billion tons of reserves, Canada and the U.S. have 54 percent of current world reserves, enough to last almost 600 years at current consumption rates (**Table 5.5**). With just over 11 billion tons of potash in the North American reserve base, there is sufficient potash to meet domestic and export needs for centuries.

Estimates of the world's potash resources vary widely, but by all accounts resources are huge. One of the reasons for the discrepancy is that published information does not always differentiate between ore and K_2O equivalent. Estimates of world resources range from about 160 to 250 billion tons K_2O (Sheldrick, 1985; USGS, 2001). Canada's potash resources are conservatively projected at 60 billion tons (PPIC, 1989), while U.S. resources are estimated at 6 billion tons (USGS, 2001), enough to produce at current levels for several thousand years.

Phosphate rock and potash ores are finite non-

Table 5.5. World potash production, reserves, and reserve life (thousand tons).

	Marketable mine production								
	1997	1998	1999	2000	2001[1]	Reserves	Reserves life[1], years	Reserve base	Reserve base life[1], years
Belarus	3,582	3,747	3,967	3,747	3,857	826,500	219	1,102,000	292
Brazil	268	268	386	386	353	330,600	996	661,200	1,992
Canada	10,250	9918	9,179	9,477	9,698	4,848,800	500	10,689,400	1,101
Chile	240	24	24	25	25	11,020	152	55,100	758
China	127	132	138	276	353	154,280	753	506,920	2,473
France	733	723	331	354	298	551	1		
Germany	3,772	3,526	3,967	3,757	3,681	782,420	209	936,700	250
Israel	1,640	1,653	1,929	1,884	2,028	44,080	24	639,160	350
Jordan	936	937	1,212	1,223	1,344	44,080	39	639,160	565
Russia	3,747	3,857	4,628	4,077	4,849	1,983,600	469	2,424,400	573
Spain	705	700	606	575	639	22,040	34	38,570	60
Ukraine	110	66	39	33	39	27,550	481	33,060	576
United Kingdom	623	634	551	661	573	24,244	40	33,060	54
United States	1,543	1,433	1,322	1,433	1,322	99,180	70	330,600	234
Other countries						55,100		154,280	
Total	28,321	27,660	28,321	27,881	30,195	9,256,800	325	18,734,000	658

[1] Life based on 1997-2001 average mine production (2001 production numbers are estimates).

Source: U.S. Geological Survey, Mineral Commodities Summaries, 1998-2002.

renewable resources. Estimates of reserves and availability of exploitable deposits are difficult to predict. It is also difficult to forecast how long existing reserves will last due to the challenges of anticipating future market growth or when known resources will become economical to use. However, at current production levels, North America has sufficient reserves of phosphate ore to last about 25 years at today's costs and practices and almost 100 years including higher cost ore. Longevity of North American potash is of no concern, with sufficient reserves available to last hundreds of years.

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Chapter Six

Organic Nutrients

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Synopsis: Livestock production operations are declining in number and growing in size. This concentration of animal units (AU, 1,000 pounds of live animal weight) has led to problems in utilizing manure for maximum agronomic and environmental benefit. The issue facing North America is how to economically transport or otherwise utilize a product of large volume and low nutrient content.

Organic nutrients are receiving increased attention in North America and around the world. They offer the opportunity of being an economic and agronomic resource to supplement inorganic fertilizer in the production of crops. Organic materials contain varying concentrations of plant nutrients and also provide organic carbon (C) that enhances the physical properties of soil.

There are, however, increasing concerns regarding the growing abundance of some sources of organic nutrients. In the case of animal manures produced in relatively confined geographic areas, nutrient loading can occur in fields in close proximity to these operations. This can pose the hazard of excessive nitrate (NO_3^-) leaching to groundwater and phosphorus (P) moving into surface waters. Significant amounts of ammonia (NH_3) can be lost to the atmosphere. Indiscriminate use of animal and human waste (sewage sludge) can also create health hazards through the accumulation of heavy metals and pathogens.

Sources and Composition

There is a large assortment of organic materials that can serve as nutrient sources. Organics may originate from animals or plants produced from agricultural endeavors or as by-products from other industries. Animal manures from various types of operations (beef, poultry, swine, etc.) have been used as sources of nutrients down through the ages. Also, green manures (plants raised specifically to be plowed down to benefit a following crop) have a long history in crop production systems. Other products and by-products, some previously thought of strictly as wastes, are being promoted for their nutrient content and other benefits. A few examples, to illustrate the breadth of materials, are apple pumice, fish scrap, sewage sludge, peanut hull meal, garbage tankage, and wood ashes. Lengthy lists of diverse organic materials and manures with their nutrient contents are given in **Appendices 6.1 and 6.2**.

The value of the various organic materials depends largely on 1) their nutrient content and 2) market availability. Many of the sources listed in **Appendix 6.1** are available in relatively small amounts or in localized areas. Of greatest concern in North America are livestock manures that are produced in large quantities in certain regions. If not managed properly, these sources of nutrients become waste material, rather than a resource, and a potential environmental hazard.

Manure and other organic material are successfully used to improve chemical (nutrient), biological, and physical properties of soil. However, as the modern fertilizer industry developed high analysis products that can be applied with great accuracy, less reliance has been placed on organic sources to sustain production. Disadvantages of organic materials include low analysis that makes them uneconomical to transport far from their source, variable analyses, timing of release of many nutrients, and a relatively fixed ratio among nutrients.

This fixed nutrient ratio common to organic sources has led to a national concern of excessive P in heavily manured soils because crops require less P compared to nitrogen (N) than that contained in manure. When manure is applied to crops based on N requirement, P will build up in soils (see Chapter Three). This issue is being addressed by the Natural Resources Conservation Service (NRCS) as mandated by the U.S. Environmental Protection Agency (EPA) for large confined animal feeding operations (CAFOs). The average $N:P_2O_5$ and $N:K_2O$ ratios of livestock manure (liquid and solid) are presented in **Table 6.1**. These ratios can be compared against the crop removal values in **Table 4.4**. Potassium (K) and N are removed in quantities of roughly the same magnitude for many forages, tree and vine crops, and vegetables. Therefore, K accumulation from long-term manuring (at appropriate rates of N) is not considered to be a problem. The exception to this generalization is grain crops where the straw or stover is not removed along with the grain. In such cases, K would tend to accumulate with repeated manure applications.

Table 6.1. Average composition of various manures.

	Total N, % by wt	NH_4^+-N, % of total N	Ratio	
			$N:P_2O_5$	$N:K_2O$
Liquid				
Hog	0.37	62	1.5:1	1.9:1
Dairy	0.29	48	1.8:1	0.9:1
Beef	0.25	64	1.4:1	1.2:1
Poultry	0.75	75	1.2:1	2.0:1
Solid				
Hog	1.00	27	0.7:1	1.2:1
Dairy	1.10	12	3.4:1	2.0:1
Beef	0.59	12	1.8:1	0.8:1
Poultry	2.00	27	1:1	1.5:1

Calculated from OMAFRA, 1998; (based on total composition).

Organic materials require biological activity to break down and release soluble nutrients. The soil microorganisms require N and other nutrients for this process. If there is insufficient N in the material being broken down, then N…NO_3^- and ammonium (NH_4^+)... already in the soil will be utilized, resulting in temporary immobilization of plant-available N. If there is ample N in the decomposing organic material, then plant-available N is released or mineralized. **Table 6.2** presents the C:N ratios for a range of organic materials. In general, a C:N ratio of less than 20:1 will result in net mineralization, and a ratio wider than 30:1 will result in net immobilization in the initial decomposition process.

Table 6.2. Carbon-to-nitrogen ratios of selected organic materials.

Material	**C:N Ratio**
Fish waste	2.6-5.0
Poultry, cage layer	3-10
Sewage sludge	5-16
Broiler litter	6-8.3
Swine manure	9-19
Grass clippings	9-25
Sweet clover (young)	12
Cattle manure	11-30
Clover residues	23
Horse stable waste	22-50
Corn stover	60
Grain straw	80
Leaves	40-80
Fly ash	78
Pine bark	135
Crude oil	388
Sawdust	400
Newsprint	398-852

Source: Keener et al., 2000.

Generally, the C:N ratios of animal manures are sufficiently narrow that decomposition and release of plant available N occurs relatively rapidly under favorable environmental conditions. Of course when bedding or other straw-type residues are mixed with manure, the C:N ratio widens, depending on the mixture, and temporary immobilization of N could become a factor.

The actual rate of decomposition of any organic material is difficult to predict. This presents a problem in management of these materials in crop production systems. Influencing factors include the quantity of organic material added, C:N ratio, resistance of the material to microbial attack (content of lignins, waxes, etc.), temperature, soil moisture, and thoroughness of mixing with the soil.

Production Systems

The dominant source of livestock manure potentially recoverable in North America is from confined animal operations involving beef cattle, dairy, swine, or poultry. The number of confined AU in the U.S. was about 38 million in 1997, representing 40 percent of the total AU of 95 million. Total (confined data not available) AU for Canada was 13.4 million in 1996 (**Table 6.3**). Overall, confined AU in the U.S. are increasing at a modest annual rate of 0.5 percent, compared to 0.6 percent for total AU in Canada.

Potential issues with livestock operations and manure disposal become apparent when operations are evaluated by livestock type. Poultry and swine numbers increased dramatically from 1982 to 1997 in the U.S. Swine increased 31 percent and poultry 52 percent. In Canada, the biggest increases were associated with swine at 50 percent and other beef and dairy at 23 percent. Milk cows declined in both countries during this period.

Table 6.3. Number of AU on livestock operations by livestock type in the U.S. (confined), 1982-1997, and total number of AU on farms in Canada, 1981-1996.

	Number of confined AU on livestock operations				Change,	Change, %
	1982	1987	1992	1997	1982-97	1982-97
U.S.						
Fattened cattle	9,107,719	9,273,561	8,897,383	9,318,175	210,456	2.3
Milk cows	11,366,916	10,751,485	10,204,245	9,898,546	-1,468,370	-12.9
Other beef and dairy	4,692,325	4,419,122	4,454,352	4,475,087	-217,238	-4.6
Swine	6,300,647	6,396,356	7,206,663	8,232,837	1,932,190	30.7
Poultry	4,019,413	4,858,112	5,348,144	6,118,056	2,098,643	52.2
All livestock types	35,487,020	35,698,636	36,110,787	38,042,702	2,555,681	7.2
	Total number of AU on farms				Change,	Change, %
	1981	1986	1991	1996	1981-96	1981-96
Canada						
Fattened cattle	2,370,317	1,968,400	1,961,345	2,343,305	-27,012	-1.1
Milk cows	2,395,068	1,968,193	1,777,268	1,659,097	-735,971	-30.7
Other beef and dairy	6,049,142	5,544,807	6,302,499	7,433,998	1,384,856	22.9
Swine	1,011,132	1,344,316	1,407,630	1,521,218	510,086	50.4
Poultry	177,217	163,228	174,101	186,610	9,393	5.3
All livestock types	12,002,876	10,988,944	11,622,843	13,144,228	1,141,352	9.5

U.S. data: Kellogg et al. 2000.
Canadian data: Anonymous. 1997.

Table 6.4. Number of livestock operations by farm size in the U.S. (confined AU), 1982-1997, and Canada (total number), 1981-1996.

	Number of operations with confined livestock				Change, 1982-97	Change, % 1982-97
	1982	1987	1992	1997		
U.S.						
<25 total AU	112,732	97,507	75,425	57,061	-55,671	-49
25 to < 50 AU	199,300	177,798	162,929	150,130	-49,170	-25
50 to <150 AU	302,934	265,272	241,216	209,670	-93,264	-31
150 to <300 AU	76,735	72,600	72,295	68,279	-8,456	-11
300 to <1000 AU	31,930	32,214	34,841	37,093	5,163	16
1000 or more AU	4,908	5,274	6,004	7,425	2,517	51
All livestock operations	728,539	650,665	592,710	529,658	-198,881	-27
	Number of farms reporting				Change, 1981-96	Change, % 1981-96
	1981	1986	1991	1996		
Canada						
Cattle and calves						
1-32	73,108	58,078	47,695	43,027	-30,081	-41.1
33-77	59,643	50,161	46,894	42,983	-16,660	-27.9
78-177	38,953	34,953	36,029	37,208	-1,745	-4.5
178-527	11,775	11,274	13,279	16,461	4,686	39.8
528-1,127	1,235	1,178	1,411	1,850	615	49.8
1,128 and over	359	301	439	628	269	74.9
Total	185,073	155,945	145,747	142,157	-42,916	-23.2
Pigs						
1-77	36,586	20,091	14,907	9,795	-26,791	-73.2
78-272	9,977	7,408	5,872	3,509	-6,468	-64.8
273-527	4,346	3,813	3,397	2,553	-1,793	-41.2
528-1,127	3,167	3,237	3,120	2,644	-523	-16.5
1,128-2,652	1,375	1,525	1,759	1,839	464	33.7
2,653 and over	314	398	537	765	451	143.6
Total	55,765	36,472	29,592	21,105	-34,660	-62.2
Laying hens						
1-122	59,329	34,348	24,312	18,515	-40,814	-68.8
123-972	3,701	3,289	2,194	1,707	-1,994	-53.9
973-9,977	1,291	1,295	1,109	915	-376	-29.1
9,978-20,022	500	452	426	439	-61	-12.2
20,023-45,132	161	155	162	176	15	9.3
45,133 and over	44	46	51	59	15	34.1
Total	65,026	39,585	28,254	21,811	-43,215	-66.5

U.S. data: Kellogg et al., 2000. Canadian data: Anonymous. 1997.

There has been a marked shift towards very large livestock operations in the past two decades. Both smaller operations and total number of operations in North America have declined significantly. During the 15-year period presented in **Table 6.4**, total operations in the U.S. declined from 728,539 to 529,658, a reduction of 27 percent. In Canada, declines in number of operations were especially strong for pigs and laying hens, dropping 62 and 66 percent, respectively. The biggest increases in numbers were for the largest operations. Operations with AU of 1,000 or more increased 51 percent in the U.S. In Canada, operations with cattle and calves of 1,128 head and over increased 75 percent, pigs of 2,653 head and over increased 144 percent, and laying hens of 45,133 head and over increased 34 percent.

The concentration of animals in very large confined operations creates problems of manure disposal. Adjacent cropland can effectively utilize only so much manure. The areas of the U.S. with the largest increases in these operations are:

- a region extending from Wyoming and southern Montana through southern Minnesota and northern Iowa to Wisconsin;
- a region from eastern Texas stretching north through western Arkansas to Missouri;
- several areas in the east, primarily west of the population centers ranging from New York south to South Carolina.

Recoverable Nutrients

The term recoverable manure nutrients is used to describe that portion of total excreted manure nutrients that is potentially available for land application or alternative use. Nutrients lost during collection, transfer, storage, and treatment of manure are considered non-recoverable. It is important to clarify that there are a large number of assumptions made in calculating these estimates of recoverable manure nutrients. As a result, they are subject to considerable debate. In addition, the shift from mixed farms to large

CAFOs has changed the proportion of manure nutrients that can be recovered for application to crops. However, such estimates can be useful in evaluating the potential role, including trends over time, that manure nutrients can play in meeting crop requirements.

Figure 6.1 presents the long-term trend for recoverable nutrients (N, P_2O_5, and K_2O) in the U.S. and Canada. Total nutrients recovered annually in the U.S. are increasing, actually accelerating in recent years, while in Canada there appears little change over the past two decades.

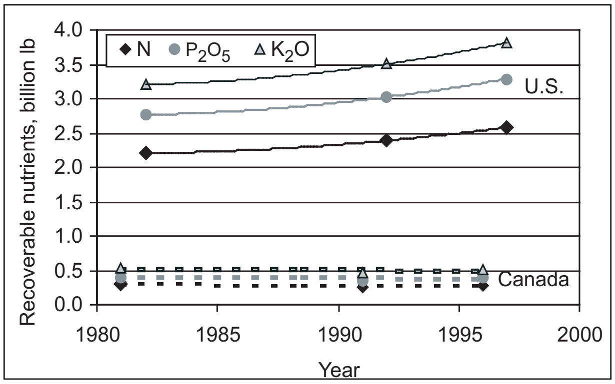

Figure 6.1. **Trends in recoverable nutrients from manure produced by all livestock in the U.S. and Canada. (U.S. N and P data: Kellogg et al., 2000. U.S. K data: Dr. C.H. Lander, NRCS (personal communication). Canadian data: Anonymous. 1997.)**

Recoverable nutrients from manure in North America were recently estimated at about 2,865 million pounds of N, 3,691 million pounds of P_2O_5, and 4,318 million pounds of K_2O (**Table 6.5**). Nearly 90 percent are from operations in the U.S. Overall, poultry is the largest source of N and P_2O_5 by a substantial margin over other livestock types, while milk cows produce the most recoverable K_2O. The fact that poultry produces the most recoverable N and P_2O_5 is very positive. Dry poultry litter is readily transportable and routinely sold to other farms. Two practices that are growing in popularity for utilizing poultry manure are feeding manure/litter as a dietary cattle supplement and burning manure/litter for energy.

Consumption of commercial fertilizer in North America during 2000 (**Appendix 5.1**) totaled 24.6 million tons of $N+P_2O_5+K_2O$. This compares to 5.4 million tons (10,874 million pounds) recoverable from manure, or 22 percent of commercial fertilizer (**Table 6.5**).

Much of this manure is already used in crop production systems, so it represents part of the current nutrient pool rather than a potential addition to it. For example, 17 percent of all U.S. corn acres receive manure, while manure is applied to only 6 percent of soybean acres (**Table 6.6**). It is uncertain, however, what proportion of the nutrients from manure is being efficiently utilized as opposed to that being disposed of as a waste.

Table 6.5. **Recoverable nutrients from manure produced by livestock in the U.S. in 1997 and Canada in 1996.**

	Million pounds of recoverable nutrients (available for soil application)		
	N	P_2O_5	K_2O
U.S.			
Fattened cattle	390	582	755
Milk cows	636	559	1,072
Other beef and dairy	131	248	364
Swine	274	634	811
Poultry	1,153	1,268	812
All livestock types	2,583	3,290	3,814
Canada			
Fattened cattle	102	153	185
Milk cows	89	78	140
Other beef and dairy	12	26	33
Swine	45	104	125
Poultry	33	39	21
All livestock types	282	400	505
Total, North America	2,865	3,691	4,318

U.S. N and P data: Kellogg et al., 2000.
U.S. K data: Dr. C.H. Lander, NRCS (personal communication).
Canadian data: Anonymous. 1997.

Table 6.6. **Manure nutrients applied to specific crops in the U.S. (avg. 1990 to 1996).**

Crop	Rate, lb/A $N+P_2O_5+K_2O$	Total applied to crop, million pounds			Manured acres, %
		N	P_2O_5	K_2O	
Corn	5+5+5	374	364	364	17
Soybeans	3+3+3	168	164	164	6
Winter wheat	1+1+1	62	62	62	3
Cotton	3+3+3	40	34	34	4
Total		644	624	624	

N and P manure data: USDA-ERS, 2000; K assumed equal to P. Crop acreage data: USDA-NASS, 2001.

The progression to fewer, but larger, livestock operations has resulted in substantial quantities of manure that cannot be effectively utilized as part of the operation where it was produced. This manure must be transported off-site. Depending on the distance, it could be sold for a profit. At uneconomical distances, it becomes a cost of the livestock operation. It is estimated that in the U.S. (data not available for Canada) farm-level excess manure is 1,473 million pounds of N, 2,128 million pounds of P_2O_5, and 2,114 million pounds of K_2O (**Table 6.7**), or 55 to 65 percent of that recoverable. Farm-level excess manure nutrients (i.e., that potentially available for sale) totals about 5,715 million pounds or 13.2 percent of commercial inorganic fertilizer sold in the U.S. during 2000. Again, it is unclear what part of this is already being used effectively as a nutrient source today. Detailed information on manure production for each state is given in **Appendix 6.3**.

The amount of farm-level excess manure will increase with a continuing increase in the number of confined livestock. Also, the percentage of recoverable nutrients will likely increase as manure handling and

Table 6.7. Manure nutrients summary: All animals, confined animals, and farm-level excess in the U.S. in 1997.

	Million pounds of nutrients		
	N	P_2O_5	K_2O
All livestock	12,905	8,794	10,387
Confined livestock	6,267	4,031	4,757
Recoverable	2,583	3,290	3,813
Farm-level excess	1,473	2,128	2,114

N and P data: Kellogg et al., 2000.
K data: Dr. C.H. Lander, NRCS (personal communication).

Table 6.8. Percent of total recoverable manure nutrients accounted for by each livestock type in the U.S. in 1997.

	Recoverable nutrients, %		
Livestock type	N	P_2O_5	K_2O
Fattened cattle	15.1	17.7	19.8
Milk cows	24.6	17.0	28.1
Other beef and dairy	5.1	7.5	9.5
Swine	10.6	19.3	21.3
Poultry	44.6	38.5	21.3
All Types	100.0	100.0	100.0

N and P data: Kellogg et al., 2000.
K data: Dr. C.H. Lander, NRCS. (personal communication).

processing facilities improve. Estimates for the U.S. show that only about 20 percent of excreted manure N is recoverable, and about 37 percent for P and K (**Table 6.7**).

Poultry contributes the largest amount of recoverable N and P of all livestock types in the U.S., while milk cows contribute the most K **(Table 6.8)**. The contributions of poultry and swine have been increasing while other livestock types have been on the decline. For example, the poultry contribution of recoverable N grew from 34 percent in 1982 to 45 percent in 1997, while the swine contribution grew from 9 percent in 1982 to 11 percent in 1997 (Kellogg et al., 2000). The greatest percent decline in recoverable manure nutrient contribution during this period occurred for milk cows.

Beneficiation Technologies

Land application of manure and other organic products for their nutrient and C contents is the dominant method of utilization/disposal. Other options being evaluated and which may contribute to significant utilization of these products in the future are (Bruulsema, 1998):

Combustion. Dry manure is combusted to produce electricity. This process is currently being used in the United Kingdom with poultry litter. The resultant bed ash and fly ash contain sufficient P and K that they can be recovered and marketed as fertilizer.

Sequencing batch reactor. This process for liquid manure is based on that used for municipal sewage treatment. The treatment is a five-step process, with each step taking 12 to 24 hours and involving both aerobic and anaerobic digestion.

Biogas generation. Methane gas is produced from manure by anaerobic digestion. Early efforts focused on mesophilic (68° to 113°F) or thermophilic (113° to 140°F) digestion. However, Swiss research suggests that total energy yields are higher with psychrophilic digestion (less than 68°F). It is also possible to capture biogas by covering anaerobic lagoons. The gas evolved contains 70 to 84 percent methane.

Composting. Composting can be used to reduce the volume of manure and produce a product free of objectionable odors and weed seeds. Commercial products are commonly sold at lawn and garden stores and are used in organic farming.

Wetlands. Constructed wetlands to treat liquid wastewaters is a relatively new technology. Aquatic vegetation is grown in cells with shallow depths of wastewater held by earthen dikes. Physical sedimentation, chemical precipitation, and biochemical reaction with photosynthetic products are some of the processes that remove nutrients from the wastewater. Microorganisms break down the organic mater and denitrify most of the N. This process is appealing to many farmers because of the low construction costs, although daily monitoring of the system is required to avoid overloading the wetland with nutrients. Land area requirements and limited nutrient sorption capacity preclude their use for disposal of liquid manure, but they can be useful for very dilute wastewaters.

Livestock feeding technologies. The use of phytase in feed rations for non-ruminant livestock can reduce the need for supplementing the diet with phosphate minerals. This can reduce the P content of excreted manure by as much as 15 to 25 percent. Low phytate genotypes of several crops have been developed that may help reduce the P content of manure. Poultry manure/litter can also be fed to cattle as a dietary supplement. Recent development of the EnviroPig, genetically modified to produce phytase in its saliva, indicates that genetic modifications can potentially contribute to improved nutrient cycling.

Perspective

Organic nutrients represent a significant percentage of the total available or potentially available nutrients for crop production in North America. The issue is not whether these products benefit crop production, but the cost associated with transporting products of large volume and low nutrient content to needed areas.

Animal feeding operations are declining in number and growing dramatically in size. This will accentuate manure disposal/utilization problems in the future. In response to environmental hazards associated with disposal methods utilized by some livestock operations, EPA has directed the NRCS to develop guidelines for preparing nutrient management plans. These plans will initially be required of all CAFOs and will detail nutrient balance of the operation, including appropriate utilization of all manure produced.

Manure has historically been applied based on N content. However, repeated applications result in a buildup of soil P as previously discussed. Therefore, guidelines are being developed by NRCS in cooperation with university scientists and industry leaders at the state/provincial and regional level to evaluate the environmental hazard associated with P. Most states are adopting standards based on a P Index concept that rates both P source and transport factors. Each factor is given a numerical rating, and the combined total indicates the potential hazard associated with P. Manure applications on fields having a medium or high hazard would be limited based on their P content.

Although disposal of manure (and to a lesser degree, some other organic materials) is of national concern, it is not a national crisis. Data from the USDA for 1997 indicate that 73 counties nationwide had a county-level manure surplus of N and 160 counties (about 5 percent) had a county-level surplus of P_2O_5. None-the-less, in the regions where this surplus does exist, appropriate action should be taken to safeguard the environment.

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Economics of Nutrient Systems and Sources

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Synopsis: Economic comparisons of different cropping systems for central Illinois and northwest North Dakota provide examples of how crop rotation influences profitability. Nutrient management is an important part of that analysis. Evaluation of various manure sources and storage systems is included to show the economic value of the nutrients supplied.

The long-term economic viability of a crop management system, like any other business, depends on economically sound management decisions. This usually is more complicated than balancing the checkbook or even comparing partial budgets. Several sources of nutrients can be used in meeting the needs of growing crops. Commercial fertilizers are the most common. However, they can be supplemented, or sometimes replaced, by nitrogen (N) generated by the crop rotation or nutrients from livestock manure, or certain industrial or municipal byproducts. When considering the option of using livestock manure or other organic sources of nutrients as part of the nutrient management plan, the economic analysis becomes even more complex.

Crop rotations should be evaluated on the basis of the entire rotation, considering nutrients and other expenses for all crops in the cycle. The corn/corn and corn/soybean systems discussed in this chapter are examples. The differences in N management in those rotations have significant impact on the economic comparison. Adding a crop like alfalfa to the system further complicates the analysis.

Where manure is available on the farm, it is a product that has value and its use in the cropping operation must be balanced with other options of removal. In enterprise budgeting, the manure may be sold to the crop enterprise, producing income for the livestock enterprise and an expense for the crop enterprise.

Even if the farm has no livestock, there may be an opportunity to obtain manure from local livestock operations to assist in their disposal needs. It is important to analyze the value of manure compared to commercial fertilizer as a nutrient source.

For the straight cash-grain farmer, answers to a range of questions dictate the profitability of decisions.

- Can the nutrients from manure be effectively used by the crop?
- Is it possible to apply manure at the best time to ensure efficient utilization?
- Is the value of the nutrient content sufficient to cover the cost of application?
- Is there intrinsic value of manure beyond the nutrient content? Research has shown manure is beneficial to soil structure and tilth and helps increase soil organic matter.

When a livestock operation is involved, additional considerations become important as well. Manure from the livestock has value from its nutrient content, but also has costs of handling and application.

- Even though the nutrient value of the manure is limited, land application for supplying crop nutrients may be the most economical means of utilizing it.
- Reducing the costs of manure disposal for the livestock operation may help the profitability of the overall farm, even if mineral fertilizer may be a more economical source of plant nutrients for the crop.

Rotation Impacts on Fertilizer Sources: Corn/Soybean Example

The type of crop rotation is an important factor in the decision of selecting among nutrient sources. Nitrogen is usually the nutrient of economic concern in rotation systems. In a corn/soybean rotation, for example, the value of the N in manure applied for the soybean year is relatively low, because it will likely only replace N that would normally be fixed through symbiotic fixation by nodulating bacteria living on the soybean roots. Planning manure application to best match the crop's need for N will help capture more of the value of the manure. If the N is lost or not needed by the growing crop, that value is forfeited if the N is lost from the crop root zone. Further, the potential for groundwater pollution increases.

A comparison of several cropping system scenarios will help illustrate an approach to evaluating the value of various nutrient sources in different crop management systems. The effect of crop residues and nutrient removals from the crops in the rotation form the basis for agronomic and economic comparison.

The first example is a central Illinois cash grain farm. **Table 7.1** lists budgets giving annual revenues and costs for corn and soybeans when the preceding crop is either corn or soybeans. For example, the **corn following soybeans** column gives a budget for corn, given that the previous year's crop was soybeans. Wheat and alfalfa are also included in **Table 7.1**. While multi-crop rotations are sometimes suggested as an alternative

Table 7.1. Crop budgets for central Illinois, 2001.

	Corn following soybeans	Corn following corn	Soybeans following corn	Soybeans following soybeans	Wheat	Alfalfa estab.	Alfalfa
Average yield per acre	158 bu	148 bu	49 bu	44 bu	75 bu	2.5 tons	4 tons
Price received, $/bu or $/ton	2.00	2.00	5.45	5.45	2.30	100.00	100.00
Revenue, $/A	316	296	267	240	173	250	400
Variable costs per acre							
Fertilizer and lime	58	63	20	20	42	41	46
Pesticides	32	39	33	33	0	48	32
Seed	33	33	19	19	15	48	0
Drying and storage	17	16	6	6	8	0	0
Mach. repair, fuel, and hire	34	34	28	28	19	35	42
Total variable costs, $/A	174	185	106	106	84	172	120
Fixed costs, $/A							
Labor	25	25	20	20	20	30	30
Building repair and depreciation	8	8	8	8	8	8	8
Machinery depreciation	19	19	17	17	15	15	15
Interest on investment	23	23	23	23	16	16	15
Overhead	15	15	15	15	15	20	15
Land (cash rent equivalent)	145	145	145	145	145	145	145
Total fixed costs, $/A	235	235	228	228	219	234	228
Total costs, $/A	409	420	334	334	303	406	348
Revenue less variable costs, $/A	142	111	161	134	89	78	280
Revenue less total costs, $/A	-93	-124	-67	-94	-131	-156	52

Sources: Schnitkey, 2001a; 2001b.

that could provide organic nutrient sources, these budget comparisons help illustrate why the Illinois farmers have shifted toward the corn-soybean system. Where there is a special market or need for wheat or alfalfa, such a system still has its place among economically viable options.

- The University of Illinois produces updated budgets each year to help farmers and their advisers evaluate the options that include both cash and opportunity costs. For example, labor would be an opportunity cost if the farmer does not hire labor. In that case, the $25 and $20 labor for the **Corn** and **soybeans** budgets reflects a return for the farmer's time. It would not be a cash cost. Inclusion of opportunity costs causes **Revenue less total costs** value to be negative.
- Budgets do not include the Agricultural Marketing and Transition Act (AMTA), government payments resulting from the 1996 Farm Bill. They also do not include Market Loss Assistance (MLA) payments. This treatment is appropriate for looking at rotations because payments are not tied to production practices. Prices received reflect the higher of market prices or loan rates.
- In the comparison, **Corn following soybeans** is given a higher yield than **Corn following corn** (158 bu/A compared to 148 bu/A) to reflect agronomic research suggesting that yields decline by several bushels when a rotation is not used (Emerson Nafziger, personal communication, 2001). Fertilizer and lime costs are higher for **Corn following corn** because of higher amounts of N recommended, 189 lb/A, versus 160 lb/A for **Corn following soybeans** (Illinois Agronomy Handbook, 2000-2001; **Table 7.2**). Pesticide costs are also higher because of higher insecticide applications on corn following corn. As a result, the **Corn following soybeans** rotation is more profitable than the **Corn following corn**.
- Phosphorus (P) and potassium (K) are applied at replacement levels for the grain yields shown.

The budgets shown in **Table 7.1** are used in **Table 7.3** to evaluate rotations. These examples show the annual average expenses and revenues for each of the

Table 7.2. Nutrients recommended for various Illinois crops.

Nutrient	Corn following soybeans	Corn following corn	Soybeans following soybeans	Wheat	Alfalfa estab.	Alfalfa
	- - - - - - - - - - - - - - - - - - - Recommended nutrients, lb/A - - - - - - - - - - - - - - - - - - -					
N	160	189	—	80	—	—
P_2O_5	69	62	51	75	36	80
K_2O	45	42	78	28	150	160

Calculated from recommendations in Illinois Agronomy Handbook, 2001-2002.

Table 7.3. Returns and costs of alternative rotations in central Illinois, 2001.

	Corn/ soybeans	Continuous corn	Corn/ soybeans/ wheat	Corn/ soybeans/ alfalfa (est)	Corn/ soybeans/ alfalfa (4 yrs)
Revenue, $/A	292	296	252	278	339
Variable costs, $/A					
Fertilizer and lime	39	63	40	40	43
Pesticides	33	39	22	38	35
Seed	26	33	22	33	17
Drying and storage	12	16	10	8	4
Mach. repair, fuel, and hire	31	34	27	32	37
Total variable costs, $/A	141	185	121	151	135
Fixed costs, $/A					
Labor	23	25	22	25	28
Building repair and depreciation	8	8	8	8	8
Machinery depreciation	18	19	17	17	16
Interest on investment	23	23	21	21	18
Overhead	15	15	15	17	16
Land (cash rent equivalent)	145	145	145	145	145
Total fixed costs, $/A	232	235	228	233	230
Total costs, $/A	373	420	349	384	365
Revenue less variable costs, $/A	151	111	131	127	204
Revenue less total costs, $/A	-81	-124	-97	-106	-26

Source: Calculations based on costs from Table 7.1.

rotations, providing an average cash flow picture for comparison.

- The columns in **Table 7.3** show revenues and costs for rotations. For example, the first column, labeled **Corn/soybeans**, means that corn is planted one year and soybeans the next. The second column, **Continuous corn,** assumes that corn is planted every year.
- The costs shown in **Table 7.3** come from **Table 7.1**. Revenue and costs in the **Corn/soybeans** rotation equals an average of the **Corn following soybeans** and **Soybeans following corn** budgets (see **Table 7.1**). The **Continuous corn** rotation equals the revenue and costs for the **Corn following corn** budget in **Table 7.1**.
- Revenues and costs for a rotation represent a blend of revenue and costs for the crops in the rotation. For example, the **Corn/soybean** rotation has a $39 fertilizer and lime cost. This equals half of the $58 fertilizer and lime cost from **Corn following soybeans** and half of the $20 per acre costs from **Soybeans following corn**.
- The most profitable rotation is **Corn/soybeans/ alfalfa** (alfalfa for 4 years). Most farmers do not include alfalfa in their rotations because marketing alfalfa can be difficult particularly if an outlet cannot be identified. Compared to corn and soybeans, alfalfa requires more intensive management, limiting the number of acres of alfalfa that can be grown. Moreover, alfalfa is much more labor intensive than corn or soybeans. It also requires a completely different set of equipment.
- The second most profitable rotation is **Corn/ soybeans**. The revenue less variable cost for **Corn/soybeans** is $151. The revenue less total cost is -$81 per acre.
- A 50 percent corn – 50 percent soybeans rotation is the most popular rotation in central Illinois. Much of the reason for this is that it is the most profitable grain crop combination. Moving to alfalfa or other higher end crops would add costs.
- Wheat in the rotation decreases profitability. Similarly adding alfalfa for only the establishment year to a **Corn/soybeans** rotation decreases profitability.

Part of the reason for the advantage of **Corn/ soybeans** is N credit in that rotation. While it is called an N credit, the real effect is more likely caused by more N being tied up in the organic fraction during decomposition of corn stalks following corn, so there is an apparent increase in available N following soybeans. Actually, the N that is being used by microorganisms involved in decomposing corn stalk residue will be slowly released over the following growing season and acts as a storage system for organic N. The soybean crop removes large amounts of N, considerably more than is fixed by nodules on the soybean roots, so there is normally not a net supply of residual N following soybeans as the soybean N credit concept would suggest.

Other factors influence the rotation decision. Nutrient management is obviously not the only consideration in selecting a rotation. Rotation decisions are made for a variety of agronomic, logistical, and economic reasons. Sometimes the selected rotation may not be the best nutrient management option, but provides overall benefits that make it a better choice.

- Risks. Growing two major crops helps spread the risk of unfavorable growing seasons. Typical summer weather patterns may favor one crop one year, the other the next. It also is a hedge against unfavorable markets and other external factors of profitability.

- Timing of machinery operations. As farms have become larger, timeliness for field operations has become more of a challenge. Growing more than one crop provides some flexibility in dealing with timing of planting, harvest, and other operations.
- Pest management. Rotating crops helps reduce pest problems of insects, weeds, nematodes, and diseases by breaking the organism’s life cycle or provide more opportunities for control measures.

Comparison of Corn/Soybeans to Rotations with Wheat and/or Alfalfa Included

Adding wheat offers no economic advantage in the rotation. The relative potential net income for corn, soybeans, and wheat in recent years has pushed wheat out of contention for most Corn Belt farmers. Market availability, logistics, equipment needed, pest management, and other factors have further forced wheat to the sidelines for consideration.

A Great Plains comparison (**Table 7.4**) shows budgets prepared by North Dakota State University for spring wheat and durum wheat. For each wheat class, there is a fallow and recrop budget. The fallow budget means wheat is planted one year, and the land is fallowed the next. The recrop budget means that wheat is planted every year. The fallow year is a management practice to help conserve water and may also provide time for more N to be released from soil organic matter through mineralization, thus reducing fertilizer costs. These are important processes in dryland production systems. The downside is that there is no crop income the fallow year.

The following tradeoffs exist when fallow is included in the rotation:

- Fallow budgets have higher yields leading to higher revenues. For example, spring wheat has $90.30 of revenue per acre when fallowed and $84.28 when recropped, a difference of $6.02 per acre.
- Fallow has lower herbicide cost. Fallowed wheat has $4.01 per acre cost compared to $8.66 for recrop wheat.
- Fallow has lower fertilizer cost per acre.
- Small differences exist in other cost categories.
- The other major difference is that fallow has fallow costs. The fallowed wheat has a recrop cost of $46.71 per acre. These costs represent the returns lost by fallowing a crop.

In both cases, fallow is less profitable then recrop. Spring wheat that is fallowed has a -$48.14 return per acre compared to -$17.12 for recrop wheat, a difference of $31.02 per acre.

Including fallow in a rotation is costly. Most farmers are moving away from fallow. Fallow is not attractive in many systems due to the lost revenue. Weed control has to be maintained, and other expenses such as real estate taxes must be paid, even though no crop is grown. Some equipment expenses, such as depreciation, also continue.

Considering Livestock Manure as a Nutrient Resource

Livestock manure is an important resource for some farms. Where it is available, it is a good nutrient source. However, there is not enough manure produced to meet a large percentage of the nutrient needs of intensive crop production. Perhaps even more important, the manure production tends to be in areas not geographically located near the cropland that can utilize it.

Table 7.5 shows daily nutrient production from livestock. Values come from the Midwest Plan Service (1991). Nutrient production can vary tremendously

Table 7.4. Spring wheat and durum budgets for northwest North Dakota.

	- - - - Spring wheat - - - -		- - - - - - Durum - - - - - -	
	Fallow	Recrop	Fallow	Recrop
Revenue, $/A	90.30	84.28	96.32	87.29
Direct costs, $/A				
Seed	6.50	6.50	6.20	6.20
Herbicides	4.01	8.66	4.01	8.66
Fungicides	1.50	1.50	1.50	1.50
Insecticides	0.00	0.00	0.00	0.00
Fertilizer	12.74	13.90	14.24	14.65
Crop insurance	1.90	2.80	2.00	2.90
Fuel and lubrication	5.79	6.40	5.85	6.43
Repairs	8.13	8.76	8.16	8.77
Drying	0.00	0.00	0.00	0.00
Misc	1.00	1.00	1.00	1.00
Operating interest	2.08	2.48	2.15	2.51
Total direct costs, $/A	43.65	52.00	45.11	52.62
Fixed costs, $/A				
Misc	3.14	3.27	3.17	3.28
Machinery depreciation	11.24	11.82	11.32	11.86
Machinery investment	8.74	9.35	8.80	9.38
Land taxes	3.32	3.32	3.32	3.32
Land investment	21.64	21.64	21.64	21.64
Total fixed costs, $/A	48.08	49.40	48.25	49.48
Fallow costs, $/A	46.71	—	46.71	—
Total costs, $/A	138.44	101.40	140.07	102.10
Return to labor and mgt., $/A	-48.14	-17.12	-43.75	-14.81

Current year’s budgets may be found on the North Dakota State University Extension Service website at http://www.ext.nodak.edu/extpubs/ecguides.htm

Table 7.5. Daily nutrient production from different species of livestock.

Animal type	Animal weight, lb	Manure produced	N	P_2O_5	K_2O	Value[1], $/day
		----------------	lb/day	----------------		
Dairy	1,000	82.00	0.410	0.168	0.324	0.164
Beef	1,000	60.00	0.339	0.252	0.285	0.163
Veal	200	12.40	0.054	0.013	0.056	0.022
Swine — nursery	35	2.30	0.016	0.012	0.012	0.008
Swine — grower	65	4.20	0.029	0.023	0.023	0.014
Swine — finisher	200	13.00	0.090	0.070	0.070	0.043
Gestating sow	275	8.90	0.062	0.048	0.088	0.035
Poultry — layer	4	0.21	0.003	0.003	0.001	0.001
Poultry — broiler	2	0.14	0.002	0.001	0.001	0.001

[1] Valued based on $0.22, $0.22, and $0.14 price per pound for N, P_2O_5, and K_2O, respectively.

Source: Midwest Plan Service 18, 1991.

depending on many factors, including the animal's diet. The final column gives values of daily manure production. These values represent manure as a replacement for commercial fertilizers. Dairy, for example, has a $0.164 value per day. This means that pricing the nutrients as they are produced would have a value of $0.164 as a replacement for commercial fertilizer.

Large operations can produce significant amounts of manure. Potential value from manure is high for these operations. Even with a relatively low value per animal per day, the cumulative value of manure from a large livestock operation is a significant economic value to the overall farm operation.

One of the most serious limitations of manure as a nutrient source for crops is the variability in nutrient content. Raw manure nutrients vary generally because of feeds. For example, if hogs are fed phytase to aid in the metabolism of P in their feed, P nutrient content of the manure is greatly reduced. The values in **Table 7.5** represent an upper bound, or best-case scenario, of nutrient value from manure. Storage system and duration, application method, and timing relative to crop growth will impact the amount of nutrient actually available for crop production. For example, storing manure in a lagoon leads to denitrification and volatilization losses. Hence, much of the value associated with N may not be realized. Surface application in the field may also result in a high percentage of the N lost to volatilization. If applied in winter on frozen ground, there may be significant losses due to runoff. Generally, injection or incorporation by tillage can greatly improve the ability to maximize nutrient efficiency from manure.

Table 7.6 compares nutrient content of different manure types for various types of livestock and manure handling systems. Nitrogen is the nutrient that varies most, with several opportunities for it to be lost from the system. For P and K, content varies according to animal and feed rations. Nutrient content may also vary within a storage system due to settling out of solids or separation of the liquid fraction. Phosphorus content in particular can vary greatly with depth in the storage tank or lagoon.

- Impacts of manure handling systems on value are illustrated in **Table 7.6**. These are average annual values. For example, a dairy cow will produce on average 9 lb of ammonium-N, 13 lb of organic N, 14 lb of P_2O_5, and 20 lb of K_2O, yielding a value of $10.08 per year.
- Panel A shows values for slurry manure, panel B shows values for solid manure, and Panel C shows liquid effluent, but from a holding pond.
- Nutrients and values vary with manure type.

The complexity of including manure as a part of a nutrient management plan can be illustrated by working through an example outlining the nutrient supplied in the manure produced by a single hog, as shown in **Table 7.7**.

Table 7.6. Typical nutrient content of manure by type.

	Ammonium-N	Organic N	P_2O_5	K_2O	Value,[1] $
Panel A. Slurry manure (per 1,000 gallons of manure).					
	----------------	---------------- lb	----------------		
Dairy	9	13	14	20	10.08
Beef	14	20	22	31	15.67
Swine	17	10	19	15	11.53
Panel B. Solid manure (per ton of manure).					
	----------------	---------------- lb	----------------		
Dairy	3	8	7	9	4.91
Beef (dirt lot)	5	20	18	22	11.82
Swine	6	7	13	9	6.63
Broiler	14	57	69	47	35.49
Panel C. Liquid effluent from holding pond (per acre-inch).					
	----------------	---------------- lb	----------------		
Dairy	27	18	13	113	26.55
Swine	50	29	17	86	30.72
Beef	41	4	10	203	37.59

[1] Valued based on $0.22, $0.22, and $0.14 price per pound for N, P_2O_5, and K_2O, respectively.

