

Soil Fertility

A Guide to Organic and Inorganic Soil Amendments

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May, 2013

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To Jo Josephson

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Acknowledgements

Whatever value this presentation has is due to the efforts and achievements of many people. In addition to the numerous references listed, I wish to acknowledge valuable discussions on soil microorganisms with Larry Zibilske, University of Maine, and equally important discussions on manure and compost with William Brinton, Jr, Woods End Laboratory. I thank Stuart B. Hill for the use of the Ecological Agriculture library at Macdonald College in obtaining information which would have been difficult to find elsewhere. I wish also to thank Frank Eggert, University of Maine, Winston Way, University of Vermont, Stuart Hill, and Robert Kimber, for reading the manuscript at an earlier stage of revision and offering their valuable literary and technical comments. Pam Bell, former editor of the *Maine Organic Farmer and Gardener*, devoted considerable time and effort in editing the manuscript, adding the readability that it so desperately needed, and offered further technical comments. I am grateful to Jo Josephson for her encouragement during the several years while this book was in preparation and in her help in editing this edition.

In my early years at Woods End Laboratory, William K. Kruesi sent me numerous references tabulating the nutrient content of produce. Those tables helped me considerably in interpreting soil tests, and they eventually became part of the impetus and the basis for this book.

Preface

This book is a modification of the book "Fertile Soil" published by AgAccess in 1990, which itself was an updated version of the book "Organic And Inorganic Fertilizers" published by Woods End Laboratory in 1985.

During the many years since it has been out of print, it seems to have attracted some popularity, judging by the resale market. Also in this interval, AgAccess kindly mailed me the original masters. Furthermore, noone seems to have picked up the main message in the book. The last straw was prodding (nagging may be closer to the mark) by a friend to "get up and do something".

The result is what you see: an online version freely available to the public under a creative commons license.

The book arose during the years that I ran the soil testing facility at Woods End Laboratory. Its specialty was to offer recommendations for organic fertilizers and had a working arrangement with certifying organizations in Vermont and California. The research conducted in an effort to understand the distinctions among fertilizers led to the book.

What is the main message? Actually it has two messages. One is to state as fairly as possible, subject to an occasional bias, differences among the fertilizers commonly available. I am not currently aware of any other publication with that goal.

The second message is to emphasize the need in the soil for energy required to maintain soil fertility. The book accomplishes this by identifying a value of the energy in organic residues.

The book has four parts. The first part discusses the importance of organic residues to soil fertility and proposes an energy index for comparing organic and inorganic fertilizers; addresses the controversy regarding the effect of organic and inorganic fertilizers on food quality; and discusses options for determining fertilizer applications.

The second part covers the range of organic fertilizers including unprocessed locally available residues and compost as well as cover crops; processed wastes; and commercial organic fertilizers. The third part has a chapter for each soil nutrient, except for a single chapter on trace elements. Each chapter describes the importance of the nutrient to the plant; its behavior in the soil; and common organic and inorganic fertilizers and application rates.

The final part consists of four appendices which contain the only use of chemical and mathematical equations in the book. Appendix A is a collection of conversion

factors which may be useful. Appendix B presents the details of the argument behind the energy credit proposed for organic matter in chapter 2. Appendix C offers calculations on the liming value and acidity of various fertilizers. Appendix D contains a derivation of graphs in figure 7.1 showing the loss of organic matter in a compost process under different conditions.

A perhaps controversial issue of this modified version of the book is that no tables and few references were updated; in particular, the energy index is still based on 1990 prices and oil valued at \$1 per gallon. This issue may manifest itself in a claim of laziness on my part, to which I have no defense.

Nevertheless, there is a rationale for leaving prices alone. An update value for fuel oil is likely to be in the range of \$3 and change. At some future time another update may occur, requiring a further and doubtless significant increase. But no one knows when that will happen; in the meantime readers will have to do their own update. Doing so will be much easier if updating from a base price of \$1 than from an odd number like, say, \$3.25.

A second rationale is that costs of fertilizers against which the book compares organic fertilizers are likely to have risen by a comparable amount.

Another problem with this edition is that people to whom the earlier editions referred may no longer be accessible at the address noted.

Robert Parnes
May 2013.

Part I

Background

Chapter 1

Introduction

Two questions confront most people who use fertilizers. These are what specific fertilizer to use, and how much to spread. Unfortunately, there are no universal answers, and this book does not offer any, other than a general one: a decision should take into account the energy in organic fertilizers. A major part of the book is an attempt to assign a value to this energy.

Otherwise, the book's purpose is to guide the reader to a personal answer to these questions.

One problem, however, is the wide diversity of opinions about what is a fertilizer; it varies from the well-known NPK trio to a wide range of elements including all the trace elements one can imagine.

Dictionaries offer little help. The definition of fertilizer in Merriam-Webster is: "Natural or artificial substance containing the chemical elements that improve growth and productiveness of plants;" in American Heritage Dictionary of the English Language: "Any of a large number of natural and synthetic materials ... spread on or worked into soil to increase its capacity to support plant growth;" in Macmillan: "A natural or chemical substance added to soil in order to help plants grow." They are too inclusive: water, air and organic carbon compounds are natural materials. Plants do not grow at all without water; they grow poorly without air; and they can grow without organic carbon, but only with special attention and at increased expense. An artificial boundary separates a traditional sense of a fertilizer and other elements which are, in some cases, more essential to plant growth.

So the following is a definition which is reasonably consistent with its meaning in this book: a fertilizer is any substance except water, carbon or oxygen which, upon absorption by a plant, assists in its growth and is at least potentially capable of being bought and sold.

The next task then is to determine whether a fertilizer is necessary and, if so, in what quantity. Chapters 4 and 5 should help. They discuss the nutrient requirements of plants and the possible ways of determining what the soil might supply. But they are only a rough guide. The nutrient content of a plant is an approximation to its nutrient requirement, which itself is an approximation to the fertilizer requirement. Plants may take up more than they need, and roots may

not be able to absorb all the fertilizer which is offered to them.

The data in tables 4.1 and 4.2 show the wide variation in nutrient content that can exist, as well as the wide variation in fertilizers used throughout the U.S. The ability of the roots to accumulate nutrients depends upon the supply, but it also depends on other factors, such as the soil structure, the availability of air and water, and the population of soil organisms surrounding the roots. These are noted, but they can be discussed only in a qualitative way.

Soil tests are usually good. But crops in some soils do not respond to potassium or phosphorus fertilizer even though tests show a deficiency. Cold soils in spring may cause a phosphorus deficiency even though tests show an adequate amount. We have seen those seasons with terrible crop results no matter how much nitrogen was used, and other years when nothing could go wrong.

When we add to these variables the variation in the nutrient content of organic residues, the very fertilizers that are encouraged in these pages, we must conclude that the idea of being able to calculate fertilizer applications with any hope of certainty is an illusion. At best we can apply what we think is necessary, but we should be prepared to make appropriate modifications either later in the season or in the following year, taking into account the weather and the growth of the plants.

The second task of choosing a particular fertilizer is, of course, a matter of opinion and personal philosophy, but it is not as beset with difficulty as choosing the quantity to use. The forces controlling our current state of affairs define three kinds of fertilizers: organic residues, naturally occurring inorganic minerals, and synthetic products.

Most organic residues are poor fertilizers. Fresh cow manure, for example, may have a nitrogen content of 1/2% or lower.

Natural inorganic minerals, such as calcitic limestone and other rock powders, have an intermediate to high nutrient content. Some are moderately to highly insoluble (limestone, rock phosphate, granite dust, greensand, sulfur), and some are very soluble (Chilean nitrate, potassium magnesium sulfate, epsom salts, potassium sulfate).

Synthetic fertilizers also have an intermediate to high nutrient content, but mostly high, and they are all very soluble. Common examples are urea, sodium nitrate, ammonium nitrate, liquid ammonia, ammonium phosphate, ammonium sulfate, triple phosphate, and potassium chloride. **Superphosphate** is also synthetic but is no longer common, its popularity having fallen after the development of more powerful fertilizers such as **triple phosphate** and ammonium phosphate.

Two exceptions to these categories are bone meal and wood ashes. In one sense they are organic residues, but they contain no organic matter. Neither are they natural minerals or synthetic products. So, to resolve the dilemma, we shall regard them as organic residues but keep in mind that they do not contain the advantages of organic residues noted in the book.

In view of their usually low fertilizer value, the obvious question is what is the advantage of organic fertilizers?

The discussion in chapter 2 argues that organic residues supply energy to organisms which maintain soil structure and fertility. The large amount of energy in the residues compared to the small amount of nutrients is a measure of the impor-

tance of that energy. Plants and a soil system containing thousands of different participants have adapted to such an energy-nutrient balance. Any change from this balance must take into account the complexity of interactions within such a system, interactions which are likely to make a sustainable alternative economically impractical.

The abandonment of many eastern soils, quarantine of southeastern soils, erosion of midwestern soils and compaction of western soils are results of our attention only to fertilizers and a refusal to take into account the entire agricultural system.

Moreover, in these days when energy demand is a major cause of the conflicts among nations, it should come as no surprise to learn that energy is a primary factor in the vigor and fertility of soils.

As the natural soil cycle has necessarily evolved, organic residues supplied in sufficient quantity and variety will not only maintain the energy supply but will also furnish an adequate amount of most nutrients for growing crops. In fact, gardens which receive large amounts of residues often have a surplus of nutrients.

Nevertheless, situations occur where organic residues are not available in sufficient quantity to supply the required nutrients. This may happen when the soil is chronically low in a nutrient; when a cash crop is grown on a small parcel of land with a limited availability of residues; or during a period of transition to a system relying principally on residues. At such times an alternative is necessary. What then?

Although this book promotes the use of organic fertilizers, what is irritating is the extremes that some people take to justify claims that synthetic fertilizers are harmful. Some indeed are, but the broad strictures against them all is carried to the point of absurdity.

An obvious example is nitrogen. One argument against soluble nitrogen fertilizers is that they interfere with the natural nitrogen-producing capability of the soil. A second argument is that their production is energy-intensive and is ranked either first or second in the amount of energy consumed on the farm for many crops [68]. Furthermore, their high nitrogen concentration discourages their use in conservative or moderate applications. These arguments favor the use of naturally occurring Chilean nitrate, for example, over synthetic fertilizers.

The problem with the first argument is that organic nitrogen residues also interfere with natural nitrogen-fixing processes; nitrogen-fixing processes require energy and will only occur where they are necessary in a nitrogen-deficient soil. The second argument does not take into account the energy required to mine Chilean nitrate and transport it halfway around the world, where it is unloaded and shipped by truck or rail over, on average, half a continent.

The third argument is reasonable but is equally valid for high-nitrogen organic products such as blood meal.

In choosing a mineral fertilizer, the many claims in favor of natural inorganic fertilizers over synthetics are even stranger. Why, for example, is rock phosphate preferable to superphosphate or triple phosphate?

Following is an accumulated list of claims made at various times in favor of rock phosphate over the soluble phosphates; most of the discussions where superphosphate is specified apply equally well to other phosphates.

1. Claim: As an insoluble product, rock phosphate is consistent with the assertion that one should feed the soil and let the soil feed the plant. Soluble superphosphate feeds the plant directly.

Comment: What does it mean, to feed the soil? Chapter 2 shows that the only food the soil needs, except under extraordinary circumstances, is whatever furnishes energy; it needs nothing else. Mineral fertilizers contain no energy, and rock phosphate does not feed the soil.

Apparently what is meant is not that rock phosphate feeds the soil but that the soil feeds the plant by making rock phosphate available. Why should this be important? Perhaps because non-renewable energy sources are conserved by leaving the work to soil organisms; if so let us continue this direction of thought when discussing claim 3. The only other possible rationale is a philosophical one, in which case we should defer to claim 9.

2. Claim: Despite its high degree of insolubility, rock phosphate releases its nutrients slowly over a long period of time; while superphosphate dissolves quickly but soon reacts with the soil and becomes firmly bound.

Comment: Whether superphosphate is more firmly bound than rock phosphate depends upon the pH. In very acid soils, one might expect that the phosphorus in aluminum phosphate is more firmly bound than the phosphorus in rock phosphate, but in a neutral or alkaline soil, aluminum is tied up and does not combine with superphosphate. Experimental studies comparing the residual fertilizer value are inconclusive, some favoring rock phosphate and others supporting superphosphate [31], [29].

Whatever differences may exist in a particular situation are reduced considerably with the use of organic residues to stimulate biological activity.

Furthermore, phosphorus does not leach from the soil; any phosphorus, no matter in what form, eventually becomes available at a rate dependent primarily upon biological activity.

3. Claim: Rock phosphate is a natural product; while superphosphate is chemically processed and energy-consuming.

Comment: Why, however, should a natural product be advantageous? Possibly because it contains essential trace elements, and rock phosphate does contain trace elements, very little but perhaps enough to be important in extreme cases. No one has claimed that crops are more nutritious when the soil is fertilized with rock phosphate rather than superphosphate.

The one advantage that a natural fertilizer often offers is its appeal to the consumer in the marketing of produce, especially with the implication that no pesticides were used. It is unfortunate that unscrupulous merchants mislabel food products as natural or organic, with the result that some states now have rigid labelling requirements. It is also unfortunate, however, to encounter those who thoughtlessly connect the dangers of pesticides to alleged dangers of mineral fertilizers.

Acidulated phosphates are indeed more energy-intensive to produce than rock phosphate. Owing to the additional energy required to transport rock phosphate, however, the net energy difference is small compared with other agricultural energies.

4. Claim: Rock phosphate raises the soil pH; while acidulated phosphates lower the pH. According to one source, triple phosphate can lower the soil pH down to pH 2, with a devastating effect on soil life.

Comment: No such acidifying effect has been shown, and the source referred to offers no documentation. However, it is possible. The extent of a drop in pH would depend upon the buffering capacity of the soil¹. It should not be severe in a soil with adequate organic matter, and it should be highly localized and temporary, lasting no longer than a few hours. Organic products can also destroy soil life [40].

An estimate of the acidifying tendency of superphosphate and triple phosphate is in appendix C.

5. Claim: The sulfur in superphosphate can attract soil organisms which attack beneficial soil fungi.

Comment: This is untrue and a confusion over the distinction between elemental sulfur and its oxides. The sulfur in superphosphate is in sulfate form, which is oxidized sulfur. Sulfate attracts no organisms unless the soil lacks oxygen, in which case fungi cannot survive anyway. Elemental sulfur does attract certain bacteria, which oxidize it to sulfate; but no phosphate fertilizer contains elemental sulfur. Furthermore, plants absorb sulfate for the nutrient value of the sulfur.

However, an excess of sulfate can lock up molybdenum, so superphosphate may be harmful if used in excess.

6. Claim: Rock phosphate can be spread every four years or so; while superphosphate is customarily spread every year, requiring extra labor.

Comment: This is a valid point, but only if no fertilizer other than superphosphate needs spreading annually.

7. Claim: Rock phosphate encourages the growth of certain root-associated fungi which are capable of breaking down insoluble mineral products and transferring the nutrients to the roots; while soluble phosphorus depresses their growth.

Comment: This is true inasmuch as these fungi only seem to proliferate where their usefulness has an advantage. Reliable experiments with them have been difficult, and whether they would supply enough phosphorus from unavailable reserves to meet the requirements for fast-growing and high-yielding annuals has not been established.

In a typical soil, however, rock phosphate should be no better than soluble phosphorus fertilizers in encouraging these fungi. The presence of the desirable fungi depends more upon the available phosphorus level in the soil rather than upon the availability of phosphorus in the fertilizer. Figure 5.1 is the result of a survey of soil test results, mostly of organically managed soils, and shows that most such soils have moderate to high levels of phosphorus. There is a much greater desire to assure a good start to transplants in cold soils than to worry about fungi, and the tendency to hedge by continually adding phosphorus suppresses these fungi no matter which fertilizer is used.

8. Claim: Concentrated phosphates contain significant amounts of cadmium, high enough that one brand was banned by the Canadian government [60].

¹Chapter 14 has a discussion of cation exchange and buffering

1. INTRODUCTION

Comment: This is true, but the cadmium comes from the rock phosphate ore used in production, and the amount present varies with the different ore deposits. Compared with the phosphate content, some synthetic fertilizers contain no more cadmium than the colloidal rock phosphate from Florida, but others have more. When using appreciable amounts of synthetic phosphate, one would have to pick a brand carefully.

On the other hand, since the phosphate ore itself contains cadmium, simply being natural does not mean that a fertilizer is safe; in addition to cadmium, rock phosphate contains fluorides and has a small amount of radioactivity. None of these impurities have been found to be hazardous.

However, breathing dust from colloidal phosphate without a protective mask can be detrimental. One must be careful when working with any agricultural product, whether organic, natural or synthetic.

9. Claim: Rock phosphate contains phosphorus which becomes available over a long period of time; while the acidulated phosphates are highly concentrated phosphorus carriers. We view the soil as one integrated, living organism that should be treated gently. Those of us who favor a preventive health plan can appreciate the unpleasantness of a strong medicine, whose side effects may be worse than the disease. So it is with a concentrate in the soil; even though we may not know its side-effects, we have an uneasy feeling about it. This feeling is reinforced by the realization that we do not need the concentrate. With good management we can grow superior crops without it.

Comment: The force of this argument, though compelling, is diminished by the realization that some organic products are also concentrated. Chicken manure, bloodmeal and cottonseed meal are as strong as some synthetic fertilizer blends.

If anyone has additional reasons for preferring rock phosphate, I should like to know them. In the meantime, my opinion is that the last claim, #9, is the strongest argument in its favor. The others may have merit but are essentially attempts to find a practical rationale for a philosophical point of view. If this is so, it should be so accepted. It is perhaps a manifestation of the notion that we should understand the soil and become sensitive to the effects of what we do to it.

Nevertheless, as the criterion, this philosophy limits the economic value of organic agriculture. Triple phosphate is cheaper than rock phosphate and more easily available. If the claim against synthetic phosphates is based on a philosophical argument, and if the product does not degrade the soil when used judiciously and if it does not produce crops of inferior quality, then this shuts out people who are concerned about soil and crop quality and accept the value of organic residues but cannot afford the premium for rock phosphate.

Furthermore, being more labor-intensive, organic produce is more costly; it doesn't seem fair, especially to low-income people, to add an unjustifiable cost based on irrelevant claims.

The major emphasis for good soil management should be on recycling organic residues; further restrictions based on conjectural comparisons of inorganic fertilizers are not only an unnecessary digression but also a dilution of the major value supporting organic agriculture.

Furthermore, whatever rationale is applied in establishing a prohibition against some fertilizers should apply to the entire agricultural system. No fertilizer has as traumatic an effect on soil structure, moisture and soil life as a rototiller². If we are sensitive to soil processes, we should ban the rototiller. If we are concerned about non-renewable energy use, we should ban plastic mulches and gas-powered machinery. The most aggravating part of the claims favoring natural over synthetic fertilizers is their selectivity.

One of the purposes of the book is to forget our preconceptions, if only temporarily, and to examine the consequences of all fertilizers.

Two general statements regarding fertilization for gardens may be appropriate. The first is that a garden differs fundamentally from a farm.

A farm is a source of nutrients, and a garden is a sink.

A farm produces hay and straw for mulch, and it produces animal manure, both of which contribute to the fertility of a garden. A garden takes all that fertility for producing a high intensity of valuable crops.

Moreover, the tillage required to maintain a garden tends to destroy fertility, whereas the tillage on a farm, at least under reasonable conditions on small farms, builds fertility.

These distinctions are stereotypes, but they do indicate tendencies. To build and maintain a sustainable agricultural system, people who garden should either integrate with a farm, or they should adopt some of the practices used on a farm to supply the fertility poured down their garden sink. Calculations showing the importance of farmland to garden fertility, both in terms of building humus and supplying nutrients, are presented in chapters 2 and 6.2.

The second statement is that an inverse relation exists between soil fertility and ecological diversity: over a broad range, increasing one decreases the other. A soil high in nitrates decreases the activity of those soil organisms that produce nitrates. Nitrogen fixation by bacteria associated with legumes is suppressed when available soil nitrogen is already high enough to support legumes. Those classes of fungi which supply a plant with phosphorus and other minerals are suppressed if the minerals are already abundant.

Tillage limits ecological diversity by favoring those organisms that can temporarily go into a dormant stage during unfavorable conditions.

Gardens require adequate fertility and tillage management for a satisfactory harvest, but it is not wise to go beyond a prudent course.

Finally, the tone of the book may be summarized in a statement by L. L. Van Slyke [79], who in 1912 listed four advantages of commercial fertilizers (convenience, opportunity for choice, uniformity, and uniform mixing of blends). He also discussed three disadvantages, the third of which follows: "(3) Lack of educational incentive.—The most serious disadvantage in the use of commercial fertilizers, as they are actually used in most cases, is that farmers are not stimulated to acquire needed information in regard to plant-foods and their proper use. Many farmers use commercial fertilizers blindly in somewhat the same way that people use patent medicines. In the hope of increasing yield of crops, without definitely learning why

²Chapter 2.2 offers an argument against the rototiller

1. INTRODUCTION

crops are decreasing, commercial fertilizers are tried, some brand being used in accordance with the recommendation of a neighbor or some seller of fertilizers. It is easy to acquire the 'fertilizer habit' and difficult to abandon it. This blind, slavish use of fertilizers deadens the intellectual activity and in many cases has led to actually decreased productivity of soil when sole dependence has been placed on their use for long-continued periods."

See [15], [21], [50], [86], [94] for further reading. These references are the basis for much of this book.

Chapter 2

Essentials of Soil Fertility

2.1 Organic Matter and Biological Activity

Summary

Owing to the energy which it contains, organic matter serves many purposes, on its own as well as indirectly through the soil organisms which it nourishes.

In most cases, a goal for an optimum organic content in the soil should take into account the expected content in an undisturbed state.

Through several cycles in which some varieties of organisms feed on the remains of others, and by means of purely chemical reactions, organic matter passes through several stages, each of which has a unique effect on the nutrient supply and plant growth.

Consequently fertilizers containing organic matter should get credit for the value of its energy in comparing them with inorganic fertilizers.

In most soils, biological activity is limited by the energy available from carbonaceous organic residues. For this reason, biological activity is rarely stimulated by fertilizers; their use should be timed to feed the crops rather than to stimulate biological activity.

The accumulation of humus, however, depends upon the nitrogen available. If it is supplied, though slowly enough to minimize losses, a greater amount of humus can result from the decaying organic matter. With the help of simplifying assumptions, it is possible to estimate the fraction of organic residues transformed into humus.

Fresh organic residues are a good source of plant nutrients except, in most cases, calcium and magnesium. After decomposition the result is rich in nitrogen, phosphorus and sulfur but low in potassium.

The Value of Organic Matter

Organic matter is the unifying element in the soil, having a prominent influence on soil organisms, plant growth and on the physical properties of the soil. We might regard the soil as the furnace of life, wherein organic matter is the fuel, soil

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organisms are the fire consuming the fuel, and the plant nutrients are the ashes of the combustion. The fire needs no matches, only fuel and a modest amount of air and water; it is vigorous at the first addition of residues but slows to a smouldering oxidation that can last for centuries.

Although this metaphor may be as good as any, it doesn't do justice to the value of organic matter. Organic matter can, for example:

- attract and hold cation nutrients and trace elements in an available state, reducing leaching losses;
- bind particles into aggregates, producing a **granular soil structure** which permits the accessibility of air to roots, the capillary movement of water, and the penetration of roots through the soil;
- soak up water;
- evolve into vitamins, hormones and other substances which stimulate growth in plants and soil organisms;
- inhibit weed growth.

In turn, soil organisms can:

- fix nitrogen from the air;
- form a symbiotic relationship with plant roots, thereby serving the plant as an extension in its search for mineral nutrients;
- produce (as byproducts of metabolism) vitamins, growth hormones, and organic acids, the latter an effective solvent of minerals;
- contribute to soil aggregation and the distribution of nutrients, by binding organic matter and mineral particles or by feeding on plant debris, mixing it throughout the soil, and forming tunnels and nutrient-rich fecal matter;
- prey on plant pathogens;
- produce carbon dioxide (a byproduct of metabolism), which passes through the soil and into the atmosphere and becomes a source for absorption of carbon by plant leaves.

Many of these points will be discussed later.

The Energy Index

All of the advantages that organic matter and soil organisms offer to the soil and plant growth are due to the fuel in the organic matter and the fire from the organisms. The fire is necessary to break down organic residues and make their nutrients available to plants.

2.1. Organic Matter and Biological Activity

Organic matter contains more energy than anything of value to plants, and yet few people credit it as the fuel for the soil furnace.

In fact this energy reduces the need for fertilizers by facilitating the storage of water, the fixation of nitrogen, the dissolution and accumulation of minerals, the effortless movement of roots through a superior soil structure, and the production of growth hormones and vitamins. In providing a suitable environment for predators, it reduces the need for pesticides. In encouraging a diversity of soil bacteria that feed on weed seeds, it inhibits the abundance of weeds [3].

Energy has a value, and the organic matter should receive credit for this value. Due credit justifies the cost of producing and recycling residues. It permits an estimate of the loss of depleted soil and of the value of organic fertilizers¹.

One way of quantifying the value of the energy in organic residues or fertilizers is to create an energy index: determine the amount of fuel oil with the same quantity of energy. Appendix B contains a derivation of a proposed index applied in this book.

How would such a determination work? The potential energy of #2 fuel oil is about 140,000 BTU/gallon. We can compare this value to the energy content of an organic substance. The energy is released upon the oxidation of carbon to carbon dioxide. For example, a ton of fresh cow manure with 20% organic matter has the same amount of energy as 20 gallons of #2 fuel oil. If fuel oil costs \$1/gallon², a ton of this manure is worth \$20 for its energy in addition to the value of its nutrients.

Other examples:

- Each 1% of soil organic matter contains as much energy as 1200 gallons of fuel oil per acre
- About 80 pounds of fresh kitchen wastes has as much energy as one gallon of oil
- A 40-pound bale of hay contains the energy equivalent of 1.6 gallons of oil; such hay priced at \$1.25/bale compared to oil at \$1/gallon has a market value approximately the same as the value of the energy it contains.

The proposal does have defects. Energy is more easily extracted from green manures than from wood chips. Some residues, such as manure and compost, are already partly decomposed, and the lost energy has been exchanged for beneficial organic byproducts.

Some people would dispute the claim that the energy in organic residues has the same value to agriculture as the energy in fuel oil. It would be difficult to prove or disprove it, since the fairness of the price of oil, the value of agricultural land, and a farmer's wages are based on economic and political confrontations rather than moral or long-term considerations.

We are, however, not only beginning to recognize the benefits of organic matter but also the cost incurred when the benefits are ignored in favor of short-term

¹See, for example, table 10.1 and the discussion of nitrogen fertilizers in chapter 10

²As noted and justified in the preface, quoted costs are representative of those in 1990

profits. We are familiar with the loss of quality and yield from eroded soils in the Midwest and the massive machinery necessary to manage problem soils in California. We know that the soils in southeastern states and in some areas of New York are quarantined because of the presence of pests in epidemic proportions.

When fertilizers are added without also adding energy to compensate for the loss of organic matter that inevitably results from cultivation and the removal of crops, the soil deteriorates, and the cost of preventing deterioration is the cost of the energy required to maintain the organic content.

There may be a better measure of the cost of this energy, but at the present time fuel oil is a convenient basis for calculating energy, so why not compare it to the energy in the soil? In any event, nothing is perfect, and here is one way of giving credit to organic materials for their inherent contribution to the soil.

So, the definition of an energy index as used in this book is the number of gallons of #2 fuel oil which contains the same amount of energy as a ton of organic fertilizer. It is tabulated in parts II and III for the purpose of comparing the value of fertilizers.

Optimizing Organic Matter

What is the optimum organic content of a soil? Can a soil have too much organic matter? These are questions that are difficult to answer, partly because they are difficult to define. What is meant by optimum and organic content? The word optimum may imply optimum biological activity, optimum quantity or balance of nutrients, minimum labor requirement, or an optimum profit and loss statement. In principal it should have a meaning that integrates all of these meanings, but some may have more importance than others. The term organic content is also not clear. It includes a variety of residues ranging from raw litter to highly stabilized **humus**.

One measure of an optimum organic content is the humus level in an undisturbed soil. This varies with the environmental conditions; the humus level of some acid New England soils, for example, is often about 10%, and in desert areas it is less than 1%. Within a few years of cultivation losses caused by exposure of organic matter to air result in a new equilibrium.

Most likely, maintaining the organic content in a cultivated soil at about half its natural level is a reasonable goal. A higher organic content may be better, but whether it is worth the additional effort to fight natural processes is questionable, except in an intensively managed garden.

Even this guide has limitations. A gravelly soil, for example, is likely to require much more organic matter than it might accumulate naturally within a reasonable geological period of time.

Furthermore, the optimum level of organic matter may depend upon its state of decay. A sandy soil needs organic matter for water and nutrient retention. This requires organic matter that is reasonably well decayed; fresh plant residues tend to repel water rather than absorb it ³, and fresh residues have a low capacity to retain nutrients.

³because of the natural waxes which have not yet broken down

2.1. Organic Matter and Biological Activity

In contrast, a clayey soil already has a high capacity for retaining water and nutrients; its most important requirement is something to open up the soil. Either fresh residues or **humus** might do this by different mechanisms, but a greater short-term benefit should come from fresh residues.

In warm climates, soil decomposition is rapid, and organic matter tends to stabilize in a relatively short time, so fresh residues tend to be more important. In cold climates, organic matter has less chance to stabilize, and well decomposed organic matter is at a premium.

The question of whether the organic matter is excessive implies the possibility of an adverse effect on the soil. As with the question of an optimum organic content, the answer may depend more on the state of decay of the organic matter rather than the quantity. No practical evidence seems to exist that an excess of **humus** is harmful. Nor is there a universal indication that an excess of fresh residues is harmful - many people garden successfully with massive hay mulches.

However, adverse effects of excessive unstable residues are possible:

1. the balance of nutrients may be poor: a high **C/N ratio** or a high potassium/magnesium ratio
2. some of the initial byproducts of fresh residues may be toxic to seedlings
3. insect pests may be attracted to a soil with a high content of fresh, moist residues
4. fresh residues together with soluble nitrogen fertilizer encourage nitrogen loss by **denitrification**.

Fertilizer Value of Organic Matter

Organic matter is principally a source of nitrogen, phosphorus, and sulfur - nutrients which soil organisms require and retain. These nutrients slowly become available as the organic matter continues to decompose. Most of the calcium, magnesium and potassium in the decaying organic residues are discarded by the soil organisms.

The Nature of Organic Matter

Many statements here and later in the book will depend upon an understanding of organic matter. One problem, however, is that current knowledge is not entirely clear on what organic matter is, nor are different viewpoints easy to integrate. Discussions in this chapter and indeed in the entire book concerning organic matter are an attempt to integrate different points of view, insofar as it is possible. The principle references are [15] and [83], although [17] is sometimes helpful.

Organic matter in the soil is litter or residues in various stages of decomposition and transformation. These generally fall into two contrasting groups: succulent material often rich in nitrogen and associated with rapidly growing plants; and tough, fibrous carbonaceous material associated with mature plants. The latter has a high content of **lignins**; both are high in **carbohydrates**. Examples: green

manures, hay and grass clippings are succulent, non-lignaceous residues; straw, wood and bark have a high-lignin content.

Most likely it was the slow rate of decomposition that led to the lignin theory of **humus**, which states that humus is essentially lignins that have not decomposed. The actual evidence, however, was weak, and the theory could not explain the fact that humus has the same carbon/nitrogen ratio and similar mineral levels as soil micro-organisms.

This objection resulted in the microbial synthesis theory. It postulates that humus is the remains of soil organisms [15]. Accordingly, equal quantities of organic residues, no matter what their lignin content, will eventually result in equal quantities of humus, although lignaceous residues will require more time to break down.

More recently, however, the lignin theory was revived by new evidence using radio-active carbon techniques. It indicates that microbial tissue comes from approximately the same amounts of lignaceous and non-lignaceous residues. But the greater portion of lignaceous material is converted to **humus**; while the greater portion of non-lignaceous material is oxidized to carbon dioxide[83] and is the principal source of energy for metabolic activity.