Sources: USDA-SCS. 1992; Barker and Zublena, 1995.

Table 7.7. Impacts of manure storage on manure value from one feeder pig (50 to 260 lb).

	Nutrient value, $	
Nutrient	Manure pit	Anerobic lagoon
N	1.13	0.33
P_2O_5	0.72	0.40
K_2O	0.91	0.73
Total	**2.76**	**1.46**

Based on original calculations by authors.

- This is a more specific example of manure storage values for hogs
- The two most common systems now being built:
  - ¤ Manure pit beneath finishing floor
  - ¤ Lagoon outside building
- Values are based on replacing commercial fertilizers
- Manure pit has much higher values because it gets more nutrients out on crop land:

  - Nitrogen denitrifies in the lagoon
  - Phosphorus and K settle with solids to the bottom in lagoon
- To obtain the value of these nutrients, fertilizer needs must be matched to crop needs. The value of P is lost if P soil levels are well or significantly above those needed to match N needs.

Testing the manure is an important, but mostly overlooked, part of the planning process. Transportation costs must be considered in determining manure value. The high volume, low nutrient analysis of manure makes transportation costly, so it rarely can be economically transported more than a short distance from the livestock operation. Manure is an important nutrient source if properly handled and if care is taken to balance nutrients in the manure with other fertilizer materials in a complete nutrient management plan.

Economics of organic production systems

Organic production systems that use no commercial fertilizers introduce additional limitations into the nutrient management decision process. They face the limitations discussed above for crop rotations and manure as ways of meeting crop nutrient needs, along with added restrictions on the ability to provide a balanced nutrient plan. To obtain USDA certification to market crops as **organically produced** requires three years of production without chemical fertilizer or pesticides. Since organic production systems vary widely and are often associated with special markets with special requirements, it is difficult to develop a meaningful comparison budget for organic vs. conventional systems. The discussions above relative to use of crop rotations and manure are generally applicable to organic systems, with the income side of the budget dependent on the crop and market associated with it.

Organic markets exist for corn, soybeans, specialty soybeans, small grains, oil seeds, and alfalfa, as well as a wide variety of vegetable crops. Premiums can be substantial, which can help offset the lower yields often associated with organic production. However, there are also years when no premium is paid for organic production. It is wise to have a contract before entering into such a production system.

Organic production usually involves a high level of risk. Markets are not always dependable. Pest problems tend to be higher than in conventional systems. Yields tend to be lower. These risks combined with the three-year initial entry period discourage entry into organic crop production. That, in turn, helps keep the supply of organically-grown crops lower and helps maintain the higher price.

Summary

The selection of a rotation system for crop production is largely dictated by economic considerations. Where N availability is altered by the rotation, there may be agronomic and economic advantages to including a legume crop. But the value depends on being able to utilize the nutrients and the marketability of the legume crop. The corn/soybean rotation emergence as the dominant production system in large parts of the Midwest, and the decline of fallow as part of the rotation system in the Great Plains, are results of these economic forces. Nutrient management plays an important role in these decisions.

The availability of manure is another important component of nutrient management and crop management decisions. Manure can be an important resource for supplying crop nutrients if its use fits into the crop rotation and if handling and application logistics are acceptable. Management of the manure as a nutrient resource for a crop enterprise rather than as a waste product from a livestock enterprise may change the perspective from which it is evaluated. Cooperation between a crop producer and a livestock producer may offer some new opportunities to improve profits for both, especially where large confined animal operations on small acreages are involved.

Organic production systems tend to be centered around specific markets and management contracts and must follow USDA certification guidelines to use the organically grown designation in marketing. Economics will be largely dictated by availability of organic nutrient supplies, ability to maintain yields, and availability and dependability of markets. **Organic production systems can be an economically sound alternative for those who are able to participate in the limited opportunities.**

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Chapter Eight

Nutrients and Environmental Quality

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Synopsis: When properly managed, fertilizers and animal wastes can increase soil productivity, enhance sustainability, and increase carbon (C) sequestration. In this chapter, management challenges and risks for commercial fertilizer and animal wastes are reviewed relative to: 1) nitrogen (N) and phosphorus (P) loss to water resources; 2) heavy metal accumulation; 3) pathogen accumulation; and 4) greenhouse gas production.

Nutrient use in agriculture is associated with several environmental issues. Concerns about nutrient-induced surface and groundwater pollution, greenhouse gas evolution and global warming, and accumulation of heavy metals in the environment have increased public attention toward nutrient management involving choices of sources, rates, timing, and placement. These choices determine the specific environmental impacts resulting from nutrient use, which may be either beneficial or detrimental.

Soil

Regardless of whether the nutrients are from organic or inorganic sources, plants absorb the same nutrient ions: ammonium (NH_4^+), nitrate (NO_3^-), phosphate ($H_2PO_4^-$, HPO_4^{2-}), and potassium (K^+), for example. More than 20 years ago, Foth (1978) stated, “There are no generally accepted scientific experiments that support the superiority of either organic or inorganic nutrient sources.” Still, at the beginning of the 21st century, there is widespread public misperception that organic agricultural systems are more environmentally friendly and more sustainable than conventional high-yielding farming systems.

A paper published in *Nature* recently by Trewavas (2001) points out the hazards of relying solely on organic sources for nutrients. He reported, “Manure treatment used on any mixed farm improves soil quality, but conventional crop rotation seems equally effective. Manure breakdown cannot be synchronized with crop canopy growth, as is desirable, but continues throughout the growing season. Ploughing in of legume crops (a necessary part of the organic method to build soil fertility) and continued manure breakdown leads to nitrate leaching into aquifers and waterways at identical rates to conventional farms. Degradation of organic material from manure in the soil produces significant amounts of nitrous oxide and methane, the most potent greenhouse gases. Manure is variable in composition, yielding unpredictable nutrition for crop growth; there is only a poor relationship between available nitrogen for crop growth and organic content of soil.”

Crop yields at many university experiment stations, and on many farms, are equal to or higher than those in the past. Long-term studies from around the world indicate that sustained yields and soil productivity can be accomplished with balanced nutrient addition using animal manures and/or commercial fertilizers (PPI/PPIC/FAR, 1995).

Soil Structure

Organic matter has long been known to have a positive influence on soil structure, tilth, bulk density, and moisture holding characteristics. It helps to bind soil particles together, reduces soil crusting, increases the stability of soil aggregates, helps regulate the flow of water, acts as a reservoir for nutrients, increases the soil cation exchange capacity (CEC), reduces the effects of compaction, reduces soil runoff and erosion losses, buffers the soil against rapid changes in pH, and serves as an energy source for microorganisms (Zhang and Stiegler, 1998; Wood and Hattey, 1995). The addition of organic matter in animal wastes can help maintain or increase soil organic matter levels. Appropriate rates of nutrients from inorganic fertilizers can do the same, by promoting crop growth and production of greater amounts of organic residues.

Sorption of Phosphorus

The humus fraction of the organic matter in association with cations is able to retain significant amounts of P (Sample et al., 1980). Humic acid is believed to react with aluminum (Al) to form hydroxy-Al-humic acid complexes, which can result in an increase in soil P sorption capacity. Some consider this to be only a minor mechanism of P retention in most soils (Havlin et al., 1999).

In weathered soils, with strong acidity and high iron (Fe) and Al contents, organic matter can reduce P **fixation** or sorption. (Havlin et al., 1999). For these reasons, addition of organic matter or manure to mineral soils may increase plant available P or decrease the soil P sorption capacity (Mozaffari and Sims, 1996). The release of inorganic P from decomposing crop residues and animal manures is termed mineralization and depends on their C to P (C:P) ratio. If the C:P ratio is below about 200:1, there can be a net release of P from the organic source. If the ratio is above about 300:1, there is net P immobilization. Factors that affect the mineralization and immobilization of N in soils (moisture, temperature, pH, microbial activity) also affect P mineralization and immobilization. It has been estimated that organic matter in the U.S. Midwest and Northeast soils contributes annually available P amounting to 9 to 23 lb/A of P_2O_5 (Havlin et al., 1999). This net release occurs only where soil organic matter is mineralizing on a net basis. Where soil organic matter is maintained, there is no net release of available P.

Sims et al. (1998) reported that "While the previous studies clearly show that there are some situations where the use of inorganic P fertilizers can result in P leaching (that is, deep sandy soils, organic soils, or long-term over fertilization with P), the most common agricultural situation associated with significant downward movement of P has been the accumulation of P to very high or excessive levels in soils from continuous applications of organic wastes (manures, litters, and municipal or industrial wastes and wastewaters)." Simard et al. (1995) reported that downward migration of P can increase when repeated manure applications decrease the surface soil P sorption capacity. Beauchemin et al. (1998) sampled one of the most productive agricultural regions in Quebec and found: "The generalized assumption that most mineral soils are not at risk for P leaching needs to be refined. In medium to excessively rich, flat and tile-drained soils, P loss in subsurface water is very likely to contribute to the observed eutrophication of surface waters." Preferential flow of P downward through large cracks in the subsoil and into tile drainage water was offered as the explanation for P loss in Quebec clayey soils. Long-term application of very high rates (greater than 1,200 lb/A of P_2O_5 per year) of swine manure on Coastal Plain soils in North Carolina resulted in increased groundwater-dissolved P concentrations (Novak et al., 2000). These studies illustrate that it is possible to contaminate groundwater with P when exceptionally high manure loading rates are used. Groundwater NO_3^--N levels are likely to be elevated long before elevated P levels are witnessed, since NO_3^- is exceedingly more mobile than P.

Nutrient Balance

Commercial fertilizers are the most manageable source of nutrients for crop production. Through careful selection of rates, sources, placement, and timing it is possible to provide nutrients close to the optimum levels for economical and environmental efficiency (PPI/PPIC/FAR, 1995). It is difficult, if not impossible, to provide balanced soil fertility needs and plant nutrient demands through sole reliance on animal wastes or manures. Long-term use of manures has resulted in substantial increases in soil test P levels because land application of N, P, and K is often disproportionate to the crop removal (Chapter Three). Frequently, farmers need to balance manure applications with supplemental K or N fertilization to ensure that soil fertility balance is maintained and that plant N and K requirements are met.

In order to achieve a soil supply of inorganic N (NH_4^+ and NO_3^-) to meet season-long N needs for crops, farmers must provide high rates of animal wastes early in the season. The microbial conversion to inorganic N from organic N in the waste depends on favorable soil moisture and temperature. The supply of NH_4^+ and NO_3^- to plants through inorganic fertilizer application is more readily managed and controlled. Recent research with animal wastes is helping to provide a better understanding of inorganic N release from animal wastes. Still, the control of residual (after termination of crop growth) soil inorganic N levels is more practically and predictably managed with fertilizer than with animal wastes.

Some argue that animal wastes, raw or composted, provide a more sustained slow-release of inorganic N. Such slow release characteristics are frequently cited by farmers as limitations to nutrient supply during peak crop nutrient uptake periods. If, for example, release of inorganic N and P from applied animal wastes or other organic materials continues after crop growth has terminated, it can pose a threat to groundwater and surface water quality, the same as from inappropriate application timing and/or rates of inorganic fertilizers.

Nutrient imbalances in forages due to excessive poultry litter applications have been observed (Moore et al., 1995b). Grass tetany in ruminants, which is related to a K to calcium (Ca) plus magnesium (Mg) equivalent ratio (K:Ca+Mg) in excess of 2.2, appears more likely on pastures receiving excessive rates of poultry litter, possibly due to elevated K levels from the litter (Wilkinson et al., 1971). On dairy farms growing cool season grasses and alfalfa, if manure and fertilizer applications combined supply more K than is removed, soil K can also build up. Under these conditions, K concentrations in the harvested forage may exceed desirable levels for dry cows prior to calving, resulting in higher rates of milk fever and retained placentas.

Soil Salinity

Soil salinity increases can occur where inputs of nutrient salts exceed crop removal, runoff losses, and soil profile leaching. Many irrigated soils, particularly in western North America, experience slight annual increases in soil salinity as evapotranspiration exceeds soil infiltration. Water conservation measures and prudent nutrient management can improve long-term sustainability of irrigation practices and improve soil productivity.

Both organic and inorganic nutrient sources can increase soil salinity and reduce long-term soil productivity if nutrients are applied at excessive rates. The NH_4^+-N released from organic sources through microbial decomposition is subject to the same transformations as inorganic NH_4^+-N sources. The same is true for P, K, sulfur (S), and other nutrients. Salinity damage to crops from soil buildup of N and K from high rates of animal wastes has been reported (Moore, 1998). Because soil organic matter levels are often increased with high application rates of animal waste and other organic nutrient sources (that is, with wide C:N ratios), plants may withstand soil salinity better because of improved soil moisture holding capacity, which could indirectly reduce the risk of soluble salt damage. Soil organic matter can also be increased with optimum inorganic fertilizer management and conservation tillage. Research has shown that good soil fertility management, regardless of nutrient source, can increase C sequestration, improve soil organic matter and soil organic C (SOC) levels, and can lead to improved long-term soil productivity.

Soil Biology

Soil organisms are important to crop productivity in their role as recyclers of nutrients. Their primary benefit is to break down organic materials in crop residues and release the nutrients they contain in an inorganic form. In addition, organisms like mycorrhizal fungi help plants utilize soil nutrients of limited solubility, and rhizobia in symbiosis with legumes can supply substantial quantities of N. Both organic and inorganic nutrients can have impacts on soil organisms.

The term mycorrhizae means **root-fungi**. Mycorrhizal fungi form symbiotic associations with the roots of most plant species. These associations involve a bi-directional movement of nutrients. The plant supplies carbohydrates to the fungus, and the fungus supplies inorganic nutrients to the plant. Plant responses can range from a marked growth enhancement to growth depression. Mycorrhizae can help overcome the soil diffusion limitations in supplying nutrients to plant roots. Fungal hyphae extend as far as 2 to 3 inches from root surfaces into the soil, increasing the volume of soil from which nutrients such as P and zinc (Zn) are extracted (Marschner, 1986).

Mycorrhizae are also important to soil structure and aggregation. The hyphae bind soil particles together. At least one arbuscular mychorrhizal (AM) fungus species secretes a substance called glomalin, which also helps to bind soil particles. In some mineral soils, glomalin has been reported to represent as much as 2 percent of the soil by weight and 30 percent of the SOC (Wright et al., 1999).

It was once thought that inorganic nutrient applications reduced mycorrhizal development. However, Johnson and Pfleger (1992) reported that many field experiments show a decrease while others show an increase. Wood and Hattey (1995) cited work showing long-term application of manure decreased mycorrhizal infection of plant roots, with pig slurry more inhibitory than cattle slurry. Therefore, high levels of either organic or inorganic nutrients, particularly P, may reduce mycorrhizae. Mycorrhizal root length and spore densities are often greatest under intermediate levels of fertility. Johnson and Pfleger (1992) cited work which suggested that some high-yielding crop varieties may have been inadvertently selected to be less responsive to mycorrhizae than land races of the same plants indigenous to natural areas. Studies show that the degree to which cultivars are colonized by, and benefit from, AM fungi is a heritable trait, selectable through plant breeding.

As much as 20 percent of the total C assimilated by plants can be transferred to the fungal partner (Sylvia, 2001). This transfer represents a substantial energy cost to the plant, reducing potential harvestable yields. Studies in Minnesota suggested that mycorrhizae can proliferate to the detriment of corn yields in some situations, and unbridled proliferation in soils continuously cropped to corn and soybeans could lower their yield potential relative to that of the two crops grown in rotation (Johnson et al., 1992).

Rhizobia are important symbiotic partners with legume plants, often supplying very significant quantities of N. The overview by Wood and Hattey (1995) reported no long-term reduction in clover rhizobia (*Rhizobium leguminosarum* biovar *trifolii*) or free-living N-fixing microorganisms in crop rotations receiving either inorganic or organic nutrient amendments. If nutrient sources reduce soil pH, and consequently reduce the availability of molybdenum (Mo), the population of N-fixing microorganisms can decline. The N-fixing activity of most legumes decreases as levels of inorganic N in soils increase, but substantial N fixation can take place even when soil NO_3^- levels are high. Therefore, highly effective legume crops such as alfalfa are not as able to deplete soil NO_3^- as other crops.

Animal manure and other organic wastes benefit earthworms. Ammonia (NH_3) and salts in the manure can temporarily reduce earthworm numbers, but the populations rebound fairly quickly (USDA-NRCS, 2001). The use of inorganic N fertilizers also has a beneficial effect on earthworms. Nitrogen, P, and K fertilization increases crop biomass and therefore increases the return of crop residues. Ammonia, from either manure or fertilizer, can decrease earthworm populations in the proximity of the nutrient placement. Fertilization with NH_4^+-based fertilizers when earthworms are active can reduce populations up to 10 percent. If NH_3 is applied when temperatures are colder and the earthworms have moved deeper in the soil profile, populations will be minimally impacted (Deibert and Utter, 1994). Earthworm populations and surface feeding can be encouraged through proper soil pH maintenance with liming and by minimizing tillage.

Ohio researchers (Bohlen et al., 1997) used nutrient treatments—1) ammonium nitrate (NH_4NO_3), 2) straw-pack cow manure, and 3) legume-rye cover crop supplemented with alfalfa hay—and manipulation of earthworm population levels (via electroshocking) in an investigation of litter decomposition and C and N cycling by earthworms in a corn study. They found that the nutrient treatments did not differ in their effects on mass loss or nutrient dynamics of corn litter. Nor was there a significant interaction between the nutrient treatments and earthworm populations. There were also no significant differences among nutrient treatments in earthworm population density or biomass after three consecutive annual applications. The earthworms had a greater effect on the loss of N from the surface crop litter than on the loss of litter C and increased the rate of disappearance of the surface litter. The authors also reported that earthworms select litter with lower C:N ratios as they feed from burrow entrances (middens). Thus, earthworms contribute to spatial and temporal variation in C, N, and other nutrient levels in fields. The ultimate fate of the N lost from surface litter by earthworm activity is unknown.

Trace Elements/Heavy Metals

Trace elements and heavy metals occur naturally in rock, soil, and water resources. Several heavy metals are essential or beneficial to both plants and animals, but can become toxic if accumulated in excessive amounts (**Table 8.1**). Proper agronomic and environmental nutrient and waste management planning can reduce or prevent the potential for the development of toxic levels in plant and animal systems.

Large ranges in trace element and heavy metal concentrations occur naturally in rocks, soils, and sediments (**Table 8.2**). As rocks and soils weather, small amounts of the trace elements and heavy metals naturally enter surface and ground waters.

More than 97 percent of the fertilizer materials in North America are manufactured from natural sources (atmospheric gases or mineral deposits) rather than industrial byproducts (PPI/PPIC/FAR, 1998). According to a recent USEPA report on fertilizers (USEPA, 1999), typical rates of metal additions to soil in any applied fertilizers would not exceed the U.S. biosolids annual pollutant loading rates or the Canadian Fertilizer Act limits. The Association of American Plant Food Control Officials (AAPFCO) has proposed a tentative guide for metals in phosphate and micronutrient fertilizers (**Table 8.3**). The Canadian and Washington-state standards for metal additions to soils by commercial fertilizers are much more stringent than the USEPA 503 sewage sludge annual loading limits (**Table 8.4**).

Trace element and heavy metal concentrations in animal wastes (manures) and sewage sludges vary widely, can be fairly high, and often exceed the concentrations in fertilizers (**Table 8.5**). Arsenic (As), cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), selenium (Se), and Zn are often added to poultry diets to prevent diseases, improve feed conversion and weight gains, and increase egg production (Sims and Wolf, 1994). Application of manure to meet crop major nutrient needs can result in delivery of significant amounts of some trace elements and heavy metals.

Table 8.1. Reaction of plants and animals to heavy metals and trace elements.

	Essential or beneficial to		Potentially toxic to	
Element	Plants	Animals	Plants	Animals
Arsenic	No	Yes		Yes
Cadmium	No	No	Yes	Yes
Chromium	No	Yes	Yes	DU
Cobalt	Yes[3]	Yes	Yes	Yes
Copper	Yes	Yes	Yes	Yes [2]
Lead	No	No	Yes	Yes
Mercury	No	No	DU [1]	Yes
Molybdenum	Yes	Yes	DU	Yes [2] (5-20 ppm[3])
Nickel	No[4]	Yes	Yes	Yes
Selenium	Yes	Yes	Yes	Yes (4 ppm)
Zinc	Yes	Yes	DU	DU

Source: Webber and Singh, 1995.

[1] DU=Data on critical limits unavailable

[2] Toxic to ruminants (cattle and sheep)

[3] ppm=parts per million

[4] Other sources consider Co to be nonessential and Ni to be essential (PPI Soil Fertility Manual).

The heavy metal of most concern in phosphate fertilizers is cadmium (Cd) because of the levels found naturally in the phosphate rock from which it is derived (PPI/PPIC/FAR, 1998; **Table 8.5**). Long-term applications of some phosphate fertilizer sources can increase soil trace element levels, but the increases are relatively small (**Tables 8.6** and **8.7**). A phosphate fertilizer with the highest Cd concentration shown in **Table 8.5** was compared to a typical sewage sludge to estimate the long-term accumulation of the heavy metals and trace elements of greatest concern (**Table 8.8**). With this worst-case example, it would take from 848 to 170,000 years to reach the USEPA cumulative limits using fertilizer, compared to 290 to 1,892 years for sewage sludge.

Precise data on median Cd concentrations are unavailable, but typical P fertilizers contain much less than the 205 ppm used in the example above. The typical sewage sludge in the example had only 2.3 ppm of Cd, while in Ontario, Canada, typical biosolids contain 6.3 ppm (OMAFRA, 2000). Thus, while the Cd loading rate may be as much as twice as high from P fertilizer as from biosolids in extreme examples, applying P fertilizer with a Cd concentration of 14.6 ppm at an average annual rate of 47 lb P_2O_5/A (typical for corn production) would take 38 times longer to reach the USEPA loading limit than with a typical Ontario biosolid. Thus, even for Cd, the most critical heavy metal contaminant in P fertilizer, loading rates are generally higher from biosolids than from fertilizer.

These data and estimates of impacts on soil concentrations indicate there is little long-term trace element and heavy metal risk to the environment from the sustained use of commercial N, P, and K fertilizers. The EPA 503 guidelines, however, have been criticized on a scientific basis for the level of heavy metal accumulation allowed for biosolids applications (McBride, 1995; 1998).

Trace Element Bioavailability

Pierzynski et al. (1994) interpreted bioavailability of trace elements in soils as the portion of the total trace elements that could be taken up by plants. Total trace element concentration in soil is not necessarily proportional to bioavailability, but as the content goes up, the bioavailable content will also go up to some extent. Plant availability of trace elements generally decreases as the CEC increases. Organic matter additions increase a soil's CEC. "In theory, increasing the cation exchange capacity of a soil is a potential method for reducing trace element bioavailability." (Pierzynski et al., 1994).

Many studies have confirmed the importance of organic matter (humic and fulvic acids) in micronutrient cycles in soil, although the reactions that control the nutrient solubility and thus

Table 8.2. Total concentration of selected heavy metals and trace elements in major rock types and mineral soils in North America.

	Metal								
	As	Cd	Cr	Cu	Hg	Mn	Ni	Pb	Zn	Ref.
Rocks	Mean concentration or range in concentration, ppm									
Igneous rocks										1
basalt	1.5	0.13	200	90	0.01		150	3	100	
granite	1.5	0.09	4	13	0.08		0.5	24	52	
Sedimentary rocks										
limestone	1	0.03	11	5.5	0.16		7	5.7	20	
sandstone	1	0.05	35	30	0.29		9	10	30	
shale	6.6	0.3	100		0.4			20		
Limestones		0.7	3 - 61	3 - 70		400 - 370	8 - 70	2 - 100	40 -700	2
Calcitic lime	<2	0.7	ND	2.3	ND	36.7	1.4	1.1	ND	3
Dolomitic lime	1.2	<0.2	32.3	ND	0.17	49.7	3.3	0.7	8	
U.S. sedimentary & igneous phosphate rocks									1	
central Florida	11.3	9.1	60	0.2	17		3	141	108	
north Florida	7	6.1	65		12			81	102	
North Carolina	11.2	38.2	158	0.23	8		5	65	26	
Idaho	23.7	92.3	637	0.29	12		8	107	769	
Soils	Mean concentration or range in concentration, ppm									
Canada	7-11	0.5 - 4	10 - 100	5 - 15	0.005 - 0.1		5 - 15	5 - 15	10 - 120	4
"uncontaminated" soils	7	0.8	15	25	0.1		16	15	55	4
U.S. mineral soils (n=2771)		0.01 - 2.0		0.6 - 495			0.7 -269	1.0 - 135	3 - 264	5
"Typical" soils	0.1 - 40	0.01 - 0.7	5 - 3000	2 - 100	0.01 - 0.3		10 - 1000	2 - 200	60 - 2000	2
"Typical" soils		0.35		50			30	50	15	6
"Natural"soil	1 - 50	0.01 - 7	5 - 1000	2 - 1000	0.02 - 0.2	200 - 200	10 - 1000	2 - 200	10 - 300	7
Soils "normal" range	<5 - 40	<1 - 2		2 - 60			2 - 100	10 -150	25 - 200	8
Mississippi (A horizons)										9
non-amended forest soil			17.2	2.5		19.4	6.6	6.3	8.1	
poultry littered pasture soil			23.3	55.9		195.1	12.4	9.6	60.8	
Mississippi (A horizons)										10
Blackland Prairie		0.3 - 0.9		5.4 - 15.3		253 - 224	12.2 - 27.6	18.8 - 29.1	33.2 - 86.2	
Coastal Flatwoods		0.0 - 0.4		0.8 - 8.5		4 - 29	3.7 - 20.5	6.5 - 15.8	2.1 - 13.9	
Delta		0.3 - 2.0		13.1 - 45.5		332 - 785	17.0 - 51.3	13.1 - 37.5	44.3 - 197.8	
Loess		0.3 - 0.5		4.2 - 10.7		153 - 114	4.6 - 16.9	1.8 - 21.0	13.8 - 34.5	
Lower Coastal Plain		0.2 - 0.4		1.9 - 5.2		85 - 407	1.5 - 16.0	4.4 - 65.8	3.6 - 183.2	
Upper Coastal Plain		0.2 - 1.0		1.5 - 22.0		20 - 6211	2.5 - 30.8	7.0 - 25.3	7.5 - 114.1	
Oklahoma (A horizons)		0.054 - 0.152								11
Florida mineral surface soil	0.01 - 6.1	0.068 - 0.39	0.43 - 23	0.01 - 16	0.0005 - 0.04	2.1 - 230	4.5 - 9.6	0.42 - 24	6.7 - 18	12
Ohio farm soils (A horizons)		0 - 2.9	4-23	11-37			9-38	9-39	47-138	13
Missouri soils	2.5-72	<1-11	10-150	5-150	<0.01-0.8	15-3000	<5-70	10-7000	18-640	14
Washington (Columbia Basin)										
agricultural fields (n=20) (0-12 inches)	2.10-5.68	0.05-0.21		9.49-19.0	<0.003-0.013		7.90-15.7	5.78-9.59	43.6-65.0	15
non-agricultural sites (n=13) (0-12 inches) (matched background sites)	1.50-5.56	<0.030-0.098		9.89-20.2	<0.0032-0.066		8.0-14.1	4.60-9.97	32.5-56.2	
Soils	.01-40	0.01-7	5-3000	2-100		100-4000	10-1000	2-200	10-300	16
Pennsylvania soils										
typical noncontaminated background	6.0-10.0	0.2-0.5		17-65	0.06-0.15		<5-700	<10-700	19-82	17
Soils and surficial materials (conterminous U.S.)	<0.10-97		1-2000	<1-700	<0.01-4.6	<2-7000	<5-700	<10-700	<5-2900	18
U.S. surface soils	<0.1 - 93		1 - 1500	1 - 300					<5 - 300	19
River Sediment	Mean concentration or range in concentration, ppm									
Mississippi River										20
"nonpolluted" sediment			<25	<25	<1			<40		
suspended silt								28 - 64		
suspended colloids								42 - 102		
bed sediments					0.02 - 30			5 - 44		
Upper Miss. River & Basin bed sediment	5.3 - 25	0.3 - 2.2	35 - 210	12 - 170	0.02 - 0.78	560 - 350	11 - 47	12 - 300	65 - 490	21
Illinois River & Basin bed sediments (n=20)	4.7 - 15	0.3 - 4.0	4 - 110	14 - 16	0.02 - 0.32	480 - 120	20 - 42	15 - 86	69 - 320	22
Lower Miss. River & Basin bed sediments (n=15)	5.9 - 24	0.1 - 0.6	38 - 100	11 - 41	0.03 - 0.07	540 - 3100		14 - 25	50 - 140	23

1. PPI/PPIC/FAR, 1998; 2. Hansen and Schaeffer.1995; 3. Raven and Loeppert, 1997; 4. Webber and Singh, 1995; 5. Holmgren et al., 1993; 6. Sposito and Page, 1984 (cited by Holmgren et al., 1993); 7. Bohn et al., 1979; 8. Pierzynski et al., 1994; 9. Han et al., 2000; 10. Pettry and Switzer, 1993; 11. Basta et al., 1998; 12. Ma et al., 1997; 13. Logan and Miller, 1983; 14. Hoette et al. 1995; 15. Rogowski et al. 1999; 16. Allaway, 1968; 17. Stehouwer, 1999; 18. Boerngen and Shacklette, 1981; 19. Combs et al., 1998; 20. USGS Circular 1133; 21. USGS Circular 1211; 22. USGS Circular 1209; 23. USGS Circular 1208

Table 8.3. Association of American Plant Food Control Officials (AAPFCO) Tentative Guide for Implementation under Section 12(a) of the Uniform State Fertilizer Bill. [1]

Metal	ppm per 1 % P_2O_5	ppm per 1 % micronutrients [2]
Arsenic	13	112
Cadmium	10	83
Cobalt	3,100	23,000 [3]
Lead	61	463
Mercury	1	6
Molybdenum	42	300 [3]
Nickel	250	1,900
Selenium	26	180 [3]
Zinc	420	2900 [3]

URL=http://www.aapfco.org/#Start

To use the table:

Multiply the percent guaranteed P_2O_5 or sum the guaranteed percentages of micronutrients (e.g. Zn) in each product by the value in the appropriate column in the table to obtain the maximum allowable concentration (ppm) of these metals. The minimum value for P_2O_5 utilized as a multiplier shall be 6.0. The minimum value for micronutrients uitilized as a multiplier shall be 1. If a product contains both P_2O_5 and micronutrients, multiply the guaranteed percent P_2O_5 by the value in the appropriate column and multiply the sum of the guaranteed percentages of the micronutrients by the value in the appropriate column. Utilize the sum of the two resulting values as the maximum allowable concentration.

Biosolids, and all compost products[4], shall be adulterated when they exceed levels permitted by the U.S. EPA Code of Federal regulations, 40 CFR Part 503. Dried biosolids and manure, as well as manipulated manure products, either separately or in combination, shall also be deemed adulterated when they exceed the levels permitted by the U.S. EPA Code of federal regulations, 40 CFR Part 503. Hazardous waste derived fertilizers (as defined by EPA) shall be adulterated when they exceed the levels of metals permitted by the U.S. EPA Code of Federal Regulations, 40 CFR, Parts 261, 266 and 268.

Notes:

[1] These guidelines are not intended to be used to evaluate horticultural growing media claiming nutrients, but may be applied to the sources of the nutrients added to the growing media.

[2] Micronutrients (also called minor elements) are essential for both plant growth and development and are added to certain fertilizers to improve crop production and/or quality. These micronutrients are iron, manganese, zinc, copper, molybdenum, and boron. In addition, cobalt and selenium can be considered micronutrients.

[3] Only applies when not guaranteed.

[4] Includes all compost products, separately or in combination with biosloids, manure, or manipulated manure, even those registered as fertilizers (making nutrient claims).

plant availability of micronutrients and trace elements in soils are not well known (Norvell, 1991). Micronutrient and trace element cations are maintained in soil solution through complexing with soluble organics which can be provided in animal wastes and crop residues. In some situations, metal ion concentrations can be reduced to nontoxic levels through organic complexing. The role of organic matter in micronutrient transport to plant roots and the competition of biochemicals and humic substances for metal ions is acknowledged, but details are lacking (Stevenson, 1991).

Water

Algal blooms and eutrophication of surface waters

Nutrient (N and P) input is essential for profitable crop and animal agriculture (Sharpley et al., 1999; 2000) and is also required for sustained aquatic productivity, but an excess can over-stimulate the growth of aquatic plants and algae, causing algal blooms. As the aquatic plants die, bacteria begin to decompose them and use the dissolved oxygen (O_2) When the dissolved O_2 levels become too low, some aquatic plants and animals can suffer, and the less mobile organisms may die in prolonged or severe situations of high biochemical oxygen demand (BOD). This concern has been well publicized for the coastal waters of the Chesapeake Bay (Boesch et al., 2001) in the northeastern U.S. and in the Gulf of Mexico in recent years (Rabalais et al., 2001). Nitrogen and P from commercial fertilizers have been frequently blamed as the cause of increased nutrient flux to surface water bodies, as in the Mississippi River Basin and the Gulf of Mexico (Rabalais et al., 1998; Burkart and James, 1999; Goolsby et al., 2001).

Table 8.4. Standards for the maximum addition of metals to soils by commercial fertilizers.

Trace element	Canadian lifetime [1] lb/A	Washington annual [2] lb/A/year	EPA 503 Annual loading limits for biosolids in a single year lb/A/yr
Arsenic	13.0	0.30	1.79
Cadmium	3.6	0.08	1.70
Cobalt	27.0	0.59	66.97
Lead	89.0	1.98	13.40
Mercury	0.9	0.02	0.76
Molybdenum	3.6	0.08	*
Nickel	32.0	0.71	18.75
Selenium	2.5	0.06	4.46
Zinc	330.0	7.33	125.02

(Adapted from Rogowski et al., 1999)

Notes:

[1] Long-term (45 years) cumulative metals additions to the soil. (Canadian Trade Memorandum T-4-93, August 1996. Agriculture and Agri-Food Canada)

[2] Maximum acceptable annual metals additions for Washington soils, based on the Canadian standard and assuming a 45 year loading period (WAC 16-200-7064)

* EPA 503 rule has a maximum concentration of 75 ppm for Molybdenum, but no maximum loading limit

The USEPA (2000b) has stated, "Nitrogen and phosphorus generally are present at background or natural levels below 0.3 and 0.1 mg/L (ppm), respectively. When these nutrients are introduced into a stream, lake or estuary at higher rates, aquatic plant productivity may increase dramatically. This process, referred to as cultural eutrophication, may adversely affect the suitability of the water for other uses."

Much of the blame for N and P transport to surface waters in the last five decades is often based on the presumption that nutrient losses in agricultural watersheds are directly proportional to the commercial fertilizer inputs (Goolsby and Battaglin, 2001; Smith et al., 1997). The nutrient contributions by animal wastes, soil organic matter decomposition, municipal sewage discharge, and atmospheric deposition are more difficult to quantify and are less accurately accounted for. Many source-loss assumptions are made in several publications which attempt to estimate nutrient losses to surface waters (for example, Goolsby et al., 2001; Burkart and James, 1999; Goolsby et al., 1999; Smith et al., 1997). In fact, Battaglin et al. (2001) have stated, "The amount of NO_3^- delivered by the Mississippi River to the Gulf of Mexico is well documented, but the relative contributions of different sources of NO_3^-, and the magnitude of subsequent in-stream transformations of NO_3^-, are not well understood." Smil (1999) reported, "Relatively abundant information on nitrate exports in streams and groundwaters is of little use in assessing N leaching from agricultural land as there is no reliable way to separate the contributions of atmospheric deposition, sewage sludge, and industrial processes from the flux originating in inorganic fertilizers and animal manures."

Nitrogen

The average N loss as discharge from farm fields in the Mississippi River Basin has been estimated by the USGS at about 4 lb/A/yr (Goolsby et al., 1999) and is in agreement with numerous research reports (Snyder et al., 1999a). Before North America was settled and humans disturbed the landscape, it is estimated that the natural N loss was on the order of 0.7 to 2.1 lb of N/A/yr (National Research Council, 2000). Much of the N loss for the Mississippi River Basin, which covers about 40 percent of the continental U.S., has been reported to come from the Upper Mississippi River Basin and the Ohio River Basin (Burkart and James, 1999; Goolsby et al., 1999). The N discharge from some hydrologic units within these sub-basins was estimated at over 50 to 100 lb/A/yr.

In a six-year study of the 119,000-acre Embarrass River watershed at Carmago in east-central Illinois, the NO_3^--N export from fields was estimated at 31 lbA/yr (David et al., 1997). This Illinois watershed has little urban influence, little livestock production, is dominated (> 90 percent) by corn and soybean fields, and has 70 to 85 percent tile drainage. A four-year study of a tile-drained corn and soybean field in central Iowa was conducted using low, medium, and high N rates for corn (50 to 60, 100 to 120, and 150 to 180 lb N/A, respectively; Jaynes et al., 2001). The researchers found that the NO_3^--N in tile drainage exceeded the USEPA maximum contaminant level (MCL) of 10 ppm for the low N rate only during the years when corn was grown. The higher N rates resulted in tile drainage concentrations above the MCL every year, regardless of the crop grown. The researchers concluded, "Economic corn production can not be sustained within this field under the current rotation and management scheme without producing tile drainage water that exceeds the MCL for NO_3^-. The problem is not one simply of N fertilizer use, but of a corn-soybean production system created by artificial soil drainage and intensive tillage."

Nitrate-N losses through tile drainage in corn and soybean cropping systems will vary depending on the crop rotation, the tillage system, the N rate and timing, and whether a nitrification inhibitor is used or not (Randall and Mulla, 2001; Weed and Kanwar, 1996; Snyder et al., 2000; Randall, 1993). These management practices may have as much or more impact on NO_3^- losses than source and rate of N inputs. Randall and Mulla (2001) stated, "Noncontrollable factors such as climate and soil organic matter have a profound influence on nitrate N concentrations and loadings in subsurface drainage water. The dynamics of N behavior in drained agricultural soils during these periodic climatic events and the management of both crops and nutrient inputs (controllable factors) must be considered carefully by agriculturalists as they manage the land."

In spite of these challenges, there are many opportunities to improve N use efficiency and to reduce the potential for environmental N loss. For example, a long-term study with corn in Kansas (Schlegel et al., 1996) showed that optimum P fertilization, at the optimum N rate, decreased residual soil profile NO_3^--N by 66 percent (**Figure 8.1**). Similarly, high soil test K levels increased N uptake by corn, increased yields, and reduced residual soil profile NO_3^--N (Johnson and Reetz, 1995). Progress in improving N use efficiency and opportunities for additional improvement have been recently reviewed (Fixen and West, 2002; Cassman, et al., 2002).

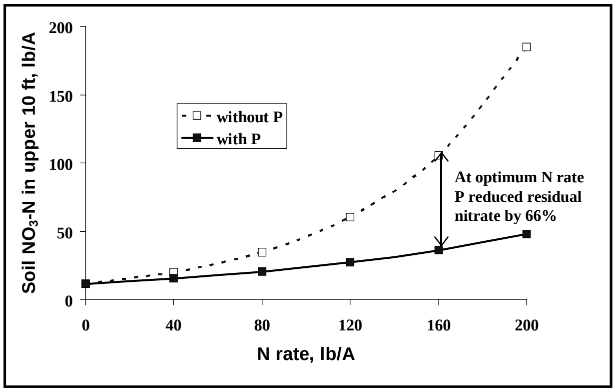

Figure 8.1. Adequate P reduces residual soil nitrate and the potential for nitrate leaching. (30-year results, Schlegel et al., 1996)

Table 8.5. Total concentration of selected heavy metals and trace elements in fertilizers, manures, and biosolids.

	Mean or range in nutrient concentration, ppm on dry weight basis					
Source	As	Cd	Cr	Cu	Hg	Pb
Fertilizer						
urea (46-0-0)		<0.1	<3	<0.4		<3
triple superphosphate (0-46-0)		9	92	3		3
muriate of potash (0-0-60)		<0.1	<3	<0.6		3
urea	<0.4	<0.2	ND	<0.6	<0.4	<0.4
ammonium nitrate	<0.4	<0.2	ND	<0.6	<0.4	<0.4
ammonium sulfate	0.4	<0.2	ND	<0.6	<0.4	<0.4
monoammonium phosphate	10.9 - 13.7	<0.3 - 4.0	25	<2 - 13.2	<0.4	<0.2 - 2.9
diammonium phosphate	9.9 - 16.2	4.6 - 35.5	5.5	<2 - 41.8	<0.4	2.1 - 3.7
triple superphosphate	15.3 - 16.2	5.0 - 6.2	13.4	3.2 - 3.5	<0.4	11.1 - 13.2
muriate of potash	0.4	<0.2	<1.0	<2 - 3.5	<0.4	<0.4 - 1.0
potassium-magnesium sulfate	0.6	0.8 - 48.8	2.75	1.4 - 5	<0.4	1.1 - 1.4
diammonium phosphate	12.3	10	48	1.6		9.8
monoammonium phosphate	12.7	7.1	57	<1.5		9.1
triple superphosphate	10.3	15	133	3.5		11
muriate of potash		1.6		1.6		9.1
ammonium nitrate	ND	0.042	ND		ND	0.74
ammonium phosphate sulfate	0.6	160	196		0.019	2.9
triple superphosphate	1	106	378		ND	3.19
muriate of potash	ND	ND	ND		ND	0.28
elemental sulfur	ND	ND	ND		ND	0.4
mixed fertilizer 17-5-25		0.2		3.4		0.5
N fertilizers						
ammonia	<0.01	0.005 - 0.05	<0.01	0.02	<0.1	<0.01 - 0.05
ammonium nitrate	<0.10 - 10	<0.012 - 1.0	<0.19 - 3.0	<2 - 10	<0.02 - 0.1	<0.03 - 5.0
ammonium sulfate	<1.0	<0.05 - 1.0	<0.01 - 3.0	<1.0 - 3.0	<0.02 - 1.0	<0.01 - 1.0
calcium ammonium nitrate	<0.10	<0.10			<0.10	<0.10
urea ammonium nitrate	<0.10 - 0.50	<0.10 - 1.0	<3.0	<3 .0	<0.02 - 0.10	<0.10
urea	<0.01 - 0.50	<0.01 - 0.10	<0.01 - 3.0	<0.01 - 3.0	<0.02 - 0.10	<0.01 - 0.10
P fertilizers						
diammonium phosphate	1.5 - 16	0 - 134	6.6 - 622	1 - 10	0.001 - 0.5	3.5 - 26.4
monoammonium phosphate	0.96 - 25	0.5 - 205	67 - 648	1 - 76	0.005 - 0.5	0.05 - 36
liquid ammonium polyphosphate	0.6 - 16	10.3 - 13	153 - 193	<2.0 - 14.4		<3.0 - 18.4
triple superphosphate	1 - 21	1.8 - 106	52 - 428	1 - 9	0.003 - 1.3	1 - 22.9
single or ordinary superphosphate	2 - 31	0.5 - 34	31.9 - 840	2.5 - 29.8		<0.01 - 9.4
raw phosphate rock	6.6 - 17	2.4 - 41	54 - 195	<5.0 -58	0.04 - 0.18	7.9 - 18.7
K fertilizers						
muriate of potash	<0.01 - 0.05	0	<0.01 - 3.0	0.01 - <3.0	<0.1 - 0.2	<0.03 - 0.82
potassium-magnesium sulfate	<0.16	<0.01	<0.02 - 21.1			<0.02 - 9.2
Manure						
cow manure		0.8 - 1	56	62	0.2	16
dairy manure				3		
feedlot manure						
bagged manure				55 - 62		
dairy solid manure	0.12 - 1.18		0.30 - 11.57	11.7 - 200.2		
dairy liquid manure	0.19 - 1.86		1.14 - 10.61	16.4 - 1319.6		
poultry manure				2		
poultry manure		1		20 - 232		
poultry litter	0 -77	6		25 - 1003		
broiler litter	26	0.4	9	225	0.2	6
stacked broiler litter		0.4		80		1.86
poultry manure	0.35 - 110.5		0.66 - 19.68	35 - 1350.2		
swine manure				36		
swine sludge		0.2	3.2	58		4
swine liquid manure	0.68 - 5.17		7.97 - 24.18	146.6 - 1923.1		
swine solid manure	0.49 - 8.87		22.76 - 33.06	269.6 - 515.3		
Biosolids						
EPA 503 maximum for EQ biosolid	41	39	1200	1500	17	300
EPA 503 maximum for sewage sludge	75	85	3000	4300	57	840
sewage sludge		1	145	79		46
sewage sludge (PA; n >1000)	3.6	2.3	35	511	1.5	65

Note: ND = not detected

Table 8.5. (Continued)

	Mean or range in nutrient concentration, ppm on dry weight basis						
Source	Mn	Ni	Se	U	V	Zn	Ref
Fertilizer							
urea (46-0-0)		<1				<1	1
triple superphosphate (0-46-0)		36				108	
muriate of potash (0-0-60)		4				<1	
urea	0.3	<0.2	ND	ND	0.2	ND	2
ammonium nitrate	0.5	<0.2	ND	ND	<0.2	ND	
ammonium sulfate	0.4 - 0.8	<0.2 - 0.6	<0.6	<0.51	<0.2	6.4	
monoammonium phosphate	318 - 433	7.4 - 22.2	1.18	<5.82	146 - 205	10.3	
diammonium phosphate	34 - 333	15.5 - 48.3	<1.16	198	177 - 237	386	
triple superphosphate	298 - 347	15.6 - 25.2	<1.2	232	154 - 189	61.3	2
muriate of potash	0.2 - 5.3	<0.2	<0.22	<0.98	<0.2 - 0.3	4.59	
potassium-magnesium sulfate	11.1	0.3 - 0.5	<0.2	<0.46	0.7 - 9.0	8.75	
diammonium phosphate	291	19	0.1			170	3
monoammonium phosphate	366	17	0.3			75	
triple superphosphate	258	17	2.1			159	
muriate of potash	4.5	2.9				1.5	3
ammonium nitrate		ND	ND			ND	4
ammonium phosphate sulfate		219	ND			2110	
triple superphosphate		167	ND			1350	
muriate of potash		ND	ND			ND	
elemental sulfur		ND	ND			9.9	
mixed fertilizer 17-5-25	42	1.1				7	5
N fertilizers							6
ammonia	<0.01	0.02 - 0.05	<0.1			0.03 - 0.1	
ammonium nitrate	<2.0 - 3.0	<0.16 - 3.0	<0.1 - 3.0	<3.0	<20	<0.01 - 2.0	
ammonium sulfate	<1.0 -3	<0.1 - 3.3	<0.50	<1.0 - 10	<20	<1.0 - 13	
calcium ammonium nitrate		0.80	<0.10			2	
urea ammonium nitrate	<3.0	0.3 - 3.0	<0.10 - 0.50	<3.0	<20	<0.2 - 15	
urea	<0.01 - 3.0	0.0015 - 1.5	<0.03 - 0.5	<3.0	<20 - 50	<0.01 - 18	
P fertilizers							6
diammonium phosphate	73 - 516	7.9 - 130	0.025 - 5	20 - 181	11 - 896	0.01 - 2320	
monoammonium phosphate	181 - 312	9.9 - 235	<0.05 - 5	25 - 284	35 - 1083	50 - 3360	
liquid ammonium polyphosphate	174 - 195	<19.0 - 142	2.08		49 - 105	126 - 225	
triple superphosphate	149 - 283	10 - 29	0.025 - 5	95 - 200	87 - 812	42 - 97	
single or ordinary superphosphate	2870 - 4100	10.8 - 26.9	0.025 - 4.3		52 - 202	30 - 243	
raw phosphate rock	22 - 584	7.8 - 351	0.39 - 2.1	14 - 21	86 - 267	30 - 305	
K fertilizers							6
muriate of potash	<0.1 - 5	.18 - <3.0	<0.1 - 0.5	<3	0.001 - 10	<0.02 - 12	
potassium-magnesium sulfate		<0.16 - 10.5					
Manure							
cow manure		29			43	71	1
dairy manure	25					34	7
feedlot manure	66 - 90						
bagged manure	286 - 340					71 - 298	
dairy solid manure	47.3 - 534.7		0.17 - 2.94			23.8 - 542.6	8
dairy liquid manure	70.9 - 345.2		0.74 - 2.37			45.6 - 397.1	
poultry manure	16					20	7
poultry manure	217 - 660					230 - 660	9
poultry litter	1 - 669		1			105 - 669	
broiler litter		7	0.2			315	
stacked broiler litter	287	12.2				282	5
poultry manure	123.8 - 763		0.22 - 2.23			51 - 536.5	8
swine manure	76					790	7
swine sludge	39	2.3				110	10
swine liquid manure	177.8 - 740.2		1.68 - 4.04			443..9 - 4,425.9	8
swine solid manure	758.1 - 1055		1.44 - 2.15			432.6 - 767.8	
Biosolids							
EPA 503 maximum for EQ biosolid		420	36			2800	11
EPA 503 maximum for sewage sludge		420	100			7500	11
sewage sludge	18	42				176	10
sewage sludge (PA; n >1000)		22	4.3			705	12

1. Webber and Singh,1995
2. Raven and Loeppert,1997
3. Charter et al., 1993
4. Rogowski et al., 1999
5. Eichhorn, 1999
6. Weinberg Group, Inc., 1998
7. Hansen and Schaeffer, 1995
8. Combs et al., 1998
9. Sims and Wolf, 1994
10. King, 1981
11. Pierzynski et al., 1994; Walker et al., 1994; USEPA, 2001a
12. Stehouwer, 1999

Table 8.6. Total soil concentrations of some heavy metals in long-term research studies.

Location	Treatment	Year sampled	Soil concentration, ppm			
			Cd	Cu	Ni	Zn
University of Illinois Morrow Plots	Control	1933	0.206		29	70
	(No manure or fertilizer)	1978	0.225		29	72
	Farmyard manure (FYM) at 2 ton/A	1933	0.206		29	73
	FYM at 2 ton/A	1978	0.220		30	74
	Control	1933	0.210		29	63
	Fertilizer 0-46-0	1978	0.192		30	68
	FYM	1933	0.210		29	67
	FYM + Fertilizer 0-46-0	1978	0.206		30	71
University of Missouri Sanborn Field	Control	1938	0.291		21	62
	(no fertilizer or manure)	1978	0.290		25	66
	FYM applied since 1888	1938	0.346		23	69
	FYM applied since 1888	1978	0.402		32	80
	Fertilizer 0-46-0 since 1914	1938	0.360		22	65
	Fertilizer 0-46-0 since 1914	1978	0.426		31	74
Oklahoma State Univ. Magruder Plots	Control	1980	0.139	11	11.5	37
	FYM applied since 1899	1980	0.142	11	12	37
	0-46-0 since 1930	1980	0.139	11	10.6	36
Auburn Univ. (six location average)	Control	1929	0.087			
	Control	1980	0.093			
	Fertilizer 0 - 45 (P-K; lb/A/yr)	1980	0.098			
	Fertilizer 22 - 45 (P-K; lb/A/yr)	1980	0.115			
	Fertilizer 22 - 45 (P-K; lb/A/yr)	1980	0.110			

Source: Mortvedt, 1987.

Phosphorus

Sharpley et al. (1996 and 2000) and Simard et al. (1995) reported that use of manure or fertilizer P can lead to buildup of soil P levels and offered potential options for management action. Decades of P application, at rates in excess of crop removal, can lead to a heightened risk of P loss to surface waters. Historically, P has been considered immobile in soils, but P leaching can occur when the P sorption capacity of the soil is exceeded (Simard et al., 1995; Sims et al., 1998).

Where soil test P levels have risen to excessively high levels in mineral soils, it is not unusual to find a prevalence of confined animal feeding operations (CAFOs). The manure produced by CAFOs is usually land-applied over a period of many years, and soil P levels can increase markedly in some fields (Sharpley et al., 1993, 1996 and 2000; Simard et al., 1995; Snyder et al., 1993). Soils used intensively for crops that require more P input than they remove (for example, tobacco or potatoes) may also attain excessively high levels.

The transport of P bound to sediments can pose a significant water quality nutrient impairment threat to nearby streams (Wood, 1998; Daniel et al., 1998) where erosion is a risk. In many grassed watersheds, where erosion is controlled, the loss of P in surface runoff may be dominated by soluble inorganic P, referred to as dissolved reactive P (DeLaune and Moore, 2001; Moore et al., 1995b; Pote et al., 1999). In these studies, the inorganic P lost in runoff originated from animal waste applications.

The approximate percentages of the total P in different manures as inorganic P has been reported as: 45, 60, 30, 50, and 55 percent for beef, dairy, broiler, layer, and swine manures, respectively (Mikkelsen and Gilliam, 1995). According to personal communications (2001) with Philip Moore, Jr. (USDA-ARS, Fayetteville, AR), Brad Joern (Purdue University), and Peter Kleinman (USDA-ARS, University Park, PA), the water-extractable or water-soluble P in different manures ranges from about 0.4 to 5 percent of the total P. Swine manures may contain as much as 60 percent of the total P as dissolved phosphate (personal communication, Brad Joern, 2001). Most commercial P fertilizers have water soluble P levels greater than 60 to 80 percent (Mullins and Evans, 1991). Typical rates of manure may therefore provide levels of water-soluble P or inorganic P (phosphate) comparable to moderate rates of commercial P fertilizers.

The natural nutrient loss of P to surface waters before human settlement was estimated at about 0.4 lb of P/A/yr (National Research Council, 2000). “Given the site-specific nature of phosphorus export and the paucity of information on background phosphorus losses from a given location prior to cultivation, no baseline for the natural rate of phosphorus export exists.” (National Research Council, 2000). Based on numerous research studies and USGS estimates, the average loss (discharges) of P in recent decades from farm fields in the Mississippi River Basin is below 1.0 lb/A/yr (Snyder et al., 1999a; Goolsby et al., 1999). The P loss in the landscape “clearly depends on the phosphorus content of the parent rock-material, the rate of weathering, and other environmental conditions, including the rate of erosion.” (National Research

Table 8.7. Effects of Cd applied via farmyard manure or 0-46-0 inputs on changes in total soil Cd level.

Location and treatment	Estimated total Cd inputs from treatments[2], lb	Changes in total soil Cd[3], ppm
Morrow Plots, Illinois		
Farmyard manure (FYM)	0.004	0.014
FYM + 0-46-0	0.010	-0.004
0-46-0 [1]	0.007	-0.012
Sanborn Field, Missouri		
FYM	0.013	0.112
0-46-0	0.042	0.136
Magruder plots, Oklahoma		
FYM	0.009	0.003
0-46-0	0.029	0
Auburn Univ., Alabama		
0-46-0	0.030	0.017

Source: Mortvedt, 1987

[1] 0-46-0 = Triple superphosphate fertilizer

[2] Estimated by Mortvedt (1987) assuming the FYM, rock phosphate, and 0-46-0 fertilizer had an average concentration of 0.05, 0.1 and 5 ppm, respectively.

[3] Change in concentration calculated by subtracting control plot concentration from total soil Cd concentration in the treated plot

Council, 2000). These observations are supported by research conducted by David Mulla at the University of Minnesota. He reported significant municipal sources of P dominate the water quality impacts during low flow and that agricultural sources affect water quality during medium to high flow periods. According to Mulla (1998), "In the Minnesota River Basin, significant progress has occurred in managing P emissions to surface water from both point and non-point sources. Some of the gains in P management on agricultural lands have been offset, however, by an increasing wetter climate in recent years. This has caused greater than average rates of erosion, runoff, and delivery of P to surface waters from agricultural lands."

Many interacting factors affect the potential for P transport from the landscape. Numerous versions of an environmental P index have been developed to integrate the diverse source and transport factors controlling P loss into a risk assessment tool. Watershed hydrology forms an important component of the P Index (Lemunyon and Gilbert, 1993; Gburek and Sharpley, 1998; Snyder et al., 1999b). In many instances, a small percentage (<10 percent) of a given watershed may contribute the majority of the P loss or potential for loss (Gburek and Sharpley, 1998; Gburek et al., 2000). University and USDA scientists are developing state-specific adaptations of the P Index to help identify and manage lands where runoff P loss risks could threaten water quality (for example, DeLaune and Moore, 2001).

Phosphorus concentrations in the first runoff event from fields that have recently received manure/poultry litter are often very high. After the second or third runoff event, the concentrations return to background levels (Moore, 1998). Work by Edwards et al. (1996) comparing swine manure and poultry litter at high P loading rates showed that vegetative filter strips can be quite effective in reducing runoff P losses (**Figure 8.2**). Also, if runoff-producing rainfall does not occur for a week or two after manure or fertilizer application, the runoff P loss can be substantially reduced (**Figure 8.3**). These facts illustrate the importance of proper application timing. Combining conservation tillage and vegetative filter strips can also significantly reduce the risk of runoff losses of N and P from cropland, based on research in Kentucky (Thom and Blevins, 1996).

With effective use of best management practices (BMPs), less than 2 to 10 percent of the applied nutrients are lost in surface runoff from most fields. The literature indicates that conservation tillage can decrease N and P surface runoff losses by 50 to 90 percent and 0 to 80 percent, respectively (Snyder et al., 1999c). Research in eastern Kansas by Janssen et al. (1996) showed that subsurface placement of P fertilizer decreased soluble P in the runoff of grain sorghum plots in each of three tillage systems: chisel disk, ridge-till, and no-till. Interestingly, soluble P loss was greatest from broadcast P application in the no-till system, followed by the ridge-till and the chisel-disk systems (**Figure 8.4**). Similarly, soluble P losses were greater in conservation and no-till system demonstrations in Mississippi (personal communication, Richard Rebich, 2001, USGS). Crop residues on the surface in the no-till system may have limited direct P fertilizer contact with the soil, limited soil binding of P, and maintained more of the broadcast fertilizer P in the soluble form. Averaged

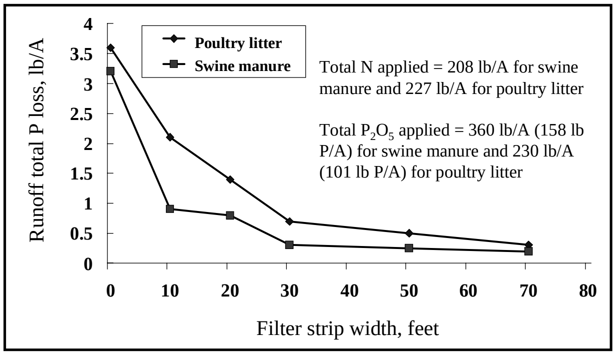

Figure 8.2. **Effect of grassed filter strip width on runoff P loss for swine manure and poultry litter. (Edwards et al. 1996. Arkansas)**

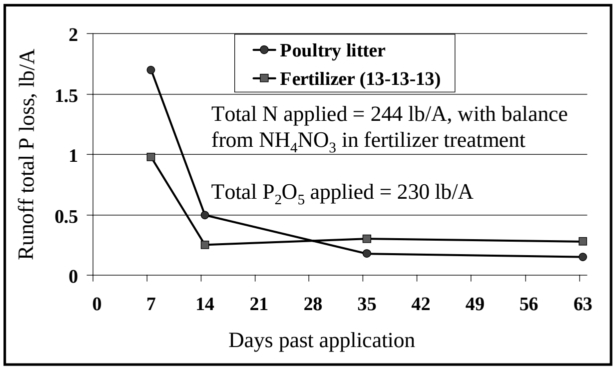

Figure 8.3. **Relationship between time past application and runoff P loss for ferilizer and poultry litter on fescue plots. (Edwards et al. 1996. Arkansas)**

Table 8.8. Potential cumulative total soil trace element response to sewage sludge and fertilizer.

Trace element	Typical background concentration for non-contaminated soils[1] (range in parentheses)	Median concentration in Pennsylvania sewage sludges[1]	Theoretical soil concentration at U.S. EPA cumulative sewage sludge loading limit[2]	Number of years required to reach U.S. EPA cumulative loading limit with example sludge[3]
	ppm	ppm	ppm	Years
Arsenic	8 (6-10)	3.6	26	1,138
Cadmium	0.4 (0.2-0.5)	2.3	17.4	1,696
Copper	41 (17-65)	511	701	290
Lead	15 (8-22)	65	282	457
Mercury	0.11 (0.06-0.15)	1.5	7.7	1,133
Nickel	26 (7-45)	22	213	1,892
Zinc	51 (19-82)	705	1,298	393

Trace element	Maximum trace element concentration in an example monammonium phosphate fertilizer[4]	Theoretical soil concentration if using Canadian lifetime (45 years) fertilizer loading limit	Theoretical soil concentration using the example fertilizer for 45 years	Number of years required to reach cumulative limit with example fertilizer, Table 8.5
	ppm	ppm	ppm	Years
Arsenic	25	15	8.1	7,321
Cadmium	205	2.2	1.3	848
Copper	76	217	217	94,733
Lead	36	60	15.2	37,500
Mercury	0.5	0.6	0.112	170,000
Nickel	235	42	27	7,925
Zinc	3,360	216	66	3,714

[1] From Stehouwer (1999)

[2] Theoretical maximum level to which soil concentrations of these elements would be increased after application of the EPA maximum allowable amount of that element .

[3] Assumes an annual application rate of 4.5 tons/A of a dry sewage sludge with trace element concentrations as shown for Pennsylvania sewage sludge in **Table 8.5.**

[4] Worst-case scenario example from **Table 8.5.**

[5] Assumes application at a rate of 200 lb/A/yr.

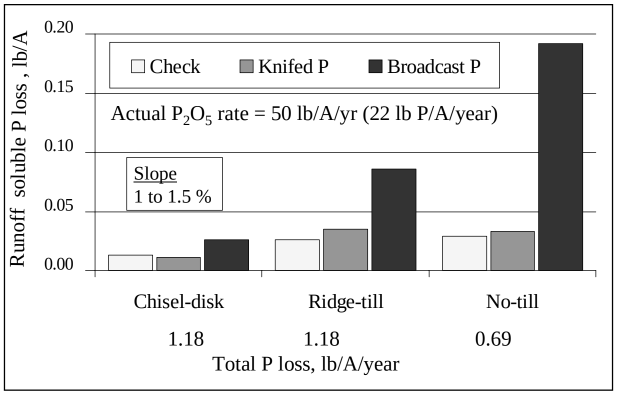

Figure 8.4. Three-year average soluble P losses from tillage systems and P placement methods. (Janssen et al. 1996. Ottawa, KS)

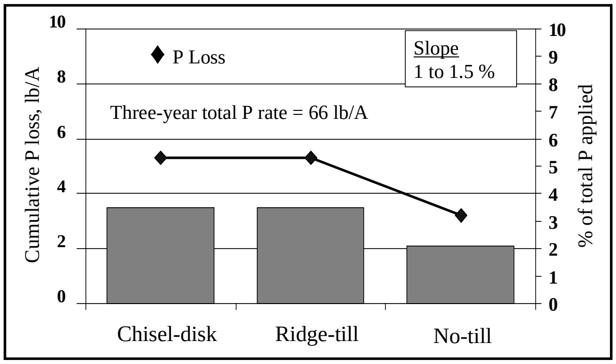

Figure 8.5. Three-year cumulative total P loss from different tillage systems (bars), and as percentage of P applied (line). (Janssen et al. 1996. Ottawa, KS)

across P fertilizer rates and placement in the Kansas study, the three-year total P loss was lowest with no-till, while the total P loss in the disk-till and ridge-till systems did not differ (**Figure 8.5**). The percentage of the total P lost in this P rate x P placement x tillage system research in eastern Kansas was equivalent to less than 6 percent of the applied P fertilizer. In other words, 94 percent of the applied P was in the standing crop, harvested grain, or in the soil. While sources of P can be placed subsurface or incorporated, placement is usually easier for mineral fertilizers than for manures.

Properly designed vegetative filter strips have decreased N and P losses from 40 to 90 percent. Utilizing both conservation tillage and vegetative filter strips can significantly reduce the risk of runoff losses of N and P from cropland, based on research in Kentucky (Thom and Blevins, 1996). Site-specific soil, crop, and nutrient management improvements like these can lead to increased yields and environmental protection. There is a continuing challenge to determine how to implement changes in a cost-effective, timely manner in individual fields.

A recent publication (USGS, 2001) reported, "Nutrient concentrations in water samples from Midwestern streams and rivers were not correlated with measures of agricultural intensity, such as the percentage of cropland, rates of fertilizer application, or the number of livestock in the basin....Although the application of nutrient fertilizers to cropland is considerable in all stream basins, nutrient concentrations vary among streams because of differences in natural factors such as riparian tree density, soil properties, and unit basin water yield." The USGS report also stated, "Nutrient concentrations in Midwestern streams during late summer were related more to antecedent runoff and algal nutrient processes than rates of fertilizer or manure application." The report concluded that "Temporal and spatial variability of natural factors are likely to influence the chemical and biological classification of water quality in streams and rivers, as well as the effectiveness of land-use management practices."

Excessive N and P in domestic water supplies can result in algal blooms and expensive water treatment to purify and reduce offensive odors and tastes. Excess P in water can stimulate certain algae strains to produce geosmin. Geosmin is an earthy-smelling compound and is also a metabolite of *Streptomyces*. *Streptomyces* belong to a group of organisms called actinomycetes and have long been recognized as a source of earthy odors in soils and earthy tastes and odors in waters. Actinomycetes resemble bacteria but share some features with fungi, primarily their branching network of filaments. Certain blue-green algae (e.g., *Anabaena, Cyanophyta, Microcystis, Oscillatoria, etc.*), chrysophytes or Chrysophyceae (e.g., *Dinobryon, Synura, Uroglena,* etc.), and diatoms (e.g., *Asterionella, Cyclotella,* etc.) are also known to produce the earthy-muddy odors and fishy tastes. In addition to geosmin production, 2-methylisoborneol (MIB) is produced. Both compounds are resistant to oxidation by conventional water treatment methods. Concentrations of these two compounds at very low levels [less than 0.03 parts per billion (ppb)] can cause serious taste and odor problems in domestic water supplies (Izaguirre et al., 1982 and personal communication with Philip Moore, Jr., 2001). These two compounds can also be used as substrates (food sources) by certain bacteria (e.g., *Bacillus* and *Pseudomonas* species).

Outbreaks of the organism *Pfiesteria piscicida* in near-shore waters of the eastern U.S. may also have been influenced by nutrient enrichment. Although the direct cause of these outbreaks is unclear, environmental scientists believe that excess nutrient loading helps create an environment rich in microbial prey and organic matter that *Pfiesteria* use as a food supply (Sharpley, 2000). Nutrient inputs in the agriculture near these waters is dominated by manure sources. However, the organism *Pfiesteria piscicida* has not been detected in these areas since Hurricane Floyd struck in September of 1999 (J. Burkholder, personal communication, June 2001).

Groundwater contamination

Nitrate

Excessive NO_3^- in groundwater was first identified as a human health problem when methemoglobinemia in an infant was associated with high NO_3^- well water in Iowa (Comly, 1945). Fatalities caused by methemoglobinemia are rare because drinking water guidelines, providing a good margin of safety, have detected and prevented consumption of contaminated sources, and only a small segment of the human population (infants less than three months old) is sensitive (Chambers et al., 2001). Some recent reports (e.g., Ward et al., 1996) indicate some degree of association between high NO_3^- levels in drinking water and elevated risk of non-Hodgkin's lymphoma, but previous speculation that NO_3^- could cause stomach cancer through ingestion of nitrosamines has been proven unfounded (Addiscott et al., 1991; McKnight et al., 1999).

Contamination of groundwater with NO_3^- from agricultural sources occurs mostly in humid or irrigated areas where sandy soils overlay shallow aquifers. In clay or clay loam soils that drain slowly, denitrification can significantly reduce NO_3^- and prevent its leaching to groundwater (Chambers et al., 2001).

A survey of drinking water from rural Ontario wells in the early 1990s indicated that about 14 percent exceeded the drinking water standard of 10 ppm NO_3^--N (Goss et al., 1998). A similar survey conducted in the early 1950s found nearly an identical percentage exceeding the standard (Johnston, 1955). Nitrogen fertilizer use across the same geographic area increased from about 6,000 tons annually in 1950 to over 250,000 tons in 1985, before declining to about 190,000 tons per year in the 1990s. Over the 40-year period, the increase in fertilizer use did not increase the frequency of contaminated wells. One of the reasons was that, throughout the period, the total supply of N in animal manures amounted to approximately 200,000 tons annually, and thus the relative change in total N input to agricultural soils was not as large as was indicated by the change in fertilizer use.

Large applications of animal waste can increase the soil's total N content as well as the inorganic N content. Smith and Peterson (1982) stated, "Constant animal manure applications that will supply enough N for the present crop will ultimately cause excessive fertilization. Therefore, to meet annual crop requirements with manure applications, decreasing amounts should be applied each year." Nitrate is the main end product of manure decomposition and may accumulate to excessive levels in the soil and pose environmental risks when manure is applied at N rates above crop needs. If soils are not poorly drained or if tile drainage has been installed, the potential for NO_3^- leaching will increase as animal waste applications increase.

High levels of P, unlike NO_3^- do not pose a direct toxicity threat to humans (Moore, 1998).

Pathogens and antibiotic risks

Animal waste can be an effective nutrient source, but the pathogen risk must be seriously considered. The EPA (USEPA, 2000a) cited pathogenic bacteria as a leading cause of water quality impairment in the nation's streams, rivers and estuaries.

Animal wastes contain intestinal bacteria, many of which present substantial human health threats if ingested through drinking water. Complications from ingesting the *E. coli* O157:H7 organism can result in kidney failure and death. Other organisms, present in animal intestines, can commonly be found in low levels in surface waters and groundwater in many parts of North America and are considered a natural occurrence. There is increasing concern that pathogenic *E. coli*, *Salmonella*, *Cryptosporidium*, and *Campylobacter* species can be found in drinking water supplies. The U.S. Centers for Disease Control has estimated there are more than 70,000 cases of infection and more than 60 deaths each year caused by *E. coli* O157:H7 alone. (L.A. Times, June 26, 2001). "Land application of manure is particularly associated with *Salmonella* and *Eschericea coli*, but other organisms such as *Bacillus anthracis*, *Mycobacterium tuberculosis*, *Clostridia* species, and *Leptospira* species can survive and be spread in manure." (Mikkelsen and Gilliam, 1995). Readers may recognize two of these organisms as the cause of anthrax and tuberculosis.

Fecal coliform and streptococci from dairy manure were found to move 35 inches downward through large soil pores (macropores) in the profile of a silt loam soil near Lexington, Kentucky, with the first leaching rain after manure application, regardless of the time of year when applied. The water quality returned to normal levels within 60 days (Coyne et al., 1996; Stoddard et al., 1998). Additional work showed fecal coliform recovery in the leachate under one cubic-foot soil blocks. The concentration ranged from 2 to 680 coliforms/100 milliliters (ml). For comparison, the potable water standard in Kentucky (and other states) is less than 1 fecal coliform/100 ml and the standard for bathing and swimming water is 200 fecal coliforms/100 ml (Coyne et al., 1997; McMurry et al., 1998). Coliform numbers decline with soil depth, but may still be high enough to be a health concern in domestic wells.

There was no indication that inorganic N fertilizer affects pathogen concentrations in runoff water differently than animal manure (poultry litter) in a study of grazed watersheds in Arkansas (Edwards et al., 1997).

Viruses have also been reported in manure. Viruses in poultry litter may present a bigger environmental problem than bacteria (Sims and Wolf, 1994). According to Moore (1998), "Potential contaminants in runoff water from fields fertilized with poultry litter include bacteria, carbon compounds, metals, pesticides and phosphorus." A number of antibiotics, growth hormones, and disinfectants have been used in poultry and livestock production to protect animal health and to improve weight gains, but the consequences and fate have not been thoroughly assessed (Sims and Wolf, 1994).

Air

Odor and ammonia

Ammonia and other odors are released from animal waste at the animal production facilities, in waste storage lagoons, stockpiles, composted wastes, and in excreta by grazing animals (Janzen et al., 1998). Odor-causing gases can arise from the decay of organic substances in the absence of O_2 (e.g., hydrogen sulfide). Besides offensive odors, some of the gases cause health problems for humans and other animals. High NH_3 concentrations in poultry houses, for example, can be detrimental to the birds as well as the farm laborers (Moore et al., 1995a). Once NH_3 is in the air, it plays a role in the formation of fine particulate matter. It quickly reacts with oxidized S and N oxides and forms fine particles of ammonium sulfate [$(NH_4)_2SO_4$] and NH_4NO_3. These aerosols can cause respiratory problems, may lead to adverse health effects, and contribute to smog and acid rain formation. Ammonia sources include animal waste, urea, anhydrous NH_3, and other urea or NH_4^+-containing fertilizers, soils, crop residues, plant canopies (Francis et al., 1997), industry/manufacturers, refrigeration, electric utilities, automobiles, and waste treatment facilities. Agriculture is thought to be the dominant NH_3 source. Total NH_3 emissions by animal agriculture account for about 82 percent of the U.S. total NH_3 emissions and were estimated by the USDA-NRCS (2000) as follows: cattle and calves – 43.4 percent; swine – 10.7 percent; poultry – 26.7 percent; sheep and lambs – 0.7 percent.

Loss of NH_3 (volatilization) from fertilizers can range from three to over 50 percent of the applied N (ASA-CSSA-SSSA, 1982). Global average losses of NH_3 under current management range from 2 to 23 percent, depending on source (**Table 8.11**). For both urea and manure sources, crop producers pay attention to managing volatilization losses since they are economically significant. Urease inhibitors can significantly reduce NH_3 emissions from urea. Their effectiveness depends on management and environmental conditions. Their acceptance by farmers has depended on cost, convenience, and the prevailing market price of N.

The portion of total N as NH_4^+ in animal manures ranges widely from as little as 10 percent in solid manure to over 80 percent in liquid manure in anaerobic lagoons (Lorimer, 2001). Ammonia losses from land-applied animal wastes can occur rapidly under warm temperatures, usually peak at midday, and can range from 2 to 95 percent of the total N applied, depending on environmental conditions and management practices. Much of the loss from land-applied wastes occurs within the first two to three days after application. There have been a number of studies using chemical amendments to reduce the NH_3 loss in animal wastes in confinement houses and from the land-applied waste (Moore et al., 1995a). Ventilation in animal confinement buildings can decrease concentrations of NH_3 in the buildings, but it does not eliminate emissions. McCrory and Hobbs (2001) recently reviewed the potential for additives to reduce NH_3 loss and odor from livestock wastes. They reported that acidifying and adsorbent additives can be beneficial, but microbial-based digestive additives did little to reduce odors or NH_3 emissions.

Nitrous oxide, carbon dioxide, and methane

Increased emissions of greenhouse gases (GHGs) are thought to increase the potential for global warming and climate change and have been the subject of international debate (e.g., the 1997 Kyoto, Japan conferences on GHGs). Agriculture in the U.S. contributes only about 2 percent of the global human-caused GHGs (DOE, 1999), and Canadian agriculture contributes even less (**Table 8.9**). In the U.S., agriculture contributes about 10 percent of the total GHG emissions.

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the three most important greenhouse gases associated with agriculture (Griffith and Bruulsema, 1997). A pound of CH_4emission has the same GHG potential as 21 pounds of CO_2, and a pound of N_2O the same as 310 pounds of CO_2. On a CO_2 equivalent basis, the ranking of the quantity of the U.S. agricultural emissions of these gases is: N_2O, 44 percent; CH_4, 31 percent; and CO_2, 25 percent (DOE, 1999). In Canada, the ranking is $N_2O > CO_2 > CH_4$ (Janzen et al., 1998).

Carbon dioxide emissions in agriculture come from the burning of fossil fuels (e.g., diesel and gasoline) and decomposition of soil organic matter and crop residues. Methane from North American agriculture is predominantly from ruminant animals, livestock manure, wetlands, and rice production. Little CH_4 emission is associated with fertilizer use. Some government reports list fertilizer N as a principal source of N_2O (USEPA, 2001b), while others do not attempt to separate fertilizer N from soil N (DOE, 1999) as a potential source. Most nutrients like P, K, S, and micronutrients do not contribute directly to GHG emissions.

Any N source, organic or inorganic, is ultimately subject to denitrification reactions in soil. All forms of N can, therefore, contribute to N_2O emissions through denitrification (Bruulsema and Johnston, 2000). Additionally, ammoniacal and organic sources contribute to N_2O emission during the process of nitrification. Denitrification is the natural reduction of N oxides, usually NO_3^- and nitrite (NO_2^-), to molecular N (N_2) or N_2O. According to Reddy and Patrick (1984), several factors influence the rate of denitrification in soil, directly or indirectly. They include: absence of O_2, presence of readily available C, temperature, soil moisture, soil pH, presence of denitrifying microbes, soil texture, and the presence of overlying floodwater. As soils become anaerobic (less oxygenated), there is a greater tendency for denitrification to result in evolution of N_2 gas as opposed to N_2O (Firestone, 1982). The complexity of these factors helps explain the wide variation in rates of N_2O evolution and denitrification in agricultural, wetland forest, fresh water, and coastal ecosystems (**Table 8.10**).

Drury et al. (1998) found that denitrification capacity in agricultural soils was correlated with CO_2 production, microbial biomass, and organic C. Long-term fertilization resulted in 35 percent higher denitrification capacity and 65 percent higher CO_2 production than in nonfertilized soils. Once NO_3^--N leaches below the root zone, where temperatures are generally lower and organic C (source of energy) is lower, there is less potential for denitrification. Brye et al. (2001) reported that denitrification below the root zone in agricultural ecosystems was less than about 25 percent of the NO_3^--N leached and depended on both the amount of dissolved organic C and NO_3^--N which were leached. Cole et al. (1997) stated, "The underlying concept in limiting N_2O emissions is that if N inputs are better utilized by the crop, the amount of N needed to meet the growing demand for food will be less, therefore, less N_2O will be produced, and less will leak from the system."

While Eichner (1990) reported that the amount of N_2O emitted from soils was sizeable and possibly related to the fertilizer N source, a more recent review of global data by Bouwman et al. (2001) shows that N_2O losses directly attributable to fertilizer applications are often less than 1 percent of the N applied and do not differ greatly among inorganic sources (**Table 8.11**). However, liquid manure can greatly increase rates of N_2O loss, because it contains the three main ingredients —soluble organic C, N, and water—required for denitrification. For example, in coastal plain soils in Georgia, high rates of liquid manure application produced rates of denitrification 10 to 100 times higher than with inorganic N fertilizer (Lowrance et al., 1998). In fact, the manured soils produced N_2O at a rate greater than the total denitrification rate (N_2 plus N_2O) of the fertilized soils. According to Cole et al. (1997), "Cropping systems, soils management, and unpredictable rainfall inputs influence N_2O emissions more than different mineral N sources."

Agriculture has considerable potential to reduce the potential emissions of GHGs. Cole et al.(1997) reported that N_2O and CH_4 emissions could be reduced by 17 and 25 percent, respectively. High-yield agriculture has the potential to significantly reduce CO_2 emissions by sequestering more C in the standing crop (**Table 8.12**). Carbon isotope studies with corn in Ontario (Gregorich and Drury, 1996), showed that fertilization over a 35-year period increased the amount of corn-derived C in soil, while maintaining native soil C (**Table 8.13**). Fertilization and crop rotation not only increase crop yields, they also increase organic matter levels. Adequate fertilization contributes to the increase of soil organic matter and does not alter the turnover of native soil organic matter.

"Agricultural intensification through the adoption of scientifically proven BMPs can solve, rather than cause, numerous environmental problems, including CO_2 emission. BMPs can improve SOC content, enhance soil quality, restore degraded ecosystems, increase biomass production, improve crop yield, and encourage investment in soil resources for soil restoration" (Lal et al., 1998).

Crop Carbon Contribution to Soil

There is a strong body of evidence which suggests

Table 8.9. Evolution of nitrous oxide and methane from animal waste, fertilizer, and other sources in North America.

	Carbon dioxide, CO_2	Methane, CH_4		Nitrous oxide, N_2O		
Source	M tons* of gas	M tons of gas	M tons of CO_2 equivalent**	M tons of gas	M tons of CO_2 equivalent***	Ref.
Global emissions from natural sources	606,100.00	121-231	2,546-4,860	6.6-13.2	2,050-4,099	1
Global emissions from anthropogenic sources	28,685.06	331-496	6,943-10,414	4.4-8.8	1,366-2,733	
Emissions from all U.S. Sources	5,826.27	34.16	717.40	0.52	160.89	
Emissions from U.S. agriculture	173.01	9.92	208.28	0.19	59.44	
Human-caused GHG emissions, 1997						2
Global	28,652.00	413.25	8,683.76	6.61	2,049.72	
U.S (all sources)	6,061.00	34.60	726.22	1.42	440.80	
U.S. agricultural	179.63	10.47	218.20	1.01	267.79	
Global fertilizer-derived global annual emissions (estimated for 1984)				0.25-7.26	79-2250	3
Canada agriculture emissions estimates (1996)						4
direct from soils	1.98	-0.01	-0.28	0.08	23.91	
from manure		0.23	4,813.54	0.03	8.20	
indirect	17.96			0.04	12.98	
livestock		0.97	20.34			
fuels		0.001	0.023			
Total from Canada agriculture	30.42	1.19	24..90	0.15	45.09	
Emissions from cropland receiving fertilizer N and animal manure, 1995						5
U.S.				1.09	338.20	
Canada				0.23	72.08	
World				10.91	3,382.04	
Emissions from grasslands receiving fertilizer N and animal manure, 1995						5
U.S.				0.11	33.14	
Canada				0.02	7.52	
World				1.14	353.24	
U.S. nitrous oxide emission from agricultural sources (1997)						2
soil nitrogen				0.97	299.30	
animal waste				0.04	12.23	
crop residue burning					0.55	
U.S. nitrous oxide emissions from agricultural soil management (estimated for 1999)						6
Direct				0.77	240.24	
managed soils				0.63	194.61	
commercial fertilizers				0.22	68.10	
livestock manure				0.04	15.21	
sewage sludge				0.002	0.77	
N fixation				0.24	75.16	
crop residue				0.14	31.19	
organic soil (Histosol) cultivation				0.01	4.30	
pasture, range, and padddock livestock				0.15	45.62	
beef cattle				0.13	40.44	
dairy cows				0.004	1.32	
swine					<0.6	
sheep					<0.6	
goats					<0.6	
poultry					<0.6	
horses					2.98	

Continued next page.

Table 8.9. Continued

	Carbon dioxide, CO_2	Methane, CH_4		Nitrous oxide, N_2O		
Source	M tons* of gas	M tons of gas	M tons of CO_2 equivalent**	M tons of gas	M tons of CO_2 equivalent***	Ref.
Indirect				0.29	88.49	
volatilization and atmospheric deposition				0.05	13.89	
commercial fertilizers				0.02	6.06	
livestock manure				0.02	7.60	
sewage sludge					<0.6	
surface leaching and runoff				0.24	74.61	
comercial fertilizers				0.15	45.40	
livestock manure				0.09	28.65	
sewage sludge				0.002	0.66	
U.S. methane emissions from agricultural sources (1997)						2
enteric fermentation		5.91	124.04			
animal waste		3.05	64.10			
rice cultivation		0.47	9.95			
biomass burning		0.04	0.93			
U.S. methane emissions from agriculture (1999)						6
enteric fermentation		6.67	140.17			
manure management		1.81	37.91			
rice cultivation		0.56	11.79			
agriculture residue burning		0.03	0.66			

* M tons = million tons **CH_4 x 21 = CO_2 equivalent ***N_2O x 310 = CO_2 equivalent

Ref. 1. Lal et al. 1998 2. DOE, 1999 3. Eichner, 1990 4. Janzen et al., 1998 5. Bouwman et al., 2001 6. USEPA, 2001 b

that in recent years (from 1980 to 1994), there has been a relatively stable sink for CO_2 in North America (Pacala et al., 2001). The U.S. exports more C in agricultural and wood products than it imports. It also stores between one-third to two-thirds of a billion tons of C annually, evenly divided between forest and non-forest sectors. According to Pacala et al. (2001), “The relative constancy of the U.S. sink is surprising because the early 1990s were, relative to the 1980s, a period of reduced growth in atmospheric CO_2 and a large global terrestrial carbon sink.” These observations imply that the agricultural sector is increasingly storing C in soil organic matter and crop residues. This may be related to increased conservation tillage practices since the 1980s. Data compiled by the Conservation Technology Information Center (CTIC, 2001) indicate more than a 40 percent increase in conservation-tilled acres in the U.S. since 1990. According to the former Assistant Secretary of U.S. Agriculture, C.E. Hess, agriculture has a great opportunity to help mitigate climate change by stashing CO_2 as C in soil and vegetation. Practices requiring good agricultural husbandry, which should be implemented anyway, can be quite effective for sequestering C. For cropland, these practices include building soil organic matter levels, improving soil fertility, and growing more food on less land (Follet, 1993).

Role of Nutrients in Stabilizing Carbon in Soil Organic Matter

A good soil fertility program aids the capture of atmospheric CO_2, improves photosynthesis, enhances O_2 release to the atmosphere, and increases SOC storage. Nitrogen fertilization can enhance SOC accumulation and productivity, based on a USDA-ARS study in the central Great Plains (Halvorson and Reule, 1999). In this study, C sequestration efficiency was improved by N fertilization, SOC increased and total soil N content rose after 11 crops. It showed that managing no-till cropping systems for optimum yield with adequate N fertility had positive environmental impacts.

Long-term studies show that SOC and N levels are highest when conservation tillage (for erosion control) is combined with rotations of high residue crops and an adequate fertility program to increase crop yields (Griffith and Bruulsema, 1997). Fertilizer N increased SOC and N slightly in the long-term (more than 25 years) research in Kansas with sorghum, soybean, and corn rotations (Havlin et al., 1990). Compared with unfertilized soil, Blevins et al. (1983) reported 37 percent and 12 percent more SOC at 0 to 2 in. under no-till and conventional–till corn, respectively, after 10 years of applying modest rates of N fertilizer.

In a 24-year crop rotation study in western Canada, Campbell and Zentner (1993) found that soil organic matter increased under well-fertilized annually cropped rotations during the first 15 years and was maintained in the fallow-containing systems and in the continuous wheat systems receiving inadequate N fertilizer. A balance investigation showed that annually cropped systems that were fertilized based on soil tests were not receiving sufficient fertilizer N to replace that being removed in the grain. Systems which included fall-seeded cereals tended to experience less NO_3^--N leaching loss than the other systems studied. Crop rotation systems of wheat and lentil which included N and P fertilization tended to have higher soil organic matter than continuous wheat receiving N and P

Table 8.10. Nitrous oxide and dinitrogen emissions from natural systems, constructed wetlands, fertilized soils, and manured soils.

Ecosystem	Emission as N_2O mg N_2O	Emission as N_2O mg N	Emission as N_2 mg N	Comments	Ref.
	per m^2/day				
Hardwood wetland					
Cache River (Arkansas)	12.0 - 18.0	7.6 - 11.5		Carbon limited system	1
Fresh waters					
Delaware River			28 - 58		2
Lake Okechobee sediment (Florida)			0.34 - 4.20		2
Lac Des Allemands (Louisiana)			21.5 - 22.2		3
Brackish waters					
Little Lake (Barataria Basin in Louisiana)			24 - 25.8		3
a variety of salt marshes			1.9 - 13.7		4
Four League Bay (Atchafalaya Basin in Louisiana)					
bay bottom			5.7		5
marshland			4.7		
Louisiana Gulf Coast ecosystem					6
fresh water	0.24	0.15			
brackish water	0.21	0.13			
salt water	0.13	0.08			
Constructed wetland from agriculture					
reed canarygrass, barnyardgrass, smartweed, yellow nutsedge (Illinois)			50.4 - 283.20	Low in winter, high in summer NO_3^- load exceeded denitrification capacity (60% of NO_3^- in water column was recovered as N_2)	7
Agriculture					
soils receiving fertilizers (96-day study) (Iowa)				Loss as portion of applied N, after adjusting for the control	8
control	0.54	0.34			
calcium nitrate, 111 lb N/A	0.63	0.4		0.04%	
calcium nitrate, 223 lb N/A	0.59	0.38		0.01%	
urea, 111 lb N/A	0.82	0.52		0.14%	
urea, 223 lb N/A	1.01	0.64		0.12%	
ammonium sulfate, 111 lb N/A	0.91	0.58		0.18%	
ammonium sulfate, 223 lb N/A	0.98	0.62		0.11%	
soils receiving dairy manure (year round, Georgia)				Loss as portion of applied N, after adjustment for pre-treatment levels	9
pretreatment	2.6 - 12.9	1.7 - 8.2			
219 lb N/A/yr (adjusted for pretreatment)	16	14.3		15%	
380 lb N/A/yr (adjusted for pretreatment)	13	13.4		7%	
573 lb N/A/yr (adjusted for pretreatment)	90	65.5		33%	
715 lb N/A/yr (adjusted for pretreatment)	43	29.3		13%	
(Two-year average data for treatments - Emissions at pretreatment year were subtracted from subsequent 2-year average, to determine values shown)					
soils receiving N fertilizer (129 day study, Tennessee)				Loss as % of applied N	10
control (no N fertilizer)	1.8	1.1			
anhydrous ammonia, injected, 150 lb N/A	11.8	7.5		7.3	
urea solution (18%), injected, 150 lb N/A	9.5	6.1		3.8	
soils receiving poultry manure, simulated rainfall (Kentucky)					11
tilled soil					
unamended control	17- 212	10.8 - 135			
poultry manure at 400 lb N/A	205 - 502	131 - 320			
grass filter strip					
receiving runoff	2.7 - 51	1.7 - 32.5			
control	0.4 - 16	0.3 - 10.2			

Note: Metric units are commonly used to express emissions.