With some compromise on both sides, the two theories are compatible, because the lignin theory hypothesizes what humus is, and the microbial synthesis theory tries to explain how it is produced. Compromise is necessary. Although humus may be predominantly derived from **lignins**, a significant amount of humus nevertheless must come from non-lignaceous material; after all, humus does contain a large amount of nitrogen and minerals not present in lignins.

On the other hand the production of humus is not entirely microbial. Humus materials produced microbially can bond to one another chemically, increasing in size and stability. Furthermore, a non-lignaceous material can also bond to humus chemically, the result of which increases the stability of the non-lignin.

So it is plausible to adopt the following model of humus formation: humus develops from the decomposition of dead microbes, whose tissue consists of both lignaceous and non-lignaceous materials. Living microbes attacking the dead tissue use both portions, but more of the latter for energy. Left behind are also portions of both, but primarily modified lignaceous materials which contribute to the pool of humic substances. In time, these humic substances bond to one another, growing and stabilizing further.

With this model we can postulate some of the properties of organic matter, which may help in choosing the best agricultural management of the soil.

For example, we can visualize two stages in the formation of humus: the initial decomposition of organic residues to a point where they are unrecognizable, and the buildup of **humus**⁴.

In the first stage, fungi are prominent in the decay of the residues, using some of the residues for energy and some for building cell tissue for growth and reproduction.

⁴This division of decomposition into two stages was noted by E.E. Pfeiffer, in his studies of the preparation of compost by Biodynamic methods, long before our current theory of organic matter became important, but the theory helps to explain his observation.

Their initial domination is at least partly because not only do they require less nitrogen for cell growth than other micro-organisms, but they are alone in their ability to attack woody tissue.

In the second stage, the early feeders are preyed upon by other, different organisms, or they die when the food supply runs out, and their remains are subject to attack by others. In like manner the second generation of decay leads to a third and still different generation. With each successive cycle of consumption and decay, some energy is removed, different types of organisms flourish, and the cellular tissues of those organisms become increasingly stable and more resistant to further attack and decomposition.

Throughout this process of consumption and transformation, the properties of the residues change. The initial instability makes them chemically and biologically active. They are easily broken down, and so their nutrients become readily available; they attract heavy metals, so they can **chelate** trace elements⁵ and make them available. At the same time they can lock up excess amounts of toxic metals.

Such instability, however, is also a disadvantage. Many of these active organic substances are water soluble and leach easily, hastening the depletion of soils, especially in humid climates.

As organic matter continues to decompose, it becomes less active. It is not as influential in chelating trace elements, and it has little influence on the soil structure⁶. Its value lies in the nitrogen and minerals it contains, which eventually become available, and in its buffering capability⁷.

Requirements For Biological Activity

The conditions needed for a diverse mixture of soil life are a warm soil, adequate moisture and drainage, and a soil **pH** above 6. These conditions also assure a high biological activity. Both diversity and high activity are important to achieve the benefits of organic matter.

The same conditions that enhance soil life usually produce maximum plant growth, although exceptions do occur. The most common exception is the pH requirement. Blueberries, azaleas, rhododendron and other plants evolved in very acid soils and do not grow well at a pH above 6. Many varieties of potatoes are subject to a scab which is most prominent at a pH above 6. Sandy soils along the Atlantic coast and in the south have difficulty in supplying manganese when the pH is much higher than 6.

Some of these adverse effects of a higher pH, however, can be controlled. With potatoes for example, there is evidence that a supply of fresh organic residues without an excess of nitrogen will reduce the incidence of potato scab, by encouraging competition from other soil organisms. Moreover, as discussed in chapter 16.2, the nutritional value of potatoes is likely to be better in a less acid soil owing to higher availability of molybdenum.

⁵Chapter 16.3

⁶Chapter 2.2

⁷For a discussion of buffer capacity and **cation exchange**, see chapter 14

2. ESSENTIALS OF SOIL FERTILITY

In sandy soils, an organic mulch will supply manganese and other trace elements and also reduce leaching losses.

In practice, carbon is always the element limiting biological activity in agricultural soils, even though it may be in excess. It is not just the amount, but also the nature of the organic matter which determines the limiting factor. Lignaceous material is so resistant to decomposition that the rate of decay in soil is low enough to allow existing reserves to supply whatever nitrogen is necessary to meet demand.

For most soils the **C/N ratio** lies in the range from about 8 (8:1) to 14 (14:1). Consequently the soil is rich in nitrogen compared to carbon. Although much of it is in relatively stable humus, enough does become available to supplement whatever the residues offer. Lignaceous residues offer little nitrogen, but the decay rate is slow enough that nitrogen reserves are available when needed.

Sawdust is an example. If 1% softwood sawdust is added to a soil containing 1% organic matter, nitrogen fertilizer does not increase the rate of decomposition. This is because the resins in softwood slow down the decomposition process to the extent that organisms can easily meet their nitrogen requirement.

However, if 1% hardwood sawdust is added, nitrogen fertilizer can increase the rate of decomposition, but enough fertilizer to reduce the carbon/nitrogen ratio of the sawdust from about 500 to 35 only increases the rate of decomposition by about 50%⁸.

In the field, 1% sawdust amounts to a layer about 1/2 inch thick turned into the soil. Normally, raw, uncomposted sawdust is not tilled into a soil but rather spread as a mulch; in which case the soil is exposed to a much smaller amount at one time.

Consequently, adding nitrogen fertilizer to increase biological activity and hasten the decomposition of carbonaceous residues is not worthwhile. In fact, doing so is wasteful if the nitrogen is soluble or readily available, because it is likely to be lost by **denitrification**⁹.

The issue is not food for the soil organisms but for the plants. If carbonaceous residues are worked into the soil, most of the nitrogen which might otherwise be available to plants will instead be immobilized within the cell tissue of soil organisms. Eventually biological activity will burn up enough carbon to release nitrogen; but this delays availability to the plants.

Consequently nitrogen fertilizer is necessary at the proper time for the plants rather than for soil organisms. If residues are turned into the soil in the fall, nitrogen need be spread only in the spring for the sake of the crop.

The other nutrients in humus - phosphorus, sulfur - are even less likely to be a limitation to biological activity.

⁸[59]. This article did not state the organic content of the soil used, but it did state a nitrogen content of 0.057%. With the assumption of a C/N ratio of 10 and a carbon content of 50% of the organic matter, the organic content is calculated to be 1.1%.

⁹Chapter 10 section 10.3

Humus Renewal and Conservation

Even though fertilizer nitrogen is unnecessary for biological activity, it may increase the amount of **humus** produced. The efficiency with which an increase occurs depends on two factors: the rate at which nitrogen becomes available for consumption and the nature of the residues.

Nitrogen constitutes an anchor for cell tissue. Additional nitrogen produces a corresponding addition in the growth of living organisms; having died, the organisms contribute to the pool of humus. For efficient use of the nitrogen, however, its availability must not occur at a rate in excess of the need. This rules out soluble fertilizers for increasing humus efficiently^[45].

However, the flow of organic matter is a dynamic process; there is no such thing as an absolutely stable state. A steady loss of humus through biological activity is always occurring and must be replaced by fresh sources.

Consequently, there are two objectives, to increase biological activity and to build **humus**. To maximize biological activity, we need adequate warmth, aeration, moisture, a near-neutral **pH**, growing plants, and organic residues. To increase humus we need organic residues as a source of food for the organisms and a slow but steady increase in nitrogen. These are most likely to be effective with minimum losses of humus by cultivation.

Trying to predict how much **humus** will remain from the application of organic residues is a hazardous undertaking; there is no clear distinction between residues and humus, and even humus continues to degrade. The main problem is choosing the **C/N ratio** at which residues become stable enough that further decomposition can be measured in months or maybe years rather than days or weeks.

Nevertheless, it may be worthwhile to try, if only to get an idea of what is happening. The minimum C/N ratio in soils is about 8. Since 10 is a round number and convenient to use, we'll choose that as the criteria for the definition of stable humus.

If we start with cow manure having a C/N ratio of 20 and a moisture content of 80%, and if 25% of the original nitrogen remains for humus buildup, then the final amount of humus will be about 1/40 of the fresh weight of the original manure¹⁰.

With these assumptions, an application of 10 tons of cow manure/acre should result in a humus addition of about a quarter of a ton/acre. The weight of an average plow-depth layer of soil is about 1000 tons/acre. So 10 tons of manure should increase the humus content by about 1/4000. At this annual application rate it would take 40 years to increase the humus content by 1%¹¹.

¹⁰As a rule, about half the nitrogen in fresh manure becomes available to plants or is lost in the first season. At least half of the remaining nitrogen will become available during the next several years. So only one-quarter or less remains for humus development. If we assume that one-quarter remains, then the carbon content must also drop to one-quarter in order to maintain a carbon/nitrogen ratio of 20, and it must drop to one-eighth for the carbon/nitrogen ratio to fall to 10, the value that we defined for humus. If the manure contains 80% water and 20% dry matter, then the final amount of humus will be 20% of 1/8, or 1/40 of the fresh weight of the original manure.

¹¹This may be an overly conservative estimate. Possibly the assumption that the **C/N ratio** must drop to 10 before the organic residues are stable enough to be considered as

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A long time is required to build humus on a depleted farm. Manure can be spread at a higher rate, and this may result in a faster buildup of humus if nitrogen losses do not become too high; rates up to 25 tons/acre for growing corn are sometimes recommended, and gardeners may spread more than that.

Organic matter could be increased more rapidly in a garden with the use of a hay mulch. If we begin with air-dried hay at 16% moisture and having a carbon/nitrogen ratio of about 40, and if we assume, as we did with manure, that 25% of the nitrogen is available for humus formation, we shall find that about 1/20 of the mass of the original mulch will remain by the time the carbon/nitrogen ratio drops to 10¹².

If one were to spread baled hay to a depth of about 3 inches, the total amount of hay spread would be equivalent to approximately 40 tons/acre. If the above estimate is correct, this should add about 2 tons of humus/acre, or about 0.2% with a one-year application. It would then require only 5 years to raise the organic content by 1%, a much more optimistic result than we got with the manure calculation.

On the other hand, we are comparing a moderate application of manure with a massive application of hay; we would have to grow a 5-ton crop of hay on 8 acres of land to supply 40 tons for a one-acre garden. Furthermore it would still take several years for the mulch to become incorporated as humus in the soil.

Similarly, green manures have little chance of increasing humus. The fact that the tops are not lignaceous may be partly compensated by the roots. Even so, to expect to grow within a few weeks enough organic bulk on one acre of land to be equivalent to a hay crop grown during an entire season on 4 - 8 acres should seem like an unfounded hope.

Compost is a third alternative for increasing the humus content, but the nitrogen content of the compost and the losses are much more difficult to estimate. However, with practically no limitation on the application rate, humus can be increased faster and probably more safely with compost than with fresh manure, and humus stabilization could be faster with compost than with a hay mulch.

Nevertheless we are not getting something for nothing. To do as well as we might with our 40 tons of hay, we would have to compost those 40 tons with no loss of nitrogen; so we would still need a full crop of hay from at least 8 acres of land in order to increase the humus level of 1 acre by 0.2%. One advantage of compost, however, is that we do not need hay; any waste product will do.

Whatever the merit of these calculations may be, they should be good enough to indicate that **humus** development is a slow process. If we also take into account losses from tillage, the result is that we often have to work hard just to stay even.

humus is too strict, and perhaps less nitrogen is available to plants and more kept for humus development. Nevertheless, it is difficult to see how the assumptions could be loosened up enough to predict a humus increase of 1% in less than 20 years.

¹²Following the same reasoning as we did with manure, we find that the carbon content of the decomposing hay will drop to 1/16 of its original value. A moisture content of 16% means a dry matter content of 84%, so that the amount of humus remaining is about 1/20 of the fresh, air-dried weight of the original hay

The point, however, is not to discourage people from working to increase humus but to illustrate in one additional way how fragile our environment is and the loss to the future of using resources developed over centuries of time for short-term gain.

No matter how long it takes to rebuild soil, someone should start sometime or civilization as we know it will disappear.

2.2 Air and Water

Summary

Air and water are necessary in photosynthesis, metabolism, growth and plant structure and temperature regulation.

A good soil structure permits movement of air and optimum use of available water. In a well-structured soil, the soil particles are bound together in small **aggregates** of variable size. Soil structure is determined by various physical and biological processes which influence the formation and stabilization of the aggregates.

The Importance of Oxygen and Water

Air and water are essential to the storage and release of energy in the plant. During photosynthesis, energy from the sun is trapped by the plant leaves. The energy provides the means to break up carbon dioxide from the atmosphere into carbon and oxygen. The plant manufacturers sugars from carbon, oxygen and water for temporary storage of the energy. Eventually the plant grows by the construction of **carbohydrates** from sugars.

During respiration, various plant mechanisms expose oxygen to the sugars and carbohydrates. This oxidizes some back to carbon dioxide, during which time the stored energy is released and utilized in metabolic reactions. The release of energy from the oxidation of carbon is the source of energy for plants and soil organisms; it is the same energy that we gain from burning fuel oil, peat and wood.

In addition to its contribution as a constituent of sugars, water has physical effects: by filling plant cells, it supplies a structure that keeps the plant erect; without it, the plant wilts. Water evaporating from leaves cools them, in the same way that we are cooled by perspiration. Water also carries dissolved nutrients across the root surface.

Water is usually a limiting element to plant growth at some time during a growing season. Shallow-rooted crops require special attention to water because of the limited ability of the roots to scavenge for phosphorus.

Plants do not have a mechanism to transport gases. So roots need an independent source of oxygen in order to utilize the sugars produced by the leaves. They obtain it from air present in soils.

The higher the soil fertility, the greater the demand for oxygen. A high fertility results in greater plant growth and biological activity. This results in a higher rate of respiration. As respiration increases, so does the need for oxygen. Soil organisms

compete with plant roots for available oxygen, and in a marginally aerated soil the roots may not get enough. Roots lacking oxygen are stunted.

As it turns out, a lack of oxygen in the soil is not all bad. Iron, manganese and copper are more available to plants in their oxygen-deficient state. Ferrous phosphate is more soluble than ferric phosphate and can be a significant source of phosphorus.

Almost all soils, however, are anaerobic at some time to a sufficient extent to produce the necessary benefits without our having to deliberately induce such a state. Usually the greater concern is to satisfy the conflicting requirements of adequate water and oxygen.

Soil Structure

An important function of a soil derives from its physical characteristics. Soil supports a plant while permitting movement of the growing roots, and it provides air and water. Fresh rainwater carries dissolved oxygen needed by the soil, so the soil must be porous enough to permit good drainage and to prevent the water from standing and becoming stale. If drainage is too rapid, however, the soil is droughty. Ideal drainage occurs in a soil which contains open spaces of various sizes; wide spaces permit drainage and access to oxygen; small spaces trap water and allow its movement by capillary action.

The texture and structure of the soil influence the dimensions of the open spaces. The texture refers to the proportions of sand, silt and clay particles. Structure refers to the extent to which the soil particles are bound together. The two are sometimes correlated; in pure sand, the particles are not bound at all, and in clay they are so strongly bound that the resulting blocky chunks can be broken up only with great difficulty.

A good soil structure is important in two ways:

1. it permits the movement of water and air through the soil
2. it facilitates the development of an efficient root system by minimizing the work required by root hairs in their growth.

In turn a good root system can better forage for nutrients and water. A good soil structure can substitute for some of the fertilizer and irrigation that would otherwise be necessary.

The texture of a soil is not easy to change, except on a small scale where sand may improve a clay soil. The structure, however can be altered by encouraging the formation of **aggregates** of varying size. We often say that the soil has good tilth or good crumb or a granulated structure if it is well-aggregated.

Soil aggregation occurs in two phases, formation and stabilization. Formation occurs by physical forces, such as freezing and thawing cycles, or wetting and drying cycles. These clump the particles together, but without stabilization the same forces will break them up.

Stabilization can occur either physically - by fungi surrounding the aggregates - or chemically - with cements from decaying starches.

Plant roots contribute to both formation and stabilization. Roots pushing through the soil and absorbing water create differential pressures which form the aggregates. And they slough off dead tissue, some of which decays into cements that bind the aggregates. Grasses and grains are particularly effective in promoting good soil structure, owing to the extensive network of their root system.

Regardless of the soil texture, organic residues have a significant effect on soil structure. They provide the raw materials for the cements which bind and stabilize soil aggregates, and they stimulate the growth of micro-organisms and soil animals that contribute to aggregate stability.

Residues high in **carbohydrates** are best in promoting stable aggregates[15], [83, chapter 11]. Simple sugars also produce cementing agents and at a faster rate than carbohydrates; but their stability is poorer because they are more easily attacked by further biological activity. The higher the molecular weight of a cementing product, the slower but more long-lived its effect. In particular, cellulose produces the most stable aggregates.

An argument could be made for the claim that the most important agricultural value of organic residues, though certainly not the only one, is their effect on soil structure. Alternates exist commercially for other benefits, whatever their merits: fertilizers, pesticides, hormones, etc. There is, however, no practical way to create a stable and effective soil structure without organic residues; people have tried and failed.

Three practices are necessary to encourage a good soil structure:

1. keep a crop growing as much as possible, to encourage maximum root growth
2. recycle residues to replace **carbohydrates** lost through biological activity, carbohydrates which are necessary for the cements binding soil aggregates
3. minimize disturbance of the soil which would reduce biological diversity and accelerate the destruction of soil structure and organic matter.

Tillage

Tillage can improve soil structure by breaking up clods, and it can contribute to the forces which form the soil aggregates. But tillage can also be damaging; when the soil is too dry, it shatters the aggregates; when too wet it compacts them.

Moisture conditions are especially important with heavy clay soils. These soils should be moist when tilled but not sticky. One criterion for estimating the best time for working a clay soil is that it should be just dry enough that a person can walk onto it without soil sticking to boots. Another is that a handful of soil squeezed into a ball should have no excess water running out and should crumble slightly when released.

Tillage tends to dry out a soil and must be timed carefully. Rewetting, especially after a long period of dryness, causes a flush of biological activity which rapidly oxidizes organic matter. Sandy soils suffer from improper tillage, because they need the organic matter for water and nutrient retention, and clayey soils because they lose soil structure.

2. ESSENTIALS OF SOIL FERTILITY

Be aware of the degree to which rototillers degrade the soil environment. They dry out the soil; they whip it up and shatter the aggregates; they destroy the capillarity; most compact the subsoil¹³; they reduce the diversity of micro-organisms to those able to survive a temporarily hostile environment; and they destroy earthworms and other soil animals.

Rototillers are especially inadvisable in dry climates because they increase the frequency needed for irrigation. They should also be avoided where organic matter is low: although the subsequent release of nutrients by increased exposure to oxygen may offer a short-term benefit to plant growth, the result accelerates the loss of organic matter.

¹³Rototillers with a horizontal axis of rotation compact the subsoil through the action of the tines, which push down on the soil at the low end of their rotation about the shaft. Tillers with a vertical axis of rotation do not compact the subsoil, although they are destructive otherwise.

Chapter 3

Food Quality

3.1 Summary

A common practice is to fertilize with **NPK** fertilizer for maximum yield, with the assumption that a high nitrogen, phosphorus and potassium concentration in a plant produces maximum quality. But it is protein, not nitrogen, which affects quality. And quality depends on other essential minerals, which drop with unbalanced increases in these three.

Whether organic fertilizers produce higher quality than inorganic fertilizers is unsettled. What appears to be more important factors are the use of pesticides and the crop variety.

The quality of produce also depends on environmental factors such as water, soil structure, temperature and sunlight.

Table **3.1** lists effects of an adverse environment on crop quality, and table **3.2** of a nutrient imbalance.

Table 3.1: **Effects Of A Non-Nutrient Disorder On Crop Quality**¹

High temperature

- Brassicas
 - * Tiny heads in cauliflower; premature flowering of broccoli
 - * Poor heading of brussels sprouts; halt in growth of kale;
 - * Premature flowering and peppery taste in mustard; peppery
 - * Radishes; bolting of turnips and rutabagas
- Fruit crops
 - * Blossom drop of eggplant, peppers, tomatoes
 - * Peppers with lush foliage but little fruit
- Leafy crops
 - * Bolting of lettuce and spinach
- Root crops
 - * Potatoes with streaking or brown spots in tubers and dying leaves and/or with no tuber formation if nights are too warm
 - * Beets stringy and tough with bland flavor, sometimes with a whitish ring
 - * Carrots bitter and stringy or stunted

Low temperature

- Brassicas
 - * Tiny heads in cauliflower
 - * Premature small heads or bolting of broccoli
 - * Cabbage may flower prematurely with extended period of cold
- Fruit crops
 - * Blossom drop of eggplant, peppers, tomatoes
 - * Eggplant stunted
 - * Peppers and tomatoes with lush foliage but little fruit
 - * Tomatoes misshapen if pollinated when cold
 - * Tomatoes blotchy
- Root crops
 - * Carrots with stringy or stunted roots, may flower prematurely
 - * Sweet potatoes have no flavor

Rapid temperature fluctuations

- Fruit crops
 - * Beans and okra may drop blossoms if temperature rises suddenly
 - * Bitter cucumbers
- Leafy crops
 - * Celery produces leaves but no stalk

¹Most of the data in this table is from [62]

Table 3.1: **Effects Of A Non-Nutrient Disorder On Crop Quality (Cont.)**

Low moisture

- Fruit crops
 - * Incomplete growth of bean pods
 - * Leaves of corn roll inward
- Root crops
 - * Potatoes have knobby tubers

Excessive moisture

- Fruit crops
 - * Peppers and tomatoes with lush foliage but little fruit
 - * Tomatoes blotchy with leaves that roll inward
- Root crops
 - * Sweet potatoes long and slender

Excessive moisture fluctuations

- Brassica crops
 - * Splitting of cabbage
- Fruit crops
 - * Blossom end rot in peppers, tomatoes
 - * Tomatoes crack, especially if fruit is exposed to full sun
 - * Canteloupe with mushy or bitter taste or leathery area on blossom end of fruit
 - * Bitter cucumbers
- Root crops
 - * Longitudinal cracks in carrots and parsnips
 - * Splitting of onions

Too much sun

- Fruit crops
 - * Sunscald of peppers and tomatoes
- Leafy crops
 - * Lettuce leaves turn brown
- Root crops
 - * Potato tubers turn watery and brown
 - * Poor pollination: female flowers of cucumbers and squash may bloom before males
 - * Corn ears are only partially filled
 - * Peppers with lush foliage

Table 3.1: **Effects Of A Non-Nutrient Disorder On Crop Quality (Cont.)**

Plant spacing too close

- Brassicas
 - * Radish bulbs fail to form
- Fruit crops
 - * Corn produces small ears
- Leafy crops
 - * Head lettuce fails to form good heads

Failure to harvest promptly

- Fruit crops
 - * Beans, cucumbers, peas stop producing
 - * Peas become tough
- Root crops
 - * Radishes, turnips, rutabagas become tough

Table 3.2: Effects Of A Nutrient Disorder ¹ On Crop Quality

This is a compilation of effects that have been found from studies with specific crops. Other soil conditions, however - such as a deficiency or excess of moisture, disease or variations in moisture - may produce similar results.

Boron deficiency

- Common characteristics
 - * Corkiness
 - * Reduced sugar content
 - * Bitter taste
- Brassicas
 - * Cabbage: corky and cracked or crosshatched leaves, brown leaf margins, water-soaked or hollow stems, bitter heads
 - * Brown cauliflower curds, watersoaked in spots
- Fruit crops
 - * Corky and bitter apples and pears, with brown lesions
 - * Irregular corn ears, with corky brown bands at base of kernel
 - * Withered small grains
 - * Darkened or dried areas in tomatoes.
- Leafy crops
 - * Alfalfa low in carotene
 - * Celery cracked, sometimes with brown checking
 - * Lettuce malformed.
- Root crops
 - * Brown heart
 - * Sweet potatoes misshapen, with rough & leathery skin
 - * Beets corky with leaves becoming reddish and tips dying
 - * Carrots with longitudinal cracks

¹Data is from [22], [62], [30], [50], [82], [87], [4]

Table 3.2: **Effects Of A Nutrient Disorder On Crop Quality (Cont.)**

Calcium deficiency, aggravated by a nitrogen or potassium excess

- Common characteristics
 - * Dieback of growth tips in tops and roots
- Fruit crops
 - * Bitter pit in apples
 - * Blackening & death of beans
 - * Blossom end rot in tomatoes & peppers
- Leafy crops
 - * Inner tipburn of cabbage
 - * Black heart in celery
 - * Escarole & lettuce have brown heart, rosetting, increased susceptibility to disease
- Root crops
 - * Roots forked & turned in beets & mangels
 - * Cavity spot in carrots; dwarfed potato tubers

Copper deficiency or nitrogen or phosphorus excess

- Fruit crops (peas, peppers, sunflowers, tomatoes)
 - * Flowers abort or fail to develop
- Grains (oats)
 - * Seeds light-colored or shriveled
- Leafy crops (cabbage & lettuce)
 - * Poor heading or absence of heads
- Root crops
 - * Poor root development of carrots
 - * Thin and yellow onion scales
 - * Onion bulbs lack solidity

Iron deficiency

- Leafy crops
 - * Reduction of carotene

Table 3.2: **Effects Of A Nutrient Disorder On Crop Quality (Cont.)**

Magnesium deficiency or potassium or calcium excess

- Common characteristics possible
 - * Delayed flowering
 - * Poor root development
 - * Reduced vitamin C
 - * Decrease in number of female flowers
 - * Abortion of pollen
- Leafy crops
 - * Magnesium yellowing in celery
- Fruiting & root crops
 - * Small size
 - * Nonuniform ripening
 - * Poor color & flavor
 - * Reduced vitamin C, soluble solids and sugars in citrus.
 - * Reduced green color of beans
 - * Magnesium yellowing in tomatoes

Manganese deficiency or possibly A phosphorus or potassium excess

- Beans & peas
 - * March spot (brown spot or cavity in the seed)
- Rutabaga
 - * Roots rough, cracked and with discolored skin near the top
 - * Interior of roots discolored brown

Molybdenum Deficiency

- Common characteristics when combined with a nitrogen deficiency
 - * Reduced carotene in carrots
 - * Increased susceptibility to the aflatoxin-producing fungus
- Cauliflower
 - * Flower curds irregular.
- Fruit crops (barley, oats, peas, tomatoes, wheat)
 - * Flowering & fruit formation suppressed
- Leafy crops (cabbage, lettuce)
 - * Poor heart formation,

Table 3.2: **Effects Of A Nutrient Disorder On Crop Quality (Cont.)**

Nitrogen deficiency

- Fruit Crops
 - * Small and brightly colored apples, pears & plums
 - * Reduced sugar content of canteloupe
 - * Light-colored cucumbers, pointed at blossom end
 - * Reduced size of grains
 - * Tomato flower buds turn yellow and drop
 - * Corn may have increased susceptibility to aflatoxin.
- Leafy crops
 - * Lettuce grows slowly, is bitter and bolts readily
- Root crops
 - * Beets & radishes have small and imperfectly developed roots
 - * Reduced carotene in carrots

Phosphorus Deficiency or Nitrogen Excess

- Common characteristic
 - * Vigorous vegetative growth with late flowering and maturity
- Fruit crops
 - * Reduced size of apples, with poor storage life and lack of firmness
 - * Irregular formation of corn ears
 - * Dull bronze-green coloration of cucumbers
 - * Reduction of vitamin C in tomatoes
- Leafy crops
 - * Alfalfa hay of poor quality
 - * Celery tends to remain rosetted
 - * Lettuce heads poorly formed
- Root crops
 - * Internal lesions of potato tubers, with increased susceptibility to mechanical damage
 - * Poor root development of radishes
 - * Reduction of carotene and sugar in carrots

Table 3.2: **Effects Of A Nutrient Disorder On Crop Quality (Cont.)**

Potassium Deficiency or Nitrogen Excess

- Common characteristics
 - * Low starch, high amino acid content
 - * Reduction of vitamin C
 - * High succulence, low dry weight
 - * Accumulation of nitrates
 - * Early winter kill of annuals
 - * Poor survival off perennials
 - * Increased susceptibility to disease
- Brassicas
 - * Hollow stem in broccoli
 - * Poor development of brussels sprouts
 - * Soft & small cabbage heads, and poor color of red cabbage
 - * Vein discoloration of Chinese cabbage
- Fruit crops
 - * Apples small and with poor color
 - * Canteloupe splits at the flower end
 - * Corn ears poorly filled at the tip
 - * Cucumbers narrow at the stem end
 - * Small grain stalks lodge, and grains are shriveled
 - * Grapes ripen unevenly
 - * Pea pods poorly filled
 - * Tomatoes ripen unevenly, lack solidity
- Leafy crops
 - * Celery leaf stems short, with streaks of dead & discolored tissue
- Root crops
 - * Beets dark & susceptible to rot
 - * Carrots spindly with short growth
 - * Onions have poor bulb formation
 - * Potatoes have reduced starch and dry weight, oversize and possibly distorted tubers with hollow heart & discolored interior, possibly increased levels of toxic glycoalkaloids in some varieties
 - * Sweet potatoes spindly & long

Zinc Deficiency or Possibly A Phosphorus or Potassium Excess

- Apples & peaches small & malformed
- Bean pods fail to develop
- Corn silking & tasseling delayed
- Peas have no flowers

3.2 Food Quality

See [30], [53, chapter 10], [58, chapter 7], [73], [74], [76], [75], [77], [89] for the sources of most of the information in this chapter.

One must guard against the assumption that maximizing fertilizer use maximizes the quality of produce. This is especially necessary when the fertilizer referred to contains only nitrogen, phosphorus and potassium (NPK). Assessing protein by a measure of the nitrogen content is a particularly good example of why this is wrong.

The traditional way of reporting protein in animal feed is to multiply the nitrogen content by a constant to get what is called crude protein. The constant is 6.25, which is the average value of the nitrogen in protein. Nitrogen, however, may be present in a plant in forms and amounts that neither benefit nor are healthy for the human or animal consumer. Consequently, crude protein has no relation to food quality.

A nitrogen measurement includes:

1. the true proteins, which are constructed from a variety of amino acids
2. free amino acids which have not yet been integrated into true proteins
3. mineral nitrogen, usually present as free nitrates but sometimes as nitrites or ammonium.

Only the true proteins are directly involved with the growth and health of the plant. Free amino acids constitute a reservoir for constructing proteins. Each protein requires a different combination of amino acids. In a satisfactory environment, a plant's amino acid reservoir is small because the plant creates proteins as soon as the proper amino acids are present.

A large reservoir of amino acids implies an amino acid imbalance. Some amino acids require magnesium, sulfur and/or trace elements in addition to nitrogen. If the soil is deficient in these, the plant will be deficient in amino acids which require them.

Amino acid balance in feed is not critical for domestic ruminants (cattle and sheep) because they manufacture all of the amino acids they need. But others must get certain amino acids in their food; for many of them, plants are the only source.

An excessive supply of NPK fertilizer, unsupplemented by other essential minerals, can lead to problems of protein formation in the plant. Vigorous plant growth stimulated by a fertilizer, especially nitrogen, can deplete the soil of other minerals. If the depleted mineral is needed for the production of a particular amino acid, that amino acid will not be produced.

Excess nitrogen favors the production of some amino acids. Nitrogen fertilization of corn tends to increase the amino acid Zein, producing a relative deficiency of the other amino acids and a large amount of free amino acids. Some amino acids are inversely related to the nitrogen content of the plant.

Also, an excessive amount of free amino acids causes a characteristic flavor and aroma which may attract insect pests to the growing plant [64].

Nevertheless, although an imbalance of free amino acids may produce a nutritionally inferior product, it is not dangerous to human or animal health. Nitrates and nitrites, however, are toxic to both ruminants and nonruminants when present at abnormally high levels. Metabolism in the body reduces nitrates to nitrites; nitrites produce an anemia in animals, particularly ruminants, and in humans, especially infants. Nitrites can also hinder circulation in peripheral blood vessels.