Ref. [1]DeLaune et al., 1996 [2] cited by DeLaune et al., 1996 [3] DeLaune and Lindau, 1989 [4] cited by Smith et al., 1985 [5] Smith et al., 1985 [6] DeLaune et al., 1990 [7] Xue et al., 1999 [8] Breitenbeck et al., 1980 [9] Lowrance et al., 1998 [10] Thornton et al., 1996 [11] Coyne et al., 1995

Table 8.11. Global estimate of N_2O and NH_3 emissions from different fertilizers, expressed as a percentage of the N applied as fertilizer.

Fertilizer	N_2O loss, %[1]	NH_3 loss, %[1]
Anhydrous ammonia	0.8	2
Ammonium nitrate	0.9	6
Ammonium phosphates	0.8	11
Ammonium sulfate	1	16
Calcium ammonium nitrate	0.6	3
Urea	1.1	21
Nitrogen solutions	0.9	5
Other straight nitrogen	1	15
Compound NP-N	0.8	11
Compound NK-N	0.8	2
Compound NPK-N	0.7	9
Total mineral fertilizers	1	14
Organic fertilizers	0.6	
Animal manure		23
Total mineral and organic fertilizers	0.8	

Source: Bouwman et al., 2001

[1] Calculated as the total emission minus that of unfertilized fields, expressed as a percentage of the N input

Table 8.12. Three-year average corn yields in the U.S. for selected years, and the effect on total C assimilated and the amount remaining in crop residue and roots.

Three-year periods	Average yields, bu/A	Total C assimilated	Carbon remaining after harvest
		------- tons/A -------	
1984-1986	114.6	3.1	1.8
1990-1992	119.5	3.2	1.9
1994-1996	126.4	3.4	2.1
1997-2000	135.1	3.6	2.2

Source: Cole et al., 1997

Table 8.13. Total organic C, corn-derived C, and native C found in fertilized and unfertilized corn plots, using ^{13}C isotope analyses.

Fertilization $N\text{-}P_2O_5\text{-}K_2O$, lb/A	Total C	Corn-derived C	Native C
		---------- tons/A ----------	
0-0-0	36	5	31
115-70-30	40	9	31

Source: Gregorich and Drury, 1996

fertilizer and experienced less leaching of NO_3^--N below the root zone than under continuous wheat.

Mitchell et al. (1991) concluded that "Long-term studies have shown that crop rotations and attention to recognized and established soil fertility practices, which may or may not include legumes and manuring, are essential to maintaining high, sustained production." Crop rotation could not restore nutrients, other than some N, back into the soil. This emphasizes the need for good soil fertility management with P, K, S, and other nutrients, in consideration of crop nutrient removal, for sustained soil productivity.

While N fertilizer is one of the direct contributors to N_2O emission, it also plays a positive role in the stabilization of soil C and can help to mitigate CO_2 emissions. There are extensive reports from long-term trials indicating that wherever N enhances the yields of crops, the accumulation of C in the soil is also enhanced. In addition, there is evidence that N itself is chemically involved in stabilizing soil C. Data from a long-term experiment in Sweden provide the best demonstration of N stabilizing C in soil (**Figure 8.6**). In this experiment, the addition of N...71 lb/A as calcium nitrate [$Ca(NO_3)_2$]...promoted the growth of the cereal crop. The increased root growth provided additional C to the soil, but the net storage in the long term was enhanced even more. Addition of N enhanced the net C stored in response to additions of straw and sawdust as well. It is thought that N compounds react with lignin in the process of humus formation, as a mechanism of C stabilization (Paustian et al., 1992). In addition, most soil organic matter stabilizes with a C:N ratio of approximately 10:1, indicating again that if soil C storage is to increase, N is needed.

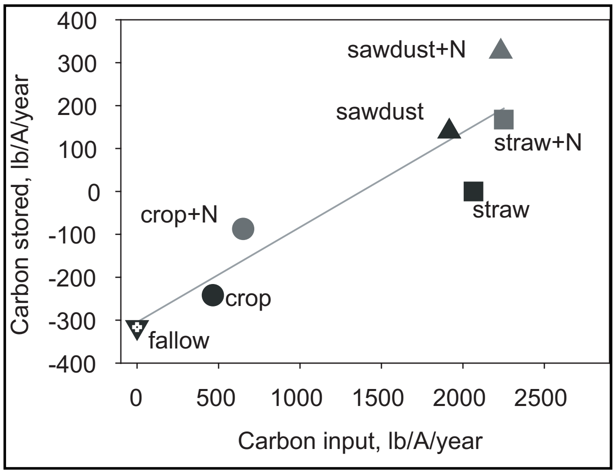

Figure 8.6. Annual change in soil C storage over 30 years in response to additions of N, presence of a crop, added straw, and added sawdust. In all plots other than fallow, a cereal crop was grown each year and all above-ground crop residues were removed (adapted from Paustian et al., 1992).

Summary

Fertilizers and animal manures are essential nutrient sources in meeting the world's food and fiber demands. Fertilizers are more predictable and therefore, more manageable nutrient sources. Improperly managed, each can potentially pollute soil, water, and air. The growing challenge for agriculture is to find ways to increase crop yields and improve nutrient use efficiency while stabilizing nutrients, (not removed in harvested crops and forages) in crop residues and in the soil. Nutrient management must be site-specific and cost-effective to protect the viability of North American agriculture.

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Chapter Nine

Nutrients and Product Quality

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Synopsis: Both organic and inorganic nutrient sources influence proteins, minerals, and vitamins in crop products, and affect their bioavailability. They also impact pests that reduce quality. With recent science on nutraceuticals, today's crop producers are beginning to be more effective in meeting human nutritional needs for promoting health and preventing disease.

Nutrients applied in agriculture influence the quality of crop products in both direct and indirect ways. Direct effects include nutrient influence on the composition of crop products: dry matter, carbohydrates, proteins, minerals, and vitamin content – which affect nutritive value and shelf life. Recent science on nutraceuticals is opening up a new opportunity to manage mineral nutrient inputs to optimize production of functional foods that promote health and prevent disease. Indirectly, nutrients influence insects and diseases that potentially reduce crop quality. Food safety issues such as nitrate (NO_3^-) and pathogens also relate to nutrients. And finally, consumers perceive a holistic effect depending on systems of production labeled organic, bio-dynamic, or chemical-independent. The aim of this chapter is to describe the effects of specific nutrients, nutrient sources, and nutrient use within production systems on these aspects of crop end-product quality.

Composition of Food and Feed

Source – mineral versus organic

The traditional belief that organic manure promotes **quality** while mineral fertilizers promote **quantity** was shown to be over simplistic by Werner Schuphan (1974). In experiments conducted in Germany from 1960 to 1972, soils fertilized only with organic substances produced lower yields, higher levels of ascorbic acid, and a higher proportion of the amino acid methionine in spinach, savoy cabbage, potatoes, and carrots, and lower levels of NO_3^- in spinach, compared to soils fertilized with inorganic nitrogen (N), phosphorus (P), and potassium (K). Sensory quality did not differ between treatments. However, carotene levels in the spinach and carrots were higher where inorganic nutrients were added.

In fact, older experiments indicated that nutritional value to infants was higher for vegetables grown with mineral NPK sources. One reported: "Vegetables produced with farmyard manure together with mineral NPK fertilizer had a higher content of carotene (carrots), iron (carrots, parsnips, spinach), and copper (carrots, parsnips, spinach, kohlrabi) compared with vegetables produced with farmyard manure alone" (Woese et al., 1997). The two treatments did not differ in nutritional value to adults. Schuphan (1972) concluded from these experiments that: 1) "The biological value of our fodder and food plants is not impaired when the dressings of organic and inorganic manures are accurately adjusted to the physiological requirement of the plant" and 2) "In the field of plant nutrition, the cry of 'only natural' has no justification on a scientific basis."

One form of plant culture that could be considered extremely inorganic is the nutrient film technique (NFT) often used in greenhouse production of tomatoes. One experiment in Belgium found that NFT-grown tomatoes had 20 percent higher firmness, 9 percent more vitamin C (ascorbic acid), 8 percent higher sugar, and 45 percent lower NO_3^- than those grown in soil with conventional inorganic fertilizers (Benoit and Ceustermans, 1987). Unfortunately, these researchers supplied no information on the nature of the soil used or on the exact nutrient composition of either treatment. It is likely that these differences arise from differences in the balance of inorganic nutrients supplied. Nevertheless, the quality obtainable in systems with absolutely no organic matter is consistent with the known principle that plants take up nutrients in the inorganic form.

High quality in NFT culture does not imply that organic matter has no value. It requires great technical sophistication to maintain nutrient balance in such systems. It is likely that, in field culture, organic matter contributes to maintaining nutrient balance.

In India, an optimum combination of 180-90-90 lb/A of mineral N-P_2O_5-K_2O fertilizer produced tomatoes with 51 percent higher yield, 44 percent higher soluble solids, 95 percent higher protein, 12 percent higher sugar, 81 percent higher vitamin C, and 94 percent higher lycopene than a control, even though all plots received 9 tons/A of farmyard manure (Bagal et al., 1989).

Nitrogen and protein

Protein in wheat can be manipulated by rate and timing of applied N. However, late-applied N may raise grain N without increasing the proteins desirable for wheat milling and baking quality. Up to the optimum rate for yield, however, N applications generally improve both the protein and bread-making quality of bread wheats.

Regarding wheat produced using organic fertilizer sources, Woese et al. (1997) stated, "Given its higher protein content and superior protein quality, conventionally grown or minerally fertilized wheat corresponds better to the common baking requirements."

In forage grasses, high yields of dry matter are usually negatively related to protein content. However, N fertilization boosts yields without decreasing protein content (Bélanger et al., 2001), enhancing nutritive value.

Phosphorus, phytate, and trace mineral bioavailability

Phytate, or phytic acid, an organic form of P found in seeds of all higher plants, is important nutritionally because of its interactions with trace elements. Deficiencies of trace minerals [iron (Fe), zinc (Zn), iodine (I), and selenium (Se)] and vitamin A currently affect more than two billion people worldwide (Welch and Graham, 1999).

Phytic acid comprises about 70 percent of total soybean seed P. When soybeans grow in soil richer in P, seed P increases primarily as an accumulation of phytate P (Raboy and Dickinson, 1993). For pigs, bioavailability of grain P is increased by as much as five-fold in genotypes of corn that contain phytate levels of 0.1 percent rather than 0.2 percent (Spencer et al., 2000). Phytic acid generally reduces bioavailability of minerals such as calcium (Ca), Zn and Fe, but is also considered a major storage form for those elements in seeds (Lott et al., 2000). Nevertheless, low-phytate mutants of barley had no reduction in seed K, magnesium (Mg), Ca or Zn, suggesting that impaired phytate accumulation did not affect mineral storage capacity (Hatzack et al., 2000).

The total quantity of phytic acid harvested in the world's grain crops and fruits amounts to 38 million tons per year (Lott et al., 2000). This phytic acid contains about 25 million tons of P_2O_5 (roughly 65 percent of world fertilizer consumption) and 11 to 16 million tons of K_2O. While phytate is vital for grain development and seedling growth and may have a positive nutritional role as an anti-oxidant and anti-cancer agent, it also functions as an anti-nutrient and contributes to the inefficiency of P use in agricultural systems. One recent study reported that low phytate mutants, now available for key staple food crops, such as corn and barley, offer potential benefits related to the sustainability of lands used to grow crops, the mineral nutrition of humans and animals, and reduction in the pollution of waterways (Lott et al., 2000).

Within seeds of all plants, phytate is the storage form of not only P, Ca, and Mg, but also for important trace elements such as Fe and Zn. In fact, phytate can enhance Zn uptake in plants by providing a sink for it. This may explain why P fertilization often increases the concentrations of trace elements [Zn, Fe, copper (Cu), manganese (Mn)] in whole grains (Rengel et al., 1999). Phytic acid forms insoluble precipitates with many trace metal ions (for example, Zn^{2+} and Fe^{3+}) at the basic pH in the small intestine. While phytic acid inhibits Fe and Zn bioavailability to humans and animals, the naturally occurring form, phytin, may actually increase Fe bioavailability under some circumstances (Welch, 1997). Thus, the low-phytate strains of wheat, rice, and corn under development may have substantially altered food quality from a trace element point of view. The seedling vigor of low-phytate genotypes of corn in low-P soils can be markedly reduced, even after addition of fertilizer P (R.M. Welch, pers. comm.).

NPK and sugar or vitamins

In research conducted in Quebec, sugar in sweet corn was dramatically increased by any combination of N, P and K, relative to a control with zero NPK. Potassium in particular increased sugar content as measured by Brix by 36 percent (Chamberland, 1978).

Nitrogen generally improves carotene content of leaves, but excessive N can reduce vitamin C by as much as 30 percent. In carrots, increasing levels of N improved carotene content by 8 to 12 percent (Salunkhe and Desai, 1988).

Increasing levels of K boosted Vitamin C levels in spinach, lettuce, beets, kale, endive, and brussel sprouts by 8 to 21 percent (Mengel, 1979). Through its role in maintaining turgor and by improving carbohydrate content, K helps delay the wilting that can reduce both carotene and vitamin C in stored vegetables.

Phytochemicals, Functional Foods and Nutraceuticals

Functional foods are defined as foods that contain bio-active ingredients thought to enhance health and fitness. They are also called designer foods or pharma-foods. The active ingredients are **phytochemicals**, such as lycopene in tomatoes. These phytochemicals are not among the traditional nutrients (carbohydrates, proteins, fats, minerals, and vitamins) and are often called **nutraceuticals**, although that term is increasingly being used specifically for extracted concentrates (Zeisel, 1999). The therapeutic value of the active ingredients may differ depending on whether they are taken as supplement or consumed in whole food.

Functional foods are associated with the prevention and treatment of at least four of the leading causes of death: cancer, diabetes, hypertension, and heart disease (Hasler, 1998). In addition, some help with other medical ailments including neural tube defects, osteoporosis, abnormal bowel function, and arthritis.

Many types of plants, including field crops such as grains and soybeans, horticultural crops like broccoli and tomatoes, and specialty crops like ginseng and echinacea, contain nutraceutical ingredients (see **Table 9.1** for more examples). Many of these are commonly cultivated species and contain widely varying amounts of the active phytochemicals. The modes of action of these health-promoting compounds are many and diverse, as listed in **Table 9.2**. While the compounds may be grouped into four classes, their total number exceeds 5,000 (**Table 9.3**). The science relating each compound to its specific effects on human health is still developing.

Role of NPK in phytochemical synthesis

Few of the many phytochemicals with nutraceutical properties contain N, P, or K in their chemical structure. However, most are products of

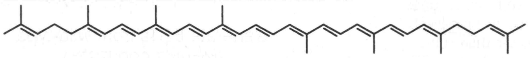
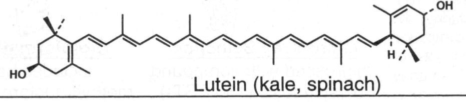
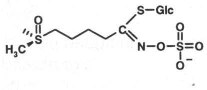
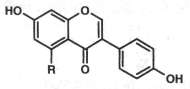
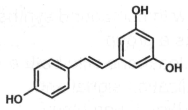
Table 9.1. Examples of functional foods and their active phytochemical ingredients.

Functional food	Nutraceutical ingredients
Blueberries	anthocyanins, ellagic acid, flavonol
Broccoli, cabbage, cauliflower	sulphoraphane, indole, carotenoids
Cranberries	quinic acid
Echinacea	echinacosides
Flax	lignans
Garlic	allicin, flavonoids, organosulfur compounds
Ginseng	more than 30 ginsenosides
Oats	beta-glucan
Red grapes, red wine	resveratrol, quercetin, anthocyanidins
Soybean	isoflavones, lignans, saponins
Tomato	lycopene, carotenoids
Whole grains (oats, wheat, barley)	saponins, terpenoids, phytic acid

Table 9.2. Modes of action of functional food ingredients.

Mode of action	Examples
Antibacterial substances	quinic acid in cranberry juice
Anticarcinogens	indoles, phenols, flavones, isoflavones, allyl sulfur compounds, sulphoraphanes
Antihypertensives	green and black tea polyphenols
Antioxidants	vitamins A, C, E; glutathione, polyphenols, flavonoids, isoflavones, lycopene
Gastrointestinal function	beta-glucans in oats
Hypocholesterol agents	green and black tea polyphenols, soy foods, phytosterols
Immunomodulators	vitamin E
Phytoestrogens	isoflavones, extracts of rosemary and garlic
Substances that improve the bioavailability of minerals	fructooligosaccharides

Table 9.3. Selected phytochemical classes, health-promoting properties, example active compounds, and good plant sources.

Phytochemical Class (no. of compounds)	Diseases ameliorated or prevented	Example active compound and plant source
Carotenoids (>700)	Prostate, esophageal and other cancers, cardiovascular disease, macular degeneration (*14*)	 Lycopene (tomatoes)  Lutein (kale, spinach)
Glucosinolates (>100)	Cancers (*12*)	 Glucoraphanin (broccoli and broccoli sprouts)
Phytoestrogens (>200)	Cardiovascular disease, osteoporosis, breast, prostate and colon cancers (*13*)	 Genistein (R=OH); Daidzein (R=H) (soybeans, tofu, soy products)
Phenolics (>4,000)	Cardiovascular disease, cancers (*42*)	 Resveratrol (red wine, red grapes)

Adapted with permission from: DellaPenna, D. 1999. Nutritional genomics: Manipulating plant micronutrients to improve human health. Science 285: 375-379. Copyright 1999. American Association for the Advancement of Science.

secondary anabolic metabolism, demand photosynthetic energy for their production, and thus depend on the absence of nutrient limitations to photosynthesis. Nevertheless, some of these compounds are produced in reaction to certain environmental stresses and disease pressure. It cannot be concluded that all nutraceutical components improve with improved plant nutrition, but the individual effects of specific nutrients must be clarified by science.

The pentose phosphate pathway, a set of biochemical reactions unique to plants, is directly involved in the synthesis of many phytochemicals, including anthocyanins and flavonoids. Phosphate is an important energy carrier in this biochemical pathway.

Nitrogen is involved in the metabolism and structure of alkaloids. Tobacco nicotine levels have long been known to be influenced by levels of N fertilization.

Potassium is essential to the function of many plant enzymes, mainly conferring charge balance to the negative charges that comprise part of their protein structure. The concentration of K in the cytoplasm influences the conformation or shape of the protein molecules that comprise the functioning enzyme.

Crop nutrient impacts on specific phytochemicals

Potassium and soybean isoflavones

The soybean is not only a source of high quality protein, it is also thought to play preventive and therapeutic roles in cancer, cardiovascular disease, osteoporosis, and the reduction of menopausal symptoms (Hasler, 1998). Several classes of anticarcinogens have been identified in soybeans. Of these, isoflavones (genistein and daidzein) are particularly noteworthy because soybeans are the only significant dietary source of these compounds. Isoflavones have also been credited with the cholesterol-lowering effect of soy and the reduction in the frequency and intensity of hot flashes in menopausal women (Riaz, 1999).

Recent research in Ontario, Canada, shows that K fertilizer can influence soybean isoflavone content (**Table 9.4**). The increase in isoflavone levels caused by K averaged 13 percent over two sites and three years. The two sites differed in soil K levels, one very low and the other high, but both were similar in that yields responded to K as well. In sites where soybean yield did not respond to K, isoflavone levels did not differ. Thus, it can be concluded that K deficiency reduces isoflavone levels in soybeans.

Table 9.4. Concentration of isoflavones in soybean seeds in response to applied K fertilizer (two sites, three years, 1998-2000).

K_2O application	Genistein	Daidzein	Glycitein	Total[1]
Spring banded	938	967	146	2,051
None	831	854	130	1,815
Increase due to K, %	13	13	12	13

[1] Total isoflavone concentration expressed as aglycone; sum of three components; parts per million (ppm).

Soybeans grown at various levels of fertility in several field trials in 1998 and 1999 were analyzed for K and total isoflavone content. These analyses revealed a positive relationship between K and isoflavone concentrations in the harvested soybeans (**Figure 9.1**). There was also a positive association across these sites between yield and isoflavone concentration (**Figure 9.2**).

The observation of a positive effect of a plant mineral nutrient on a secondary metabolite contradicts the general expectation on ecological principles of a higher level of secondary metabolites in nutrient-deficient plants. Brandt and Molgaard (2001) stated that organically produced foods were likely to contain higher levels of secondary metabolites because of lower nutrient inputs and greater reliance on varieties resistant to insects and diseases. The observed positive association between yield and isoflavone level suggests that high yield production is compatible with quality from a functional food perspective and that it should not be generalized that high nutrient inputs reduce the levels of phytochemicals that may contribute to nutritive value.

Potassium and lycopene in tomato

Lycopene is considered a nutraceutical because it is not essential for humans and animals. Recent research has shown it to be beneficial even though it is not converted to vitamin A in the body. Beta-carotene, on the other hand, is an excellent source of the essential vitamin A and is sometimes called pro-vitamin A. In tomatoes grown in sand culture, most of the carotenoids increased as K content of the nutrient solution increased from 0 to 260 ppm (Trudel and Ozbun, 1971). Lycopene in particular was increased by 73 percent over this range, while in contrast beta-carotene decreased by 22 percent. These results indicate that specific enzymes involved in metabolic transformations of carotenoids depend on K.

N and P effects on fennel

Soil and foliar applications of fertilizers containing N and P influenced the relative amounts of different essential oils in fennel (a mild spice crop) grown in India (Khan et al., 1999). These authors concluded that the functional properties of the crop could be manipulated by management of mineral nutrient inputs.

Diseases and Insects

Mineral sources

Plant diseases are influenced by mineral nutrition. No diseases are eradicated, but many can be suppressed by management of the balance of nutrients applied. In addition, the microflora and associated organic materials in manures and biosolids may influence the soil

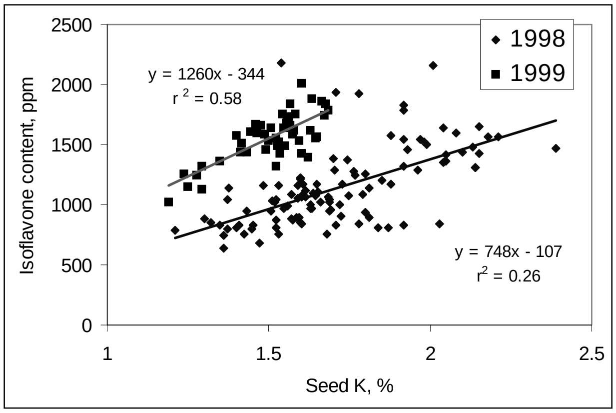


Figure 9.1. Isoflavone levels in soybean seeds at harvest in relation to seed K content, from various locations in Ontario, Canada, 1998-1999.

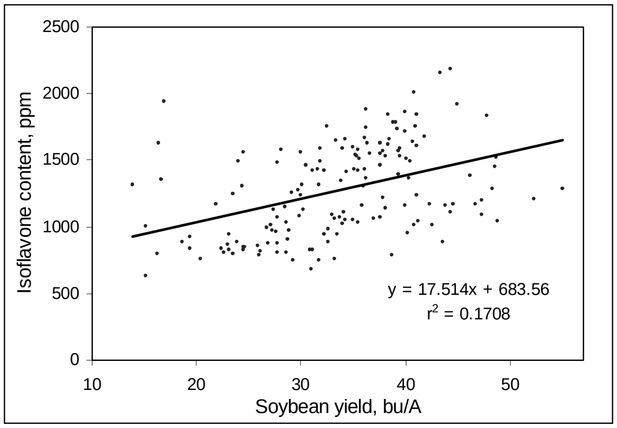


Figure 9.2 . Isoflavone levels in soybean seeds at harvest in relation to yield, from various locations in Ontario, Canada, 1998-1999.

microflora, particularly through effects on soilborne pathogens that include bacteria, fungi and nematodes. These diseases influence the quality of crop end products. For example, diseases in soybeans often produce discolored and shrunken seeds that reduce grade. Mold diseases in corn may produce toxic compounds such as aflatoxin, while in wheat, barley or corn, Fusarium infection may produce deoxynivalenol (DON) or vomitoxin.

Effects of various nutrients from different sources are shown in **Table 9.5**. This list is selected to show the most common field crops and effects that are most consistent. There are many reports on plant disease effects with contradictory results. For example, Ca in gypsum can increase, decrease, or have no effect on bacterial soft rot in potatoes (Bartz et al., 1992). Some results may be variety specific. Optimum rates of N and P reduced *Verticillium* wilt in Russett Burbank, but not in Yukon Gold potatoes (Davis et al., 1994; Platt and Arsenault, 2001).

Foliar application of KCl reduces symptoms of powdery mildew on wheat by an osmotic effect on spore germination by increasing the leaf water potential (Kettlewell et al., 2000).

Chloride (Cl^-) is known to affect many plant diseases, but the mechanisms are uncertain. It may affect soil pathogens through suppression of nitrification and enhancement of ammonia (NH_3) nutrition (mainly in slightly acid soils), through increasing the solubility of Mn and other micronutrients, through changes in osmotic potential, or through influences on root exudates.

Potash fertilizer reduces black spot (enzymatic discoloration) formation in potatoes. Large doses (560 lb K_2O/A) of Cl^- and sulfate (SO_4^{2-}) forms of K reduced enzymatic discoloration and phenolic content by 13 and 8 percent, respectively (Mondy and Munshi, 1993). Both treatments also increased the lipid and water contents of the potatoes.

Stalk rot of corn is suppressed by Cl^- (Heckman, 1995). When K was supplied to corn grown in a maximum yield environment at rates of 400 lb/A, the

Table 9.5. **List of selected diseases of major field crops reported to have been impacted by nutrients.**

Crop plant species	Disease or pathogen	Nutrient and source	Effect on disease	Reference
Barley	Common root rot	Inorganic P	Infection reduced from 42% to 21%; yield improved by 7%	PPI, 1999
Cereals	Rust (*Puccinia*)	Inorganic K	Decreased	Huber and Arny, 1985
Cereals	Powdery mildew (*Erysiphe graminis*)	Inorganic K	Decreased	Huber and Arny, 1985
Corn	Stalk rot (*Fusarium, Gibberella, Diplodia*)	Inorganic K	Lodging reduced from 42% to 32%	PPI, 1998 Huber and Arny, 1985
Corn	Stewart's wilt (*Erwinia*)	Inorganic K	Decreased	Huber and Arny, 1985
Cotton	Leaf spot (*Alternaria*)	Inorganic K	Disease rating reduced from 76% to 46%	PPI, 1998
Cotton	Angular leaf spot (*Xanthamonas*)	Inorganic K	Decreased	Huber and Arny, 1985
Cotton	Wilt (*Verticillium, Fusarium*)	Inorganic K	Decreased; occasionally no effect	Huber and Arny, 1985
Cotton	Leaf Blight (*Cercospora, Alternaria*)	Inorganic K	Decreased	Huber and Arny, 1985
Potato	Late Blight (*Phytophthora infestans*)	Inorganic K	Decreased	Huber and Arny, 1985
Potato	Scab (*Streptomyces scabies*)	Inorganic K	Increased	Huber and Arny, 1985
Potato	Stem end rot (*Fusarium*)	Inorganic K	Decreased	Huber and Arny, 1985
Potato	*Rhizoctonia* stem canker	Excessive inorganic N	Increased	Crozier et al., 2000
Potato	Verticillium wilt	Inorganic N and P	Split application of N and highest rate of P minimized infection and produced highest yields	Davis et al., 1994
Soybean	Pod and stem blight	Inorganic P and K	Infection reduced from 12% to 1% by K; from 12% to 8% by P	PPI, 1999
Soybean	Purple seed stain (*Cercospora*)	Inorganic P and K	Incidence reduced from 14% to 4%	PPI, 1999 Huber and Arny, 1985
Soybean	Pod rot (*Diaporthe sojae*)	Inorganic K	Decreased	Huber and Arny, 1985
Wheat	Leaf rust	Inorganic P and K	Disease reduced 27%	PPI, 1999
Wheat	Leaf rust	Inorganic Cl	Rust reduced from 68% to 29%	PPI, 1998
Wheat	Leaf rust (*Puccinia*)	Inorganic P and KCl	Both suppressed severity and improved yields	Sweeney et al., 2000

source that produced the highest yields and lowest stalk rot was muriate of potash (KCl), compared to sulfate of potash (K_2SO_4) or potassium hydroxide (KOH). Among several combinations varying the proportion of SO_4^{2-} and Cl^-, 100 percent Cl^- produced the best result.

In soybeans grown under controlled conditions, sudden death syndrome severity decreased by 36 percent when K was applied in the Cl^- form, but increased by about 45 percent when applied as a SO_4^{2-} or NO_3^- (Sanogo and Yang, 2001).

Leaf rust in hard red winter wheat in Kansas was influenced by inorganic P and K fertilizers (Sweeney et al., 2000). Phosphorus fertilizers moderately suppressed leaf rust symptoms and boosted the yield of rust-resistant cultivars (by 59 percent) more than that of susceptible cultivars (by 43 percent). On the other hand, KCl reduced leaf rust symptoms and boosted the yield of susceptible cultivars (by 12 percent) more than that of resistant cultivars (by 4 percent). This response may have been partially related to the Cl in the fertilizer.

Contradictory views are also predominant in literature on the relation between plant nutrition and disease. For example: "For crops with large losses due to diseases and insects, such as many fruit crops, the products must be grown…under restricted nutrient conditions" (Brandt and Molgaard, 2001). This statement contradicts the many observations cited in **Table 9.5** of positive effects of increased levels of several nutrients. Huber and Arny (1985) pointed out that withholding nutrients to prevent disease can reduce yield to the same extent that severe infection would and that, "There is no reason to starve the plant into an unproductive state to escape disease."

Organic sources

Liquid swine manures and fresh poultry manures have been tested for their efficacy in reducing soil pathogens that cause scab and Verticillium wilt in potatoes. While there are frequent occasions when these materials reduce these soil-borne pathogens, consistent control across different soil types and using different sources of manure is difficult to obtain (Lazarovits and Conn, 1997). A number of plant diseases have been shown to be reduced following manure application, including *Fusarium* diseases of tomato and lettuce, *Rhizoctonia solani* diseases of radish and rice, and *Sclerotinia sclerotiorum* disease of lettuce.

Management of nutrients to enhance resistance to disease and insects should recognize that:

- No nutrient controls all diseases.
- Nutrient balance is as important as any single nutrient's level.
- Nutrients help more by stimulating growth than by increasing resistance.
- Damage or predisposition imposed by early deficiencies and imbalances may not be offset by later applications.
- Local environmental conditions may enhance or nullify the effect of a particular nutrient.

Organic Production Systems

Comparing systems

Comparison of food produced from systems labeled organic and conventional is quite different from comparison of nutrients supplied by organic and inorganic sources. Producers in conventional production systems commonly apply a combination of organic and inorganic nutrient sources and so do organic producers. The differences have more to do with solubility and manufacture.

Organic (also known as biological, bio-dynamic, biological-dynamic, or ecological) production systems are characterized by standards that minimize or eliminate use of synthetic or manufactured inputs and encouraging maximum use of natural resources. Organic food producers rarely use readily soluble mineral nutrients, and they also exclude some organic sources, such as sewage sludge and composts derived from wastes. Thus, they must rely to a greater extent on green manures, crop rotation, and animal manures. They may also include mineral nutrients in their naturally occurring state; for example, rock phosphate as a source of P, and, in restricted situations, K_2SO_4 or sylvinite as a source of K. Nutrient input levels in organic farming systems also tend to be lower than in conventional systems because the philosophy is aimed at growing crops under more natural conditions, and deficiencies of N, P, and K are natural conditions.

Organic systems may also vary more widely in nutrient availability because of reliance on indigenous soil fertility which exhibits strong spatial variability (Brandt and Molgaard, 2001). Farming systems using optimum levels of soluble nutrients, particularly those with the best and most site-specific management, achieve greater uniformity in nutrient levels across a field. On the regional scale, nutrient sources acceptable for organic farming will be plentiful and applied in great quantities in some areas (for example, nearby organic livestock farms), whereas in others, such nutrients are available only at great cost. In contrast, the cost of using commercial fertilizer does not vary greatly by region.

It can be difficult to do objective comparisons of whole systems. The skill sets required of producers in the two types of systems differ strongly, and few research scientists have extensive knowledge of both. Therefore, bias is a factor that cannot be entirely removed from published comparisons of systems.

Vitamins, protein and nitrate

System comparisons frequently produce conflicting results, and a wide range of differences has been reported. For example, Worthington (2001) reported that differences in vitamin C, expressing the level observed in organic systems as a percentage of that in conventional systems, ranged from -100 percent to +507 percent, across 20 published studies reporting 132 comparisons. Similarly, differences in NO_3^- content ranged from –97 percent to +819 percent.

Systems differ in many production factors simultaneously, and thus it is difficult to find the causes for observed differences in food quality. For example, in a survey study comparing carrots produced by organic and conventional farmers in France, Leclerc et al. (1991) found 12 percent higher beta-carotene in organically grown carrots. However, averaged over 12 paired comparisons conducted over two years, the conventional growers supplied 234 lb/A of N compared to 141 lb/A of N for the organic growers. Therefore, it is uncertain whether the difference in beta-carotene was due to the organic form of the nutrients, N deficiency on the organic farms, or excessive N use among the conventional growers.

Other studies have found that organic fertilization produced the same, lower, or higher levels of beta-carotene in carrots as compared to mineral fertilization. For example, Torjusen et al. (1997) in Norway found that beta-carotene levels in carrots from conventional production farms were 28 percent higher than from organic farms. In carrots grown organically, increasing levels of fertilization with green manure increased beta-carotene by about 8 percent, while decreasing ascorbic acid by about the same percentage (Brandt and Molgaard, 2001). These observations correspond with the known effects of N.

Cereals contain less protein when produced organically (Woese et al., 1997). In the case of wheat, the lower protein also results in a less desirable baking quality. Among 22 studies reviewed, organically grown potatoes were sometimes lower in NO_3^- and protein and higher in vitamin C than those grown with mineral fertilization, but the opposite occurred in some instances as well.

Comparisons of potatoes produced organically and conventionally in Germany showed higher vitamin C in the organic systems (Fischer and Richter, 1986). However, conventionally grown potatoes yielded 53 percent higher. They also received 62 percent more N, which likely was the major cause of the difference in vitamin C.

Vitamins A, B_1, and B_2 did not differ between vegetables from organic and conventional systems nor between mineral and organic fertilization methods in 27 comparative studies reviewed by Woese, et al., (1997). However, in roughly half of those studies, a trend toward slightly higher vitamin C was observed in vegetables that were organically fertilized or cultivated, while the other half indicated no difference. Vitamin C differed most strongly in leaf vegetables like savoy cabbage, spinach, and chard.

Nutritive value

In six studies involving feed selection, hens, mice, and rats preferred organically produced feed to that produced conventionally, while rabbits showed no preference (Woese et al., 1997). The reason for the preference is unknown, but may have been due to taste or to compensatory consumption to make up for the lower protein content. In one of the studies, however, rats preferred organically produced feed, but could not distinguish between feed from conventional and biological-dynamic (a more intense form of organic) systems. Fertility and growth of the animals were not consistently better with organically produced feeds.

Some claim that fruits and vegetables produced by organic production methods may result in higher levels of defense-related secondary metabolites and that the risk of sub-optimal levels of these metabolites in First World diets is far more serious than any risk of deficiencies in minerals, vitamins, proteins, and carbohydrates (Brandt and Molgaard, 2001). Yet others claim that mineral nutrient deficiencies are very much widespread (Welch and Graham, 1999).

The Swiss Association for Research and Nutrition concluded: “From a scientific viewpoint, organic foods are neither healthier nor safer than conventional or genetically modified products. Some studies show that organic foods may contain more fungal toxins than foods produced by conventional methods. Transgenic Bt (*Bacillus thuringiensis*) maize varieties, on the other hand, occasionally exhibit noticeably smaller quantities of mycotoxins in the kernels than conventional varieties do.” (Bodenmüller, 2001).

Food Safety Risks

Nitrate

Owing to lower levels of nutrient supply, organically produced vegetables can sometimes be lower in NO_3^- content than those produced conventionally (Brandt and Molgaard, 2001). This difference occurs most often in leaf, root and tuber vegetables, and to a lesser extent in fruit, seed or bulb vegetables (Woese et al., 1997). Nitrate levels in fruits like apple and strawberry are very low and have not been observed to differ in organic production. Additionally, the higher NO_3^- levels in vegetables fertilized inorganically often result from excessive rates. In beet roots and cabbages, only at high rates did inorganic sources result in higher NO_3^- and poorer storage quality than organic sources (Meier-Ploeger et al, 1989). Sound management of mineral N inputs can prevent excessive levels of NO_3^- in produce.

In cabbages and leeks, NO_3^- contents were higher when grown with organic N than with inorganic sources. Reducing the rate of fertilizer by 50 percent, whether organic or inorganic, dramatically decreased NO_3^- content to as little as 20 percent of that present at normal rate (Salunkhe and Desai, 1988).

It is questionable whether the level of NO_3^- in foods is of significance to health. Nitrate in drinking water was shown to have some degree of association with risk of non-Hodgkin’s lymphoma, but dietary NO_3^- (mainly in vegetables) had no link to that disease and, in fact, reduced the risk of stomach cancer (Ward et al., 1996; Addiscott and Benjamin, 2000; McKnight et al., 1999). Most dietary intake of NO_3^- is in fresh vegetables, but one of the most well-founded nutritional facts is the positive effect of eating more vegetables and fruits.

While high NO_3^- levels in vegetables are considered by some to be a risk, research with red beets showed that high levels of NO_3^- and free amino acids coincided with low storage losses (Raupp, 1998). If NO_3^- improves shelf life, is it a positive or a negative for food safety?

Biosolids and heavy metals

Levels of **heavy metals** are slowly increasing in agricultural soils due to atmospheric deposition, additives in animal feeds transferred in animal manures, and commercial fertilizers (primarily phosphates). In the agricultural soils of Europe, such sources have led to increases of metals such as cadmium (Cd), mercury (Hg), and lead (Pb) on the order of 10 to 15 percent in the past century. However, these increases are small compared with the potential localized increases from use of sewage sludge in agriculture (McBride, 1995).

"The use of sewage sludges as farm fertilizers, encouraged in recent years by changes to USEPA (U.S. Environmental Protection Agency) policy, has raised concerns among some scientists regarding food safety and long-term soil productivity…. Uncertainties and biases in the risk assessment would advise a more cautious approach to agricultural and home garden use of sewage sludge than is permitted by the USEPA 503 rule." (McBride, 1998).

Sludge is often treated with lime and/or cement kiln dust to raise its pH and thus its temperature and NH_3 content to the point where pathogens are killed. This rise in pH also limits the immediate availability of certain heavy metals of concern, particularly Zn, Cd, and Pb. However, it also increases the availability of molybdenum (Mo) and sulfur (S), two elements commonly found in sludge. Addition of such material to land used for forage production can produce **molybdenosis** (Mo-induced Cu deficiency) in grazing ruminants such as sheep or cattle (Cherney et al., 2001; Harrison et al., 1999). The current EPA 503 rule has no cumulative soil loading limit for Mo and allows application of products with up to 75 ppm Mo, in comparison to a typical agricultural soil level of 1 ppm.

Reasons why biosolids have more potential than mineral fertilizers to increase heavy metals of concern in crop products include:

- Since they are more concentrated, mineral fertilizers are applied at much lower rates; typically in hundreds of pounds per acre, compared to biosolids in tons per acre.
- The protection against plant uptake by immobilization of heavy metals with the organic matter in the biosolids varies, depending on composition, and eventually decreases as the organic matter decomposes (McBride, 1995).

Toxins

Aflatoxins, potent carcinogens to animals and linked to liver cancer in humans, are a chronic problem in corn production in the southern U.S. In Louisiana corn inoculated with *Aspergillus flavus*, aflatoxin levels decreased linearly from an average of 20 parts per billion (ppb) to 7 ppb as the rate of N applied as urea-ammonium nitrate increased in six steps from 0 to 250 lb/A (Tubajika et al., 1999). Starter N at 10 lb/A also reduced aflatoxin by 26 percent in the same study, and applying the N at the six-leaf stage rather than at planting reduced aflatoxin by 15 percent. The researchers concluded that N deficiency, especially failure to apply N, increases the risk of aflatoxin problems.

In soybeans, **phytic acid** was one of the factors controlling aflatoxin accumulation (DeMyers et al., 1985). This implies that adequate P nutrition is a prerequisite to the soybean plant's defense against the pathogen.

The fungal toxins **fumonisin** and **patulin** are reported to be higher in organic products (Trewavas, 2001). Aflatoxin contamination can be higher in peanut butter from alternative (organic) than from conventional shops (Woese et al., 1997).

Pathogens in manures and biosolids

Fecal coliform (*E.coli*, particularly strain O157:H7), *Streptococci,* and sometimes *Salmonella* are the main pathogenic bacteria most common to animal manures, but *Campylobaster, Listeria*, spore-forming pathogens, and viruses can also be a concern (IFST, 2001). In addition, animal manures may contain protozoan pathogens, such as *Cryptosporidium* and *Giardia* (Goss et al., 2001).

Cryptosporidium is an important pathogen in manures, and it is difficult to control. Here's why: "Although the oocyst shell is thick and resistant to many chemicals such as chlorine, it is susceptible to drying, freezing, and ultraviolet light. Drying appears to kill oocysts in a matter of hours. With 10 or more days of freezing, one study showed that more than 90 percent of the oocysts were non-infective. However, at temperatures as high as 86°F (30°C), oocysts are able to survive for up to two weeks. They are soon killed, though, at temperatures over 131°F (55°C), typical of composting. One viability study showed that a small percentage of oocysts could survive in surface water up to at least six months. Oocysts can survive for several months in typical liquid manure tanks." (Fleming, 2000).

In Britain, the Institute of Food Science and Technology concluded in a study published in March of 2001 that: "The use of animal waste as fertilizer, whether in producing organic or non-organic food, needs to be properly managed, but even so it may pose a risk of contamination with pathogens and consequent food poisoning from foods which are to be consumed without adequate, or any, cooking." (IFST, 2001). Major efforts are underway to improve the handling of animal manures and manage the risks of pathogen transfer.

Biosolids are subject to contain an even wider range of human pathogens, but treatment processes to sterilize the materials are usually required before the land application can be approved.

Summary

Managing nutrients, whether organic or inorganic, clearly can affect the quality of the output from crop production systems, be they organic or conventional. Both systems are capable of producing quality food. Nutrient inputs should be chosen to efficiently supply an appropriate balance of fertility to optimize yield and quality, specific to each soil and crop.

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Chapter Ten

Nutrient Budgets in North America

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Synopsis: Nitrogen budgets for North America show that the amount of nitrogen (N) removed in harvested crops is equivalent to 77 percent of inputs. The partial phosphorus (P) budget for North America shows that P removal exceeds P applied as fertilizer by 29 percent. When recoverable manure is included in the evaluation, removal represents 95 percent of inputs. The partial potassium (K) budget shows that crops currently remove twice the amount of K being applied as fertilizer. When all recoverable manure is considered, removal still exceeds input by 44 percent. In the leading U.S. corn states, removal of P and K exceeds fertilizer plus recoverable manure by approximately 30 percent.

Financial budgets are useful accounting tools because they establish the foundation for financial planning by evaluating the balance between income and expenses. Similarly, nutrient budgets can offer useful insight into the balance between nutrient inputs and outputs in crop production. They provide a perspective on the magnitude of nutrient sources relative to crop demand. When combined with knowledge of nutrient cycles as discussed in Chapter Two, they may be useful in identifying opportunities to improve efficiency or productivity of the system. In other cases, they may suggest topics for additional research.

Unlike financial budgets, nutrient budgets involve considerable uncertainty, especially at the regional or national scale. At best, they are partial budgets, because of our inability to accurately determine all inputs and outputs. Sources of error in the budgets used in this bulletin and complications in interpretation include:

- Regional variation in nutrient removal per unit of crop yield;
- Absence of information on nutrient removal by some fertilized specialty crops;
- Uncertainty in the amount of manure actually applied to cropland and the concentration of nutrients in the manure;
- Lack of information on how manure nutrients are distributed among production fields relative to agronomic need;
- Estimation of the amount of N fixed by legumes;
- Fertilizer sold in one state or province but applied in another;
- Unaccounted for inputs and outputs such as soil erosion and N deposition; and
- Soil properties that influence nutrient fixation or release and that affect the agronomically desired balance for a specific region.

The nutrient budgets in this bulletin utilize comprehensive fertilizer consumption data generated by legal mandate and rather crude estimates of recoverable manure and crop removal. The resulting budgets contain unavoidable bias that tends to underestimate removal relative to nutrient use. Factors contributing to this underestimation include the following.

- Governments require reporting of all commercial fertilizer sold, no matter how the fertilizer is used.
- Clearly some fertilizer is consumed in applications that are not included in our removal estimates. Examples are fertilizers used on lawns, gardens, turfgrass, golf courses, and parks. This fertilizer is included as an input in the budgets, but is not accounted for on the output side.
- Nutrient removal from grazing animals on fertilized pasture is not available and not included in our budgets.
- In many states there are significant acreages of specialty crops that are not of a commercial scale adequate to be included in formal databases or simply are not collected.

The limitations of the budgeting procedure, including the bias discussed above, should be recognized when interpreting the data.

Inorganic fertilizer is the primary input to compensate for nutrient deficiencies in agricultural systems of North America. While we do depend on symbiotic fixation of N in legume crops and utilize manure nutrients in many areas where they are available, commercial fertilizer is the dominant nutrient source. The literature review in Chapter Five supported the estimate that 30 to 50 percent of crop yield in North America is due to supplemental nutrients. Globally, commercial fertilizer N today supplies basic food needs for at least 40 percent of the population (Smil, 2001).

In this chapter we integrate information from previous chapters and estimate the balance between nutrient inputs and outputs in North America. We will also evaluate the amount and distribution of recoverable nutrients from livestock manure, so that its impact on nutrient balance is placed in a realistic perspective.

Inputs

Inorganic fertilizer consumption based on sales

A review of the consumption of inorganic N, P, and K fertilizer in North America shows that only N has increased in the last 20 years **(Figure 5.3)**. While the total volumes differ significantly, the 12 percent increase in fertilizer N used in the U.S. is minor compared to the 90 percent increase in Canada between 1981 and 2000. Phosphorus and K fertilizer consumption has varied over the past 20 years, with the overall trend resulting in a minor decline in both Canada and the U.S.

An interesting way to evaluate fertilizer nutrient use is to consider the ratio of the macronutrients, $N:P_2O_5:K_2O$. In the U.S. in 1981, the ratio of these nutrients consumed as fertilizer was 1.9:0.9:1.0 (calculated from data in **Appendix 5.1**). In the year 2000, it was 2.5:0.9:1.0. While the ratio of P_2O_5 to K_2O has remained the same, the amount of N in the ratio has increased by 25 percent. In Canada, the ratio in fertilizer sales was 2.6:1.8:1.0 in 1981, and 5.0:2.0:1.0 in 2000 (calculated from data in **Appendix 5.1**). The ratio of N to P_2O_5 and K_2O in fertilizer use almost doubled over the 20-year period, while there was no change in the ratio of P_2O_5 to K_2O. This shift in the balance of nutrients reflects the declining N supplying capacity of many soils and the intensification of crop production systems. Given that the average nutrient removal ratio by field crops is in the range of 1.6:0.6:1.0 (Ludwick, 2001), we continue to depend heavily on soil reserves of P and K to meet crop requirements.

Consumption of N, P_2O_5, and K_2O has increased in both Atlantic Canada and the western provinces. These increases range from 53 to 114 percent for N, 10 to 30 percent for P_2O_5, and 33 to 116 percent for K_2O. In all cases, the largest increase was in the western provinces, where the adoption of conservation tillage practices has resulted in a significant reduction in fallow acres. In central Canada, there was a decline in fertilizer consumption during this same 20-year period. Fertilizer N use declined only 4 percent, while P_2O_5 and K_2O use dropped by 41 and 36 percent, respectively.

Organic nutrients (manure) based on livestock numbers and manure/AU

In Chapter Six of this publication, the shift in the livestock population in both the U.S. and Canada is presented **(Table 6.3)**. Dairy cattle numbers showed the largest decline between the early 1980s and the late 1990s in both countries, reflecting improvements in milk production per cow with feed and genetic management. In contrast, there has been a large expansion in swine production in both countries, and poultry in the U.S. The method in which livestock are raised has also changed during this time period, with a reduction in small farm operations and an expansion in the number of large confined animal feeding operations. This has resulted in a shift from manure being widely distributed in small amounts around the country to its being concentrated in areas where the large populations of livestock are managed.

In the U.S., estimated recoverable manure nutrients increased over the period from 1982 to 1997 for N, P_2O_5, and K_2O **(Figure 6.1)**. Recoverable N increased by 17 percent, and both P_2O_5 and K_2O increased by 20 percent. In Canada, the estimated total amount of recoverable nutrients in manure remained relatively unchanged during the period of 1981 to 1996.

In Atlantic Canada and Quebec, recoverable manure P_2O_5 estimates are 47 and 62 percent, respectively, of crop removal **(Appendix 10.2)**. These estimates could help explain the large decline in fertilizer P consumption recorded in this region. However, in western Canada with its extensive land base and relatively small livestock numbers, estimated recoverable P and K in manure are less than 25 percent of estimated crop removal.

Nitrogen fixation and deposition

The other major form of N input into the soil-plant system is N fixation through the symbiotic association between *Rhizobium* bacteria and legume crops. A wide range of N fixation capability exists among the grain and forage legume crops, with estimates being influenced by the *Rhizobium* strain, crop cultivar used, and environmental conditions. Ranges in N fixation of major crops include soybeans at 13 to 400 lb N/A, 33 to 183 lb N/A for peanuts, 3 to 94 lb N/A for beans, and 58 to 534 lb N/A for alfalfa (Smil, 1999). Utilizing N fixing crops in a crop rotation can result in a reduced demand for fertilizer N depending on the residual N left in the soil by the legume. Legume N fixation is a substantial N input in both U.S. and Canadian crop production systems, accounting for approximately one third of total N inputs in North America **(Appendix 10.1)**. This estimate assumes 100 percent of the N removed by soybeans, peanuts, and alfalfa and 54 and 49 percent of the N removed in field pea and lentil, respectively, come from N fixation.

Nitrogen is the only primary macronutrient that has any significant deposition from the atmosphere. Nitrogen compounds, derived mainly from nitrate (NO_3^-) generated during the combustion of fossil fuels and ammonia (NH_3) loss from plants, soils, and animal manures, return to the Earth in the form of wet or dry deposition. Location has a profound influence on the amount of N coming from atmospheric deposition, with the highest levels being in areas that are intensively farmed, densely populated, or heavily industrialized. It is estimated that lands in North America west of the Mississippi River receive 1 to 2 lb N/A/yr in the form of wet deposition (Jaworski et al., 1997). However, in the industrialized coastal regions of northeastern North America, the amount of total N in precipitation can be greater than 6 lb/A/yr. Given the nutrient demand by many of the crops grown in these regions, atmospheric deposition represents a minor contribution to crop requirements. It was not included in the nutrient budgets in this chapter.

Outputs

Crop removal of nutrients based on yields and nutrient uptake estimates

Crop nutrient removal from the agricultural system occurs in the form of grains, oilseeds, pulses, and feed and fiber crops grown either for local consumption, processing or export. It is important to distinguish crop removal from total crop uptake, as in many instances nutrients remaining in the non-marketable portion of the crop are left in the field and returned to the soil system. While most are not immediately available, they contribute to future crop production.

Nutrient removal estimates are based on the nutrient content in the marketable portion of the crop and annual production of the major crops. Nutrient removal was discussed in detail in Chapter Four, and typical examples of nutrient removal values per unit of production are shown in **Table 4.4**. These values are used in combination with crop production estimates to calculate nutrient removal levels in both the U.S. and Canada **(Tables 4.6a and 4.6b)**. Corn, soybeans, forages, and wheat make up 88 percent of the total nutrient removal by crops in the U.S. Soybeans remove the largest amount of N, corn removes the largest amount of P, and alfalfa accounts for the largest amount of K removal **(Table 4.6a)**. In Canada, wheat, forages, barley, and canola dominate nutrient removal and make up 76 percent of the total. Wheat removes the largest amounts of N and P by far, while alfalfa accounts for the largest removal of K **(Table 4.6b)**. When considered in combination with N fixation estimates, crop removal data provide some insight as to how shifting patterns of crop production can impact the N demand by agricultural crops. An expansion in the production of legumes can dramatically reduce the demand for N fertilizer, while either increasing or not affecting P and K demand.

Other losses

Erosion removes soil and the plant-available nutrients the soil contains from the production fields. It has been estimated that the cost of soil loss due to erosion ranges from $4 to $20 per ton, when considering the lost production and off-farm damage (Fox and Dickson, 1990). However, estimated soil erosion today in the U.S. is about one-third of what it was 30 years ago. While erosion is on the decline, it still accounts for an estimated loss of 1.9 billion tons of soil per year (USDA-NRCS, 2000). However, 68 percent occurs on only 29 percent of U.S. cropland (108 million acres). These erosion rates are an incentive to continue to develop and promote soil conservation practices that will improve soil quality, sequester carbon, and support crop production. Erosion losses were not considered in the budgets of this chapter.

Leaching, denitrification, and volatilization are other significant N loss pathways that were discussed in Chapter Two. Estimation of these specific losses goes beyond the scope of this publication. Net immobilization of N in soil organic matter as a result of changes in soil and crop management practices can represent a temporary loss of N relative to the nutrition of crops. It is most apparent where tillage intensity is significantly reduced and cropping intensity is increased as has occurred in much of the Great Plains region of North America. This does not represent a true N loss, but can make budgets appear more negative during transition periods.

Partial N Budgets

Partial N budgets for the six leading corn-producing states in the U.S. (Illinois, Indiana, Iowa, Minnesota, Nebraska, and Ohio), U.S., Canada, and North America are presented in **Table 10.1**. All values are averages of 1998-2000 crop production years except recoverable manure nutrients that are estimates for 1997. The leading corn states are separated from other states because of their dominance in North American nutrient cycles. These six states represent 45 percent of the N removed by crop production in the U.S. and 54, 36, and 19 percent of the N fixed by legumes, N fertilizer consumed, and N recoverable from manure, respectively.

The partial N budgets show that for North America the amount of N removed in harvested crops is equivalent to 77 percent of N inputs (legume fixation, fertilizer, and recoverable manure). Canada's recovery of 94 percent compares to 75 percent for the U.S. The higher Canadian recovery is at least partially due to the N budget for Saskatchewan **(Appendix 10.1)** which shows N removal by crop production exceeding the sum of fertilizer, legume, and recoverable manure inputs. This suggests that net mineralization of soil organic matter is still contributing significant N to crop production in Saskatchewan. Since this province represents over a third of all N removal by crops in Canada, it has a strong influence on the national data. In contrast, in much of the U.S., soil organic matter levels are likely close to steady state where net mineralization approaches zero.

Table 10.1. Partial N budgets for North America (average of 1998-2000).

	Crop removal[1]	Legume fixation[2]	Applied fert.[3]	Recoverable manure[4]	Balance[5]	Removed by crop harvest, %	
Region	billion lb					w/o manure	w/ manure
Six leading corn states	14.5	8.4	8.8	0.5	3.3	84	82
U.S.	32.1	15.6	24.7	2.6	10.8	80	75
Canada	5.02	1.41	3.64	0.28	0.31	99	94
North America	37.1	17.0	28.3	2.9	11.1	82	77

[1] U.S. from **Table 4.6a**; six leading corn states and Canada from **Appendix 10.1.**

[2] N removed in harvested portion of alfalfa, soybeans, peanuts, 49% of lentils, and 54% dry peas. It was assumed that any fixed N not recovered in the harvested crop was countered by soil N taken up during the growing season.

[3] Terry and Kirby, 2000, 2001.

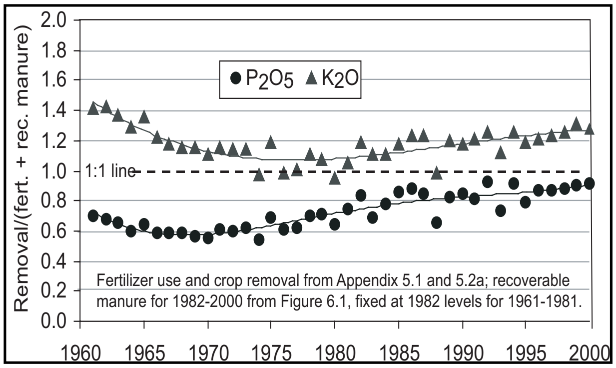
[4] U.S.: Kellogg et al., 2000 (1997 production). Canada: Anonymous, 1997 (1996 production).

[5] (Fixation+fertilizer+manure)-removal.

Table 10.2. Partial P and K budgets for North America (average of 1998-2000).

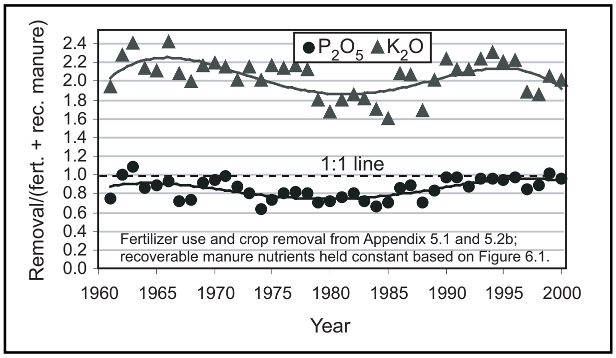
Nutrient	Region	Crop removal[1]	Applied fert.[2]	Recoverable manure[3]	Balance[4]	Removal to use ratios	
		-------------------	billion lb	------------------		w/o manure	w/ manure
P_2O_5	Six leading corn states	5.1	3.0	0.9	-1.3	1.71	1.33
	U.S.	11.4	8.8	3.3	0.7	1.30	0.95
	Canada	1.87	1.51	0.40	0.04	1.24	0.98
	North America	13.3	10.3	3.7	0.7	1.29	0.95
K_2O	Six leading corn states	6.6	4.1	1.0	-1.5	1.62	1.30
	U.S.	19.3	10.1	3.8	-5.4	1.91	1.39
	Canada	2.64	0.78	0.50	-1.36	3.40	2.06
	North America	21.9	10.9	4.3	-6.7	2.02	1.44

[1] U.S. from **Table 4.6a**; six leading corn states and Canada from **Appendix 10.2 and 10.3.** [2] Terry and Kirby, 2000, 2001.
[3] U.S.: Kellogg et al., 2000 (1997 production). Canada: Anonymous, 1997 (1996 production). [4] (fertilizer+manure)-removal.



Fertilizer use and crop removal from Appendix 5.1 and 5.2a; recoverable manure for 1982-2000 from Figure 6.1, fixed at 1982 levels for 1961-1981.

Figure 10.1a. Ratio of P and K removal by common crops to fertilizer P and K use plus recoverable manure in the U.S.



Fertilizer use and crop removal from Appendix 5.1 and 5.2b; recoverable manure nutrients held constant based on Figure 6.1.

Figure 10.1b. Ratio of P and K removal by common crops to fertilizer P and K use plus recoverable manure in Canada.

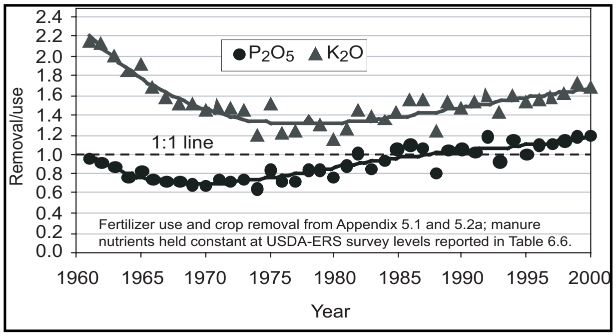
Nitrogen recovery by harvested crops in the leading corn states is 82 percent, exceeding the average recovery for the U.S. of 75 percent. Though some criticize the nutrient use efficiency of agriculture in the Corn Belt, this analysis suggests that N is utilized more efficiently in this region than for the U.S. as a whole. A likely contributing factor to higher N recovery in the Corn Belt is the 35 percent increase in apparent N fertilizer use efficiency for corn that has occurred over the last 20 years, as was discussed in Chapter Five and illustrated in **Figure 5.12**.

Partial P Budgets

The partial P budget for North America shows that crop removal of P exceeds P applied as fertilizer by 29 percent **(Table 10.2)**. When P from recoverable manure is included, removal represents 95 percent of P inputs. Considering the distribution problems associated with manure, the budget suggests that many production fields in North America are likely being managed with P outputs exceeding inputs. For example, in the six leading corn producing states, estimated P removal by crops exceeds P fertilizer application by 71 percent and exceeds the sum of P fertilizer applied and recoverable manure P by 33 percent. The budget shows that at least a third of the P leaving production fields of these states is being supplied by soil reserves that are not at this time being replaced. Negative nutrient budgets of this magnitude should result in declining soil test P levels over time as was shown in Chapter Three for these same six states **(Figure 3.5)**.

Unlike N, crops can remove significantly more P than is applied as fertilizer or manure for many consecutive years without yield potential reductions, provided soil P reserves are sufficiently high. At the same time, soils retain the vast majority of P applied as fertilizer or manure in excess of crop removal in the form of soil P reserves measured by soil tests. A discussion of the processes involved is given in Chapter Two. Because of the well buffered nature of P in most agricultural soils, it is important to relate current nutrient budgets to past budgets and to the soil test level information presented in Chapter Three.

Historical trends in partial P budgets for the U.S. and Canada are shown in **Figures 10.1a** and **10.1b** as the ratio of P removed by common crops to the sum of



Fertilizer use and crop removal from Appendix 5.1 and 5.2a; manure nutrients held constant at USDA-ERS survey levels reported in Table 6.6.

Figure 10.2 Ratio of P and K removal by common crops to fertilizer use plus manure nutrients applied to corn, soybeans, wheat, and cotton in the U.S.

fertilizer P and recoverable manure P. Over the entire 40-year period in the U.S., P removal has been less than inputs. In fact, in the late 1960s and early 1970s, P removal was only 60 percent of P inputs. This resulted in build up of soil test P in many regions of the U.S., especially the Corn Belt. Since 1970, the removal to use ratio has consistently trended higher and is now over 0.90 for the U.S. as a whole and greater than 1.0 for much of the Corn Belt, as discussed earlier.

The previous P budget analysis includes all recoverable manure P in the U.S. even though an unknown quantity of that manure is applied to pastures and disposed of in ways other than in accordance with the nutritional needs of crops. Thus, the analysis utilizes an inflated estimate of the P agronomically applied to the common crops included in the removal estimates. In an attempt to avoid the over estimation of manure P in the budget, **Figure 10.2** utilizes the estimates of manure P applied to corn, soybeans, wheat, and cotton presented earlier in **Table 6.6**, which was derived from USDA-ERS surveys for 1990 to 1996. These four crops represent approximately 75 percent of P removal in the U.S. Using this estimate of manure P, the P removal to use trend line crosses 1.0 in the late 1980s and suggests that P removal exceeded use by approximately 20 percent in the year 2000.

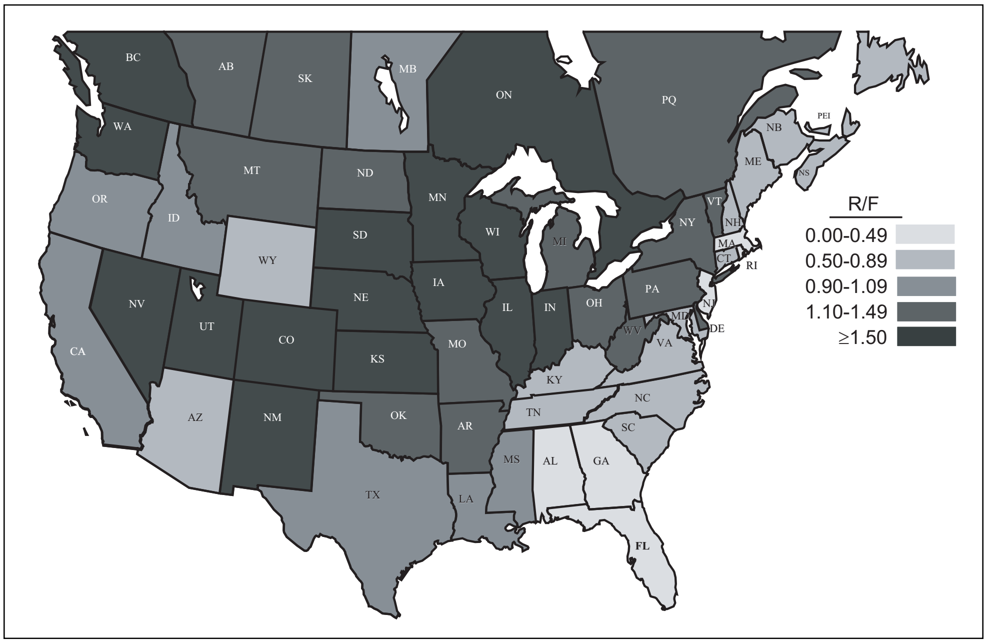


Figure 10.3. Ratio of P removal by common crops to fertilizer applied.

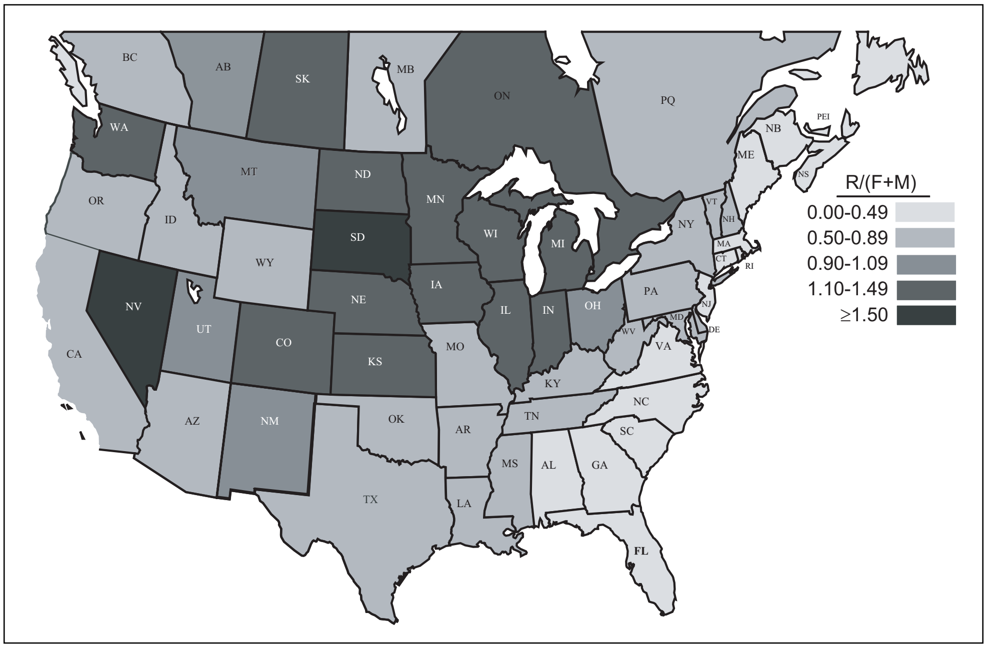


Figure 10.4. Ratio of P removal by common crops to fertilizer applied plus recoverable manure.

In Canada, P removal was slightly less than inputs (utilizing all recoverable manure P) during much of the 40-year period. The low point in the trend line was 0.75 and occurred in about 1980 **(Figure 10.1b)**. During the 1990s, P inputs and outputs were essentially equal. Considering that the problems associated with distribution and agronomic utilization of manure P in the U.S. are equally relevant in Canada, a good portion of Canadian crop production is dependent on soil P reserves.

Considerable variation exists in P budgets within both the U.S. and Canada and should be recognized when interpreting national budgets. **Figures 10.3** and **10.4** and **Appendix 10.2** show P removal to use ratios for the states and provinces of North America, excluding and including recoverable manure P. Ratios were divided into five ranges with the middle range representing a ratio approximately equal to 1.0 and two categories above and two categories below 1.0.

If manure P is excluded from the ratio (**Figure 10.3**), P removal exceeds fertilizer P applied for the entire Corn Belt, most of the Great Plains, and all of Canada except Manitoba. In contrast, P removal by common crops is less than fertilizer P applied for all states and provinces along the East Coast, Wyoming, and Arizona. Even though Florida, Georgia and Alabama have the lowest P removal to P fertilizer use ratios in North America, percent soils testing medium or below in P are 51, 61 and 79, respectively. This indicates that much of the region continues to be rather low in plant available P, possibly due to the P fixing tendencies of the acid soils of the region. The southeastern U.S. serves as a good example of a situation where target regional removal to use ratios for optimum crop production should not be assumed to be 1.0.

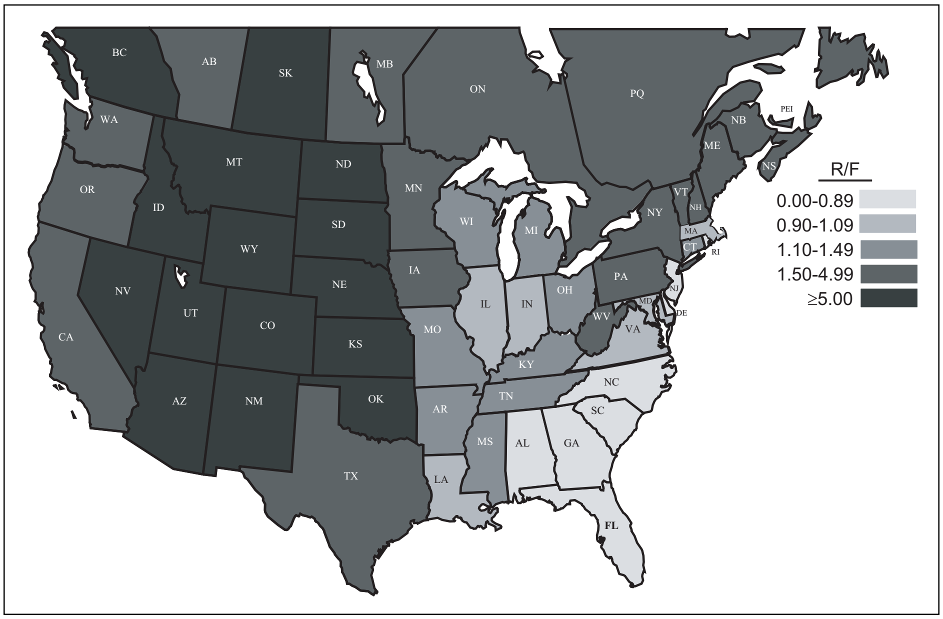


Figure 10.5. Ratio of K removal by common crops to fertilizer applied.

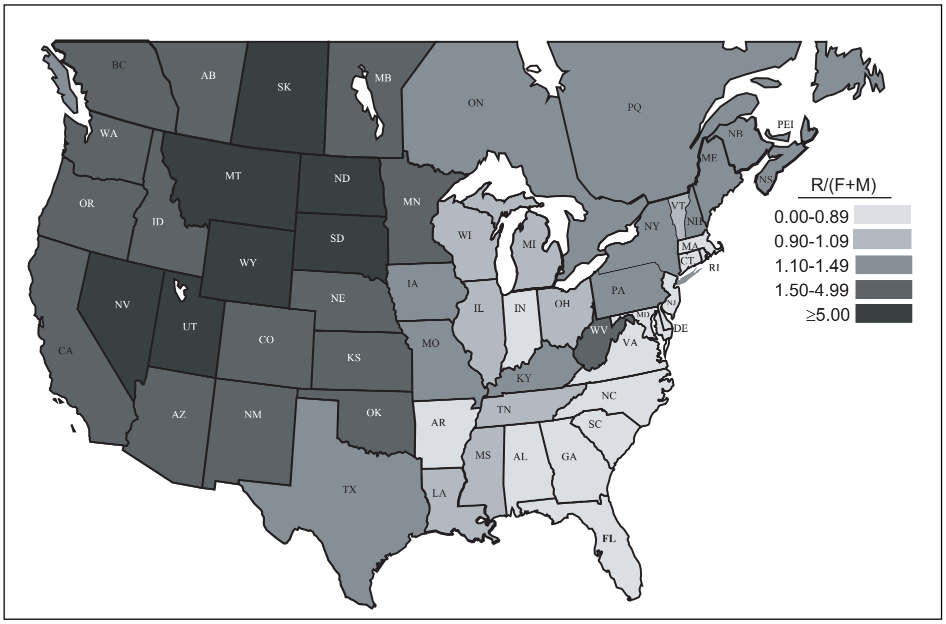


Figure 10.6. Ratio of K removal by common crops to fertilizer applied plus recoverable manure.

Including recoverable manure P in the removal to use ratio **(Figure 10.4)** expands the area along the East Coast, in the southern U.S., and in Canada where P removal is less than P applied. However, P removal continues to be greater than P applied for five of the six leading corn-producing states and for much of the Great Plains. The impact of livestock concentration in certain states and provinces is quite apparent in the map.

Partial K Budgets

The partial K budget for North America shows that crops currently remove twice as much K (2.02) as is being applied from fertilizer **(Table 10.2)**. When K from all recoverable manure is included, removal still exceeds inputs by 44 percent, indicating that soil K reserves are currently supplying over 40 percent of the K leaving production fields.

Similar to P, K in most agricultural soils is well-buffered, making it important to relate current nutrient budgets to past budgets and to soil test levels and trends. Historical trends in partial K budgets for the U.S. and Canada are shown in **Figures 10.1a** and **10.1b.** Unlike with P, the trend line for the K removal to use ratio has been greater than 1.0 for the entire 40-year period in both the U.S. and Canada. In Canada, it has generally been near 2.0, while in the U.S. it was at 1.4 in the early 1960s, decreased to about 1.1 in the late 1970s, and has since been increasing to where it is today, near 1.3. Restricting manure K estimates to what is applied to corn, soybeans, wheat, and cotton increases the ratios and results in a current value near 1.6 (**Figure 10.2**).

As pointed out in Chapter Three, indigenous K levels in North American soils vary markedly, with western areas generally much higher in soil K than the eastern states and provinces. Therefore, it is useful to examine K budgets on a regional basis (**Figures 10.5 and 10.6)**. No state west of the Mississippi River has K removal less than fertilizer K applied, and in 13 of the 22 states, removal is at least five times greater than fertilizer K applied. When K in recoverable manure is considered, Arkansas is the only state west of the Mississippi River in which K removal is less than K applied. None of the provinces has a budget showing K removal less than K applied. Clearly, agriculture of western North America is currently highly dependent on soil reserves for supplying K to crop plants. Recently, this has resulted in an increase in frequency of K deficiency symptoms in crops in some regions such as the western Corn Belt and in California.

East of the Mississippi River, K budgets are more mixed, with the southeastern states generally having the lowest removal to use ratios. However, it should be noted that even though removal is less than K applied in these states, many continue to have a high frequency of medium and below soil test levels, as was illustrated in Chapter Three. In fact, the Southeast has the lowest soil test K levels of any region in North America. One of the factors contributing to low soil test levels, even though K use exceeds removal, is the low K holding capacity of Coastal Plain and other coarse-textured, highly weathered soils of the region. Annual application of K is an important practice in these soils because of the difficulty in building soil test levels.

Potassium budgets for the states of the eastern Corn Belt have removal to use ratios close to 1.0 when recoverable manure K is considered. Despite this, some states such as Illinois, Indiana, and Ohio appear to be showing trends of declining soil test levels **(Figure 3.9)**. This should not be surprising since these budgets are calculated at a statewide level and can mask significant nutrient distribution problems, just as looking at averages for a single field can mask distribution problems within the field. Also, no attempt was made to account for soil erosion losses or the potential for loss of plant-available K to unavailable forms in the soil.

When present and historical K budgets are considered along with soil test summary information, the need for diligence in K management throughout much of North America becomes apparent.

Review of future crop and livestock production requirements

The future of fossil fuel energy sources is continually being challenged in much of the developed world, for both supply and environmental concerns. The management of fast-growing crops as a source of biomass for energy production, such as ethanol and burning material, has the potential to increase the use of fertilizer in commercial forests and nonfood crops (Socolow, 1999).

The use of grain production for feeding livestock is estimated at 40 percent of total global production (World Resource Institute, 1998). Such use of grains is highest in the U.S. at 70 percent. However, it increased from 15 percent to 24 percent between 1987 and 1997 in Asia. Increasing incomes in many developing countries of the world have increased pressure on meat supplies and, in turn, on the use of grains and plant protein sources as livestock feed.

Summary

Although the nutrient budgets presented and discussed in this chapter involve some limitations and assumptions, we believe this to be a comprehensive attempt at estimating and understanding the application and use of plant nutrients in North America. Overall, it paints a picture of fairly high and improving efficiency of nutrient use.

For the nutrient budget of North America as a whole, there is no evidence of P or K surpluses. All the fertilizer P and K currently being used and all the P or K recoverable from manure can be used in crop production. However, there is an obvious problem with distribution of the manure nutrients

The nutrient budgets do identify cause for concern. Many of our historically most productive soils are at risk of being systematically depleted of nutrients necessary to maintain their productivity. This chronic under-replacement of essential nutrients will eventually reduce the productivity and competitiveness of agricultural systems in these regions. Care must be used to avoid mistaking management practices that cause soil fertility depletion with practices that appear to increase nutrient use efficiency.

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List of Appendices

Note: References listed in Appendices can be found at the end of the corresponding chapter number in text.

Appendix 4.1. Nutrient removal by crops within state or province in North America, average for years 1998 to 2000.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb			% of removal by crop		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O
AL	Corn (grain)	14.64	bu	10.98	6.44	4.25	9.58	15.19	3.95
	Corn (silage)	0.20	ton	1.66	0.72	1.66	1.45	1.70	1.54
	Cotton	0.57	bale	18.36	8.03	10.90	16.02	18.94	10.14
	Oats	0.86	bu	0.69	0.21	0.17	0.60	0.51	0.16
	Other hay	1.57	ton	45.54	18.84	78.52	39.73	44.44	73.02
	Peanuts	383.88	lb	13.44	2.11	3.26	11.72	4.98	3.03
	Potatoes	0.79	cwt	0.28	0.12	0.44	0.24	0.28	0.41
	Sorghum (grain)	0.28	bu	0.24	0.12	0.06	0.21	0.28	0.06
	Sorghum (silage)	0.019	ton	0.15	0.07	0.15	0.14	0.16	0.14
	Soybeans	4.37	bu	17.49	3.50	6.12	15.26	8.25	5.69
	Sweet potatoes	0.50	cwt	0.26	0.12	0.50	0.23	0.27	0.47
	Wheat	4.25	bu	5.53	2.13	1.49	4.82	5.01	1.38
	Total removal			**114.61**	**42.41**	**107.53**	**100.00**	**100.00**	**100.00**
AZ	Alfalfa	1.63	ton	91.13	24.41	97.64	57.13	46.36	64.52
	Apples	0.57	cwt	0.17	0.10	0.48	0.11	0.19	0.32
	Barley	5.78	bu	6.36	2.31	2.02	3.98	4.39	1.34
	Broccoli	2.41	cwt	1.06	0.41	1.01	0.66	0.78	0.67
	Cantaloupes	4.41	cwt	1.63	0.53	2.87	1.02	1.01	1.89
	Carrots	0.58	cwt	0.20	0.08	0.46	0.13	0.14	0.31
	Cauliflower	0.94	cwt	0.51	0.17	0.75	0.32	0.32	0.50
	Corn (grain)	5.86	bu	4.39	2.58	1.70	2.75	4.89	1.12
	Corn (silage)	0.50	ton	4.13	1.79	4.13	2.59	3.40	2.73
	Cotton	0.72	bale	23.10	10.10	13.71	14.48	19.19	9.06
	Grapefruit	1.37	cwt	0.15	0.04	0.33	0.09	0.08	0.22
	Grapes	0.02	ton	0.01	0.00	0.01	0.01	0.01	0.01
	Lemons	2.32	cwt	0.37	0.09	0.49	0.23	0.16	0.32
	Lettuce (all)	20.90	cwt	5.02	1.57	10.45	3.14	2.98	6.91
	Melons (honeydew)	0.65	cwt	0.24	0.08	0.42	0.15	0.15	0.28
	Melons (watermelon)	2.66	cwt	0.45	0.35	0.72	0.28	0.66	0.47
	Onions	1.40	cwt	0.42	0.18	0.38	0.26	0.34	0.25
	Oranges	0.81	cwt	0.36	0.07	0.45	0.22	0.14	0.30
	Other hay	0.16	ton	4.64	1.92	8.00	2.91	3.65	5.29
	Potatoes	2.60	cwt	0.91	0.39	1.46	0.57	0.74	0.96
	Tangerines	0.060	cwt	0.01	0.00	0.01	0.01	0.00	0.01
	Wheat	10.98	bu	14.27	5.49	3.84	8.95	10.43	2.54
	Total removal			**159.52**	**52.66**	**151.34**	**100.00**	**100.00**	**100.00**
AR	Alfalfa	0.055	ton	3.08	0.83	3.30	0.46	0.38	1.00
	Apples	0.0028	ton	0.02	0.01	0.05	0.00	0.00	0.01
	Blueberries	0.00052	ton	0.00	0.00	0.01	0.00	0.00	0.00
	Corn (grain)	19.08	bu	14.31	8.40	5.53	2.15	3.88	1.68
	Corn (silage)	0.052	ton	0.43	0.19	0.43	0.06	0.09	0.13
	Cotton	1.35	bale	43.33	18.96	25.73	6.51	8.75	7.79
	Grapes	0.0046	ton	0.04	0.01	0.06	0.01	0.01	0.02
	Melons (watermelon)	0.333	cwt	0.06	0.04	0.09	0.01	0.02	0.03
	Oats	0.91	bu	0.73	0.23	0.18	0.11	0.10	0.05
	Other hay	2.45	ton	70.99	29.38	122.40	10.66	13.56	37.08
	Peaches	0.0070	ton	0.04	0.02	0.06	0.01	0.01	0.02
	Pecans	0.018	cwt	0.28	0.15	0.16	0.04	0.07	0.05
	Rice	89.10	cwt	113.15	59.69	31.18	16.99	27.55	9.45
	Sorghum (grain)	8.86	bu	7.44	3.72	1.95	1.12	1.72	0.59
	Sorghum (silage)	0.038	ton	0.31	0.14	0.31	0.05	0.06	0.09
	Soybeans	85.91	bu	343.63	68.73	120.27	51.61	31.72	36.44
	Strawberries (98 & 99 only)	0.0094	cwt	0.01	0.00	0.01	0.00	0.00	0.00
	Tomatoes	0.014	ton	0.03	0.01	0.08	0.01	0.01	0.02
	Wheat	52.27	bu	67.96	26.14	18.30	10.21	12.06	5.54
	Total removal			**665.85**	**216.64**	**330.09**	**100.00**	**100.00**	**100.00**
CA	Alfalfa	7.11	ton	397.88	106.58	426.30	39.68	30.21	39.21
	Almonds (shelled)	0.34	ton	44.20	17.00	57.80	4.41	4.82	5.32
	Apples	0.40	ton	2.41	1.44	6.82	0.24	0.41	0.63
	Artichokes	1.03	cwt	0.53	0.23	0.63	0.05	0.06	0.06
	Asparagus	1.04	cwt	2.00	0.69	2.26	0.20	0.20	0.21
	Avocados	0.15	ton	1.18	0.36	2.64	0.12	0.10	0.24
	Barley	6.79	bu	7.47	2.71	2.38	0.74	0.77	0.22

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Appendix 4.1. Continued.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb			% of removal by crop		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O
	Beans (snap-fr.mkt.)	0.49	cwt	0.85	0.20	1.01	0.08	0.06	0.09
	Broccoli	17.09	cwt	7.52	2.91	7.18	0.75	0.82	0.66
	Brussels sprouts	0.52	cwt	0.26	0.11	0.32	0.03	0.03	0.03
	Cabbage (fr.mkt.)	4.56	cwt	1.78	0.42	1.64	0.18	0.12	0.15
	Carrots (all)	29.29	cwt	10.25	3.69	23.43	1.02	1.05	2.16
	Cauliflower	6.31	cwt	3.38	1.12	5.03	0.34	0.32	0.46
	Celery	16.24	cwt	3.09	1.79	8.12	0.31	0.51	0.75
	Corn (grain)	36.87	bu	27.65	16.22	10.69	2.76	4.60	0.98
	Corn (silage)	8.42	ton	69.89	30.31	69.89	6.97	8.59	6.43
	Corn (sweet-fr.mkt.)	4.42	cwt	6.90	2.30	6.67	0.69	0.65	0.61
	Cotton	2.08	bale	66.54	29.11	39.51	6.64	8.25	3.63
	Cucumbers (fr.mkt.)	1.93	cwt	0.39	0.14	0.64	0.04	0.04	0.06
	Dates	0.40	cwt	0.14	0.06	0.31	0.01	0.02	0.03
	Dry beans	2.04	cwt	7.26	1.90	3.12	0.72	0.54	0.29
	Figs	1.00	cwt	0.47	0.14	0.74	0.05	0.04	0.07
	Garlic	6.51	cwt	1.95	0.85	1.76	0.19	0.24	0.16
	Grapefruit	5.02	cwt	0.53	0.15	1.20	0.05	0.04	0.11
	Grapes (all)	5.95	ton	49.38	17.85	77.35	4.92	5.06	7.12
	Kiwifruit	0.03	ton	0.31	0.14	0.37	0.03	0.04	0.03
	Lemons	14.24	cwt	2.34	0.52	2.98	0.23	0.15	0.27
	Lettuce (all)	67.96	cwt	16.31	5.10	33.98	1.63	1.44	3.13
	Melons (cantaloupe)	12.74	cwt	4.65	1.47	8.28	0.46	0.42	0.76
	Melons (honeydew)	3.83	cwt	1.42	0.46	2.49	0.14	0.13	0.23
	Melons (watermelon)	6.41	cwt	1.09	0.83	1.73	0.11	0.24	0.16
	Mushrooms	1.32	cwt	0.67	0.29	0.81	0.07	0.08	0.07
	Oats	2.08	bu	1.67	0.52	0.42	0.17	0.15	0.04
	Olives	0.090	ton	0.92	0.41	1.10	0.09	0.11	0.10
	Onions (all)	19.29	cwt	5.79	2.51	5.21	0.58	0.71	0.48
	Oranges	42.25	cwt	18.59	3.80	23.24	1.85	1.08	2.14
	Other hay	1.53	ton	44.36	18.36	76.48	4.42	5.20	7.04
	Peaches	0.89	ton	5.60	2.40	7.11	0.56	0.68	0.65
	Pears	0.32	ton	1.82	0.54	2.02	0.18	0.15	0.19
	Peppers (bell)	7.54	cwt	5.73	2.19	9.05	0.57	0.62	0.83
	Pistachios	0.092	ton	5.52	2.21	2.76	0.55	0.63	0.25
	Potatoes	15.52	cwt	5.43	2.33	8.69	0.54	0.66	0.80
	Prunes	0.17	ton	1.01	0.34	1.46	0.10	0.10	0.13
	Pumpkins	1.80	cwt	0.92	0.40	1.10	0.09	0.11	0.10
	Radishes	0.38	cwt	0.54	0.18	0.77	0.05	0.05	0.07
	Raspberries	0.19	cwt	0.10	0.04	0.12	0.01	0.01	0.01
	Rice	37.20	cwt	47.24	24.92	13.02	4.71	7.06	1.20
	Spinach	2.70	cwt	0.96	0.48	1.98	0.10	0.14	0.18
	Squash	1.38	cwt	0.58	0.14	0.83	0.06	0.04	0.08
	Stone fruit	0.60	ton	3.78	1.62	4.80	0.38	0.46	0.44
	Strawberries	14.62	cwt	11.70	5.48	14.62	1.17	1.55	1.34
	Sugarbeets	3.07	ton	12.28	4.61	20.26	1.22	1.31	1.86
	Sweet potatoes	2.39	cwt	1.24	0.55	2.39	0.12	0.16	0.22
	Tangerines	1.60	cwt	0.24	0.06	0.39	0.02	0.02	0.04
	Tomatoes (fr.mkt.)	10.80	cwt	1.35	0.50	3.08	0.13	0.14	0.28
	Tomatoes (processing)	10.47	ton	26.18	9.63	59.68	2.61	2.73	5.49
	Walnuts	0.13	ton	9.47	2.68	5.30	0.94	0.76	0.49
	Wheat	37.78	bu	49.11	18.89	13.22	4.90	5.35	1.22
	Total removal			**1,002.79**	**352.83**	**1,087.14**	**100.00**	**100.00**	**100.00**
CO	Alfalfa	3.38	ton	189.50	50.76	203.04	35.43	24.34	51.32
	Apples	0.018	ton	0.11	0.06	0.30	0.02	0.03	0.08
	Barley	10.18	bu	11.20	4.07	3.56	2.09	1.95	0.90
	Cabbage	0.848	cwt	0.33	0.08	0.31	0.06	0.04	0.08
	Carrots	1.902	cwt	0.67	0.24	1.52	0.12	0.11	0.38
	Corn (grain)	154.68	bu	116.01	68.06	44.86	21.69	32.63	11.34
	Corn (silage)	2.33	ton	19.37	8.40	19.37	3.62	4.03	4.90
	Corn (sweet)	1.059	cwt	1.65	0.55	1.60	0.31	0.26	0.40
	Dry beans	2.53	cwt	9.01	2.35	3.87	1.68	1.13	0.98
	Lettuce	0.741	cwt	0.18	0.06	0.37	0.03	0.03	0.09
	Melons (cantaloupe)	0.335	cwt	0.13	0.03	0.12	0.02	0.01	0.03