Toxic quantities of nitrates are not usually present in plants, because plants normally reduce them to ammonium, from which they produce amino acids. Under any of several conditions, however, nitrates may accumulate in the plant:

- a deficiency of iron or molybdenum necessary for the reduction of nitrates
- a lack of energy to carry out the reactions; perhaps from low light levels, a shortage of water, or a deficiency of phosphorus, potassium, copper, iron, magnesium or manganese
- a lack of sugars to form amino acids; perhaps owing to a lack of water, insufficient photosynthesis, or poor plant metabolism from an inadequate supply of oxygen.

Consequently, acceptable food quality requires a small free amino acid content and a low level of nitrates. The only exception is that free amino acids may be high when the feed is for ruminants.

A simple nitrogen content converted to crude protein is no measure of these criteria.

Nor do phosphorus and potassium serve uncritically as measures of quality. An increase in the concentration of one nutrient in a plant leads to a decrease in another. An increase in phosphorus may cause a decrease in a trace element, and a rise in potassium is likely to result in a drop in calcium and magnesium.

The application of NPK fertilizer increases the vigor of plant leaves and roots, growth which increases the plant's ability to scrounge the soil for magnesium and trace elements not present in the fertilizer. Consequently, fertilized plants will remove more of these nutrients from the soil than unfertilized plants. But the additional amount taken up is not in proportion to the added growth, so that the concentration of minerals in the plant is lower.

This conclusion became evident in a survey of pastures in Austria, where intensively fertilized fields were compared with fields fertilized only with cow manure. The intensively fertilized fields produced an increase in plant yield but a decrease in dry matter content. Plants in the manured fields had higher concentrations of magnesium and trace elements. The manured fields also contained a greater diversity of plant species, and the milk cows were more fertile.

If NPK fertilizer is spread, the amount used should be adjusted according to the needs and availability of other nutrients; and it should take into account nonnutrient factors. One should take care, for example, against overfertilizing greenhouse crops in the hope of forcing growth. Experiments have demonstrated an accumulation

of nitrates, especially in a heated greenhouse, owing to the lack of energy to metabolize the nitrogen.

3.3 Organic Versus NPK Fertilizers

The distinction between organic and NPK fertilizers is more controversial than the question of fertilizing for quality. One could defend any claim by citing at least a half dozen references, all produced by researchers of the highest authority.

Most of the studies which found no difference were done, however, at about 1940 or before. Since then, experiments have shown that produce grown with organic fertilizers (animal manure or compost) has a lower yield on a fresh weight basis but a higher dry weight yield (less water and more minerals) and a higher quality, whether measured by chemical tests or by the effect of the food on animal or human health. There is also evidence that the highest quality is obtained by a mixture of organic and NPK fertilizers, although the conclusions seem to be contradictory¹.

There are also anecdotal references to the advantages of organic fertilization, so called because they do not meet the rigid requirements of scientific enquiry. In one such reference, a group of students were found to be perceptibly healthier after their lunches were prepared from an organic garden. In another, a doctor noted that a postoperative spread of cancer disappeared completely from five patients after they began eating organically grown foods.

We know that many diseases, including cancer, can be strongly influenced by the patient's mental attitude, a parameter which would be difficult to control in a scientific experiment. So we are left with a choice between anecdotes, which do not reveal all the controlling factors, and scientific experiments, which do not include them.

In any event, the best improvement in quality that can be expected with organic fertilization, so far as scientific enquiry is concerned, is perhaps 20%, possibly more in some situations. Though important, this is a small improvement compared to quality differences among different varieties of the same crop. The amount of vitamin C in different varieties of apples, for example, was found to vary more than 9-fold while the carotene content of carrots varied by a factor of 2-1/2 [74]

Furthermore, any benefits in quality that may be gained by careful production are often lost by improper storage. Nutritious elements can be destroyed by light, heat, oxygen and inadequate moisture control. Overcooking and disposal of cooking water also results in an excessive loss of nutrients [53].

In view of all the qualifications, the scientific evidence for or against the value of organic fertilizers on food quality is weak.

What is so damaging about this controversy is the tendency to ignore - and with that action to belittle - the far more important value of organic residues. This

¹See [76]. The nutritional tests in the article indicate that produce fertilized with manure or compost alone was of superior quality to produce fertilized with a manure-NPK mixture; however reference is made to another study showing the mixture to be better in all respects. Moreover, the manure used was acknowledged to be of poor quality, having a low nitrogen content, which may have been the reason why it was fortified

is its contribution of energy to an agricultural system. There is no substitute for it.

One issue that has not entered into this discussion is the use of pesticides. That is even more contentious than the question of organic vs commercial inorganic fertilizers. On the one hand is the claim that the acute toxicity of the pesticide residues consumed by the average person in one year is less than that of the aspirin in one tablet or the caffeine in one cup of coffee².

On the other hand are the precautions that are necessary in the application of these pesticides and the existence of some evidence of manifestations after years of accumulations from exposure to small amounts at any one time[84].

Furthermore, documentation does exist showing that insects and disease can be controlled at least partly with organic residues and sound practices. The following references are an uneven survey of the subject.

- Suppression of diseases with organic residues [37], [28], [91], [56], [35].
- Soybeans as a cover crop to prevent potato scab [16], [54].
- Reduction of the cabbage root fly by intercropping with clover [36].
- Promotion of beneficial insects with weeds [95], [52], [80], [34].
- Beneficial effects of intercropping and crop rotations [66], [27].

3.4 Effects of Environment and Culture on Quality

Many people, when they see something wrong with their crops, immediately assume that fertilizer is lacking, and they instinctively ship off a soil sample to be tested for nutrients. More often than not they are wrong, and they are almost always wrong when only one crop out of several is adversely affected.

Experience shows that fertilizers are not the only determinant of plant growth. There are years in which mountain laurel blooms more profusely than any other. In other years, locust trees are never more fragrant, or horse chestnut more beautiful. In some years, tomatoes bear a record crop, no matter how they are abused; in others squash will not bear at all. Whenever crops do not meet expectations, we should look first of all to the environment for causes and only consider fertilizers as a last resort. Nutrients are often as detrimental in excess as in deficiency; if we pour on the fertilizers without thought, we risk additional problems.

Excluding nutrient availability, the most common influences on the success of crops are water, soil structure, temperature, sunlight, pollination and crop variety. Sometimes these produce effects which are typical of nutrient imbalances. Poor drainage or overwatering may result in stunted plants with yellow leaves, typical of a nitrogen or trace element deficiency. Underwatering may cause plants to wilt or

²[20]. The argument is based upon a comparison of the LD 50 values for pesticides and for aspirin and coffee. The author stated that more recently introduced pesticides have even lower LD 50 values. The LD 50 is a specification of the quantity of a substance which is likely to kill half of an exposed population.

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blossoms to fall off. Insufficient sun may lead to weak, spindly plants, also true of an excess of nitrogen. A cold spring or low temperatures at any time may cause a phosphorus deficiency, even though soil phosphorus is adequate.

Poor germination is not caused by a soil nutrient deficiency, because seeds contain enough nutrients to sprout and produce an initial set of leaves. More likely causes are insufficient or excessive water, cold soil, a crust on the surface of the soil, or animals. Lettuce seeds fail to germinate if the soil is too warm. If soil water is marginally low, the presence of dry soluble fertilizers may inhibit seed germination indirectly by absorbing some of this water and limiting its availability to the seeds.

Some disorders are due to plants growing too closely together.

If plant flowers are numerous and healthy, nutrients may affect the quality of the fruits that do form. But the lack of fruiting is not likely to be due to a nutrient imbalance, and fruit quality may not be. Likely alternate causes are poor pollination, low moisture (causing flowers to drop prematurely) or low or high temperatures.

Some of the effects of an improper environment or culture are shown in more detail in table 3.1. Also a Cooperative Extension agent should be familiar with problems of this kind or can recommend a state specialist. Usually a telephone conversation suffices.

If a problem is not likely to be traceable to an environmental cause, then a nutrient imbalance or a disease is possible. As a guide, table 3.2 is a summary of some of the effects of nutrient deficiencies or excesses on the quality of produce.

Chapter 4

Nutrient Requirements

4.1 Summary

Tables 4.1 - 4.4 show the nutrient contents and typical fertilizer use for a variety of crops. Although they represent averages, an acquaintance with local yields should lead to an estimate of nutrient requirements.

The tables follow the usual convention in expressing quantities of phosphorus as phosphate (P_2O_5) and potassium as potash (K_2O).

Several options are available for estimating the soil supply.

A careful inspection of plant roots can reveal information about conditions affecting growth.

4.2 Fertilizer Uptake

A reasonable first step in choosing the amount of fertilizer that is likely to be necessary for growing crops is to determine how much of a particular nutrient is used by the crops. Considerable information is available, but it is so inconsistent that one is tempted to give up the attempt. The only hope is that plants can be grouped into types having similar requirements, and by taking enough averages, one might obtain a reasonable estimate of plant requirements.

Tables 4.1 and 4.2 are summaries of yields, nutrient uptake and fertilizer use in growing field crops and vegetable crops for market¹.

In both tables, the first column of data states the range of crop yield and the average yield in tons/acre. The yields of some crops are often reported as bushels/acre, but using tons for some crops and bushels for others may be confusing. Instead, a conversion factor is shown for those crops which are reported in bushels.

So, for example, a bushel of corn weighs 56 lbs and a bushel of potatoes 60 lbs. To find the average yield of corn in bushels, one divides 8000 (the average

¹Data for yields and nutrient removal are from [14], [23], [30], [46], [51], [70], [72], [49], [61], [1]. Fertilizer use is from [68] and is a summary of data from states where the crop is economically important.

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Table 4.1: **Estimated Fertilizer Requirements - Field Crops** *Yield*
in tons/acre, nutrients in lb/ton of harvested crop

	Yield	<i>(T): Total of nutrients removed from crop and residue</i>			Nitrogen			Phosphate, P_2O_5			Potash, K_2O			Sulphur	
		Nutrients Removed		Fertilizer	Nutrients Removed		Fertilizer	Nutrients Removed		Fertilizer	Nutrients Removed		Crop	Residue	
		Crop	Residue		Crop	Residue		Crop	Residue		Crop	Residue			
Grains															
Barley															
48 lb/bu	1-2	43-53	20	18-89	19-21	7	0-53	14-17	53	0-15	3-5	5			
Average	1.5	48		36	20		20	15		3	4				
Buckwheat															
48 lb/bu	0.7	65(T)			31(T)			54(T)			12(T)				
Corn															
56 lb/bu	0.7-5	43-64	21-45	7-100	10-24	3-13	4-42	11-16	29-63	1-53	4-6	3-5			
Average	4	51	29	47	18	9	23	13	49	23	4	4			
Flax															
56 lb/bu	0.6	107(T)			3(T)			89(T)			5(T)				
Oats															
32 lb/bu	0.4-2	19-26	10-11	38-63	2-9	2-5	18-54	5-6	16-40	12-42	1.6-2	3-4			
Average	1.3	21	11	48	7	4	33	6	27	24	1.6	3			
Rye															
56 lb/bu	1	63	26	53	24	15	53	18	45	0	13	6			
Sorghum															
56 lb/bu	2-4	45-53	31-59	10-53	16-24	11-18	1.4-14	12-46	63-87	0.6-1.2	4-8	3-6			
Average	3	49	47	39	20	13	6	21	72	0.6	6	4			
Soybeans															
60 lb/bu	0.8-2	190-320	30-190	0-32	31-49	12-19	2-61	58-87	58-118	0-81	6-12	12			
Average	1.3	220	100	11	45	16	21	75	79	25	12				
Sunflowers															
Average	0.6	127(T)			43(T)			83(T)			12(T)				
Wheat															
60 lb/bu	1.8-3	57-108	27-50	12-76	14-43	5-15	1-43	14-23	36-101	0-43	4-7	8-12			
Average	2	79	34	44	34	8	17	18	62	9	5	10			
Hay															
Alfalfa															
Average	4-8	44-56		0	10-14		6-16	32-60		14-48	3-6				
Average	6	49			11		7	43		28	5				
Clover															
Average	2-5	34-70			5-20			22-60			3-5				
Average	4	42			11			36			4				
Cowpeas															
Average	2-3	39-62			5-19			33-45							
Average	2	52			15			38							
Field peas															
Average	2	38-66			5-13			13-34							
Average					47			24							
Hairy vetch															
Average	2-4	73			19			49							
Lespedeza															
Average	1-3	41			15			22							
Soybeans															
Average	2	48			12			34			5				
Sweetclover															
Average	2-6	52			12			32							
Coastal															
Bermuda grass	8-10	23-57			9-14			25-40			2				
Average	8	34			11			33							
Kentucky															
bluegrass	1.5	26			10			34			4				
Millet															
Average	1-4	15-26			6-9			10-43							
Average					7			27							
Orchard grass															
Average	4-6	25-50			7-17			33-63			6				
Average	5	33			11			42							
Sudan grass															
Average	2-5	30													
Timothy															
Average	2-5	20-31			3-10			24-39			2-3				
Average	3	22			7			24			2				
Mixed hay															
Average				0-50			0-16			0-11					
Average				15			4			3					
Corn silage															
Average	31	7		20-40	3		10-17	9		3-28	1				
Average				29			13			16					

4.2. Fertilizer Uptake

Table 4.2: **Estimated Fertilizer Requirements - Vegetables and Fruits** *Yield in tons/acre, nutrients in lb/ton of harvested crop*

	Yield	Nitrogen			Phosphate, P ₂ O ₅			Potash, K ₂ O			Sulphur	
		Crop	Residue	Fertilizer	Crop	Residue	Fertilizer	Crop	Residue	Fertilizer	Crop	Residue
Vegetables												
Asparagus	1-2	6-8			1.6-2			2-6				
Average	1.5	7			1.8			4				
Beans, dry												
60 lb/bu	0.8-2	55-114	40-67	77-82	12-48	12-14	20-95	26-55	87-91	0-95	5-10	
Average	1.5	100	54	80	30	13	57	44	89	48	8	
Beans, snap	2-4	30-74	12-24	11	2-6	1-3	33	5-6	14-22	22		
Average	3	51	19		4	2		6	19			
Beets	10	4-7	9		0.8-2			8-10	5			
Average		5			1.4			9				
Broccoli	6			10			3	8				
Brussels sprouts	8	12			3			14				
Cabbage	7-25	4-9	4	7-11	1-4	5	6-10	0.8-1.3	10	6-10	1-2	
Average	12	6		9	2		8	?		8	1.6	
Cantaloupe	5-11	4	3	38-42	1.4-2	0.8	21-27	5-9	3-4	0		
Average	8	4		40	1.6		24	8	3	0		
Carrots	15-25	2-5	1.5-5		1.2-2	0.5-0.7		4-10	2-10			
Average	19	4	3		1.6	0.5		6	7			
Cauliflower	7-10	3-10			2-4			5-7				
Average	9	7			3			6				
Celery	10-75	3-8		3-7	1.7-6		7-14	9-22		16-23		
Average	30	5		5	3		10	12		20		
Collards	5	8			1.8			10				
Cucumbers	6	1.8-3	5	18	0.6-2	1.2	10	3-5	6	0		
Average		2			1.5			4				
Kale	5	8			3			7				
Lettuce	8-21	4-5		17-18	1.2-2		5-15	5-12		0-5		
Average	17	5		17	1.6		10	8		2		
Mustard greens	5	8			3			7				
Okra	5	3	2		1	1		8	5			
Onions	7-20	3-7	0.8-3		0.8-3	0.3-0.6	2-8	2-6				
Average	13	5	2		2	0.5		5	3			
Parsley	8	3			0.8			3				
Parsnips	10	4	4-6		1.6-4	1.6		4-12	1-5			
Average		4	5		3	1.6		8	3			
Peanuts	1-2	60-80	39-73		10-15	5-20		13-20	41-75		5	6
Average	1.4	71	54		12	11		16	61			
Peas	1-4	13-20	20-36		2-5	4-11		3-10	17-35			
Average	2	17	29		4	8		6	25			
Peppers	2	3	9	27-36	10	17	4-15	6	13	0-15		
Average				32			10			8		
Potatoes, white												
60 lb/bu	6-20	8-15	4-18	13-28	1.6-7	0.9-3	9-27	10-26	6-21	6-24	0.7-0.9	1.2
Average	14	12	10	19	4	1.7	19	19	14	18	0.8	
Potatoes, sweet												
90 lb/bu	7-18	4-5	2-4		1.4-3	0.6-1.1		7-11	3-6		0.3-0.6	0.6
Average	12	5	3		1.9	0.7		9	4		0.4	
Pumpkins	9-10	2-4	3		0.8-3			1.8-5	3			
Average	10	3			1.7			4				
Rutabaga	10	4			1-2		1.9	3-10	6.5			
Average		4			1.8			6.6				
Spinach												
15 lb/bu	4-10	7-16		7-18	2-3	0-9		5-25		0	1	
Average	6	10		13	3		4	12				
Squash	9	2	6		0.8	0.8		3	8			
Tomatoes	10-40	3-8	2-4		0.5-3	0.2-2	5-12		2-12		0.7-1.3	0.6
Average	19	5	3		1.6	1.1		8	7		0.9	
Turnips	10	4-5	8		1.6-2	0.9		6-9	4			
Average		4			1.8			7				
Fruits												
Apples												
44 lb/bu	7-44	0.3-5	1.6-5	23	0.2-2	0.3-2	0	1.6-5	0.6-5	0	0.1-1	
Average	15	2	4		0.7	0.9		4	3		0.4	
Mature tree		1.5 (T)			0.5 (T)			1.5(T)				
Blueberries highbush				40 lb/A					41			
Grapes	10	3	3	9-48	2	1	0	5	3	0-89		
Average				28						28		
Oranges												
90 lb/box	11-36	10-14	4	6-13	3-4	1.2	4-6	16-22	4	7-13	1	
Average	26	12		10	4		5	20		10		
Peaches												
50 lb/bu	8-15	1.4-7	5-7	5-10	0.8-4	1.3-3	5-25	6-12	5-6	0-5	0.2-0.8	
Average	13	4	6	7	1.7	1.9	15	7	5	2	0.5	

4. NUTRIENT REQUIREMENTS

number of lbs/acre - 4×2000) by 56 to get about 140 bushels of corn/acre; a similar calculation for potatoes ($14 \times 2000 / 60$) leads to an average yield of about 470 bushels of potatoes/acre.