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Appendix 4.1. Continued.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb			% of removal by crop		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O
	Oats	1.75	bu	1.40	0.44	0.35	0.26	0.21	0.09
	Onions	5.200	cwt	1.56	0.68	1.40	0.29	0.32	0.35
	Other hay	1.04	ton	30.24	12.51	52.13	5.65	6.00	13.18
	Peaches	0.007	ton	0.04	0.02	0.06	0.01	0.01	0.01
	Pears	0.0023	ton	0.01	0.00	0.01	0.00	0.00	0.00
	Potatoes	29.06	cwt	10.17	4.36	16.27	1.90	2.09	4.11
	Rye	0.07	bu	0.11	0.04	0.02	0.02	0.02	0.01
	Sorghum (grain)	8.55	bu	7.19	3.59	1.88	1.34	1.72	0.48
	Sorghum (silage)	0.17	ton	1.40	0.61	1.40	0.26	0.29	0.35
	Spinach	0.112	cwt	0.04	0.02	0.08	0.01	0.01	0.02
	Sugar beets	1.32	ton	5.55	1.98	8.73	1.04	0.95	2.21
	Sunflower	240.12	lb	6.72	2.64	1.44	1.26	1.27	0.36
	Wheat	94.01	bu	122.22	47.01	32.90	22.85	22.54	8.32
	Total removal			**534.80**	**208.56**	**395.60**	**100.00**	**100.00**	**100.00**
CT	Alfalfa	0.021	ton	1.18	0.32	1.26	12.69	8.51	10.87
	Apples	0.010	ton	0.06	0.04	0.17	0.66	1.00	1.49
	Corn (silage)	0.56	ton	4.65	2.02	4.65	50.16	54.49	40.10
	Corn (sweet)	0.25	cwt	0.39	0.13	0.37	4.16	3.47	3.22
	Other hay	0.10	ton	2.86	1.18	4.93	30.88	32.00	42.57
	Tobacco	4.07	lb	0.13	0.02	0.20	1.45	0.53	1.75
	Total removal			**9.27**	**3.70**	**11.59**	**100.00**	**100.00**	**100.00**
DE	Alfalfa	0.032	ton	1.79	0.48	1.92	3.31	2.66	8.56
	Barley	2.08	bu	2.29	0.83	0.73	4.24	4.62	3.25
	Corn (grain)	18.16	bu	13.62	7.99	5.27	25.18	44.26	23.48
	Corn (silage)	0.15	ton	1.26	0.55	1.26	2.33	3.03	5.62
	Other hay	0.023	ton	0.66	0.27	1.13	1.22	1.51	5.05
	Potatoes	1.07	cwt	0.38	0.16	0.60	0.69	0.89	2.68
	Soybeans	7.24	bu	28.95	5.79	10.13	53.52	32.08	45.18
	Wheat	3.96	bu	5.14	1.98	1.38	9.51	10.96	6.17
	Total removal			**54.09**	**18.05**	**22.43**	**100.00**	**100.00**	**100.00**
FL	Beans (snap)	2.51	cwt	4.32	1.03	5.12	1.83	1.33	1.71
	Cabbage	2.02	cwt	0.79	0.18	0.73	0.33	0.23	0.24
	Corn (grain)	3.08	bu	2.31	1.35	0.89	0.98	1.74	0.30
	Corn (silage)	0.62	ton	5.12	2.22	5.12	2.18	2.86	1.71
	Corn (sweet)	5.62	cwt	8.77	2.92	8.49	3.72	3.76	2.84
	Cotton	0.10	bale	3.22	1.41	1.91	1.37	1.81	0.64
	Cucumbers	3.23	cwt	0.55	0.42	0.87	0.23	0.54	0.29
	Eggplant	0.53	cwt	0.10	0.04	0.14	0.04	0.05	0.05
	Grapefruit	46.75	cwt	5.14	1.40	11.22	2.18	1.81	3.75
	Limes	0.45	cwt	0.07	0.02	0.09	0.03	0.02	0.03
	Melons (watermelon)	8.78	cwt	1.49	1.14	2.37	0.63	1.47	0.79
	Oranges (all)	217.48	cwt	95.69	19.57	119.61	40.64	25.22	40.00
	Other fruits & veg.	8.06	cwt	4.11	1.77	4.92	1.75	2.28	1.64
	Other hay	0.67	ton	19.37	8.02	33.40	8.23	10.33	11.17
	Peanuts	235.73	lb	8.25	1.30	2.00	3.50	1.67	0.67
	Pecans	0.030	cwt	0.02	0.01	0.01	0.01	0.02	0.00
	Peppers (bell)	5.93	cwt	4.51	1.72	7.12	1.91	2.22	2.38
	Potatoes	9.30	cwt	3.26	1.40	5.21	1.38	1.80	1.74
	Radishes/carrots	1.12	cwt	1.62	0.53	2.30	0.69	0.68	0.77
	Rice	0.16	cwt	0.20	0.11	0.06	0.09	0.14	0.02
	Sorghum (grain)	0.54	bu	0.45	0.23	0.12	0.19	0.29	0.04
	Soybeans	0.53	bu	2.11	0.42	0.74	0.90	0.54	0.25
	Squash	1.42	cwt	0.60	0.14	0.85	0.25	0.18	0.28
	Strawberries	1.89	cwt	1.51	0.66	1.89	0.64	0.85	0.63
	Sugar cane	17.02	ton	34.05	21.28	59.58	14.46	27.42	19.92
	Tobacco	14.63	lb	0.48	0.07	0.73	0.21	0.09	0.24
	Tomatoes	0.77	cwt	1.94	0.71	4.41	0.82	0.92	1.48
	Wheat	0.51	bu	0.66	0.25	0.18	0.28	0.33	0.06
	Wood (soft and hard)	5.56	cord	24.74	7.28	18.96	10.51	9.39	6.34
	Total removal			**235.46**	**77.60**	**299.05**	**100.00**	**100.00**	**100.00**
GA	Apples	0.0060	ton	0.04	0.02	0.10	0.01	0.02	0.04
	Beans (snap & lima)	0.76	cwt	1.31	0.31	1.55	0.43	0.30	0.68
	Cabbage	2.41	cwt	1.01	0.27	0.89	0.33	0.26	0.39

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Appendix 4.1. Continued.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb			% of removal by crop		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O
	Corn (grain)	28.51	bu	21.38	12.54	8.27	7.00	12.09	3.63
	Corn (silage)	0.60	ton	5.01	2.17	5.01	1.64	2.09	2.20
	Corn (sweet)	3.28	cwt	3.41	0.98	3.74	1.12	0.95	1.64
	Cotton	1.59	bale	50.90	22.27	30.22	16.67	21.46	13.28
	Cucumbers	2.34	cwt	0.40	0.30	0.63	0.13	0.29	0.28
	Grapes	0.0035	ton	0.03	0.01	0.05	0.01	0.01	0.02
	Melons (cantaloupe)	0.87	cwt	0.32	0.10	0.57	0.11	0.10	0.25
	Melons (watermelon)	4.87	cwt	0.83	0.63	1.31	0.27	0.61	0.58
	Oats	1.74	bu	1.39	0.44	0.35	0.46	0.42	0.15
	Onions	2.72	cwt	1.06	0.41	1.31	0.35	0.39	0.57
	Other fruits and veg.	6.76	cwt	3.45	1.49	4.12	1.13	1.43	1.81
	Other hay	1.52	ton	44.03	18.22	75.92	14.42	17.56	33.36
	Peaches	0.049	ton	0.31	0.13	0.39	0.10	0.13	0.17
	Peanuts	1,413.62	lb	49.48	7.77	12.02	16.20	7.49	5.28
	Pecans	0.80	cwt	0.65	0.35	0.36	0.21	0.34	0.16
	Peppers (bell)	0.90	cwt	0.68	0.26	1.08	0.22	0.25	0.47
	Rye	1.05	bu	1.47	0.50	0.32	0.48	0.49	0.14
	Sorghum (grain)	1.28	bu	1.08	0.54	0.28	0.35	0.52	0.12
	Sorghum (silage)	0.14	ton	1.16	0.50	1.16	0.38	0.49	0.51
	Soybeans	3.86	bu	15.45	3.09	5.41	5.06	2.98	2.38
	Sweet potatoes	0.067	cwt	0.03	0.02	0.07	0.01	0.01	0.03
	Tobacco	74.35	lb	2.45	0.36	3.72	0.80	0.34	1.63
	Tomatoes	0.057	ton	0.14	0.05	0.32	0.05	0.05	0.14
	Wheat	10.27	bu	13.34	5.13	3.59	4.37	4.95	1.58
	Wood (soft & hard)	19.00	cord	84.55	24.89	64.79	27.69	23.99	28.47
	Total removal			**305.37**	**103.77**	**227.54**	**100.00**	**100.00**	**100.00**
ID	Alfalfa	4.74	ton	265.16	71.03	284.10	44.90	35.81	55.33
	Barley	56.19	bu	61.81	22.48	19.67	10.47	11.33	3.83
	Corn (grain)	8.48	bu	6.36	3.73	2.46	1.08	1.88	0.48
	Corn (silage)	2.76	ton	22.87	9.92	22.87	3.87	5.00	4.45
	Dry beans	1.98	cwt	7.05	1.84	3.03	1.19	0.93	0.59
	Oats	1.78	bu	1.43	0.45	0.36	0.24	0.22	0.07
	Other hay	0.59	ton	17.09	7.07	29.47	2.89	3.57	5.74
	Potatoes	141.22	cwt	49.43	21.18	79.08	8.37	10.68	15.40
	Sugar beets	5.40	ton	22.68	8.10	35.64	3.84	4.08	6.94
	Wheat	105.13	bu	136.66	52.56	36.79	23.14	26.50	7.17
	Total removal			**590.54**	**198.36**	**513.47**	**100.00**	**100.00**	**100.00**
IL	Alfalfa	2.14	ton	119.84	32.10	128.40	3.72	2.85	9.93
	Corn (grain)	1,544.33	bu	1,158.25	679.51	447.86	35.92	60.35	34.63
	Corn (silage)	1.87	ton	15.53	6.74	15.53	0.48	0.60	1.20
	Oats	4.07	bu	3.25	1.02	0.81	0.10	0.09	0.06
	Other hay	0.79	ton	23.01	9.52	39.67	0.71	0.85	3.07
	Potatoes	1.64	cwt	0.57	0.25	0.92	0.02	0.02	0.07
	Rye	0.27	bu	0.38	0.13	0.08	0.01	0.01	0.01
	Sorghum (grain)	8.40	bu	7.06	3.53	1.85	0.22	0.31	0.14
	Sorghum (silage)	0.025	ton	0.20	0.09	0.20	0.01	0.01	0.02
	Soybeans	455.70	bu	1,822.80	364.56	637.98	56.52	32.38	49.33
	Wheat	56.88	bu	73.94	28.44	19.91	2.29	2.53	1.54
	Total removal			**3,224.84**	**1,125.87**	**1,293.21**	**100.00**	**100.00**	**100.00**
IN	Alfalfa	1.63	ton	91.15	24.41	97.66	5.38	4.15	13.50
	Corn (grain)	774.88	bu	581.16	340.95	224.72	34.29	58.00	31.06
	Corn (silage)	1.98	ton	16.41	7.12	16.41	0.97	1.21	2.27
	Oats	1.69	bu	1.35	0.42	0.34	0.08	0.07	0.05
	Other hay	0.89	ton	25.75	10.66	44.40	1.52	1.81	6.14
	Potatoes	1.24	cwt	0.43	0.19	0.69	0.03	0.03	0.10
	Rye	0.073	bu	0.10	0.04	0.02	0.01	0.01	0.00
	Soybeans	233.18	bu	932.71	186.54	326.45	55.03	31.73	45.12
	Tobacco	12.23	lb	0.40	0.06	0.61	0.02	0.01	0.08
	Wheat	34.87	bu	45.33	17.43	12.20	2.67	2.97	1.69
	Total removal			**1,694.79**	**587.81**	**723.50**	**100.00**	**100.00**	**100.00**
IA	Alfalfa	4.82	ton	269.64	72.23	288.90	7.53	5.73	18.55
	Corn (grain)	1,755.73	bu	1,316.80	772.52	509.16	36.77	61.34	32.70
	Corn (silage)	4.41	ton	36.62	15.88	36.62	1.02	1.26	2.35

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Appendix 4.1. Continued.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb			% of removal by crop		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O
	Oats	11.45	bu	9.16	2.86	2.29	0.26	0.23	0.15
	Other hay	0.95	ton	27.62	11.43	47.62	0.77	0.91	3.06
	Potatoes	0.22	cwt	0.08	0.03	0.12	0.00	0.00	0.01
	Soybeans	479.92	bu	1,919.67	383.93	671.89	53.61	30.48	43.15
	Wheat	1.20	bu	1.55	0.60	0.42	0.04	0.05	0.03
	Total removal			**3,581.14**	**1,259.49**	**1,557.01**	**100.00**	**100.00**	**100.00**
KS	Alfalfa	4.08	ton	228.67	61.25	245.00	13.41	9.16	28.64
	Apples	0.0020	ton	0.01	0.01	0.03	0.00	0.00	0.00
	Barley	0.37	bu	0.41	0.15	0.13	0.02	0.02	0.02
	Corn (grain)	418.38	bu	313.78	184.09	121.33	18.40	27.53	14.18
	Corn (silage)	2.24	ton	18.62	8.08	18.62	1.09	1.21	2.18
	Cotton	0.02	bale	0.62	0.27	0.37	0.04	0.04	0.04
	Dry beans	0.35	cwt	1.25	0.33	0.54	0.07	0.05	0.06
	Oats	2.73	bu	2.18	0.68	0.55	0.13	0.10	0.06
	Other hay	3.26	ton	94.59	39.14	163.08	5.55	5.85	19.06
	Pecans	0.00091	ton	0.01	0.01	0.01	0.00	0.00	0.00
	Rye	0.34	bu	0.47	0.16	0.10	0.03	0.02	0.01
	Sorghum (grain)	237.07	bu	199.14	99.57	49.78	11.68	14.89	5.82
	Sorghum (silage)	1.10	ton	9.10	3.95	9.10	0.53	0.59	1.06
	Soybeans	68.73	bu	274.93	54.99	96.23	16.12	8.22	11.25
	Sunflower	314.70	lb	8.81	3.46	1.89	0.52	0.52	0.22
	Wheat	425.03	bu	552.54	212.52	148.76	32.40	31.78	17.39
	Total removal			**1,705.14**	**668.64**	**855.52**	**100.00**	**100.00**	**100.00**
KY	Alfalfa	0.86	ton	48.07	12.88	51.50	9.80	7.15	12.26
	Apples	0.0036	ton	0.02	0.01	0.06	0.00	0.01	0.01
	Barley	0.56	bu	0.62	0.22	0.20	0.13	0.12	0.05
	Corn (grain)	139.83	bu	104.88	61.53	40.55	21.38	34.17	9.65
	Corn (silage)	1.70	ton	14.12	6.12	14.12	2.88	3.40	3.36
	Other hay	4.73	ton	137.22	56.78	236.58	27.97	31.53	56.33
	Peaches	0.00070	ton	0.00	0.00	0.01	0.00	0.00	0.00
	Sorghum (grain)	0.68	bu	0.57	0.29	0.15	0.12	0.16	0.04
	Sorghum (silage)	0.011	ton	0.09	0.04	0.09	0.02	0.02	0.02
	Soybeans	35.20	bu	140.80	28.16	49.28	28.70	15.64	11.73
	Tobacco	378.39	lb	12.49	1.82	18.92	2.55	1.01	4.50
	Wheat	24.43	bu	31.76	12.22	8.55	6.47	6.78	2.04
	Total removal			**490.63**	**180.06**	**420.01**	**100.00**	**100.00**	**100.00**
LA	Corn (grain)	42.20	bu	31.65	18.57	12.24	12.16	17.69	7.28
	Corn (silage)	0.13	ton	1.11	0.48	1.11	0.43	0.46	0.66
	Cotton	0.82	bale	26.17	11.45	15.54	10.05	10.91	9.24
	Other hay	0.77	ton	22.26	9.21	38.38	8.55	8.78	22.82
	Peaches	0.00057	ton	0.00	0.00	0.00	0.00	0.00	0.00
	Pecans	0.1800	cwt	0.15	0.08	0.08	0.06	0.08	0.05
	Rice	27.78	cwt	35.28	18.61	9.72	13.55	17.73	5.78
	Sorghum (grain)	14.87	bu	12.49	6.25	3.27	4.80	5.95	1.95
	Sorghum (silage)	0.014	ton	0.12	0.05	0.12	0.05	0.05	0.07
	Soybeans	23.20	bu	92.80	18.56	32.48	35.65	17.68	19.31
	Sugar cane	14.33	ton	28.65	17.91	50.14	11.01	17.06	29.81
	Sweet potatoes	2.92	cwt	1.52	0.67	2.92	0.58	0.64	1.74
	Wheat	6.23	bu	8.10	3.12	2.18	3.11	2.97	1.30
	Total removal			**260.30**	**104.95**	**168.19**	**100.00**	**100.00**	**100.00**
ME	Alfalfa	0.026	ton	1.47	0.40	1.58	7.12	4.72	5.54
	Apples	0.025	ton	0.15	0.09	0.42	0.73	1.09	1.49
	Blueberries	0.040	ton	0.33	0.12	0.52	1.60	1.43	1.82
	Corn (silage)	0.50	ton	4.17	1.81	4.17	20.13	21.62	14.61
	Corn (sweet)	0.13	cwt	0.20	0.07	0.19	0.96	0.79	0.67
	Oats	2.00	bu	1.60	0.50	0.40	7.74	5.99	1.40
	Other hay	0.22	ton	6.51	2.69	11.22	31.41	32.19	39.30
	Potatoes	17.93	cwt	6.28	2.69	10.04	30.30	32.16	35.18
	Total removal			**20.71**	**8.36**	**28.54**	**100.00**	**100.00**	**100.00**
MD	Alfalfa	0.23	ton	12.69	3.40	13.60	8.03	6.26	15.63
	Barley	3.85	bu	4.24	1.54	1.35	2.68	2.84	1.55
	Corn (grain)	46.62	bu	34.96	20.51	13.52	22.12	37.79	15.53
	Corn (silage)	1.12	ton	9.25	4.01	9.25	5.85	7.40	10.63

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Appendix 4.1. Continued.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb			% of removal by crop		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O
	Oats	0.29	bu	0.23	0.07	0.06	0.15	0.13	0.07
	Other hay	0.40	ton	11.51	4.76	19.85	7.28	8.78	22.81
	Potatoes	1.14	cwt	0.40	0.17	0.64	0.25	0.32	0.74
	Rye	0.13	bu	0.18	0.06	0.04	0.11	0.11	0.04
	Soybeans	17.25	bu	69.02	13.80	24.16	43.66	25.43	27.76
	Tobacco	8.82	lb	0.29	0.04	0.44	0.18	0.08	0.51
	Wheat	11.78	bu	15.32	5.89	4.12	9.69	10.86	4.74
	Total removal			**158.10**	**54.27**	**87.03**	**100.00**	**100.00**	**100.00**
MA	Alfalfa	0.034	ton	1.89	0.51	2.02	16.01	10.87	12.81
	Apples	0.024	ton	0.15	0.09	0.41	1.24	1.89	2.59
	Corn (silage)	0.40	ton	3.34	1.45	3.34	28.38	31.20	21.20
	Corn (sweet)	0.42	cwt	0.65	0.22	0.63	5.51	4.65	3.98
	Cranberries	1.90	cwt	0.97	0.42	1.16	8.23	9.00	7.35
	Other hay	0.16	ton	4.50	1.86	7.75	38.17	40.03	49.15
	Potatoes	0.69	cwt	0.24	0.10	0.38	2.04	2.22	2.44
	Tobacco	1.53	lb	0.05	0.01	0.08	0.43	0.16	0.48
	Total removal			**11.78**	**4.65**	**15.77**	**100.00**	**100.00**	**100.00**
MI	Alfalfa	3.37	ton	188.81	50.58	202.30	23.21	18.67	40.53
	Barley	1.23	bu	1.35	0.49	0.43	0.17	0.18	0.09
	Beans (snap)	0.091	ton	3.14	0.75	3.73	0.39	0.28	0.75
	Corn (grain)	241.78	bu	181.33	106.38	70.12	22.29	39.27	14.05
	Corn (silage)	3.40	ton	28.20	12.23	28.20	3.47	4.52	5.65
	Cucumbers (all)	4.469	cwt	0.89	0.31	1.47	0.11	0.12	0.30
	Dry beans	5.30	cwt	18.87	4.93	8.11	2.32	1.82	1.62
	Oats	4.83	bu	3.86	1.21	0.96	0.47	0.45	0.19
	Other hay	0.73	ton	21.22	8.78	36.58	2.61	3.24	7.33
	Potatoes	14.86	cwt	5.20	2.23	8.32	0.64	0.82	1.67
	Rye	0.59	bu	0.82	0.28	0.18	0.10	0.10	0.04
	Soybeans	74.80	bu	299.19	59.84	104.72	36.78	22.09	20.98
	Sugar beets	3.23	ton	13.59	4.85	21.35	1.67	1.79	4.28
	Wheat	36.06	bu	46.88	18.03	12.62	5.76	6.66	2.53
	Total removal			**813.35**	**270.89**	**499.09**	**100.00**	**100.00**	**100.00**
MN	Alfalfa	5.59	ton	312.85	83.80	335.20	12.21	9.44	25.66
	Barley	15.55	bu	17.10	6.22	5.44	0.67	0.70	0.42
	Canola	201.67	lb	7.66	3.63	1.86	0.30	0.41	0.14
	Corn (grain)	993.25	bu	744.94	437.03	288.04	29.07	49.23	22.05
	Corn (silage)	7.07	ton	58.65	25.44	58.65	2.29	2.87	4.49
	Corn (sweet)	0.79	ton	24.79	8.26	23.99	0.97	0.93	1.84
	Dry beans	2.50	cwt	8.90	2.33	3.83	0.35	0.26	0.29
	Oats	19.85	bu	15.88	4.96	3.97	0.62	0.56	0.30
	Other hay	1.44	ton	41.76	17.28	72.00	1.63	1.95	5.51
	Peas	0.13	ton	10.17	5.08	3.05	0.40	0.57	0.23
	Potatoes	20.14	cwt	7.05	3.02	11.28	0.28	0.34	0.86
	Rye	0.81	bu	1.13	0.39	0.24	0.04	0.04	0.02
	Soybeans	289.52	bu	1,158.07	231.61	405.32	45.20	26.09	31.03
	Sugar beets	9.47	ton	37.87	14.20	62.48	1.48	1.60	4.78
	Sunflower	154.12	lb	4.32	1.70	0.92	0.17	0.19	0.07
	Wheat	85.39	bu	111.01	42.70	29.89	4.33	4.81	2.29
	Total removal			**2,562.15**	**887.65**	**1,306.17**	**100.00**	**100.00**	**100.00**
MS	Blueberries (1998 only)	0.0014	ton	0.01	0.00	0.02	0.00	0.00	0.01
	Corn (grain)	39.26	bu	29.44	17.27	11.38	8.77	15.52	5.90
	Corn (silage)	0.26	ton	2.17	0.94	2.17	0.65	0.85	1.13
	Cotton	1.63	bale	52.12	22.80	30.94	15.53	20.49	16.04
	Melons (watermelon)	0.2005	cwt	0.03	0.03	0.05	0.01	0.02	0.03
	Other hay	1.54	ton	44.79	18.53	77.22	13.34	16.65	40.02
	Pecans	0.0323	cwt	0.52	0.29	0.29	0.16	0.26	0.15
	Rice	15.55	cwt	19.75	10.42	5.44	5.88	9.36	2.82
	Sorghum (grain)	4.64	bu	3.90	1.95	1.02	1.16	1.75	0.53
	Sorghum (silage)	0.026	ton	0.22	0.09	0.22	0.06	0.08	0.11
	Soybeans	42.47	bu	169.88	33.98	59.46	50.61	30.53	30.82
	Sweet potatoes	1.46	cwt	0.76	0.34	1.46	0.23	0.30	0.76
	Wheat	9.31	bu	12.10	4.65	3.26	3.60	4.18	1.69
	Total removal			**335.69**	**111.29**	**192.94**	**100.00**	**100.00**	**100.00**

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Appendix 4.1. Continued.

State or		Production[1],	Units	Nutrient removal[2], million lb			% of removal by crop		
province	Crop	million units	of yield	N	P_2O_5	K_2O	N	P_2O_5	K_2O
MO	Alfalfa	1.41	ton	78.87	21.13	84.50	6.28	5.15	11.46
	Apples	0.020	ton	0.12	0.07	0.34	0.01	0.02	0.05
	Corn (grain)	309.49	bu	232.12	136.17	89.75	18.48	33.23	12.17
	Corn (silage)	0.85	ton	7.10	3.08	7.10	0.56	0.75	0.96
	Cotton	0.45	bale	14.53	6.36	8.63	1.16	1.55	1.17
	Grapes	0.0027	ton	0.02	0.01	0.03	0.00	0.00	0.00
	Melons (watermelon)	1.2159	cwt	0.21	0.16	0.33	0.02	0.04	0.04
	Oats	1.07	bu	0.86	0.27	0.21	0.07	0.07	0.03
	Other hay	5.79	ton	167.81	69.44	289.33	13.36	16.94	39.23
	Peaches	0.0048	ton	0.03	0.01	0.04	0.00	0.00	0.01
	Potatoes	1.80	cwt	0.63	0.27	1.01	0.05	0.07	0.14
	Rice	9.00	cwt	11.43	6.03	3.15	0.91	1.47	0.43
	Sorghum (grain)	24.47	bu	20.55	10.28	5.38	1.64	2.51	0.73
	Sorghum (silage)	0.034	ton	0.28	0.12	0.28	0.02	0.03	0.04
	Soybeans	164.04	bu	656.17	131.23	229.66	52.23	32.02	31.14
	Tobacco	4.45	lb	0.15	0.02	0.22	0.01	0.01	0.03
	Wheat	50.35	bu	65.46	25.18	17.62	5.21	6.14	2.39
	Total removal			**1,256.33**	**409.83**	**737.60**	**100.00**	**100.00**	**100.00**
MT	Alfalfa	3.30	ton	184.61	49.45	197.80	37.27	29.25	56.23
	Barley	51.03	bu	56.14	20.41	17.86	11.33	12.07	5.08
	Corn (grain)	2.19	bu	1.64	0.96	0.64	0.33	0.57	0.18
	Corn (silage)	0.87	ton	7.20	3.12	7.20	1.45	1.85	2.05
	Dry beans	0.43	cwt	1.53	0.40	0.66	0.31	0.24	0.19
	Oats	3.02	bu	2.42	0.76	0.60	0.49	0.45	0.17
	Other hay	1.25	ton	36.20	14.98	62.42	7.31	8.86	17.74
	Potatoes	3.34	cwt	1.17	0.50	1.87	0.24	0.30	0.53
	Sugar beets	1.40	ton	5.88	2.10	9.23	1.19	1.24	2.63
	Wheat	152.77	bu	198.60	76.39	53.47	40.09	45.18	15.20
	Total removal			**495.38**	**169.07**	**351.74**	**100.00**	**100.00**	**100.00**
NE	Alfalfa	4.87	ton	272.81	73.08	292.30	13.13	8.94	27.41
	Barley	0.23	bu	0.25	0.09	0.08	0.01	0.01	0.01
	Corn (grain)	1,135.92	bu	851.94	499.80	329.42	41.00	61.13	30.89
	Corn (silage)	3.66	ton	30.35	13.16	30.35	1.46	1.61	2.85
	Dry beans	3.55	cwt	12.64	3.30	5.43	0.61	0.40	0.51
	Oats	3.95	bu	3.16	0.99	0.79	0.15	0.12	0.07
	Other hay	2.27	ton	65.93	27.28	113.67	3.17	3.34	10.66
	Potatoes	10.14	cwt	3.55	1.52	5.68	0.17	0.19	0.53
	Rye	0.35	bu	0.49	0.17	0.10	0.02	0.02	0.01
	Sorghum (grain)	44.72	bu	37.57	18.78	9.84	1.81	2.30	0.92
	Sorghum (silage)	0.29	ton	2.37	1.03	2.37	0.11	0.13	0.22
	Soybeans	173.16	bu	692.63	138.53	242.42	33.34	16.94	22.73
	Sugar beets	1.10	ton	4.63	1.65	7.27	0.22	0.20	0.68
	Sunflower	87.25	lb	2.44	0.96	0.52	0.12	0.12	0.05
	Wheat	74.60	bu	96.98	37.30	26.11	4.67	4.56	2.45
	Total removal			**2,077.73**	**817.64**	**1,066.35**	**100.00**	**100.00**	**100.00**
NV	Alfalfa	1.15	ton	64.61	17.31	69.22	81.91	74.74	76.41
	Barley	0.34	bu	0.37	0.14	0.12	0.47	0.58	0.13
	Other hay	0.38	ton	11.10	4.59	19.13	14.07	19.83	21.12
	Potatoes	2.94	cwt	1.03	0.44	1.64	1.30	1.90	1.82
	Wheat	1.36	bu	1.77	0.68	0.48	2.24	2.94	0.53
	Total removal			**78.87**	**23.15**	**90.59**	**100.00**	**100.00**	**100.00**
NH	Alfalfa	0.018	ton	1.03	0.28	1.10	16.65	11.21	13.27
	Apples	0.017	ton	0.10	0.06	0.28	1.61	2.42	3.34
	Corn (silage)	0.28	ton	2.28	0.99	2.28	37.01	40.37	27.54
	Corn (sweet)	0.11	cwt	0.17	0.06	0.16	2.73	2.29	1.97
	Other hay	0.089	ton	2.59	1.07	4.47	42.01	43.71	53.88
	Total removal			**6.17**	**2.45**	**8.29**	**100.00**	**100.00**	**100.00**
NM	Alfalfa	1.46	ton	82.00	21.97	87.86	61.10	48.67	69.71
	Apples	0.060	cwt	0.02	0.01	0.05	0.01	0.02	0.04
	Chilies (green-wet)	0.055	ton	0.83	0.32	1.31	0.62	0.70	1.04
	Chilies (red-dry)	0.024	ton	0.97	0.36	1.21	0.72	0.80	0.96
	Corn (grain)	13.55	bu	10.16	5.96	3.93	7.57	13.21	3.12
	Corn (silage)	1.48	ton	12.27	5.32	12.27	9.14	11.79	9.73

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Appendix 4.1. Continued.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb			% of removal by crop		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O
	Cotton	0.11	bale	3.37	1.47	2.00	2.51	3.26	1.59
	Dry beans	0.069	cwt	0.25	0.06	0.11	0.18	0.14	0.08
	Onions	3.380	cwt	1.01	0.44	0.91	0.76	0.97	0.72
	Other hay	0.18	ton	5.13	2.12	8.85	3.82	4.71	7.02
	Peanuts	59.54	lb	2.08	0.33	0.51	1.55	0.73	0.40
	Pecans (in shell)	0.020	ton	0.32	0.18	0.18	0.24	0.39	0.14
	Potatoes	3.58	cwt	1.25	0.54	2.00	0.93	1.19	1.59
	Sorghum (grain)	3.99	bu	3.35	1.68	0.88	2.50	3.72	0.70
	Sorghum (silage)	0.16	ton	1.32	0.57	1.32	0.99	1.27	1.05
	Wheat	7.60	bu	9.88	3.80	2.66	7.36	8.42	2.11
	Total removal			**134.22**	**45.13**	**126.04**	**100.00**	**100.00**	**100.00**
NJ	Alfalfa	0.085	ton	4.76	1.28	5.10	13.48	10.70	19.35
	Apples	0.027	ton	0.16	0.10	0.45	0.45	0.81	1.70
	Barley	0.29	bu	0.32	0.11	0.10	0.89	0.96	0.38
	Beans (snap)	0.16	cwt	0.28	0.07	0.33	0.78	0.55	1.24
	Cabbage	0.57	cwt	0.22	0.05	0.21	0.63	0.43	0.78
	Corn (grain)	7.10	bu	5.32	3.12	2.06	15.07	26.20	7.81
	Corn (silage)	0.21	ton	1.77	0.77	1.77	5.01	6.45	6.72
	Corn (sweet)	0.69	cwt	1.08	0.36	1.04	3.05	3.02	3.96
	Other hay	0.16	ton	4.67	1.93	8.05	13.22	16.22	30.55
	Peaches	0.034	ton	0.21	0.09	0.27	0.61	0.77	1.03
	Peppers (bell)	0.95	cwt	0.72	0.27	1.14	2.04	2.31	4.31
	Potatoes	0.68	cwt	0.24	0.10	0.38	0.67	0.86	1.45
	Rye	0.14	bu	0.20	0.07	0.04	0.56	0.57	0.16
	Soybeans	3.15	bu	12.58	2.52	4.40	35.62	21.12	16.71
	Sweet potatoes	0.11	cwt	0.06	0.03	0.11	0.16	0.21	0.42
	Tomatoes	0.03	ton	0.08	0.03	0.19	0.23	0.25	0.71
	Wheat	2.04	bu	2.66	1.02	0.72	7.52	8.58	2.71
	Total removal			**35.32**	**11.91**	**26.35**	**100.00**	**100.00**	**100.00**
NY	Alfalfa	1.25	ton	69.87	18.72	74.86	24.14	16.54	25.81
	Apples	0.56	ton	3.38	2.03	9.46	1.17	1.79	3.26
	Beans (snap)	2.00	cwt	3.44	0.82	4.08	1.19	0.72	1.41
	Cabbage	6.45	cwt	2.52	0.58	2.32	0.87	0.51	0.80
	Carrots	0.72	cwt	0.25	0.09	0.58	0.09	0.08	0.20
	Cauliflower	0.18	cwt	0.10	0.03	0.15	0.03	0.03	0.05
	Corn (grain)	57.58	bu	43.19	25.34	16.70	14.92	22.40	5.76
	Corn (silage)	8.25	ton	68.50	29.71	68.50	23.67	26.26	23.62
	Corn (sweet)	2.81	cwt	4.39	1.46	4.25	1.52	1.29	1.46
	Dry beans	0.40	cwt	1.42	0.37	0.61	0.49	0.33	0.21
	Grapes	0.16	ton	1.35	0.49	2.11	0.47	0.43	0.73
	Oats	5.06	bu	4.05	1.26	1.01	1.40	1.12	0.35
	Onions	3.98	cwt	1.20	0.52	1.08	0.41	0.46	0.37
	Other hay	1.81	ton	52.59	21.76	90.67	18.17	19.23	31.26
	Peaches	0.006	ton	0.04	0.02	0.05	0.01	0.01	0.02
	Pears	0.013	ton	0.07	0.02	0.08	0.03	0.02	0.03
	Peas	1.15	bu	2.75	1.38	0.81	0.95	1.22	0.28
	Potatoes	6.67	cwt	2.33	1.00	3.74	0.81	0.88	1.29
	Rye	0.55	bu	0.77	0.26	0.16	0.26	0.23	0.06
	Soybeans	4.36	bu	17.43	3.49	6.10	6.02	3.08	2.10
	Tomatoes	0.023	ton	0.06	0.02	0.13	0.02	0.02	0.04
	Wheat	7.52	bu	9.78	3.76	2.63	3.38	3.32	0.91
	Total removal			**289.46**	**113.13**	**290.08**	**100.00**	**100.00**	**100.00**
NC	Alfalfa	0.057	ton	3.17	0.85	3.40	0.89	0.73	1.51
	Barley	1.37	bu	1.50	0.55	0.48	0.42	0.47	0.21
	Corn (grain)	60.17	bu	45.13	26.47	17.45	12.59	22.79	7.77
	Corn (silage)	0.94	ton	7.80	3.38	7.80	2.18	2.91	3.47
	Cotton	1.09	bale	34.89	15.26	20.72	9.74	13.14	9.22
	Oats	1.77	bu	1.41	0.44	0.35	0.39	0.38	0.16
	Other hay	1.57	ton	45.51	18.83	78.47	12.70	16.21	34.92
	Peanuts	344.75	lb	12.07	1.90	2.93	3.37	1.63	1.30
	Potatoes	3.41	cwt	1.19	0.51	1.91	0.33	0.44	0.85
	Rye	0.54	bu	0.76	0.26	0.16	0.21	0.22	0.07
	Sorghum (grain)	0.56	bu	0.47	0.24	0.12	0.13	0.20	0.06

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Appendix 4.1. Continued.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb			% of removal by crop		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O
	Sorghum (silage)	0.042	ton	0.35	0.15	0.35	0.10	0.13	0.16
	Soybeans	37.44	bu	149.74	29.95	52.41	41.79	25.78	23.32
	Sweet potatoes	4.92	cwt	2.56	1.13	4.92	0.71	0.97	2.19
	Tobacco	469.07	lb	15.48	2.25	23.45	4.32	1.94	10.44
	Wheat	27.93	bu	36.31	13.97	9.78	10.13	12.02	4.35
	Total removal			**358.35**	**116.15**	**224.70**	**100.00**	**100.00**	**100.00**
ND	Alfalfa	2.94	ton	164.42	44.04	176.16	14.07	10.85	28.94
	Barley	87.67	bu	96.44	35.07	30.69	8.25	8.64	5.04
	Canola	1,294.17	lb	49.18	23.30	11.91	4.21	5.74	1.96
	Corn (grain)	89.69	bu	67.27	39.46	26.01	5.76	9.72	4.27
	Corn (silage)	1.26	ton	10.49	4.55	10.49	0.90	1.12	1.72
	Dry beans	8.56	cwt	30.47	7.96	13.10	2.61	1.96	2.15
	Oats	20.63	bu	16.50	5.16	4.13	1.41	1.27	0.68
	Other hay	2.00	ton	58.03	24.01	100.05	4.97	5.92	16.44
	Potatoes	27.34	cwt	9.57	4.10	15.31	0.82	1.01	2.52
	Rye	2.04	bu	2.86	0.98	0.61	0.24	0.24	0.10
	Soybeans	51.10	bu	204.40	40.88	71.54	17.49	10.07	11.75
	Sugar beets	5.22	ton	21.91	7.83	34.43	1.88	1.93	5.66
	Sunflower	2,192.57	lb	61.39	24.12	13.16	5.25	5.94	2.16
	Wheat	288.99	bu	375.68	144.49	101.15	32.15	35.59	16.62
	Total removal			**1,168.61**	**405.94**	**608.72**	**100.00**	**100.00**	**100.00**
OH	Alfalfa	2.00	ton	112.09	30.03	120.10	8.27	6.74	18.53
	Corn (grain)	453.08	bu	339.81	199.36	131.39	25.08	44.74	20.28
	Corn (silage)	2.83	ton	23.49	10.19	23.49	1.73	2.29	3.63
	Oats	6.78	bu	5.42	1.70	1.36	0.40	0.38	0.21
	Other hay	1.82	ton	52.69	21.80	90.85	3.89	4.89	14.02
	Potatoes	1.11	cwt	0.39	0.17	0.62	0.03	0.04	0.10
	Rye	0.14	bu	0.20	0.07	0.04	0.01	0.02	0.01
	Soybeans	180.55	bu	722.19	144.44	252.77	53.30	32.42	39.01
	Sugar beets	0.023	ton	0.10	0.03	0.15	0.01	0.01	0.02
	Tobacco	16.06	lb	0.53	0.08	0.80	0.04	0.02	0.12
	Wheat	75.42	bu	98.05	37.71	26.40	7.24	8.46	4.07
	Total removal			**1,354.95**	**445.56**	**647.97**	**100.00**	**100.00**	**100.00**
OK	Alfalfa	1.09	ton	60.83	16.30	65.18	13.47	9.52	20.33
	Barley	0.18	bu	0.20	0.07	0.06	0.04	0.04	0.02
	Corn (grain)	35.67	bu	26.75	15.69	10.34	5.92	9.17	3.23
	Corn (silage)	0.42	ton	3.47	1.51	3.47	0.77	0.88	1.08
	Cotton	0.15	bale	4.65	2.03	2.76	1.03	1.19	0.86
	Melons (watermelon)	0.600	cwt	0.10	0.08	0.16	0.02	0.05	0.05
	Oats	0.92	bu	0.74	0.23	0.18	0.16	0.13	0.06
	Other hay	3.33	ton	96.57	39.96	166.50	21.39	23.34	51.93
	Peaches	0.0082	ton	0.05	0.02	0.07	0.01	0.01	0.02
	Peanuts	156.65	lb	5.48	0.86	1.33	1.21	0.50	0.42
	Pecans	0.011	ton	0.18	0.10	0.10	0.04	0.06	0.03
	Rye	1.29	bu	1.81	0.62	0.39	0.40	0.36	0.12
	Sorghum (grain)	15.66	bu	13.15	6.58	3.45	2.91	3.84	1.07
	Sorghum (silage)	0.14	ton	1.13	0.49	1.13	0.25	0.29	0.35
	Soybeans	5.77	bu	23.08	4.62	8.08	5.11	2.70	2.52
	Wheat	164.07	bu	213.29	82.03	57.42	47.24	47.92	17.91
	Total removal			**451.50**	**171.19**	**320.63**	**100.00**	**100.00**	**100.00**
OR	Alfalfa	1.80	ton	100.91	27.03	108.12	40.28	31.58	45.41
	Barley	7.78	bu	8.56	3.11	2.72	3.42	3.64	1.14
	Beans (snap)	0.13	ton	4.49	1.07	5.32	1.79	1.25	2.24
	Corn (grain)	5.58	bu	4.19	2.46	1.62	1.67	2.87	0.68
	Corn (silage)	0.46	ton	3.86	1.67	3.86	1.54	1.95	1.62
	Corn (sweet)	0.33	ton	10.16	3.39	9.83	4.05	3.96	4.13
	Dry beans	0.18	cwt	0.64	0.17	0.28	0.26	0.20	0.12
	Oats	2.77	bu	2.21	0.69	0.55	0.88	0.81	0.23
	Other hay	1.40	ton	40.54	16.78	69.90	16.18	19.60	29.36
	Potatoes	28.31	cwt	9.91	4.25	15.85	3.96	4.96	6.66
	Sugar beets	0.46	ton	1.93	0.69	3.03	0.77	0.81	1.27
	Wheat	48.56	bu	63.13	24.28	17.00	25.20	28.37	7.14
	Total removal			**250.53**	**85.58**	**238.08**	**100.00**	**100.00**	**100.00**

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Appendix 4.1. Continued.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb			% of removal by crop		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O
PA	Alfalfa	1.89	ton	105.56	28.28	113.10	27.01	19.20	33.46
	Barley	5.11	bu	5.62	2.04	1.79	1.44	1.39	0.53
	Beans (snap)	0.39	cwt	0.68	0.16	0.80	0.17	0.11	0.24
	Cabbage	0.33	cwt	0.13	0.03	0.12	0.03	0.02	0.04
	Corn (grain)	105.10	bu	78.83	46.25	30.48	20.17	31.41	9.02
	Corn (silage)	7.29	ton	60.47	26.23	60.47	15.47	17.81	17.89
	Corn (sweet)	0.90	cwt	1.40	0.47	1.35	0.36	0.32	0.40
	Grapes	0.069	ton	0.57	0.21	0.89	0.15	0.14	0.26
	Oats	8.24	bu	6.59	2.06	1.65	1.69	1.40	0.49
	Other hay	2.02	ton	58.48	24.20	100.83	14.97	16.44	29.84
	Peaches	0.033	ton	0.21	0.09	0.27	0.05	0.06	0.08
	Pears	0.0048	ton	0.03	0.01	0.03	0.01	0.01	0.01
	Potatoes	3.32	cwt	1.16	0.50	1.86	0.30	0.34	0.55
	Rye	0.55	bu	0.77	0.26	0.16	0.20	0.18	0.05
	Soybeans	14.17	bu	56.67	11.33	19.84	14.50	7.70	5.87
	Tobacco	12.35	lb	0.41	0.06	0.62	0.10	0.04	0.18
	Tomatoes	0.032	ton	0.08	0.03	0.18	0.02	0.02	0.05
	Wheat	10.10	bu	13.12	5.05	3.53	3.36	3.43	1.05
	Total removal			**390.77**	**147.24**	**337.97**	**100.00**	**100.00**	**100.00**
RI	Alfalfa	0.0037	ton	0.21	0.06	0.22	17.32	11.87	14.07
	Apples	0.0014	ton	0.01	0.01	0.02	0.71	1.09	1.50
	Corn (silage)	0.047	ton	0.39	0.17	0.39	32.68	36.27	24.77
	Corn (sweet)	0.058	cwt	0.09	0.03	0.09	7.63	6.51	5.60
	Other hay	0.015	ton	0.44	0.18	0.77	37.52	39.72	49.04
	Potatoes	0.140	cwt	0.05	0.02	0.08	4.13	4.53	5.01
	Total removal			**1.19**	**0.46**	**1.56**	**100.00**	**100.00**	**100.00**
SC	Barley	0.13	bu	0.14	0.05	0.04	0.14	0.15	0.07
	Corn (grain)	16.15	bu	12.11	7.11	4.68	11.92	20.72	6.88
	Corn (silage)	0.16	ton	1.36	0.59	1.36	1.33	1.71	1.99
	Cotton	0.34	bale	10.77	4.71	6.40	10.60	13.74	9.40
	Oats	1.68	bu	1.35	0.42	0.34	1.32	1.23	0.49
	Other hay	0.66	ton	19.24	7.96	33.17	18.93	23.21	48.76
	Peanuts	27.66	lb	0.97	0.15	0.24	0.95	0.44	0.35
	Rye	0.45	bu	0.63	0.22	0.14	0.62	0.63	0.20
	Sorghum (grain)	0.24	bu	0.20	0.10	0.05	0.20	0.30	0.08
	Sorghum (silage)	0.016	ton	0.14	0.06	0.14	0.13	0.17	0.20
	Soybeans	10.08	bu	40.33	8.07	14.12	39.70	23.52	20.75
	Sweet potatoes	0.060	cwt	0.03	0.01	0.06	0.03	0.04	0.09
	Tobacco	83.84	lb	2.77	0.40	4.19	2.72	1.17	6.16
	Wheat	8.90	bu	11.57	4.45	3.11	11.39	12.97	4.58
	Total removal			**101.60**	**34.30**	**68.03**	**100.00**	**100.00**	**100.00**
SD	Alfalfa	5.97	ton	334.38	89.56	358.26	21.77	17.53	40.37
	Barley	4.63	bu	5.09	1.85	1.62	0.33	0.36	0.18
	Corn (grain)	409.33	bu	307.00	180.11	118.71	19.99	35.25	13.37
	Corn (silage)	3.83	ton	31.79	13.79	31.79	2.07	2.70	3.58
	Oats	15.44	bu	12.35	3.86	3.09	0.80	0.76	0.35
	Other hay	2.36	ton	68.44	28.32	118.00	4.46	5.54	13.30
	Potatoes	1.02	cwt	0.36	0.15	0.57	0.02	0.03	0.06
	Rye	1.21	bu	1.69	0.58	0.36	0.11	0.11	0.04
	Sorghum (grain)	6.82	bu	5.73	2.86	1.50	0.37	0.56	0.17
	Sorghum (silage)	0.33	ton	2.76	1.20	2.76	0.18	0.23	0.31
	Soybeans	144.02	bu	576.09	115.22	201.63	37.51	22.55	22.72
	Sunflower	1,290.38	lb	36.13	14.19	7.74	2.35	2.78	0.87
	Wheat	118.58	bu	154.15	59.29	41.50	10.04	11.60	4.68
	Total removal			**1,535.96**	**510.99**	**887.53**	**100.00**	**100.00**	**100.00**
TN	Alfalfa	0.11	ton	6.38	1.71	6.84	1.87	1.39	2.28
	Apples	0.0043	ton	0.03	0.02	0.07	0.01	0.01	0.02
	Beans (snap)	0.305	cwt	0.52	0.12	0.62	0.15	0.10	0.21
	Corn (grain)	61.64	bu	46.23	27.12	17.88	13.52	22.08	5.96
	Corn (silage)	0.87	ton	7.23	3.14	7.23	2.12	2.56	2.41
	Cotton	0.62	bale	19.74	8.64	11.72	5.77	7.03	3.91
	Other hay	4.05	ton	117.45	48.60	202.50	34.35	39.57	67.56
	Peaches	0.0014	ton	0.01	0.00	0.01	0.00	0.00	0.00

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Appendix 4.1. Continued.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb			% of removal by crop		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O
	Sorghum (grain)	1.34	bu	1.13	0.56	0.30	0.33	0.46	0.10
	Sorghum (silage)	0.019	ton	0.15	0.07	0.15	0.05	0.05	0.05
	Soybeans	28.88	bu	115.52	23.10	40.43	33.78	18.81	13.49
	Squash (2000 only)	0.104	cwt	0.04	0.01	0.06	0.01	0.01	0.02
	Tobacco	109.89	lb	3.63	0.53	5.49	1.06	0.43	1.83
	Wheat	18.37	bu	23.88	9.19	6.43	6.98	7.48	2.14
	Total removal			**341.96**	**122.81**	**299.75**	**100.00**	**100.00**	**100.00**
TX	Alfalfa	0.61	ton	34.07	9.13	36.50	3.47	2.13	4.73
	Barley	0.30	bu	0.34	0.12	0.11	0.03	0.03	0.01
	Cabbage	3.54	cwt	1.38	0.33	1.28	0.14	0.08	0.17
	Carrots	0.96	cwt	0.34	0.12	0.77	0.03	0.03	0.10
	Celery	0.29	cwt	0.05	0.03	0.14	0.01	0.01	0.02
	Corn (grain)	216.31	bu	162.23	95.18	62.73	16.50	22.25	8.14
	Corn (silage)	2.59	ton	21.47	9.31	21.47	2.18	2.18	2.78
	Corn (sweet)	0.42	cwt	0.66	0.22	0.64	0.07	0.05	0.08
	Cotton	4.24	bale	135.66	59.35	80.55	13.80	13.88	10.45
	Cucumbers	0.21	cwt	0.04	0.01	0.07	0.00	0.00	0.01
	Dry beans	0.33	cwt	1.17	0.31	0.50	0.12	0.07	0.07
	Grapefruit	4.49	cwt	0.48	0.13	1.08	0.05	0.03	0.14
	Melons (cantaloupe)	1.98	cwt	0.72	0.23	1.29	0.07	0.05	0.17
	Melons (honeydew)	0.53	cwt	0.19	0.06	0.34	0.02	0.01	0.04
	Melons (watermelon)	6.52	cwt	1.11	0.85	1.76	0.11	0.20	0.23
	Oats	5.34	bu	4.27	1.34	1.07	0.43	0.31	0.14
	Onions	4.77	cwt	1.43	0.62	1.29	0.15	0.15	0.17
	Oranges	1.33	cwt	0.59	0.12	0.73	0.06	0.03	0.09
	Other hay	9.02	ton	261.58	108.24	451.00	26.61	25.31	58.60
	Peaches	0.010	ton	0.06	0.03	0.08	0.01	0.01	0.01
	Peanuts	847.73	lb	29.67	4.66	7.21	3.02	1.09	0.93
	Pecans	0.025	ton	0.40	0.22	0.23	0.04	0.05	0.03
	Peppers (bell)	0.23	cwt	0.18	0.07	0.28	0.02	0.02	0.04
	Potatoes	5.11	cwt	1.79	0.77	2.86	0.18	0.18	0.37
	Rice	15.15	cwt	19.24	10.15	5.30	1.96	2.37	0.69
	Rye	0.42	bu	0.59	0.20	0.13	0.06	0.05	0.02
	Sorghum (grain)	145.00	bu	121.80	60.90	30.45	12.39	14.24	3.96
	Sorghum (silage)	0.70	ton	5.78	2.51	5.78	0.59	0.59	0.75
	Soybeans	7.74	bu	30.96	6.19	10.84	3.15	1.45	1.41
	Spinach	0.20	cwt	0.07	0.04	0.14	0.01	0.01	0.02
	Sugar cane	1.30	ton	2.59	1.62	4.53	0.26	0.38	0.59
	Sunflower	41.67	lb	1.17	0.46	0.25	0.12	0.11	0.03
	Sweet potatoes	0.28	cwt	0.14	0.06	0.28	0.01	0.01	0.04
	Tomatoes	0.17	cwt	0.02	0.01	0.05	0.00	0.00	0.01
	Wheat	108.30	bu	140.79	54.15	37.91	14.32	12.66	4.92
	Total removal			**983.05**	**427.73**	**769.61**	**100.00**	**100.00**	**100.00**
UT	Alfalfa	2.32	ton	130.18	34.87	139.48	77.45	69.23	81.87
	Barley	6.44	bu	7.08	2.58	2.25	4.21	5.11	1.32
	Corn (grain)	3.09	bu	2.32	1.36	0.90	1.38	2.70	0.53
	Corn (silage)	0.83	ton	6.91	3.00	6.91	4.11	5.95	4.06
	Dry beans	0.031	cwt	0.11	0.03	0.05	0.07	0.06	0.03
	Oats	0.60	bu	0.48	0.15	0.12	0.28	0.30	0.07
	Other hay	0.35	ton	10.13	4.19	17.47	6.03	8.32	10.25
	Potatoes	0.58	cwt	0.20	0.09	0.33	0.12	0.17	0.19
	Wheat	8.21	bu	10.67	4.10	2.87	6.35	8.15	1.69
	Total removal			**168.09**	**50.37**	**170.38**	**100.00**	**100.00**	**100.00**
VT	Alfalfa	0.094	ton	5.25	1.41	5.62	18.01	12.14	15.17
	Apples	0.022	ton	0.13	0.08	0.37	0.45	0.68	1.00
	Corn (silage)	1.63	ton	13.55	5.88	13.55	46.51	50.77	36.56
	Corn (sweet)	0.056	cwt	0.09	0.03	0.08	0.30	0.25	0.23
	Other hay	0.35	ton	10.11	4.18	17.43	34.72	36.15	47.05
	Total removal			**29.12**	**11.57**	**37.05**	**100.00**	**100.00**	**100.00**
VA	Alfalfa	0.37	ton	20.61	5.52	22.08	9.48	7.19	11.03
	Apples	0.16	ton	0.98	0.59	2.74	0.45	0.77	1.37
	Corn (grain)	31.74	bu	23.81	13.97	9.20	10.95	18.19	4.60
	Corn (silage)	2.19	ton	18.15	7.87	18.15	8.35	10.25	9.07

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Appendix 4.1. Continued.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb			% of removal by crop		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O
	Cotton	0.15	bale	4.84	2.12	2.87	2.23	2.76	1.44
	Other hay	2.29	ton	66.51	27.52	114.67	30.59	35.84	57.29
	Peanuts	216.58	lb	7.58	1.19	1.84	3.49	1.55	0.92
	Potatoes	1.24	cwt	0.43	0.19	0.69	0.20	0.24	0.35
	Rye	0.22	bu	0.31	0.11	0.07	0.14	0.14	0.03
	Soybeans	13.80	bu	55.20	11.04	19.32	25.39	14.38	9.65
	Sweet potatoes	0.10	cwt	0.05	0.02	0.10	0.02	0.03	0.05
	Tobacco	80.46	lb	2.66	0.39	4.02	1.22	0.50	2.01
	Wheat	12.54	bu	16.30	6.27	4.39	7.50	8.17	2.19
	Total removal			**217.43**	**76.79**	**200.15**	**100.00**	**100.00**	**100.00**
WA	Alfalfa	2.35	ton	131.66	35.27	141.06	26.99	20.01	39.64
	Barley	32.34	bu	35.57	12.93	11.32	7.29	7.34	3.18
	Carrots (all)	0.24	ton	1.67	0.62	3.81	0.34	0.35	1.07
	Corn (grain)	18.50	bu	13.88	8.14	5.37	2.84	4.62	1.51
	Corn (silage)	1.45	ton	12.06	5.23	12.06	2.47	2.97	3.39
	Corn (sweet)	0.83	ton	25.91	8.64	25.08	5.31	4.90	7.05
	Dry beans	0.76	cwt	2.71	0.71	1.16	0.55	0.40	0.33
	Oats	1.13	bu	0.90	0.28	0.23	0.18	0.16	0.06
	Other hay	0.80	ton	23.31	9.64	40.18	4.78	5.47	11.29
	Peas	0.11	ton	8.49	4.25	2.55	1.74	2.41	0.72
	Potatoes	97.81	cwt	34.23	14.67	54.77	7.02	8.33	15.39
	Sugar beets	0.94	ton	3.95	1.41	6.20	0.81	0.80	1.74
	Wheat	148.82	bu	193.46	74.41	52.09	39.66	42.23	14.64
	Total removal			**487.78**	**176.19**	**355.87**	**100.00**	**100.00**	**100.00**
WV	Alfalfa	0.14	ton	7.75	2.08	8.30	18.72	12.62	13.67
	Apples	0.057	ton	0.34	0.20	0.95	0.82	1.24	1.57
	Corn (grain)	2.86	bu	2.14	1.26	0.83	5.18	7.65	1.36
	Corn (silage)	0.34	ton	2.82	1.22	2.82	6.81	7.44	4.64
	Oats	0.13	bu	0.10	0.03	0.03	0.25	0.20	0.04
	Other hay	0.95	ton	27.56	11.40	47.52	66.59	69.37	78.28
	Tobacco	1.96	lb	0.06	0.01	0.10	0.16	0.06	0.16
	Wheat	0.47	bu	0.61	0.23	0.16	1.47	1.42	0.27
	Total removal			**41.39**	**16.44**	**60.70**	**100.00**	**100.00**	**100.00**
WI	Alfalfa	5.74	ton	321.63	86.15	344.60	30.76	22.37	46.63
	Barley	3.32	bu	3.65	1.33	1.16	0.35	0.34	0.16
	Beans (snap)	0.24	ton	8.37	2.00	9.93	0.80	0.52	1.34
	Corn (grain)	391.57	bu	293.68	172.29	113.55	28.09	44.74	15.37
	Corn (silage)	11.87	ton	98.51	42.73	98.51	9.42	11.09	13.33
	Corn (sweet)	12.90	cwt	20.11	6.70	19.46	1.92	1.74	2.63
	Dry beans	0.13	cwt	0.46	0.12	0.20	0.04	0.03	0.03
	Oats	18.65	bu	14.92	4.66	3.73	1.43	1.21	0.50
	Other hay	0.88	ton	25.62	10.60	44.17	2.45	2.75	5.98
	Peas	0.092	ton	7.37	3.69	2.21	0.71	0.96	0.30
	Potatoes	32.90	cwt	11.51	4.93	18.42	1.10	1.28	2.49
	Rye	0.37	bu	0.52	0.18	0.11	0.05	0.05	0.02
	Soybeans	57.17	bu	228.67	45.73	80.03	21.87	11.88	10.83
	Tobacco	3.10	lb	0.10	0.01	0.16	0.01	0.00	0.02
	Wheat	7.95	bu	10.33	3.97	2.78	0.99	1.03	0.38
	Total removal			**1,045.44**	**385.09**	**739.03**	**100.00**	**100.00**	**100.00**
WY	Alfalfa	1.59	ton	89.00	23.84	95.36	59.44	49.08	59.50
	Barley	7.45	bu	8.19	2.98	2.61	5.47	6.13	1.63
	Corn (grain)	7.31	bu	5.49	3.22	2.12	3.66	6.62	1.32
	Corn (silage)	0.64	ton	5.30	2.30	5.30	3.54	4.74	3.31
	Dry beans	0.79	cwt	2.81	0.73	1.21	1.88	1.51	0.75
	Oats	1.46	bu	1.16	0.36	0.29	0.78	0.75	0.18
	Other hay	0.87	ton	25.34	10.48	43.68	16.92	21.58	27.26
	Potatoes	0.14	cwt	0.05	0.02	0.08	0.03	0.04	0.05
	Sugar beets	1.15	ton	4.82	1.72	7.58	3.22	3.55	4.73
	Wheat	5.82	bu	7.57	2.91	2.04	5.06	5.99	1.27
	Total removal			**149.74**	**48.57**	**160.27**	**100.00**	**100.00**	**100.00**

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Appendix 4.1. Continued.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb			% of removal by crop		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O
AB	Alfalfa	3.78	ton	211.68	56.70	226.80	17.70	12.55	37.35
	Barley & mixed grain	256.75	bu	282.43	102.70	89.86	23.62	22.74	14.80
	Canola	5,075.00	lb	192.85	91.35	46.69	16.13	20.23	7.69
	Corn (grain)	0.78	bu	0.58	0.34	0.22	0.05	0.08	0.04
	Corn (silage)	0.41	ton	3.36	1.46	3.36	0.28	0.32	0.55
	Dry beans	0.98	cwt	3.49	0.91	1.50	0.29	0.20	0.25
	Dry peas	20.35	bu	48.84	24.42	14.45	4.08	5.41	2.38
	Flaxseed	1.15	bu	2.30	1.27	0.75	0.19	0.28	0.12
	Lentils	0.34	bu	0.67	0.21	0.37	0.06	0.05	0.06
	Mustard	58.90	lbs	2.18	1.00	0.65	0.18	0.22	0.11
	Oats	46.30	bu	37.04	11.58	9.26	3.10	2.56	1.52
	Other hay	2.19	ton	63.37	26.22	109.25	5.30	5.81	17.99
	Potatoes	12.15	cwt	4.25	1.82	6.80	0.36	0.40	1.12
	Rye	2.39	bu	3.34	1.14	0.72	0.28	0.25	0.12
	Sugar beets	0.94	ton	3.76	1.41	6.20	0.31	0.31	1.02
	Sunflower	10.35	lb	0.29	0.11	0.06	0.02	0.03	0.01
	Wheat	257.95	bu	335.33	128.97	90.28	28.04	28.56	14.87
	Total removal			**1,195.76**	**451.62**	**607.23**	**100.00**	**100.00**	**100.00**
BC	Alfalfa	0.58	ton	32.48	8.70	34.80	43.02	33.12	43.90
	Barley & mixed grain	4.67	bu	5.14	1.87	1.64	6.81	7.12	2.06
	Canola	128.40	lb	4.88	2.31	1.18	6.46	8.80	1.49
	Corn (silage)	0.53	ton	4.36	1.89	4.36	5.77	7.20	5.50
	Dry peas	0.37	bu	0.89	0.44	0.26	1.18	1.69	0.33
	Oats	3.79	bu	3.03	0.95	0.76	4.02	3.61	0.96
	Other hay	0.68	ton	19.72	8.16	34.00	26.12	31.06	42.89
	Potatoes	2.04	cwt	0.71	0.31	1.14	0.95	1.16	1.44
	Rye	0.16	bu	0.22	0.08	0.05	0.30	0.29	0.06
	Wheat	3.13	bu	4.06	1.56	1.09	5.38	5.95	1.38
	Total Removal			**75.50**	**26.27**	**79.28**	**100.00**	**100.00**	**100.00**
MB	Alfalfa	2.27	ton	127.40	34.13	136.50	18.78	13.14	41.16
	Barley & mixed grain	75.40	bu	82.94	30.16	26.39	12.22	11.61	7.96
	Canola	3,605.00	lbs	136.99	64.89	33.17	20.19	24.98	10.00
	Corn (grain)	9.45	bu	7.09	4.16	2.74	1.04	1.60	0.83
	Corn (silage)	0.45	ton	3.73	1.62	3.73	0.55	0.62	1.13
	Dry beans	2.43	cwt	8.65	2.26	3.72	1.27	0.87	1.12
	Dry peas	7.10	bu	17.04	8.52	5.04	2.51	3.28	1.52
	Flaxseed	11.30	bu	22.60	12.43	7.34	3.33	4.79	2.21
	Lentils	0.41	bu	0.81	0.25	0.45	0.12	0.10	0.13
	Mustard	7.45	lb	0.28	0.13	0.08	0.04	0.05	0.02
	Oats	66.35	bu	53.08	16.59	13.27	7.82	6.39	4.00
	Other hay	0.78	ton	22.48	9.30	38.75	3.31	3.58	11.68
	Potatoes	18.10	cwt	6.34	2.71	10.14	0.93	1.05	3.06
	Rye	3.20	bu	4.48	1.54	0.96	0.66	0.59	0.29
	Sunflower	207.25	lb	5.80	2.28	1.24	0.86	0.88	0.37
	Wheat	137.55	bu	178.82	68.78	48.14	26.35	26.48	14.52
	Total Removal			**678.52**	**259.73**	**331.66**	**100.00**	**100.00**	**100.00**
ON	Alfalfa	3.02	ton	169.12	45.30	181.20	18.94	15.40	32.65
	Apples	0.30	ton	1.81	1.09	5.08	0.20	0.37	0.92
	Barley & mixed grain	29.65	bu	32.62	11.86	10.38	3.65	4.03	1.87
	Beans (snap)	0.47	cwt	0.81	0.19	0.96	0.09	0.07	0.17
	Blueberries	0.00074	ton	0.01	0.00	0.01	0.00	0.00	0.00
	Broccoli	0.13	cwt	0.06	0.02	0.05	0.01	0.01	0.01
	Cabbage	0.91	cwt	0.36	0.08	0.33	0.04	0.03	0.06
	Canola	97.00	lb	3.69	1.75	0.89	0.41	0.59	0.16
	Carrots	2.55	cwt	0.89	0.33	2.04	0.10	0.11	0.37
	Cauliflower	0.43	cwt	0.23	0.08	0.34	0.03	0.03	0.06
	Celery	0.29	cwt	0.06	0.03	0.15	0.01	0.01	0.03
	Corn (grain)	206.75	bu	155.06	90.97	59.96	17.37	30.92	10.80
	Corn (silage)	3.90	ton	32.37	14.04	32.37	3.63	4.77	5.83
	Corn (sweet)	4.07	cwt	6.34	2.11	6.14	0.71	0.72	1.11
	Cucumbers	2.42	cwt	0.48	0.17	0.80	0.05	0.06	0.14
	Dry beans	1.27	cwt	4.52	1.18	1.94	0.51	0.40	0.35
	Grapes	0.058	ton	0.48	0.17	0.76	0.05	0.06	0.14

Continued next page

Appendix 4.1. Continued.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb			% of removal by crop		
				N	P_2O_5	K_2O	N	P_2O_5	K_2O
	Lettuce	0.21	cwt	0.05	0.02	0.11	0.01	0.01	0.02
	Melons	0.10	cwt	0.04	0.01	0.07	0.00	0.00	0.01
	Oats	5.20	bu	4.16	1.30	1.04	0.47	0.44	0.19
	Onions	1.69	cwt	0.51	0.22	0.46	0.06	0.07	0.08
	Other hay	2.03	ton	58.87	24.36	101.50	6.59	8.28	18.29
	Peaches	0.025	ton	0.16	0.07	0.20	0.02	0.02	0.04
	Pears	0.0093	ton	0.05	0.02	0.06	0.01	0.01	0.01
	Peas	1.38	bu	3.32	1.66	0.98	0.37	0.56	0.18
	Peppers (bell)	0.43	cwt	0.33	0.12	0.51	0.04	0.04	0.09
	Potatoes	7.70	cwt	2.69	1.16	4.31	0.30	0.39	0.78
	Pumpkins/squash	0.43	cwt	0.18	0.04	0.26	0.02	0.01	0.05
	Rye	2.30	bu	3.22	1.10	0.69	0.36	0.38	0.12
	Soybeans	85.50	bu	342.00	68.40	119.70	38.30	23.25	21.57
	Strawberries	0.18	cwt	0.15	0.07	0.05	0.02	0.02	0.01
	Tomatoes	0.66	ton	1.64	0.60	3.74	0.18	0.21	0.67
	Wheat	51.25	bu	66.63	25.63	17.94	7.46	8.71	3.23
	Total removal			**892.90**	**294.16**	**555.01**	**100.00**	**100.00**	**100.00**
QC	Alfalfa	1.16	ton	64.96	17.40	69.60	18.18	12.82	21.02
	Apples	0.11	ton	0.63	0.38	1.77	0.18	0.28	0.54
	Barley & mixed grain	22.50	bu	24.75	9.00	7.88	6.93	6.63	2.38
	Beans (snap)	0.61	cwt	1.05	0.25	1.25	0.29	0.18	0.38
	Blueberries	0.012	ton	0.10	0.04	0.15	0.03	0.03	0.05
	Cabbage	1.59	cwt	0.62	0.14	0.57	0.17	0.11	0.17
	Canola	32.00	lb	1.22	0.58	0.29	0.34	0.42	0.09
	Carrots	2.30	cwt	0.81	0.30	1.84	0.23	0.22	0.56
	Cauliflower	0.34	cwt	0.18	0.06	0.27	0.05	0.05	0.08
	Celery	0.43	cwt	0.08	0.05	0.22	0.02	0.03	0.07
	Corn (grain)	92.30	bu	69.23	40.61	26.77	19.37	29.93	8.09
	Corn (silage)	1.43	ton	11.83	5.13	11.83	3.31	3.78	3.57
	Corn (sweet)	1.95	cwt	3.04	1.01	2.94	0.85	0.75	0.89
	Cucumbers	0.68	cwt	0.14	0.05	0.23	0.04	0.04	0.07
	Dry beans	0.28	cwt	1.00	0.26	0.43	0.28	0.19	0.13
	Lettuce	1.31	cwt	0.31	0.10	0.66	0.09	0.08	0.20
	Oats	12.25	bu	9.80	3.06	2.45	2.74	2.26	0.74
	Onions	1.41	cwt	0.42	0.18	0.38	0.12	0.14	0.12
	Other hay	3.48	ton	100.92	41.76	174.00	28.24	30.78	52.56
	Peas	0.63	bu	1.52	0.76	0.45	0.42	0.56	0.14
	Peppers (bell)	0.26	cwt	0.20	0.07	0.31	0.05	0.05	0.09
	Potatoes	10.25	cwt	3.59	1.54	5.74	1.00	1.13	1.73
	Rye	0.12	bu	0.16	0.06	0.03	0.05	0.04	0.01
	Soybeans	14.20	bu	56.80	11.36	19.88	15.90	8.37	6.00
	Strawberries	0.21	cwt	0.17	0.08	0.05	0.05	0.06	0.02
	Tomatoes	0.010	ton	0.02	0.01	0.06	0.01	0.01	0.02
	Wheat	2.90	bu	3.77	1.45	1.02	1.06	1.07	0.31
	Total removal			**357.31**	**135.69**	**331.06**	**100.00**	**100.00**	**100.00**
SK	Alfalfa	2.67	ton	149.52	40.05	160.20	8.82	5.95	25.03
	Barley & mixed grain	226.15	bu	248.77	90.46	79.15	14.67	13.45	12.37
	Canola	7,275.00	lb	276.45	130.95	66.93	16.30	19.46	10.46
	Dry peas	67.75	bu	162.60	81.30	48.10	9.59	12.08	7.51
	Flaxseed	23.00	bu	46.00	25.30	14.95	2.71	3.76	2.34
	Lentils	24.85	bu	49.70	15.41	27.34	2.93	2.29	4.27
	Mustard	419.65	lb	15.53	7.13	4.62	0.92	1.06	0.72
	Oats	101.65	bu	81.32	25.41	20.33	4.79	3.78	3.18
	Other hay	0.91	ton	26.25	10.86	45.25	1.55	1.61	7.07
	Potatoes	2.95	cwt	1.03	0.44	1.65	0.06	0.07	0.26
	Rye	4.92	bu	6.90	2.36	1.48	0.41	0.35	0.23
	Sunflower	13.68	lb	0.38	0.15	0.08	0.02	0.02	0.01
	Wheat	485.85	bu	631.61	242.93	170.05	37.24	36.11	26.56
	Total removal			**1,696.04**	**672.76**	**640.13**	**100.00**	**100.00**	**100.00**
Atlantic	Alfalfa	0.16	ton	8.96	2.40	9.60	11.51	7.97	9.63
	Apples	0.080	ton	0.48	0.29	1.34	0.62	0.96	1.35
	Barley & mixed grain	10.75	bu	11.83	4.30	3.76	15.19	14.28	3.77
	Beans (snap)	0.019	cwt	0.03	0.01	0.04	0.04	0.03	0.04

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Appendix 4.1. Continued.

State or province	Crop	Production[1], million units	Units of yield	Nutrient removal[2], million lb N	P_2O_5	K_2O	% of removal by crop N	P_2O_5	K_2O
	Blueberries	0.022	ton	0.18	0.07	0.28	0.23	0.22	0.29
	Broccoli	0.027	cwt	0.01	0.00	0.01	0.02	0.02	0.01
	Cabbage	0.17	cwt	0.07	0.02	0.06	0.09	0.05	0.06
	Carrots	0.78	cwt	0.27	0.10	0.63	0.35	0.34	0.63
	Cauliflower	0.044	cwt	0.02	0.01	0.03	0.03	0.03	0.04
	Corn (silage)	0.090	ton	0.75	0.32	0.75	0.96	1.08	0.75
	Corn (sweet)	0.059	cwt	0.09	0.03	0.09	0.12	0.10	0.09
	Lettuce	0.021	cwt	0.01	0.00	0.01	0.01	0.01	0.01
	Oats	2.61	bu	2.09	0.65	0.52	2.68	2.17	0.52
	Onions	0.23	cwt	0.07	0.03	0.06	0.09	0.10	0.06
	Other hay	1.12	ton	32.48	13.44	56.00	41.71	44.63	56.16
	Peas	0.040	bu	0.10	0.05	0.03	0.12	0.16	0.03
	Potatoes	44.90	cwt	15.72	6.74	25.14	20.18	22.36	25.21
	Pumpkins/squash	0.035	cwt	0.01	0.00	0.02	0.02	0.01	0.02
	Soybeans	0.20	bu	0.80	0.16	0.28	1.03	0.53	0.28
	Wheat	3.00	bu	3.90	1.50	1.05	5.01	4.98	1.05
	Total removal			**77.86**	**30.12**	**99.72**	**100.00**	**100.00**	**100.00**

[1] Average of 1998, 1999, 2000; USDA, 2001; Statistics Canada, 2000; CDFA, 2001; CPHA, 2002; FDACS, 1999; GDA, 2001; UGA, 1987; Cubbage and Abt, 1998; NBDOARD, 1997; NSDAM, 2001; OMAFRA, 2001; PEI, 2001; AASS, 2000. Crops considered in the U.S. were alfalfa, barley, corn (grain), corn (silage), cotton, dry beans, oats, other hay, peanuts, potatoes, rice, rye, sorghum (grain), sorghum (silage), soybeans, sugarbeets, sugarcane, sunflower, sweet potatoes, tobacco, and wheat. Crops considered in Canada were alfalfa, barley, canola, corn (grain), corn (silage), dry beans, dry peas, flaxseed, lentils, mustard, oats, other hay, potatoes, rye, soybeans, sugarbeets, sunflower, wheat. An additional 48 vegetable, fruit, and tree crops were considered in states and provinces with significant production.

[2] Calculated using the removal estimates reported in Table 4.4 and Appendix 4.2.

Appendix 4.2 Nutrient removal per unit of yield for specialty crops.

Crop	Unit of yield	Nutrient removal, lb			Source or notes
		N	P_2O_5	K_2O	
Artichokes	cwt	0.51	0.22	0.61	1
Asparagus	cwt	1.93	0.66	2.17	IFA, 2001
Avocados	ton	7.86	2.38	17.62	IFA, 2001
Beans (dry)	cwt	3.56	0.93	1.53	Roberts and Cowell, 1993
Beans (snap)	cwt	1.72	0.41	2.04	IFA, 2001
Blueberries	ton	8.3	3.0	13.0	2
Brussels sprouts	cwt	0.51	0.22	0.61	1
Carrots (all)	cwt	0.35	0.13	0.80	IFA, 2001
Cauliflower	cwt	0.54	0.18	0.80	IFA, 2001
Chilies (green-wet)	ton	15.2	5.8	24	3
Chilies (red-dry)	ton	40	15	50	4
Corn (sweet)	cwt	1.56	0.52	1.51	IFA, 2001
Cranberries	cwt	0.51	0.22	0.61	1
Cucumbers	cwt	0.20	0.07	0.33	McCollum and Miller, 1971
Dates	cwt	0.35	0.14	0.78	IFA, 2001
Eggplant	cwt	0.19	0.070	0.27	IFA, 2001
Figs	cwt	0.47	0.14	0.74	IFA, 2001
Garlic	cwt	0.30	0.13	0.27	5
Grapefruit	cwt	0.11	0.030	0.24	IFA, 2001
Kiwifruit	ton	10.2	4.5	12.2	1
Lemons	cwt	0.16	0.037	0.21	IFA, 2001
Lettuce (all)	cwt	0.24	0.075	0.50	CPHA, 2002
Limes	cwt	0.16	0.040	0.21	IFA, 2001
Melons (cantaloupe)	cwt	0.36	0.12	0.65	CPHA, 2002
Melons (honeydew)	cwt	0.37	0.12	0.65	6
Melons (watermelon)	cwt	0.17	0.13	0.27	IFA, 2001
Mushrooms	cwt	0.51	0.22	0.61	1
Mustard	lb	0.037	0.017	0.011	Roberts and Cowell, 1993
Olives	ton	10.2	4.5	12.2	1
Onions (all)	cwt	0.30	0.13	0.27	IFA, 2001
Other fruits and veg.	cwt	0.51	0.22	0.61	IFA, 2001
Other hay	ton	29	12	50	Wallingford, 1990
Pecans	cwt	0.81	0.44	0.45	IFA, 2001
Peppers (bell)	cwt	0.76	0.29	1.20	IFA, 2001
Pistachios	ton	60	24	30	IFA, 2001
Pumpkins	cwt	0.51	0.22	0.61	1
Radishes	cwt	1.45	0.47	2.05	IFA, 2001
Raspberries	cwt	0.51	0.22	0.61	1
Spinach	cwt	0.35	0.18	0.73	IFA, 2001
Stone fruit	ton	6.3	2.7	8.0	7
Strawberries	cwt	0.80	0.38	1.0	IFA, 2001
Tangerines	cwt	0.15	0.038	0.25	IFA, 2001
Walnuts	ton	75.8	21.4	42.4	IFA, 2001
Wood (soft and hard)	cord	4.45	1.31	3.41	Albaugh et al., 1998

1 Average removal for vegetable crops assumed (IFA, 2001).
2 Removal assumed to be the same as for grapes.
3 Removal assumed to be the same as for bell peppers; 8:1 used to convert to dry weight.
4 Removal assumed similar to forage crops on dry matter basis.
5 Removal assumed to be the same as for onions.
6 Removal assumed to be the same as for cantaloupe.
7 Removal assumed to be the same as for peaches.

Appendix 5.1. North American commercial fertilizer use, 1961 to 2000[1].

	U.S.[1]			Canada[2]			Total NA
Year	N	P_2O_5	K_2O	N	P_2O_5	K_2O	$N\text{-}P_2O_5\text{-}K_2O$
(end 6/30)	million tons						
1961	3.0	2.6	2.2	0.09	0.18	0.10	8.2
1962	3.4	2.8	2.3	0.10	0.20	0.11	8.8
1963	3.9	3.1	2.5	0.12	0.22	0.11	10.0
1964	4.4	3.4	2.7	0.17	0.26	0.12	11.1
1965	4.6	3.5	2.8	0.19	0.29	0.14	11.5
1966	5.3	3.9	3.2	0.24	0.37	0.16	13.2
1967	6.0	4.3	3.6	0.30	0.41	0.18	14.9
1968	6.8	4.4	3.8	0.35	0.44	0.18	16.0
1969	6.9	4.7	3.9	0.28	0.35	0.19	16.3
1970	7.5	4.6	4.0	0.29	0.31	0.19	16.9
1971	8.1	4.8	4.2	0.36	0.36	0.20	18.1
1972	8.0	4.9	4.3	0.37	0.38	0.21	18.2
1973	8.3	5.1	4.6	0.45	0.46	0.21	19.1
1974	9.2	5.1	5.1	0.56	0.54	0.22	20.6
1975	8.6	4.5	4.4	0.59	0.55	0.23	19.0
1976	10.4	5.2	5.2	0.65	0.55	0.27	22.3
1977	10.6	5.6	5.8	0.66	0.56	0.26	23.6
1978	10.0	5.1	5.5	0.76	0.62	0.30	22.3
1979	10.7	5.6	6.2	0.89	0.66	0.37	24.5
1980	11.4	5.4	6.2	0.89	0.64	0.38	25.0
1981	11.9	5.4	6.3	1.03	0.70	0.40	25.8
1982	11.0	4.8	5.6	1.06	0.70	0.38	23.5
1983	9.1	4.1	4.8	1.10	0.73	0.37	20.3
1984	11.1	4.9	5.8	1.28	0.79	0.42	24.3
1985	11.5	4.7	5.6	1.38	0.80	0.44	24.3
1986	10.4	4.2	5.1	1.35	0.77	0.41	22.2
1987	10.2	4.0	4.8	1.26	0.69	0.41	21.5
1988	10.5	4.1	5.0	1.31	0.70	0.45	22.1
1989	10.6	4.1	4.8	1.28	0.68	0.39	21.9
1990	11.1	4.3	5.2	1.32	0.68	0.40	23.0
1991	11.3	4.2	5.0	1.28	0.64	0.37	22.8
1992	11.4	4.2	5.0	1.38	0.65	0.34	23.1
1993	11.4	4.4	5.1	1.44	0.68	0.36	23.4
1994	12.6	4.5	5.3	1.55	0.71	0.36	25.0
1995	11.7	4.4	5.1	1.60	0.69	0.34	23.9
1996	12.3	4.5	5.3	1.74	0.73	0.37	24.9
1997	12.4	4.6	5.4	1.84	0.78	0.35	25.4
1998	12.3	4.6	5.3	1.82	0.79	0.39	25.3
1999	12.4	4.3	5.0	1.78	0.73	0.40	24.7
2000	12.3	4.3	5.0	1.85	0.74	0.37	24.6

[1] Terry and Kirby, 2001.

[2] Korol and Rattray, 2000.

Appendix 5.2a. Estimated total nutrient removal relative to inorganic nutrient use in the U.S. from 1961 to 2000.

	Nutrient removal[1], million tons			Nutrient removal/fertilizer use[2]				
Year	N	P_2O_5	K_2O	N	P_2O_5	K_2O	$N+P_2O_5+K_2O$	$P_2O_5+K_2O$
1961	7.69	2.79	5.38	2.6	1.1	2.4	2.0	1.7
1962	7.81	2.83	5.55	2.3	1.0	2.4	1.9	1.6
1963	8.02	2.94	5.58	2.1	1.0	2.2	1.7	1.5
1964	7.85	2.83	5.53	1.8	0.8	2.1	1.5	1.4
1965	8.66	3.13	5.95	1.9	0.9	2.1	1.6	1.4
1966	8.66	3.11	5.86	1.6	0.8	1.8	1.4	1.3
1967	9.20	3.36	6.13	1.5	0.8	1.7	1.3	1.2
1968	9.47	3.38	6.21	1.4	0.8	1.6	1.3	1.2
1969	9.61	3.43	6.32	1.4	0.7	1.6	1.3	1.1
1970	9.28	3.27	6.21	1.2	0.7	1.6	1.2	1.1
1971	10.34	3.78	6.68	1.3	0.8	1.6	1.2	1.2
1972	10.37	3.75	6.70	1.3	0.8	1.6	1.2	1.1
1973	11.19	3.98	7.08	1.4	0.8	1.5	1.2	1.1
1974	9.85	3.51	6.48	1.1	0.7	1.3	1.0	1.0
1975	11.37	4.05	7.11	1.3	0.9	1.6	1.3	1.3
1976	10.72	3.96	6.66	1.0	0.8	1.3	1.0	1.0
1977	12.21	4.33	7.43	1.2	0.8	1.3	1.1	1.0
1978	12.67	4.51	7.84	1.3	0.9	1.4	1.2	1.2
1979	14.02	4.94	8.38	1.3	0.9	1.4	1.2	1.1
1980	12.21	4.33	7.38	1.1	0.8	1.2	1.0	1.0
1981	13.99	5.06	8.25	1.2	0.9	1.3	1.2	1.1
1982	14.52	5.18	8.56	1.3	1.1	1.5	1.3	1.3
1983	11.09	3.75	7.07	1.2	0.9	1.5	1.2	1.2
1984	13.56	4.88	8.21	1.2	1.0	1.4	1.2	1.2
1985	14.39	5.24	8.50	1.3	1.1	1.5	1.3	1.3
1986	13.57	4.90	8.32	1.3	1.2	1.6	1.4	1.4
1987	12.87	4.57	7.91	1.3	1.1	1.7	1.3	1.4
1988	10.30	3.61	6.54	1.0	0.9	1.3	1.0	1.1
1989	12.68	4.55	7.79	1.2	1.1	1.6	1.3	1.4
1990	13.45	4.85	8.10	1.2	1.1	1.6	1.3	1.4
1991	13.02	4.63	8.10	1.2	1.1	1.6	1.3	1.4
1992	14.47	5.30	8.49	1.3	1.3	1.7	1.4	1.5
1993	12.37	4.36	7.72	1.1	1.0	1.5	1.2	1.3
1994	15.25	5.52	8.89	1.2	1.2	1.7	1.3	1.5
1995	13.37	4.70	8.25	1.1	1.1	1.6	1.2	1.4
1996	14.65	5.27	8.65	1.2	1.2	1.6	1.3	1.4
1997	15.36	5.44	8.99	1.2	1.2	1.7	1.3	1.4
1998	15.63	5.54	9.06	1.3	1.2	1.7	1.4	1.5
1999	15.36	5.45	9.15	1.2	1.3	1.8	1.4	1.6
2000	15.48	5.51	8.98	1.3	1.3	1.8	1.4	1.6

[1] Removal calculated using data from Table 4.4 and historic yields of 18 crops taken from Historic Track Records, May 2001b. USDA-NASS. The crops used represented an average of 98 percent of harvested acres in the U.S.

[2] Fertilizer use data taken from Appendix 5.1.

Appendix 5.2b. Estimated total nutrient removal relative to inorganic nutrient use in Canada from 1961 to 2000.