Also, yields are listed for crops in their normal marketable state. The consequence is that the moisture content is not taken into account. For example, hay yields are for field-dried hay, and vegetable yields represent fresh weight.

The remaining columns show the nutrient removal by the crops and residues. The quantity of nutrients is expressed as lbs per ton of harvested crop. For example, the average amount of nitrogen in field corn is about 51 lbs/ton. With an average yield of 4 tons/acre, the total amount of nitrogen removed by the grain is 51×4 , or 204 lbs/acre. The average amount of nitrogen removed by the residues is 29 \times 4, or 116 lbs/A. The total amount of nitrogen removed by both crop and residues is $51 + 29$, or 80 lbs/ton of crop; with a 4 ton harvest, the average total nitrogen removed is 320 lbs/acre.

Most people know the yields that are likely in their area; so they could approximate the removal of nutrients in proportion to the yield. They should realize, however, that variations are due not only to the yield, but also to varietal differences in the crop, differences in the soil, fertilization, and the weather. Average nutrient requirements shown here are probably satisfactory for most crops, but clearly they are not absolute.

As an example of how the tables might be useful, suppose we want to know the potassium requirement of alfalfa grown in New England. From table 4.1, we take the average nutrient content, 43 lb/ton, and multiply it by a typical yield for New England of 5 tons/acre, to get 215 pounds potash/acre. For comparison, the average fertilizer rate is 28 lb/ton, which for 5 tons/acre, results in a fertilizer use of 140 lb potash/acre. These two estimates are consistent if we assume that the average soil supplies about 75 pounds potash/acre. This is not much potassium - many soils furnish more than that - and some farmers may spread more potassium fertilizer than they need.

As another example, let us estimate the nitrogen requirement of potatoes. The average tuber yield is 14 lb/ton. The average indicated yield of 14 tons/acre would result in a total nitrogen requirement of 308 lb/acre. At an average fertilizer use of 19 lb/ton, the total average fertilizer applied to get the same yield is 266 lb/acre. Both figures represent a lot of nitrogen, more than can reasonably be supplied organically. Quite possibly potatoes are over-fertilized, and a lower total nitrogen rate, perhaps 15 lb/ton, is more reasonable, making the total nitrogen requirement 210 lb/acre. If the soil supplies 50-100 lb/acre, then the fertilizer requirement, assuming no losses, is about 100-150 lb/acre, still a lot to supply organically, although a heavy application of manure or a year of clover might be enough. A deep, rich topsoil, however, will furnish more than 100 lb of nitrogen/acre and bring the project closer to practicality.

Potatoes are a drain on the soil; growing them organically at high yields requires considerable effort. This is also true of corn.

Tables 4.1 and 4.2 are unnecessary for backyard gardeners and most market gardeners who grow mixed crops. As a more useful guide, table 4.3 summarizes table 4.2 by ignoring the variations and using average values for the total nutrient

content of vegetables. The nitrogen content of beans, peas and peanuts is not shown, on the assumption that the seeds of these plants are inoculated before being sown, and they should fix whatever nitrogen they need. The nutrient requirements are expressed first as lbs/acre, and then, in parentheses, lbs/1000 sq ft. The average requirements for all vegetables leads to an estimate of 81 pounds of nitrogen/acre, 31 pounds phosphate, 122 pounds potash, and 17 pounds sulfur.

Table 4.4 shows the balance that should be maintained among the four principal nutrients. The phosphate/nitrogen, potash/nitrogen and sulfur/nitrogen ratios are based upon the average values in table 4.2.

Generally, the phosphate/nitrogen ratio is about 1/3 for hay and slightly higher for other crops. The potash/nitrogen ratio is approximately 1 for hay and grains, and it varies between 1 and 2 for vegetables. Sulfur is usually about 1/10 to 1/5 of the nitrogen content. The high phosphate/nitrogen ratio shown for peppers is probably inaccurate, based upon only one experiment; the low phosphate/nitrogen ratio for parsley is also suspect.

4. NUTRIENT REQUIREMENTS

Table 4.3: **Average Nutrient Requirements For Vegetables** *Nutrients in Lb/A (Lb/1000 sq ft)*

	Nitrogen, N	Phosphate, P_2O_5	Potash, K_2O	Sulfur, S
Asparagus	11 (0.2)	3 (0.06)	6 (0.14)	
Beans, dry		65 (1.5)	200 (5)	12 (0.4)
Beans, snap		18 (0.4)	75 (1.7)	
Beets 140 (3)	14 (0.3)	140 (3)		
Broccoli	60 (1.4)	18 (0.4)	48 (1.1)	
Brussels sprouts		96 (2)	24 (0.6)	112 (3)
Cabbage	120 (3)	84 (2)	204 (5)	19 (0.5)
Carrots	143 (3)	38 (0.9)	239 (6)	
Cantaloupe	56 (1.3)	19 (0.5)	88 (2)	
Cauliflower	63 (1.5)	27 (0.6)	54 (1.3)	
Celery	159 (4)	105 (2)	387 (9)	
Collards	40 (0.9)	9 (0.2)	50 (1.2)	
Cucumbers	42 (1.0)	16 (0.4)	60 (1.4)	
Kale	40 (0.9)	15 (0.4)	35 (0.8)	
Lettuce	85 (2)	27 (0.6)	136 (3)	
Mustard greens	40 (0.9)	15 (0.4)	35 (0.8)	
Okra	25 (0.6)	10 (0.2)	65 (1.5)	
Onions	91 (2)	33 (0.8)	104 (2)	
Parsley	24 (0.6)	2 (0.15)	24 (0.6)	
Parsnips	90 (2)	46 (1.1)	110 (3)	
Peanuts		29 (0.7)	108 (3)	15 (0.4)
Peas		24 (0.6)	62 (1.4)	
Peppers	24 (0.6)	54 (1.3)	38 (0.9)	
Potatoes, white	308 (7)	80 (1.9)	462 (11)	28 (0.7)
Potatoes, sweet	96 (2)	31 (0.7)	156 (4)	12 (0.3)
Pumpkins	60 (1.4)	17 (0.4)	70 (1.6)	
Rutabagas	40 (0.9)	37 (0.9)	131 (3)	
Spinach	60 (1.4)	18 (0.4)	72 (1.7)	6 (0.4)
Squash	72 (1.7)	14 (0.3)	99 (2)	
Tomatoes	152 (4)	51 (1.2)	285 (7)	29 (0.7)
Turnips	120 (3)	27 (0.6)	110 (3)	
Average	81 (1.9)	31 (0.7)	122 (3)	17 (0.4)

Table 4.4: Phosphorus And Potassium Requirements Relative To Nitrogen

		P_2O_5/N	K_2O/N	S/N
Grains	Barley	0.40	1.00	0.13
	Corn	0.34	0.78	0.10
	Oats	0.34	1.03	0.14
	Rye	0.44	0.71	0.21
	Sorghum	0.34	0.97	0.10
	Wheat	0.37	0.71	0.13
	Non-Legume Hay	Bermuda grass	0.32	0.97
Kentucky bluegrass		0.38	1.31	0.15
Millet		0.33	1.29	
Orchard grass		0.33	1.27	0.18
Timothy		0.32	1.09	0.09
Fruits	Apples	0.27	1.17	0.07
	Grapes	0.50	1.67	
	Oranges	0.33	1.50	0.08
	Peaches	0.36	1.20	0.05
Vegetables	Asparagus	0.27	0.55	
	Beets		1.00	
	Broccoli	0.30	0.80	
	Brussels sprouts	0.25	1.17	
	Cabbage	0.70	1.70	
	Carrots	0.27	1.67	
	Cantaloupe	0.34	1.57	
	Cauliflower	0.43	0.86	
	Celery	0.66	2.43	
	Collards	0.23	1.25	
	Cucumbers	0.30	1.43	
	Kale	0.38	0.88	
	Lettuce	0.32	1.60	
	Okra	0.40	2.60	
	Onions	0.36	1.14	
	Parsley	0.08	1.00	
	Parsnips	0.51	1.22	
	Peppers	2.25	1.58	
	Potatoes, white	0.26	1.50	0.09
	Potatoes, sweet	0.32	1.63	0.13
	Pumpkins	0.28	1.17	
	Rutabagas	0.93	3.28	
	Squash	0.19	1.38	
Tomatoes	0.34	1.88	0.19	
Turnips	0.23	0.92		

Chapter 5

Soil Nutrient Supply

5.1 Summary

There are several ways to determine the nutrient supply in the soil:

- Don't bother, simply add enough fertilizer to account for nutrients removed by the crop and soil losses;
- Order a soil test to determine deficiencies and excesses and the general characteristics of the soil environment: pH, organic content, etc.;
- Order a leaf analysis, to learn what the plant actually needs, without, however, obtaining information on the cause of a deficiency;
- Use a soil test kit, which usually is poor in predicting a soil deficiency, owing principally to the difficulty in interpreting the results; but it is convenient and can become more accurate than a professional test with experience and adequate record-keeping;
- Don't bother, but rely on experience and observation.

A survey shows that many soils already have a sufficient supply of phosphorus and potassium.

5.2 Methods Of Evaluating The Soil

One way to determine the fertilizer requirement is to add to the soil whatever was removed in the previous harvest. This is a common approach taken by many gardening guides and fertilizer dealers, even those who use soil tests, and it often succeeds. But this method of adding what was removed is expensive, because it encourages the use of more fertilizer than necessary in order to hedge against

uncertainties. It ignores the ability of the soil to bring about the release of nutrients from its reservoir of minerals. And it ignores the dangers of excesses and imbalances¹.

An improvement is to have the soil tested. Tests done at intervals will determine whether or not nutrients are accumulating. A soil test done only once is still useful in determining what kind of fertilizer is necessary.

Soil tests have several drawbacks, owing to the approximations that are necessary to carry them out quickly and cheaply. Even so, they are often good in establishing the nutrient status of the soil.

Anyone obtaining a soil test should distinguish between the test results and interpretation on the one hand and the recommendations on the other. Some laboratories recommend a maintenance fertilizer application even though the tests show no fertilizer is necessary. Some laboratories recommend fertilizer even though they do not test for nitrogen or estimate the nitrogen release. When in doubt about the basis of a fertilizer recommendation, one should question the laboratory about its policy.

Another type of test is a plant tissue test. Tissue tests bypass some of the problems of a soil test by revealing directly whether a nutrient is deficient in the plant. A tissue test, however, does not indicate the cause of the deficiency. If nitrogen is deficient, is it because the soil has none or because bad weather or insect damage limited root growth? Is phosphorus low because the soil has none or because the pH is too low or too high? If one already suspects why and wants confirmation, a tissue test is excellent.

Soil tests and tissue tests are not alternatives, but complements, and the ideal arrangement is to use both. In an orchard, where roots descend below the level at which soil is tested, tissue tests are good for revealing deficiencies, especially in trace elements. A soil test will show the state of the topsoil, which is a major influence in determining the nutrients which eventually reach the roots. A soil test is particularly helpful if a cover crop is grown between the trees.

A soil test kit is an alternative to a professional soil test. The results are less accurate, but the tests are cheaper and much more convenient. One useful test, however, that kits do not offer is one for organic matter.

The major disadvantage of a kit is that it is weakest in the most important part of testing, the interpretation of the results. This can be overcome, however, by testing frequently and keeping records of test results, fertilizer use, the weather and the harvest.

If the tests and records are done carefully, the experience is invaluable, and eventually the results can be better than professional tests. This is so because professional tests cannot take into account all of the variations in soils and weather conditions that may exist from one area to another. Good records and on-site experience can more than compensate for the lower accuracy of a soil test kit.

¹One common example of the effect of excess fertilizer in the eastern states is a magnesium deficiency brought about by overuse of potassium fertilizer and/or low-magnesium limestone. For more details on the dangers of excesses, see table 3.2 and the discussions of nutrients in part III.

Despite these tools of modern agriculture, some people are intransigent in their refusal to test their soil or to routinely dump fertilizers for maintenance. As it turns out, many of them do very well, and it must be admitted that soil and tissue tests are not necessary in determining what the soil can supply. What is necessary? I don't know, because I am not one of those who can confidently get along without a test. Chances are, however, that some useful practices are:

- maintaining a good level of organic matter with a diverse combination of residues
- good record-keeping
- experimentation: with crop varieties and with quantities and timing of fertilizer applications.

An aid to all of these methods for assessing the soil capability is a knowledge of deficiency symptoms. Though helpful, signs of a nutrient deficiency are ambiguous, partly for the same reasons that a tissue test reveals the deficiency but not the cause. Often a plant will show signs of a phosphorus deficiency because the soil is cold; as the soil warms up, the symptom disappears.

Also, many nutrient deficiency signs look similar; it is often difficult to distinguish a nitrogen deficiency from a shortage of sulfur or iron; magnesium, manganese and copper deficiencies often have similar manifestations. Furthermore, water stress or a disease could produce the same symptoms as a nutrient deficiency.

A number of references are available, however, for those who want to develop their sense of plant deficiency symptoms [22], [25], [82], [32], [39].

Additional information on possible soil problems is available by looking not only at the leaves and top growth of the plant, but by carefully digging up a plant, gently removing the soil, and examining the roots for vigor and signs of disease or pest damage.

Roots growing in a fertile soil are more branched than in a poor soil, and they have a profusion of root hairs. Root hairs are fragile; plants must be gathered carefully to avoid losing them. If the roots are growing laterally and are long and stringy, with few hairs, they are searching for nutrients; if they are also long and seem to be searching for something but are growing vertically, they need water. If they are growing only near the surface the soil is too wet. If they are stunted they may lack oxygen; the soil may be too wet or compact. If they are thick and short, they may be suffering from a toxic element, perhaps aluminum or excess manganese in an acid soil, or the soil may have a high salt content.

Inspect legume roots for healthy, nitrogen-fixing nodules. These are round growths attached to the roots. Their size varies with the plant variety and is no indication of plant health; the number of nodules, however, is useful. A large number of nodules indicates that the plant is supplying a large amount of carbohydrates. Usually this is a sign of a healthy, vigorous plant, but it could also mean that the plant is missing an important trace element, such as molybdenum or iron, for metabolizing nitrogen. The nodules should be distributed throughout

the roots; if concentrated only near the crown, especially in a heavy soil, most likely the nitrogen-fixing bacteria were unable to move through the soil and onto the roots.

Splitting the nodules should reveal a pinkish color in the interior. It indicates the presence of an essential enzyme-molybdenum-iron combination and is a sign of a healthy, viable nodule. It would confirm a sufficient supply of molybdenum and iron.

Another clue to a possible soil imbalance is to note any groups of plants that seem to be growing poorly as a whole. In most soils, for example, poor growth of grasses, grains and sometimes beets may be due to a nitrogen deficiency. A shortage of potassium often leads to poor growth of legumes and potatoes. Phosphorus and potassium are dominant requirements for most root crops.

On the other hand, weather variations may be of critical importance and could result in poor growth of one variety in a group without affecting the others. Peas, for example, growing in unusually cool and damp weather with too much nitrogen might be disappointing, because the onset of flowers may be delayed into the hot weather, when growth stops.

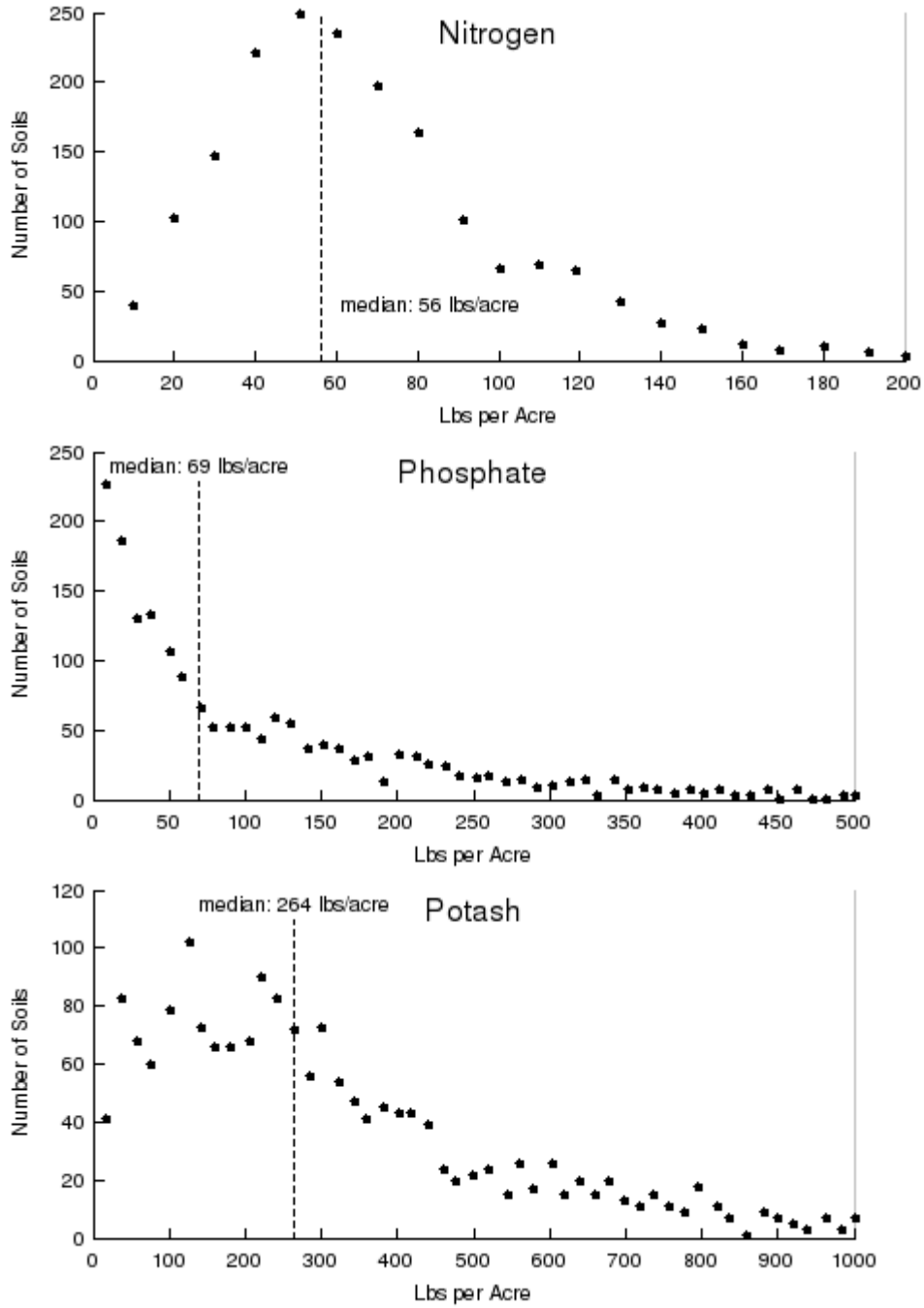
5.3 A Survey Of Soils

Figure 5.1 contains the results of a survey of about 1800 soils tested by Woods End Laboratory. More than half are from the northeast; about a third from the west and southwest; most of the remainder from the upper midwest, and some from the southeast. The availability of nitrogen was estimated from the organic content. The Bray P1 test estimates available phosphorus; it does not indicate the amount of available phosphorus but only whether the amount actually present is satisfactory. Usually a P1 value of about 40 lb/A infers that the soil has sufficient phosphorus for crops with a low requirement, and 70 lb/A for crops with a high requirement, although this may vary somewhat, depending on other soil characteristics.

Figure 5.1 infers that many soils have more than enough phosphorus and potassium for good plant growth and at least a third to half of the necessary nitrogen for a single crop. High phosphorus values, especially in the Northeast, are often due to a previous history of continual fertilization. Low phosphorus values are typical of many semi-arid soils, soils with a high pH, and many forest soils. Soils with low potassium are usually highly leached or from played-out hayfields.

The soils illustrated here are not representative of agricultural soils but only of those tested by Woods End Laboratory. Most were personal and market gardens managed organically.

Figure 5.1: Survey of the Nutrient Content of 1800 Soils



Part II

Organic Fertilizers

Chapter 6

Unprocessed Residues

6.1 Summary

The value of animal manure varies considerably, depending on the feed and the age and productivity of the animal. Estimates are shown in tables 6.1 - 6.4. These results should be corrected for losses of nutrients.

With nitrogen losses taken into account, most manures are reasonably balanced fertilizers.

Nitrogen losses in animal manure may be due to leaching, volatilization of ammonia, or **denitrification** of nitrates. Possible ways of controlling them are composting, rotting, and adding chemicals (ammonia losses only).

Typical application rates are about 2 tons/acre for poultry manure and in the range from 5 to 40 tons/acre for other manures.

The nutrient values of hay and straw are tabulated in tables 6.5 - 6.7. Both are good sources of nutrients, and legume hay is comparable to manure in nutrient balance. The advantages and disadvantages of mulches, their contribution to humus, and their effect on nitrogen availability are discussed.

Other useful residues are leaves, paper, seaweed, and pond dredgings.

6.2 Animal Manure

Data for the tables in this section are from [21], [19], [90], [26], [33], [2], [69], [43], [44], [47], [70], [81], [85], [61], [79], [92], [88], [94], [55].

The Value of Manure

Animal manure is the oldest known fertilizer, recognized for its benefit to the soil and to plant growth. How one thing can be both a disgusting mass of putrefaction and an inestimable treasure to mankind is surely one of the miracles of our world.

A farmer is faced with problems on both sides of this miracle. On the one hand is the necessity of getting rid of a socially undesirable pile of waste; on the other

Table 6.1: Manure Production

	Excrement			Urine			Sum		Lbs Bedding	Total Lbs
	Lbs	% Total	% Water	Lbs	% Total	% Water	Lbs	% Water		
Cow	19,000	70	80	8,000	30	93	27,000	84	3,000	30,000
Horse	14,400	80	80	3,600	20	90	18,000	74	6,000	24,000
Pig	18,300	60	78	12,000	40	96	30,500	85	6,000	36,500
Sheep	8,300	67	55	4,200	33	87	12,500	66	7,000	19,500

Daily Production Per Animal of Average Weight (or as noted)

	Lbs	% Water
Beef	60	80
Cow	70	
Horse	44	
Pig	9	
Sheep	4	
Poultry, 100 animals		
Cage layer	30	75
Broiler	7	20

the task of conserving a product whose value represents most of the expense of animal feed.

Tables 6.1 - 6.4 illustrate the dilemma. Table 6.1 shows the total manure production per 1000 lbs live weight; also shown are estimates of the daily production from animals of average size. Table 6.2 permits an approximate weight to volume conversion by listing the density and air content of different manures. Table 6.3 indicates the range and average value of the major nutrients in manure. Table 6.4 shows the value of the major minerals relative to nitrogen.

Several factors determine the nutrient value of manure. In general, the richer the feed, the more that passes through the animal and the richer the manure. Feed grain, which is richer than hay, produces a richer manure.

The value of manure is inversely related to the weight gain and productivity of the animal. Young animals produce poorer manure than mature animals. Milk-producers generate poorer manure than non-producers. Work animals primarily need only **carbohydrates**, and most of the nutrients in the feed pass through them.

Animals which do not gain weight or produce a product require nutrients only to replace tissue; the old, dead tissue is sloughed off, and so the nutrient value of their manure is similar to the value of the feed.

The proportionate production and nutrient content of the solid and liquid portion depend upon the feed. The solid part contains live and dead organisms plus components of the feed which are resistant to absorption by the animal. Waste

Table 6.2: **Density And Porosity Of Manure**¹

	% Moisture	Density		% Air
		Lb/bu	Lb/cubic yard	
Cattle				
Beef	80	75	1620	7
Dairy	84	77	1670	3
Horse	60	36	780	57
Pig	75	77	1670	5
Sheep	65	68	1480	17
Poultry				
Cage layer	75	81	1760	0
Broiler	20	47	1030	47

¹ The values for the air content were calculated on the assumption that cage layer manure contains no air and that the density of the solids is the same for all manures.

Table 6.3: **Principal Nutrient Content Of Manure** *Nutrients Expressed as Lbs/ton of Manure*

	Nitrogen, N			Phosphate, P_2O_5			Potash, K_2O			Sulfur, S	%	C/N	Energy Index
	Sol.	Liq.	Total	Sol.	Liq.	Total	Sol.	Liq.	Total	Total	Moisture	Ratio	Gal/Ton
Cow	5	6	5-16	3		1.5-8	1	8	5-34	0.7-1.5	67-87	18	20
Average			11			3			9	0.9	75		
Horse	5	7	9-14	4		3-8	2	8	7-19	0.7-1.4	59-78	22	25
Average			12			4			10	1.1	70		
Pig	5	8	9-18	7	0.8	0.2-15	2	5	2-16	0.3-2.8	65-91	14	18
Average			13			8			7	1.6	77		
Sheep	8	10	10-29	5	0.2	3-15	6	14	3-25	1.2-1.9	60-74	16	32
Average			20			5			20	1.5	63		
Poultry													
Cage layer			20-50			8-40			8-20	1.2-7.2	75-80	7	20
Average			30			20			10	4.2	75		
Broiler			9-72			4-32			4-38		20		
Average			30			15			10				

Table 6.4: **Mineral Content & Feeding Capabiity Of Manure Relative To Nitrogen** *Feeding Capability As Surplus Or (In Parenthesis) Deficit*

	Phosphate, P_2O_5			Potash, K_2O			Sulfur, S	
	P_2O_5/N	Feeding Capability Hay & Grains	Vegs.	K_2O/N	Feeding Capability Hay & Grains	Vegs.	S/N	Feeding Capability
No nitrogen loss								
Cow	0.3	(30%)	(40%)	0.8	(20%)	(40%)	0.08	(60%)
Horse	0.3	(8%)	(20%)	0.8	(20%)	(40%)	0.09	(40%)
Pig	0.6	70%	40%	0.5	(50%)	(60%)	0.1	(8%)
Sheep	0.3	(30%)	(40%)	1.0	(1%)	(30%)	0.08	(60%)
Poultry								
Cage layer	0.7	90%	60%	0.3	(70%)	(80%)	0.1	8%
Broiler	0.6	60%	30%	0.5	(50%)	(70%)		
50% Nitrogen loss								
Cow	0.5	50%	30%	1.6	60%	20%	0.2	20%
Horse	0.7	80%	50%	1.7	60%	20%	0.2	40%
Pig	1.2	240%	190%	1.1	7%	30%	0.2	90%
Sheep	0.5	40%	20%	2.0	100%	40%	0.2	20%
Poultry								
Cage layer	1.3	270%	210%	0.7	(40%)	(50%)	0.3	120%
Broiler	1.1	220%	170%	0.9	(9%)	(40%)		

products generated during metabolism pass through the kidneys and are voided in the urine.

Consequently, a high roughage diet will produce a greater proportion of feces, while a more succulent or high nitrogen feed will result in a higher urine content and a higher quantity of nitrogen in the urine. The comparative differences in the nutrient value of the feces and urine are important; nitrogen is more stable in the solid part - which is already partly composted - than in the liquid.

With all the factors that influence the nutrient content of manure, it is of little surprise that tests show such variability. The variability of the distribution of nitrogen and potassium between the solids and liquid of manure is not shown in table 6.3, because little data is available and the table is already crowded, but it should be high.

Anyone using a dependable, constant source of manure should have it tested at the time of application, rather than relying on uncertain figures. Animal owners should, in addition, obtain a test when the manure is voided, in order to monitor the losses during storage.

Despite the variations shown in the tables, they do tend to confirm some of the generalizations often made to characterize manures. For example, **cage layer**

manure (or hen manure) is very strong and also wet and difficult to handle. Hen feed is the most concentrated of animal feeds, and the manure is unusually rich, particularly in nitrogen, phosphorus and calcium, the last owing to the lime usually added to the feed.

In contrast, **broiler manure** is drier, because it contains litter to absorb moisture. The nutrient content of broiler manure is the most difficult to predict, probably because of differences in the amount of free run the birds are allowed and in the frequency with which the manure is collected and piled.

The other manures are better balanced than poultry manure, but their value is difficult to predict without information on the diet and purpose of the animals. The least variable appears to be horse manure, perhaps an indication that the diet of horses is more predictable. On the basis of its reputation and also the average values in table 6.3, sheep manure is the strongest of the nonpoultry manures, and indeed it is often sold dried and bagged.

Moisture content is an important characteristic. Horse manure is coarse, light and dry; it is little more than half as dense as other manures. Having a high air content, it heats up very fast. On the other hand, pig and cow manures are wet and cold, and they rot more easily and with less nitrogen loss than horse manure. Sheep manure lies between these extremes; it is moderately coarse and dry and is hotter than cow manure but not as much as horse manure.

The value of manure as a balanced product can be assessed with the help of table 6.4, which lists the average ratio of phosphorus, potassium and sulfur to nitrogen. The table shows that cow manure has about 1/3 as much phosphate as nitrogen and almost as much potash as nitrogen, assuming all the nutrients are conserved.

By comparing such equivalents to the corresponding ratios for crop requirements shown in table 4.4, we can determine how well balanced manure is as a fertilizer. This is done in table 6.4, which lists the percent deficits (surpluses are underlined). It shows that cow, horse and sheep manure are low in phosphorus and sulfur, and all manures are low in potassium. For example, if enough cow manure is used to supply all the nitrogen, it will be shy of phosphorus by about 30% for growing hay and grains and about 40% for vegetables.

We are, of course, using a great many averages, and the ability of manure to provide a balanced ration will vary considerably in individual cases. Also, we might be able to minimize losses of most minerals, but it is unrealistic to assume that we can conserve all of the nitrogen. Losses of at least 30% are the rule more than the exception. The second part of table 6.4 shows the results of assuming a 50% loss of nitrogen. Then the balance of nutrients is very good, and manure is as close to a complete and balanced fertilizer as one would want. The only exception is poultry manure, which is still significantly short in potassium and overly rich in phosphorus¹

¹A recently obtained 10-year average indicated that, taking losses into account, the phosphate content is about half the nitrogen content of cow manure, 3/4 the nitrogen content of pig manure, and equal to the nitrogen content of poultry manure. Potash is 1-1/4 times the nitrogen content of cow manure, half the nitrogen content of pig manure, and 1/3 the nitrogen content of poultry manure. See [18].