	Nutrient removal[1], million tons			Nutrient removal/fertilizer use[2]				
Year	N	P_2O_5	K_2O	N	P_2O_5	K_2O	$N+P_2O_5+K_2O$	$P_2O_5+K_2O$
1961	0.91	0.28	0.68	10.6	1.6	6.7	5.1	8.3
1962	1.28	0.40	0.81	13.0	2.1	7.6	6.2	9.7
1963	1.43	0.46	0.87	11.7	2.0	7.8	6.0	9.8
1964	1.25	0.40	0.79	7.5	1.5	6.5	4.4	8.0
1965	1.36	0.44	0.81	7.2	1.5	6.0	4.2	7.5
1966	1.63	0.53	0.98	6.8	1.4	6.3	4.1	7.7
1967	1.36	0.44	0.89	4.5	1.1	5.0	3.0	6.1
1968	1.43	0.47	0.86	4.1	1.1	4.7	2.8	5.8
1969	1.53	0.50	0.94	5.5	1.5	5.0	3.7	6.5
1970	1.43	0.48	0.97	4.8	1.6	5.0	3.6	6.6
1971	1.64	0.55	0.97	4.6	1.5	4.8	3.5	6.3
1972	1.51	0.50	0.92	4.1	1.3	4.4	3.1	5.8
1973	1.59	0.53	0.99	3.5	1.2	4.7	2.8	5.9
1974	1.44	0.47	0.95	2.5	0.9	4.3	2.1	5.1
1975	1.65	0.55	1.03	2.8	1.0	4.5	2.4	5.5
1976	1.83	0.61	1.10	2.8	1.1	4.1	2.4	5.2
1977	1.83	0.62	1.10	2.8	1.1	4.3	2.4	5.4
1978	1.93	0.66	1.17	2.5	1.1	3.8	2.2	4.9
1979	1.76	0.60	1.11	2.0	0.9	3.0	1.8	4.0
1980	1.78	0.61	1.05	2.0	0.9	2.8	1.8	3.7
1981	2.03	0.69	1.16	2.0	1.0	2.9	1.8	3.9
1982	2.13	0.73	1.17	2.0	1.0	3.1	1.9	4.1
1983	1.98	0.67	1.12	1.8	0.9	3.1	1.7	4.0
1984	1.92	0.66	1.13	1.5	0.8	2.7	1.5	3.6
1985	2.03	0.70	1.11	1.5	0.9	2.5	1.5	3.4
1986	2.45	0.83	1.37	1.8	1.1	3.4	1.9	4.5
1987	2.33	0.79	1.36	1.8	1.2	3.3	1.9	4.5
1988	1.85	0.63	1.17	1.4	0.9	2.6	1.5	3.5
1989	2.18	0.73	1.29	1.7	1.1	3.3	1.8	4.4
1990	2.50	0.85	1.44	1.9	1.3	3.6	2.0	4.9
1991	2.39	0.81	1.32	1.9	1.3	3.6	2.0	4.8
1992	2.25	0.75	1.25	1.6	1.2	3.6	1.8	4.8
1993	2.46	0.84	1.36	1.7	1.2	3.8	1.9	5.0
1994	2.49	0.87	1.41	1.6	1.2	3.9	1.8	5.1
1995	2.44	0.85	1.30	1.5	1.2	3.8	1.7	5.0
1996	2.61	0.90	1.37	1.5	1.2	3.7	1.7	5.0
1997	2.34	0.82	1.14	1.3	1.1	3.2	1.5	4.3
1998	2.46	0.88	1.19	1.4	1.1	3.0	1.5	4.1
1999	2.67	0.95	1.32	1.5	1.3	3.3	1.7	4.6
2000	2.54	0.90	1.25	1.4	1.2	3.4	1.6	4.6

[1] Removal calculated using data from Table 4.4 and historic yields of 17 crops taken from Statistics Canada (2001).

[2] Fertilizer use data taken from Appendix 5.1.

Appendix 5.3a. Average rates of N, P_2O_5, and K_2O for major crops in the U.S.

	Corn			Soybeans			Wheat			Cotton		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
Year	Average rate applied, lb/A											
1964	49	32	25	1	4	4	13	10	3	53	28	16
1965	66	41	37	1	5	7	15	11	5	64	32	25
1966	78	49	46	2	9	10	16	12	6	64	32	26
1967	86	52	49	3	10	11	19	14	7	57	31	22
1968	96	57	55	3	10	12	20	14	6	58	32	25
1969	102	56	55	2	11	13	21	15	7	68	32	22
1970	105	64	61	3	10	14	24	13	7	54	26	21
1971	101	55	52	3	11	13	23	14	5	56	27	23
1972	110	59	59	3	12	16	29	16	6	58	30	25
1973	106	55	57	3	13	18	30	17	6	54	29	24
1974	97	54	61	3	11	15	30	17	7	62	31	25
1975	99	50	55	3	10	14	29	15	7	51	22	18
1976	123	60	66	3	12	18	36	19	8	61	28	21
1977	123	60	67	4	15	20	34	17	8	61	27	16
1978	120	59	65	4	16	22	32	13	5	52	24	17
1979	130	61	69	4	17	26	35	17	8	50	24	12
1980	125	57	70	4	16	25	39	17	7	51	22	14
1981	133	60	72	4	15	27	41	18	9	54	24	14
1982	131	57	72	3	12	20	41	17	7	58	19	17
1983	132	56	71	4	14	22	43	19	10	55	20	16
1984	134	57	71	3	14	23	47	18	8	62	23	17
1985	136	52	66	3	12	22	46	17	6	61	23	18
1986	125	51	61	3	12	22	47	17	8	62	22	20
1987	127	51	64	3	12	21	50	18	6	62	19	15
1988	133	55	66	4	12	24	53	20	9	62	23	12
1989	127	50	61	3	13	24	50	20	8	66	23	13
1990	128	51	65	4	11	23	47	19	8	68	22	15
1991	123	49	59	4	10	18	50	19	9	68	22	14
1992	125	47	57	3	10	19	52	19	7	70	23	21
1993	119	46	56	3	10	20	55	20	6	76	25	21
1994	126	48	58	3	10	21	58	21	7	95	23	20
1995	125	46	58	5	12	21	56	21	7	83	24	20
1996	134	52	62	4	12	23	55	19	5	75	27	31
1997	131	48	58	5	14	29	59	21	8	76	31	34
1998	130	47	60	4	12	24	59	22	9	69	30	33
1999	131	47	60	3	12	23	59	22	8	73	27	35
2000	130	44	54	4	12	22	59	22	8	73	29	42

Data derived from total nutrient use by crop (personal communications with Harold Taylor, USDA-ERS, Washington, DC) and crop acreage from Historic Track Records, May 2001 (USDA-NASS, 2001b).

Average rates were calculated based on harvested acres and estimated nutrients applied to harvested acres.

Appendix 5.3b. Ratio of production to estimated N, P_2O_5, and K_2O use on harvested acres of major crops in the U.S.

	Corn			Soybean			Wheat			Cotton		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O[1]	N	P_2O_5	K_2O
Year	unit of production[2] /lb nutrient used											
1964	1.28	1.97	2.50	23.23	6.32	5.13	2.03	2.65	8.48	9.74	18.20	32.51
1965	1.12	1.81	2.00	22.32	4.79	3.70	1.78	2.33	5.06	8.23	16.23	21.00
1966	0.93	1.49	1.60	11.76	2.87	2.58	1.68	2.16	4.74	7.52	14.80	18.40
1967	0.94	1.53	1.63	8.99	2.46	2.16	1.39	1.88	3.90	7.85	14.51	20.31
1968	0.83	1.40	1.46	8.49	2.68	2.20	1.41	2.07	4.64	8.84	16.17	20.70
1969	0.84	1.54	1.56	12.02	2.57	2.12	1.44	2.05	4.62	6.36	13.39	19.52
1970	0.69	1.13	1.18	9.07	2.67	1.87	1.30	2.35	4.31	8.12	16.61	21.37
1971	0.88	1.61	1.68	9.66	2.62	2.13	1.49	2.44	6.73	7.90	16.54	19.38
1972	0.88	1.63	1.63	9.03	2.28	1.76	1.15	2.01	5.73	8.77	16.75	20.26
1973	0.86	1.66	1.61	8.27	2.07	1.58	1.04	1.85	5.16	9.63	17.85	21.52
1974	0.74	1.33	1.19	7.18	2.06	1.54	0.90	1.56	3.68	7.16	14.36	17.45
1975	0.88	1.73	1.57	10.70	2.89	2.10	1.06	2.03	4.16	8.94	21.07	24.96
1976	0.71	1.46	1.34	9.32	2.22	1.45	0.84	1.64	3.90	7.66	16.89	22.46
1977	0.74	1.52	1.35	7.96	2.06	1.50	0.90	1.79	3.94	8.55	19.25	32.28
1978	0.84	1.71	1.56	6.91	1.86	1.32	0.99	2.36	5.78	8.01	17.29	25.10
1979	0.84	1.78	1.59	7.73	1.84	1.23	0.97	2.04	4.41	10.86	22.80	46.07
1980	0.73	1.58	1.31	6.78	1.65	1.05	0.86	2.00	4.65	7.90	18.30	29.27
1981	0.82	1.81	1.51	7.95	1.98	1.13	0.85	1.88	3.67	10.05	22.68	39.32
1982	0.86	1.98	1.57	10.91	2.72	1.60	0.86	2.13	4.81	10.13	31.28	35.75
1983	0.62	1.44	1.15	7.27	1.94	1.17	0.91	2.11	4.11	9.22	25.64	32.54
1984	0.80	1.89	1.50	8.28	2.04	1.22	0.82	2.14	4.96	9.75	26.06	35.40
1985	0.87	2.29	1.78	13.37	2.83	1.58	0.81	2.23	6.50	10.37	27.40	35.65
1986	0.95	2.33	1.96	12.34	2.67	1.51	0.73	1.99	4.12	8.95	25.07	28.29
1987	0.95	2.37	1.88	11.30	2.88	1.61	0.76	2.15	5.84	11.33	36.48	47.56
1988	0.64	1.54	1.28	7.67	2.16	1.10	0.64	1.74	3.64	9.92	27.30	49.61
1989	0.91	2.34	1.91	10.55	2.51	1.36	0.65	1.67	3.95	9.36	27.05	47.92
1990	0.93	2.32	1.83	8.35	3.02	1.45	0.85	2.10	4.71	9.34	29.43	43.52
1991	0.87	2.21	1.84	8.58	3.25	1.78	0.69	1.76	3.98	9.60	30.26	46.77
1992	1.07	2.81	2.31	11.40	3.48	1.91	0.75	2.06	5.59	9.94	30.38	33.19
1993	0.84	2.19	1.80	11.64	3.22	1.53	0.69	1.87	6.42	8.01	23.87	29.01
1994	1.10	2.92	2.40	12.72	4.40	2.04	0.64	1.82	5.82	7.49	30.51	34.81
1995	0.91	2.51	1.95	7.16	2.97	1.66	0.63	1.72	5.23	6.49	22.29	26.31
1996	0.95	2.45	2.03	10.43	3.07	1.70	0.65	1.94	6.76	9.39	26.75	22.20
1997	0.97	2.65	2.17	8.80	2.82	1.27	0.68	1.96	5.48	8.90	22.02	19.91
1998	1.03	2.86	2.26	12.08	3.32	1.63	0.73	1.95	5.71	9.08	21.12	19.16
1999	1.02	2.88	2.24	11.44	3.18	1.59	0.72	1.93	5.64	8.31	22.20	17.23
2000	1.05	3.10	2.53	10.08	3.18	1.74	0.71	1.90	5.55	8.64	21.83	15.17

Data derived from total nutrient use by crop (personal communications with Harold Taylor, USDA-ERS, Washington, D.C.) and total production from Historic Track Records, May 2001. USDA-NASS.

Nutrient use by crop was adjusted to estimate use on harvested acres only.

[1] Original K_2O data for 1996 wheat did not include Illinois. These data include a 1996 estimate for Illinois assuming average rate of K_2O application of 95 lb/A (average of 1995 and 1997 rates).

[2] Unit of production is bu for corn, soybeans, and wheat, and lb for cotton.

Appendix 6.1. Nutrient content of organic materials.

	Percentage by weight						
Material	N	P_2O_5	K_2O	Ca	Mg	S	Cl
Apple pomace	0.2	—	0.2	—	—	—	—
Blood (dried)	12 to 15	3	—	0.3	—	—	0.6
Bone meal (raw)	3.5	22	—	22	0.6	0.2	0.2
Bone meal (steamed)	2	28	0.2	23	0.3	0.1	—
Brewers grains (wet)	0.9	0.5	—	—	—	—	—
Common crab waste	2	3.6	0.2	—	—	—	—
Compost (garden)			varies with components and amendments				
Cotton waste from factory	1.3	0.4	0.4	—	—	—	—
Cottonseed hull ash	0	—	27	—	—	—	—
Cottonseed meal	6 to 7	2.5	1.5	0.4	0.9	0.2	—
Cotton motes	2	0.5	3	4	0.7	0.6	—
Cowpea forage	0.4	0.1	0.4				
Dog manure	2	10	0.3	—	—	—	—
Eggs	2.2	0.4	0.2	—	—	—	—
Egg shells (burned)	—	0.4	0.3	—	—	—	—
Egg shells	1.2	0.4	0.2	—	—	—	—
Feathers	15.3	—	—	—	—	—	—
Fermentation sludges	3.5	0.5	0.1	7.3	0.1	—	—
Fish scrap (acidulated)	5.7	3	—	6.1	0.3	0.2	0.5
Fish scrap (dried)	9.5	6	—	6.1	0.3	0.2	1.5
Fly ash:							
coal	0.3	—	0.1	0.48	—	—	—
wood	0.1	0.6	10	9.8	0.66	—	—
Frittercake:							
enzyme production	—	2.2	0.5	—	—	—	—
citric acid production	—	2	0.3	—	5.2	—	—
Garbage tankage	2.5	1.5	1	3.2	0.3	0.4	1.3
Greensand	—	1 to 2	5	—	—	—	—
Grape skins (ash)	—	3.6	31	—	—	—	—
Hair	12 to 16	—	—	—	—	—	—
Hay							
legume	3	1	2.4	1.2	0.2	0.3	—
grass	1.5	0.5	1.9	0.8	0.2	0.2	—
Leather (acidulated)	—	7 to 8	—	—	—	—	—
Leather (ground)	10 to 12	—	—	—	—	—	—
Leather scrap (ash)	—	2	0.4	—	—	—	—
Milk	0.5	0.3	0.2	—	—	—	—
Oak leves	0.8	0.4	0.2	—	—	—	—
Peanut hull meal	1.2	0.5	0.8	—	—	—	—
Peanut meal	7.2	1.5	1.2	0.4	0.3	0.6	0.1
Peat/muck	2.7	—	—	0.7	0.3	1	0.1
Pine needles	0.5	0.1	—	—	—	—	—
Poultry processing:							
DAF sludge	8	1.8	0.3	—	—	—	—
Potato tubers	0.4	0.2	0.5	—	—	—	—
Potato, leaves & stalks	—	0.6	0.2	0.4	—	—	—
Potato skins, raw ash	—	—	5.2	27.5	—	—	—
Sawdust	0.2	—	0.2	—	—	—	—
Sea marsh hay	1.1	0.2	0.8	—	—	—	—
Seaweed (dried)	0.7	0.8	5	—	—	—	—
Sewage sludge (municipal)	2.6	3.7	0.2	1.3	0.2	—	—
Shrimp heads	7.8	4.2	—	—	—	—	—
Shrimp waste	2.9	10	—	—	—	—	—
Siftings from oyster shell	0.4	10.4	0.1	—	—	—	—
Soot from chimney flues	—	0.5 to 11	—	1	0.4	—	—
Soybean meal	7	1.2	1.5	0.4	0.3	0.2	—
Spanish moss	0.6	0.1	0.6	—	—	—	—
Spent brewery yeast	—	7	0.4	0.3	0.04	0.03	—
String bean strings & stems (ash)	—	5	18	—	—	—	—
Sweet potato skins boiled (ash)	—	3.29	13.9	—	—	—	—
Sweet potatoes	0.2	0.1	0.5	—	—	—	—
Tankage	7	1.5	3 to 10	—	—	—	—
Textile sludges	2.8	2.1	0.2	0.5	0.2	—	—
Wood ashes	0	2	6	20	1	—	—

Continued on next page.

Appendix 6.1. Continued.

	Percentage by weight						
Material	N	P_2O_5	K_2O	Ca	Mg	S	Cl
Wood processing wastes	—	0.4	0.2	0.1	1.1	0.2	—
Tobacco leaves	4	0.5	6	—	—	—	—
Tobacco stalks	3.7	0.6	4.5	—	—	—	—
Tobacco stems	2.5	0.9	7	—	—	—	—
Tomatoes, fruit	0.2	0.1	0.4	—	—	—	—
Tomato leaves	0.4	0.1	0.4	—	—	—	—

Note: Approximate values are given. Have materials analyzed for nutrient content before using.
Source: North Carolina State University website.

Appendix 6.2. Nutrient content of manures.

	TKN	P_2O_5	K_2O	Ca	Mg	S
Type	- - - - - - - - - - - - - -	- - - - - - - - - - - - - -	-Wet basis	- - - - - - - - - - - - - -	- - - - - - - - - - - - - -	- - - - - - - - - - - - - -
Dairy						
Fresh (lb/ton)	10	5	8	4	2	1
Paved surface scraped (lb/ton)	10	6	9	5	2	2
Liquid manure (lb/1,000 gal)[1]	23	14	21	10	5	3
Lagoon liquid (lb/acre-inch)[2]	137	77	195	69	35	25
Anaerobic lagoon sludge (lb/acre-inch)[2]	15	22	8	12	4	4
Beef						
Fresh (lb/ton)	12	7	9	5	2	2
Paved surface scraped (lb/ton)	14	9	13	5	3	2
Unpaved feedlot (lb/ton)	26	16	20	14	6	5
Lagoon liquid (lb/acre-inch)[2]	83	77	129	24	19	—
Lagoon sludge (lb/1,000 gal)[1]	38	51	15	36	5	—
Broiler						
Fresh (lb/ton)	26	17	11	10	4	2
House litter (lb/ton)	72	78	46	41	8	15
Stockpiled litter (lb/ton)	36	80	34	54	8	12
Duck						
Fresh (lb/ton)	28	23	17	—	—	—
House litter (lb/ton)	19	17	14	22	3	3
Stockpiled litter (lb/ton)	24	42	22	27	4	6
Goat						
Fresh (lb/ton)	22	12	18	—	—	—
Horse						
Fresh (lb/ton)	12	6	12	11	2	2
Layers						
Fresh (lb/ton)	26	22	11	41	4	4
Undercage paved (lb/ton)	28	31	20	43	6	7
Deep pit (lb/ton)	38	56	30	86	6	9
Liquid (lb/1,000 gal)[1]	62	59	37	35	7	8
Lagoon liquid (lb/acre-inch)[2]	179	46	266	25	7	52
Lagoon sludge (lb/1,000 gal)[1]	26	92	13	71	7	12
Rabbit						
Fresh (lb/ton)	24	23	13	19	4	2
Sheep						
Fresh (lb/ton)	21	10	20	14	4	3
Unpaved (lb/ton)	14	11	19	24	7	6
Swine						
Fresh (lb/ton)	12	9	9	8	2	2
Surface scraped (lb/ton)	13	12	9	12	2	2
Liquid manure (lb/1,000 gal)[1]	31	22	17	9	3	5
Lagoon liquid (lb/acre-inch)[2]	136	53	133	25	8	10
Lagoon sludge (lb/1,000 gal)[1]	22	49	7	16	4	8
Turkey						
Fresh (lb/ton)	27	25	12	27	2	—
House litter (lb/ton)	52	64	37	35	6	9
Stockpiled litter (lb/ton)	36	72	33	42	7	10

Notes: Approximate nutrient contents are given. Have materials analyzed for nutrient content before using. North Carolina mean waste analysis 1981 to 1990 supplied by J.C. Barker, NCSU Department of Biological and Agricultural Engineering.

[1] Pounds per thousand gallons of manure liquid (slurry). Corrected from pounds per thousand pounds (lb/1,000 lb) in original source.

[2] Pounds per acre-inch. Estimated total lagoon liquid includes total liquid manure plus average annual lagoon surface rainfall surplus; does not account for seepage.

Source: North Carolina State University website.

Appendix 6.3. Manure nutrient production on livestock operations by state, 1997.

		All animals on farms			Confined animals on farm		
State	Tons of manure as excreted	Pounds of manure N as excreted	Pounds of manure P_2O_5 as excreted	Pounds of manure K_2O as excreted	Tons of manure as excreted	Pounds of manure N as excreted	Pounds of manure P_2O_5 as excreted
Alabama	19,953,459	294,931,035	210,250,117	202,321,668	5,824,865	151,749,984	103,544,635
Alaska	98,541	998,592	654,017	864,695	26,775	287,525	138,231
Arizona	9,179,933	94,496,044	60,097,505	80,595,031	3,888,525	43,267,633	23,773,369
Arkansas	26,105,216	407,001,174	297,424,291	268,916,893	11,129,533	257,164,642	186,685,540
California	61,802,058	692,413,196	408,327,019	528,556,779	34,450,533	435,993,694	243,005,221
Colorado	31,755,091	333,327,897	235,834,441	288,518,640	12,168,227	150,234,558	103,168,068
Connecticut	1,068,741	13,822,663	8,539,923	9,371,183	793,346	11,359,696	7,012,694
Delaware	1,686,832	38,679,888	25,394,653	19,558,213	1,516,191	37,371,721	24,594,852
Florida	20,521,352	230,609,163	162,235,316	190,080,222	2,926,624	50,200,083	31,607,936
Georgia	19,937,498	314,574,421	217,917,119	203,628,384	8,766,914	202,780,459	136,212,850
Hawaii	1,866,525	19,735,735	14,229,007	17,114,310	318,463	4,069,115	2,666,961
Idaho	19,933,506	201,847,562	127,366,846	172,685,660	7,966,846	87,460,189	44,375,515
Illinois	21,821,309	238,836,659	161,767,620	199,156,434	11,814,706	144,545,061	94,699,984
Indiana	17,920,446	223,808,494	157,126,069	168,340,999	10,470,265	154,278,324	110,748,602
Iowa	57,356,117	640,886,851	441,394,312	529,567,429	34,177,723	429,182,735	289,619,332
Kansas	58,586,280	602,539,518	424,302,973	528,932,669	23,134,027	278,999,452	192,173,709
Kentucky	24,665,734	262,628,335	183,662,830	224,472,115	5,099,696	66,099,294	40,396,310
Louisiana	10,004,065	116,413,893	81,712,872	93,851,953	1,522,104	29,545,569	18,413,723
Maine	1,572,191	20,040,981	12,358,828	13,768,298	1,030,890	15,084,218	9,453,699
Maryland	5,062,105	79,560,648	49,913,715	49,087,024	3,482,166	64,973,547	40,626,464
Massachusetts	880,436	9,392,153	4,914,095	7,211,050	546,842	6,295,087	3,123,766
Michigan	13,993,621	152,221,670	89,109,662	118,562,947	9,358,065	111,250,480	62,693,811
Minnesota	38,878,083	466,404,079	306,954,914	350,924,794	27,028,891	362,911,963	237,436,033
Mississippi	14,744,517	208,470,697	146,497,703	146,737,630	5,348,651	113,847,464	76,609,587
Missouri	48,743,596	551,169,335	398,738,194	453,945,674	13,989,348	204,718,739	145,223,989
Montana	27,508,371	280,490,246	208,807,884	253,089,394	1,144,821	13,204,277	8,526,822
Nebraska	66,016,138	695,027,090	497,349,798	604,729,040	26,445,847	324,548,303	227,046,023
Nevada	5,261,458	53,786,209	38,475,403	47,882,162	783,841	8,376,868	4,658,529
N. Hampshire	606,110	6,249,234	3,097,431	4,876,441	378,778	4,152,251	1,902,443
New Jersey	818,989	9,962,433	6,233,199	7,211,354	476,094	6,695,511	4,130,109
New Mexico	17,270,812	175,129,226	112,704,168	150,591,765	5,293,562	57,633,449	28,123,939
New York	20,555,714	207,272,566	97,924,419	162,652,241	13,552,877	144,315,223	63,949,136
N. Carolina	34,251,580	500,834,484	363,735,814	345,921,272	24,992,125	417,823,786	304,075,779
North Dakota	18,051,594	186,280,180	135,348,430	164,743,450	1,585,505	20,356,703	12,217,626
Ohio	18,126,823	218,671,606	144,090,785	163,487,146	10,545,271	147,702,187	95,521,561
Oklahoma	47,290,671	500,814,552	358,854,248	431,504,142	8,083,697	116,021,629	77,842,605
Oregon	15,375,594	159,425,889	111,853,431	138,591,770	2,545,051	31,248,492	19,091,256
Pennsylvania	25,021,710	294,336,855	171,194,428	214,654,081	16,073,564	214,124,103	124,049,465
Rhode Island	81,581	891,118	493,974	686,723	47,208	561,956	287,771
S. Carolina	6,777,436	104,043,878	78,098,755	69,274,809	2,667,641	62,734,015	47,805,326
South Dakota	37,055,085	384,466,481	277,441,375	338,090,308	8,678,344	102,850,049	69,570,120
Tennessee	21,585,742	232,905,684	164,295,704	197,989,049	4,022,365	55,659,370	35,007,049
Texas	135,160,272	1,446,533,637	1,036,282,813	1,240,231,659	35,358,486	472,684,317	321,503,242
Utah	10,122,283	109,293,914	75,153,222	91,093,270	3,047,582	39,097,417	24,268,802
Vermont	4,500,761	44,871,322	20,293,666	35,277,442	3,513,186	36,496,101	15,615,082
Virginia	19,186,110	250,495,566	181,250,605	183,707,156	6,490,331	124,438,329	91,247,926
Washington	14,342,673	151,152,570	91,823,575	123,366,458	6,670,321	78,377,425	42,397,703
West Virginia	4,810,434	62,302,216	45,697,206	46,394,908	1,117,229	25,219,942	18,343,502
Wisconsin	44,827,301	453,757,958	227,148,125	358,494,981	30,749,007	332,649,616	154,375,754
Wyoming	15,865,969	161,232,483	119,723,760	145,539,457	1,453,665	16,198,259	11,385,905
All states	1,138,608,463	12,905,038,080	8,794,096,259	10,386,851,172	452,496,614	6,266,840,810	4,030,948,356

*Values calculated as 45.8% of "Pounds of manure excreted — All animals on farms".
Source: U.S. N and P data, Kellogg et al. 2000.
All K data for the U.S. supplied by Dr. Charles Lander, NRCS. (personal communication).

Appendix 6.3. Continued.

Pounds of manure K_2O excreted*	Pounds of recoverable manure N available for application	Pounds of recoverable manure P_2O_5 available for application	Pounds of recoverable manure K_2O available for application	Pounds of farm level excess N	Pounds of farm level excess P_2O_5	Pounds of farm level excess K_2O
92,663,324	88,530,793	85,998,447	64,599,488	73,100,187	71,956,927	52,039,163
396,030	105,750	114,663	196,974	10,443	17,502	29,617
36,912,524	15,893,322	19,137,019	29,824,533	13,706,874	17,986,368	27,459,227
123,163,937	138,202,988	154,998,302	117,970,479	102,761,059	115,369,030	80,726,519
242,079,005	190,091,487	201,721,953	266,397,731	134,283,685	168,971,733	193,700,204
132,141,537	54,511,380	80,921,084	102,000,834	42,369,281	68,995,717	84,348,403
4,292,002	5,775,541	5,865,991	6,378,402	3,405,069	3,826,798	2,286,353
8,957,662	21,341,236	20,410,761	16,280,373	14,644,243	16,550,382	12,280,712
87,056,742	26,793,674	26,380,228	25,715,681	20,681,526	21,157,573	18,993,205
93,261,800	113,890,442	113,113,492	91,162,205	95,250,231	97,065,335	73,839,900
7,838,354	1,687,755	2,200,949	2,618,541	1,228,417	1,466,734	1,967,051
79,090,032	33,472,019	35,918,178	59,464,352	19,386,990	27,837,311	41,630,521
91,213,647	43,643,938	76,727,093	98,477,578	11,128,012	27,029,768	34,071,497
77,100,178	58,971,130	90,786,613	92,674,461	29,703,024	52,176,448	44,437,000
242,541,882	133,273,599	234,051,715	289,796,459	40,690,095	96,759,045	117,139,432
242,251,162	97,560,061	149,243,475	194,197,313	72,840,086	120,151,738	154,558,235
102,808,229	26,730,740	33,472,392	41,928,826	9,339,592	12,182,294	11,049,717
42,984,194	15,981,121	15,327,043	14,277,947	11,585,140	11,107,139	8,713,011
6,305,880	7,664,338	7,905,030	8,403,618	4,530,009	5,100,403	3,197,304
22,481,857	34,427,368	33,794,670	32,101,827	19,625,550	23,725,822	17,702,909
3,302,661	2,623,812	2,614,605	4,038,898	687,881	897,256	864,526
54,301,830	42,837,815	51,748,925	71,841,278	10,274,312	19,925,846	18,118,068
160,723,556	137,051,117	195,282,454	224,463,757	59,040,973	106,442,472	91,810,752
67,205,835	61,185,977	63,585,464	54,275,361	48,751,780	48,801,008	37,640,001
207,907,119	80,059,784	119,622,790	123,667,179	43,886,779	68,778,973	59,159,813
115,914,942	4,421,810	6,874,697	9,306,711	694,081	1,387,967	1,902,162
276,965,900	112,119,762	178,504,119	224,053,910	52,223,570	111,128,273	136,568,072
21,930,030	2,986,168	3,836,829	5,985,919	1,136,618	1,760,426	2,702,837
2,233,410	1,678,157	1,596,233	2,734,388	266,209	348,701	332,027
3,302,800	3,270,903	3,446,622	3,844,952	1,820,724	2,108,943	1,438,973
68,971,028	22,407,774	22,993,846	38,943,143	15,862,639	18,874,420	31,550,714
74,494,726	56,993,749	53,666,663	96,714,417	4,168,880	7,587,361	7,577,467
158,431,943	165,848,300	249,673,023	235,147,140	127,952,474	224,349,915	208,375,111
75,452,500	7,995,559	10,008,074	12,707,115	2,208,488	4,223,816	3,707,401
74,877,113	64,184,136	78,943,074	87,580,115	27,448,809	42,285,947	31,541,679
197,628,897	46,431,386	62,437,468	70,750,331	34,921,290	51,486,068	57,720,688
63,475,031	12,885,215	15,648,742	20,349,792	6,776,602	8,782,425	9,915,519
98,311,569	94,565,379	103,119,893	127,727,643	33,796,025	54,386,378	40,022,028
314,519	236,515	240,404	355,298	67,436	91,018	79,706
31,727,863	33,169,234	39,699,763	28,301,987	26,360,750	34,130,705	22,153,702
154,845,361	34,458,202	56,592,209	71,844,079	5,222,343	14,076,870	15,509,043
90,678,984	23,736,321	29,070,080	34,125,403	10,417,131	11,296,918	9,672,202
568,026,100	192,081,845	255,852,522	302,294,368	147,483,719	202,478,640	233,634,351
41,720,718	15,582,923	20,047,695	24,425,236	7,447,500	12,680,939	11,557,678
16,157,068	14,141,885	13,119,941	24,807,049	571,386	1,548,365	1,882,056
84,137,877	61,036,274	75,833,714	62,424,711	42,278,649	56,772,650	36,064,586
56,501,838	32,210,623	34,691,139	50,938,594	17,235,946	24,690,372	30,498,486
21,248,868	13,633,161	15,254,803	11,396,562	9,300,179	11,668,516	6,912,976
164,190,701	129,693,909	128,969,056	221,925,737	12,314,182	21,742,359	20,607,826
66,657,071	5,098,864	9,199,924	12,051,239	1,833,137	3,492,877	4,538,387
4,757,177,837	2,583,175,241	3,290,263,869	3,813,489,934	1,472,720,005	2,127,660,491	2,114,228,817

Appendix 10.1. Partial N budgets by state or province in North America.

State	Crop removal[1]	Legume fixation[2]	Applied fert[3]	Recov. manure[4]	Balance		Removal to use ratios			
or	(R)	(L)	(F)	(M)	F+L-R	F+L+M-R	R/	R/	(R-L)	(R-L)/
province	N, million lb						(F+L)	(F+L+M)	/F	(F+M)
AL	115	31	248	89	164	253	0.41	0.31	0.34	0.25
AZ	160	91	168	16	99	115	0.62	0.58	0.41	0.37
AR	666	347	624	138	305	443	0.69	0.60	0.51	0.42
CA	1,003	398	1,136	190	531	721	0.65	0.58	0.53	0.46
CO	535	190	355	55	10	65	0.98	0.89	0.97	0.84
CT	9.3	1.2	17.7	5.8	9.6	15.4	0.49	0.38	0.46	0.34
DE	54	31	41	21	18	39	0.75	0.58	0.57	0.38
FL	235	10	487	27	262	289	0.47	0.45	0.46	0.44
GA	307	65	382	114	140	254	0.69	0.55	0.63	0.49
ID	589	265	430	33	106	139	0.85	0.81	0.75	0.70
IL	3,225	1,943	1,922	44	640	684	0.83	0.83	0.67	0.65
IN	1,695	1,024	1,024	59	353	412	0.83	0.80	0.66	0.62
IA	3,581	2,189	1,996	133	604	737	0.86	0.83	0.70	0.65
KS	1,705	504	1,578	98	376	474	0.82	0.78	0.76	0.72
KY	491	189	464	27	162	189	0.75	0.72	0.65	0.61
LA	260	93	413	16	246	262	0.51	0.50	0.41	0.39
ME	20.7	1.5	43.2	7.7	24.0	31.7	0.46	0.40	0.45	0.38
MD	158	82	148	34	72	106	0.69	0.60	0.52	0.42
MA	11.8	1.9	27.5	2.6	17.6	20.2	0.40	0.37	0.36	0.33
MI	813	488	508	43	183	226	0.82	0.78	0.64	0.59
MN	2,562	1,476	1,317	137	231	368	0.92	0.87	0.82	0.75
MS	335	170	372	61	207	268	0.62	0.56	0.44	0.38
MO	1,256	735	892	80	371	451	0.77	0.74	0.58	0.54
MT	495	185	362	4.4	52	56	0.91	0.90	0.86	0.85
NE	2,077	965	1,713	112	601	713	0.78	0.74	0.65	0.61
NV	79	65	23	3.0	8.7	12	0.90	0.87	0.62	0.55
NH	6.2	1.0	7.6	1.7	2.5	4.2	0.71	0.60	0.68	0.55
NM	134	84	73	22	23	45	0.85	0.75	0.69	0.53
NJ	35	17	68	3.3	50.0	53.3	0.41	0.40	0.26	0.25
NY	289	89	168	57	-33	24	1.13	0.92	1.19	0.89
NC	358	165	431	166	238	404	0.60	0.47	0.45	0.32
ND	1,168	369	857	8.0	58	66	0.95	0.95	0.93	0.92
OH	1,355	834	801	64	280	344	0.83	0.80	0.65	0.60
OK	452	89	632	46	270	316	0.63	0.59	0.57	0.53
OR	250	101	288	13	138	151	0.64	0.62	0.52	0.50
PA	391	162	208	95	-21	74	1.06	0.84	1.10	0.75
RI	1.2	0.21	6.0	0.24	5.0	5.3	0.19	0.18	0.16	0.16
SC	102	41	166	33	106	139	0.49	0.42	0.36	0.30
SD	1,536	910	560	34	-65	-31	1.04	1.02	1.12	1.05
TN	342	122	316	24	96	120	0.78	0.74	0.70	0.65
TX	983	95	1,907	192	1,019	1,211	0.49	0.45	0.47	0.42
UT	168	130	64	16	26	42	0.87	0.80	0.59	0.47
VT	29.1	5.2	15.6	14.1	-8.3	5.8	1.40	0.83	1.53	0.80
VA	217	83	226	61	92	153	0.70	0.59	0.59	0.47
WA	488	136	426	32	75	107	0.87	0.82	0.82	0.77
WV	41.4	7.7	27	13.6	-6.6	7.0	1.19	0.86	1.25	0.83
WI	1,045	554	496	130	5	135	1.00	0.89	0.99	0.78
WY	149	89	231	5	171	176	0.47	0.46	0.26	0.26
U.S.	**31,979**	**15,625**	**24,666**	**2,581**	**8,312**	**10,894**	**0.79**	**0.75**	**0.66**	**0.60**
BC	76	33	35	16	-8	8	1.11	0.90	1.22	0.84
AB	1,196	238	1,067	72	110	182	0.92	0.87	0.90	0.84
SK	1,696	262	1,163	22	-272	-250	1.19	1.17	1.23	1.21
MB	679	137	725	22	183	205	0.79	0.77	0.75	0.73
ON	893	513	377	75	-3	72	1.00	0.93	1.01	0.84
QC	357	123	210	64	-24	40	1.07	0.90	1.11	0.85
Atlantic	78	10	63	11	-5	6	1.07	0.93	1.08	0.92
Canada	**4,974**	**1,316**	**3,639**	**282**	**-19**	**263**	**1.00**	**0.95**	**1.01**	**0.93**
NA Total	**36,953**	**16,941**	**28,305**	**2,863**	**8,293**	**11,157**	**0.82**	**0.77**	**0.71**	**0.64**

[1] From Appendix Table 4.1.

[2] N removed in harvested portion of alfalfa, soybeans, peanuts, 49% of lentils, and 54% of dry peas. It was assumed that any fixed N not recovered in the harvested crop was countered by soil N taken up during the growing season.

[3] Terry and Kirby, 2000, 2001.

[4] U.S.: Kellogg et al., 2000 (1997 production). Canada: Anonymous, 1997 (1996 production).

Appendix 10.2. Partial P budgets by state or province in North America.

State or province	Crop removal[1] (R)	Applied fertilizer[2] (F)	Recoverable manure[3] (M)	Balance		Removal to use ratios	
				F-R	F+M-R		
	------------------- P_2O_5, million lb -------------------					R/F	R/(F+M)
AL	42	125	86	83	169	0.34	0.20
AZ	53	70	19	17	36	0.75	0.59
AR	216	188	155	-28	127	1.15	0.63
CA	353	366	202	13	215	0.96	0.62
CO	209	108	81	-101	-20	1.93	1.10
CT	3.7	5.7	5.9	2	8	0.65	0.32
DE	18	15	20	-3	17	1.20	0.52
FL	77	181	26	104	130	0.43	0.37
GA	104	279	113	175	288	0.37	0.27
ID	198	191	36	-7	29	1.04	0.87
IL	1,126	705	77	-421	-344	1.60	1.44
IN	588	384	91	-204	-113	1.53	1.24
IA	1,259	621	234	-638	-404	2.03	1.47
KS	669	427	149	-242	-93	1.57	1.16
KY	180	226	33	46	79	0.80	0.70
LA	105	107	15	2	17	0.98	0.86
ME	8	13.6	7.9	5.2	13.1	0.61	0.39
MD	54	63	34	9	43	0.86	0.56
MA	4.6	12	2.6	7.4	10.0	0.39	0.32
MI	271	183	52	-88	-36	1.48	1.15
MN	888	515	195	-373	-178	1.72	1.25
MS	111	103	64	-8	56	1.08	0.66
MO	410	358	120	-52	68	1.14	0.86
MT	169	153	6.9	-16	-9	1.10	1.06
NE	818	438	179	-380	-201	1.87	1.33
NV	23.2	10	3.8	-13.2	-9.4	2.32	1.68
NH	2.45	2.83	1.60	0.38	1.98	0.87	0.55
NM	45	26	23	-19	4	1.74	0.92
NJ	11.9	25.5	3.5	14	17	0.47	0.41
NY	113	91	54	-22	32	1.24	0.78
NC	116	207	250	91	341	0.56	0.25
ND	406	320	10	-86	-76	1.27	1.23
OH	446	338	79	-108	-29	1.32	1.07
OK	171	144	62	-27	35	1.19	0.83
OR	86	89	16	3	19	0.96	0.82
PA	147	110	103	-37	66	1.34	0.69
RI	0.46	2.35	0.24	1.89	2.13	0.20	0.18
SC	34	68	40	34	74	0.50	0.32
SD	511	280	57	-231	-174	1.82	1.52
TN	123	186	29	63	92	0.66	0.57
TX	428	474	256	46	302	0.90	0.59
UT	50	33	20	-17	3	1.53	0.95
VT	11.6	8.2	13.1	-3	10	1.41	0.54
VA	77	130	76	53	129	0.59	0.37
WA	176	99	35	-77	-42	1.78	1.31
WV	16.4	14.8	15.3	-1.6	13.7	1.11	0.55
WI	385	206	129	-179	-50	1.87	1.15
WY	49	61	9.2	12	21	0.80	0.69
U.S.	**11,364**	**8,763**	**3,290**	**-2,601**	**689**	**1.30**	**0.94**
BC	26	17	19	-10	9	1.58	0.74
AB	452	393	111	-59	52	1.15	0.90
SK	673	494	35	-179	-144	1.36	1.27
MB	260	264	37	4	41	0.99	0.86
ON	294	168	100	-126	-26	1.76	1.10
QC	136	119	84	-17	67	1.14	0.67
Atlantic	30	52	14	22	36	0.58	0.46
Canada	**1,871**	**1,506**	**400**	**-365**	**35**	**1.24**	**0.98**
NA Total	**13,235**	**10,269**	**3,690**	**-2,966**	**724**	**1.29**	**0.95**

[1] From Appendix Table 4.1.

[2] Terry and Kirby, 2000, 2001.

[3] U.S.: Kellogg et al., 2000 (1997 production). Canada: Anonymous, 1997 (1996 production).

Appendix 10.3. Partial K budgets by state or province in North America.

State or province	Crop removal[1] (R)	Applied fertilizer[2] (F)	Recoverable manure[3] (M)	Balance		Removal to use ratios	
				F-R	F+M-R	R/F	R/(F+M)
	K_2O, million lb						
AL	108	171	65	63	128	0.63	0.46
AZ	152	4.2	30	-147	-117	36.09	4.43
AR	330	280	118	-50	68	1.18	0.83
CA	1,087	272	266	-815	-549	4.00	2.02
CO	396	29	102	-367	-265	13.64	3.02
CT	11.6	8.1	6.4	-3.5	2.9	1.43	0.80
DE	22	28	16	6	22	0.80	0.51
FL	299	469	26	170	196	0.64	0.60
GA	228	390	91	162	253	0.59	0.47
ID	513	60	59	-453	-394	8.56	4.31
IL	1,293	1,243	98	-50	48	1.04	0.96
IN	723	723	93	-0	93	1.00	0.89
IA	1,557	880	290	-677	-387	1.77	1.33
KS	856	113	194	-743	-549	7.57	2.79
KY	420	294	42	-126	-84	1.43	1.25
LA	168	163	14	-5	9	1.03	0.95
ME	28.5	11.8	8.4	-16.7	-8.3	2.42	1.41
MD	87	80	32	-7	25	1.09	0.78
MA	15.8	15.7	4.0	-0.1	3.9	1.00	0.80
MI	499	419	72	-80	-8	1.19	1.02
MN	1,306	584	224	-722	-498	2.24	1.62
MS	193	149	54	-44	10	1.29	0.95
MO	737	513	124	-224	-100	1.44	1.16
MT	352	42	9.3	-310	-300	8.37	6.86
NE	1,066	86	224	-980	-756	12.39	3.44
NV	90.6	3.7	6.0	-87	-81	24.48	9.34
NH	8.29	3.9	2.7	-4.4	-1.7	2.13	1.26
NM	126	20	39	-106	-67	6.30	2.14
NJ	26.4	35	3.8	8.6	12.4	0.75	0.68
NY	290	142	97	-148	-51	2.04	1.21
NC	225	392	235	167	402	0.57	0.36
ND	609	52	13	-557	-544	11.71	9.36
OH	648	546	88	-102	-14	1.19	1.02
OK	320	57	71	-263	-192	5.62	2.50
OR	238	89	20	-149	-129	2.68	2.18
PA	338	139	128	-199	-71	2.43	1.27
RI	1.56	3.5	0.36	1.9	2.3	0.45	0.41
SC	68	130	28	62	90	0.52	0.43
SD	887	45	72	-842	-770	19.72	7.59
TN	300	271	34	-29	5	1.11	0.98
TX	770	271	302	-499	-197	2.84	1.34
UT	170	8.6	24	-162	-138	19.81	5.23
VT	37.1	11	25	-26.1	-1.1	3.37	1.03
VA	200	186	62	-14	48	1.08	0.81
WA	356	83	51	-273	-222	4.29	2.66
WV	60.7	19	11	-41.7	-30.7	3.19	2.02
WI	739	567	222	-172	50	1.30	0.94
WY	160	5.4	12	-155	-143	29.68	9.21
U.S.	**19,117**	**10,108**	**3,809**	**-9,009**	**-5,200**	**1.89**	**1.37**
BC	79	13	23	-66	-43	5.98	2.19
AB	607	128	136	-479	-343	4.74	2.30
SK	640	59	43	-582	-538	10.93	6.28
MB	332	92	45	-240	-195	3.60	2.42
ON	555	282	126	-273	-147	1.97	1.36
QC	331	142	113	-189	-76	2.32	1.30
Atlantic	100	60	18	-40	-22	1.66	1.28
Canada	**2,644**	**777**	**504**	**-1,867**	**-1,363**	**3.40**	**2.06**
NA Total	**21,761**	**10,885**	**4,313**	**-10,877**	**-6,564**	**2.00**	**1.43**

[1] From Appendix Table 4.1.

[2] Terry and Kirby, 2000, 2001.

[3] U.S.: Kellogg et al., 2000 (1997 production). Canada: Anonymous, 1997 (1996 production).

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