Manure Losses

Just because manure has to lose nitrogen in order to be balanced does not mean that we should encourage losses. In the first place we may not need a balanced fertilizer; most soils are lower in nitrogen than in the other nutrients. Secondly, losses will take place without our help. So we need to do all we can to minimize them.

The non-nitrogenous minerals in manure can be conserved by protecting the manure from rain and snow and taking care that the urine does not leach out. With little or no leaching losses, nitrogen will suffer the major loss.

Initially, the major cause of nitrogen loss is volatilization of ammonia. Urine is easily attacked by soil organisms, with the ultimate formation of alkaline ammonium hydroxide. The pH of the manure rises rapidly after it leaves the animal, owing partly to the ammonium hydroxide but primarily to the existence of carbonates in the manure, the result of biological activity while still in the animal's gut.

The instability of ammonium hydroxide under these conditions causes the formation of ammonia, which is lost as a gas. Normally, the ammonia is attacked by bacteria and converted to nitrate by the process of nitrification, but these particular bacteria function poorly if the pH is too high. Thus loss of ammonia can continue for a long time.

Once the pH is below an excessive level (about pH 8), the production of nitrates from ammonia is high and introduces enough acidity to control the pH. This stabilizes the manure, at least so far as ammonia losses are concerned, and then all we need worry about is the loss of nitrates. Even when leaching is controlled, nitrogen losses can occur from denitrification of nitrates². Denitrification is difficult to control in the soil and even more so in a manure pile.

The solid part of manure has already been partly decomposed in the animal, and nitrogen in the solids is stable compared to the nitrogen in the urine. The rapid formation of nitrates from the ammonium in the urine is probably the source of most of the nitrogen lost by leaching and denitrification. When urine is collected with the solid portion, nitrogen losses on the order of 50-60% are typical.

Some farmers, particularly in Europe, collect the urine separately and keep it tightly enclosed, with a layer of oil over the surface. The oil cover minimizes losses of ammonia, and denitrification is reduced as well, since the lack of oxygen keeps the ammonium from being oxidized into nitrate³.

Is the trouble required to minimize nitrogen losses worthwhile? It is certainly arguable whether nitrogen is the most important component of manure. Much of the phosphorus is available, and the trace elements in manure are inconvenient to supply in inorganic form. Perhaps most important are organic substances in manure - various enzymes, vitamins and hormones - whose benefits individually are largely unknown, but which together give manure an aura otherwise reserved for

²see chapter 10.3

³One innovation which was developed by a farmer in Quebec for stabilizing animal urine is to use molasses as a starter in an aerated tank of urine (anyone interested in further information should contact Joe Smillie, RR #3 Erle, Weedon, PQ-C JOB 3JO, Canada)

gold. Indeed some people prize manure most highly for its non-nitrogenous value, and they plant clover to supply the nitrogen.

On the other hand, many farmers rely on manure for much if not all of the nitrogen they need, and minimizing losses for them is important.

One way to reduce losses, though not often practical, is to spread the manure immediately as it becomes available. If manure is so fresh that no substantial amount of ammonia has formed, and if it is spread thinly on a warm, dry day, it need not be tilled in quickly, because drying will delay the breakdown of the urea.

If manure is not entirely fresh it should be turned under or spread before a rain, because drying will hasten the volatilization of ammonia which will have already formed. Some crops, however, do not respond well to fresh manure, and the flavor of others is tainted. Manure should not be spread on frozen ground or when runoff losses are likely to be high.

One possible way to store manure is to compost it, by mixing it with carbonaceous material and enough air and water. According to theory, carbonaceous residues intercept and stabilize the nitrogen. In practice, nitrogen is often lost from compost for three reasons:

- the pH usually climbs too quickly for biological activity to take place soon enough to avoid some loss
- carbonaceous materials are not efficient at absorbing ammonia
- it is difficult to keep the pile sufficiently aerated to avoid denitrification losses and yet wet enough to maintain biological activity.

Another option for storing manure is to rot it by keeping it in an **anaerobic** state. In the absence of oxygen, organic acids produced by fermentation help to keep the pH down. Furthermore, with the lack of air, the ammonia is not transformed to nitrate, and denitrification cannot take place. To make a good pile, the manure should be slightly moist and well packed; traditionally it is trampled by the animals. If allowed to dry out, air will seep in and the manure will lose ammonia. If too moist, it will putrefy and emit offensive odors.

The problems of rotting are similar to those of composting, but the tolerances are not so narrow. Even if the surface dries out, the interior is usually moist enough to maintain a state of rotting. If the manure is too wet, the addition of soil will absorb excess moisture.

A third way to reduce losses of nitrogen is to add material that will absorb the ammonia directly. Bedding is one possibility, but bedding is usually chosen for economy and used only in sufficient quantity to absorb enough moisture so that the animals are clean and comfortable. The most common materials, wood chips and straw, are poor at absorbing ammonia. The best are peat moss and soil, with as much humus as possible; even then a large amount is necessary.

An experiment in France showed that about half as much soil as cow manure, on a volume basis, is required for effective absorption of ammonia, and about 1-1/4 times as much peat as cow manure. Most northeastern American soils contain

more humus than French soils, so perhaps less would be required, but one would have to experiment to find out.

Adding soil with manure to a compost pile may be an effective way to reduce nitrogen losses.

A fourth way possible for those who have the animals that produce manure is to separate the urine from the solids and treat it separately, as already noted. Decomposition of urine is the main source of excess ammonia.

Yet another way to reduce nitrogen losses is to add chemicals to stabilize the ammonia by neutralizing the rise in pH. Pure sulfur, for example, is oxidized by sulfur-loving bacteria to sulfuric acid. Or sulfuric acid itself has been used on occasion. Other chemicals, such as gypsum, ferrous sulfate, and superphosphate (which contains gypsum) have also been tried with mixed results. Any neutralizing effect of gypsum or ferrous sulfate is due to the calcium in gypsum or the iron in ferrous sulfate; these precipitate the carbonate associated with ammonium carbonate.

One problem with using chemicals to precipitate carbonates is that eventually the precipitates redissolve, driving the pH back up again. But the hope is that by then the ammonia will have been stabilized. In this respect, ferrous sulfate is better than gypsum, because the precipitate of iron carbonate takes longer to redissolve.

Another problem, however, is that enough chemicals must be added to also neutralize all the carbonates in the manure, not just those associated with ammonium. And a third problem is that no one has investigated the effects of these chemicals on the availability of other nutrients. The iron in ferrous sulfate, for example, is likely to lock up phosphorus and manganese.

There is a small amount of evidence that gypsum improves biological activity in some unexplained way, and this may hasten the stabilization of ammonia. Experiments with gypsum, however, have had variable results, and quantities varying from a few percent, on a weight basis, to over 100% (for poultry manure) have been recommended. Experimentation is still being carried out with all these chemicals, but so far their advantages are uncertain.

Another proposed claim for stabilizing nitrogen is the use of rock phosphate. If it is successful, however, the reason is obscure. Rock phosphate has a slow but definite liming capability, which is the opposite to what one would want to prevent a rise in pH. In addition rock phosphate is extremely insoluble at the pH level to which manure rises. Perhaps in some unknown way rock phosphate improves biological activity; or the clay in **colloidal rock phosphate** may be able to adsorb ammonia; or it may be able to adsorb gases from putrefaction, leading one to believe that ammonia is being conserved.

Even when chemical additives do work, they only limit ammonia losses and have no effect on denitrification. Loss of ammonia occurs only initially, while the pH is still high; denitrification is a threat as soon as nitrates begin accumulating.

Of the three alternatives - composting, rotting, and the use of chemicals - rotting is probably the easiest and may be the most satisfactory if the conservation of nitrogen is the primary objective. However cage layer manure is difficult to rot successfully. It tends to putrefy instead, giving off disagreeable odors. It is probably best composted or spread directly.

Cold composting with added soil may be a reasonable alternative.

Manure Application Rates

Although desirable, it is not always practical to test manure, and so guidelines are necessary. Recommended application rates are usually based upon the contribution of nitrogen.

We can make an approximate estimate of the amount of nitrogen added by manure as follows: According to table 6.3, fresh cow manure with urine can be expected to contain about 11 lbs of nitrogen/ton. About half of that nitrogen should be available the first year. With losses taken into account, the actual amount available should be about 3-4 lbs nitrogen/ton of manure.

At the opposite extreme, cage layer manure might contain about 30 lbs of nitrogen/ton. The nitrogen is much less stable in poultry than in cow manure, and perhaps about 25 lbs should be available the first year. After losses, the amount of nitrogen remaining in the soil might be half this amount, or about 12 lbs of nitrogen/ton, 3-4 times that of cow manure.

Usual rates of application of cow manure are 5-40 tons/acre. For corn or hay, 20-30 tons are often spread, applied to corn before planting or spread onto hayfields in three applications. Vegetables would benefit from 5-20 tons/acre, and small grains from 0-8 tons/acre (depending on the chances of lodging), applied before seeding. These rates should be decreased if manure is spread every year⁴

Horse manure can be applied at similar rates. However, sheep and pig manure usually have a higher nitrogen content, and less should be used. Rotted manure can be used at a lower rate also.

The nutrients from **rotted manure** are more available than from fresh manure, owing to the additional decomposition. A customary practice is to use rotted manure on fast-growing crops and fresh manure on slower ones. Fresh manure has adverse effects on root crops, especially carrots, which tend to produce forked roots. Rotted manure is good for improving nutrient and water retention of sandy soils; the coarseness of fresh manure loosens up heavy soils.

Poultry manure is much more concentrated than other manures, and its nitrogen is available more quickly. Pollution from poultry manure is a greater threat to groundwater supplies than other manures. Application rates of 2 tons/A are often satisfactory. Rates should not exceed 5 tons/acre without monitoring groundwater purity.

A reasonable comparison among manures is that one ton of poultry manure is equivalent to two tons of pig manure and four tons of cow manure, all at a semi-dry state (about 25% moisture) [18].

6.3 Hay And Straw

Hay is the air-dried cuttings of a green field crop, and straw is the cuttings taken with the grain. If the hayfield is managed without herbicides, it often sustains many varieties of plants, maturing at different times. As a result, hay usually contains

⁴Summarized from [92].

weed seeds. Seed-free straw is easier to obtain. Hay, however, has a better balance of nutrients.

Table 6.5 shows the nutrient content of various varieties of hay and table 6.6 of straw [19], [50], [70], [71], [72], [85], [1], [79]. Table 6.7 compares the value of hay and straw with cow manure.

If legume hay and manure are supplied in such quantities that the nitrogen content is the same, then table 6.7 shows that the hay supplies approximately the same amount of major nutrients as manure but less of the trace elements. The outstanding exception is boron, but that is because the boron data for legumes came from a single test of alfalfa and is unlikely to be representative of all legumes, maybe not even of alfalfa⁵.

The results are similar with nonlegume hay and straw. They have, however, relatively more of the major elements, because they contain much less nitrogen.

Table 6.7 indicates that, as a fertilizer, legume hay is a reasonable alternative to manure, and nonlegume hay might be also if it were supplemented with nitrogen. Hay, however, has disadvantages. Bulkier than manure, it is more difficult to spread over a large area; it does not have the decomposition products of manure; and it may have more weed seeds.

Hay does have advantages over manure. It has a greater energy content and will contribute more to total biological activity of the soil; possibly its decomposition will produce similar organic byproducts already present in manure. Because nitrogen is more stable in hay than in animal urine, its loss is less likely.

Straw also has a respectable amount of nutrients, although it has lost most of its nitrogen and phosphorus to the harvested grain.

Hay and straw are excellent mulches. Hay adds more nutrients, but straw usually has fewer weed seeds. Weeds, however, are not as much of a problem in mulch as they are in residues turned into the soil. Weeds which become a nuisance grow from the mulch and can be easily pulled out, and those that come up the following year can be smothered by another layer of mulch.

Mulches provide several non-nutrient benefits to the soil. They establish an excellent physical environment for soil organisms, and they are food for organisms which prey on pathogens. Varieties of fungi which consume nematodes are stimulated by mulches.

Mulches, however, have disadvantages. Some of the decay products may be toxic to seeds and new seedlings; to avoid this, mulch should be applied only after a plant is well established.

Mulches also keep the ground cool and render it unsuitable for warm-weather crops. The cool and damp environment may encourage insect pests. It may induce plant rot if the mulch is packed too closely around the base of the plants.

One should be cautious about purchasing bales of hay or straw or any mulch material that has been stored for a long time. If the material was stored under anaerobic conditions while moist it may have turned sour; if so, it could damage growing crops. Sour residues smell sour, with an odor similar to vinegar, ammonia,

⁵Alfalfa has a high boron requirement, but this does not necessarily mean that it is a good accumulator: it may simply be inefficient at extracting boron from the soil.

6.3. Hay And Straw

Table 6.5: **Nutrient Content Of Hay** *Nutrients in lbs/ton dry weight*

	N	P ₂ O ₅	K ₂ O	S	Ca	Mg	Cu	Mn	Zn	B	Mo	Fe	C/N ratio	Energy index gal/ton
Legumes														
Alfalfa	44-56	10-14	32-60	3-6	19	0.4	0.014	0.08	0.07	5 ¹	0.006	0.2	16	77
Average	49	11	43	5										
Clover	34-70	5-20	32-60	3-5	26	5	0.016	0.2	0.14				19	78
Average	42	11	36											
Cowpea	39-62	5-19	33-45										16	81
Average	52	15	38											
Field pea	38-66	5-13	13-34										17	80
Average	47	9	24											
Hairy vetch		19	49											76
Lespedeza	41	15	22											
Lupine	53	13	18										15	79
Serradella	41-54	8-21	13-64										16	78
Average	48	16	37											
Soybean	48	12	34	5			0.02	0.2	0.08					
Sweetclover	52	12	32											
Composite	34-73	5-21	13-64	3-6						5 ¹	0.006	0.2		
Average	50	13	33	5	22	3	0.02	0.2	0.1				16	78
Nonlegumes														
Annual ryegrass	34	13	37										24	81
Bermuda grass	23-57	9-14	25-40	2	7	3	0.03							
Average	34	11	33											
Buckwheat	13-25	12-17	48-66										41	82
Average	20	14	54											
Kentucky bluegrass	26	10	34	4	6	4	0.01	0.15	0.04				33	86
Millet	15-26	6-9	10-43										37	78
Average	21	7	27											
Oats	24	13	51											
Orchard grass	25-50	7-17	33-63	6									24	80
Average	33	11	42											
Rye	21	10	34											
Sudan grass	30													
Timothy	20-31	3-10	24-39	2	3	2	0.01	.01	0.08				35	78
Average	22	7	24											
Composite	13-50	6-17	24-66	2-6	3-7	2-4								
Average	25	11	38	4	4	3	0.01	0.1	0.06				32	81

¹ The value for the boron content of legume hay was taken from one experiment with alfalfa and may not be typical for all legumes.

6. UNPROCESSED RESIDUES

Table 6.6: **Nutrient Content Of Straw** *Nutrients in lbs/ton dry weight*

	N	P_2O_5	K_2O	S	Ca	Mg	Cu	Mn	Zn	Si	C/N ratio	Energy index gal/ton
Legumes												
Field pea	20-29	7	20								35	80
Average	23											
Soybean	23-35	2-9	11-51	4								
Average	27	6	28									
Composite	20-35	2-9	11-51							4	35	80
Average	25	6	24									
Nonlegumes												
Barley	11-26	4-6	21-42	2	8	2	0.008	0.26	0.04		58	81
Average	14	5	28									
Buckwheat	25	3	23		40	6						
Corn	16-21	2-9	17-51	4	8	2	0.008	0.3	0.05	42		80
Average	19	6	28									
Oat	9-13	2-6	21-40	5	12	3	0.015		0.14	7	70	82
Average	12	4	30									
Rice	10-22	3-5	11-40	2				0.6			46	73
Average	16	4	30									
Rye	8-22	3-6	16-40	2	6	1	0.007	0.09	0.05		84	82
Average	10	4	13									
Sorghum	21-33	6-8	31-43	4								
Average	27	7	37									
Wheat	10-19	2-6	12-45	3	3	1	0.007	0.1	0.03		78	83
Average	11	4	18									
Composite	8-33	2-9	11-51							7	42-84	
Average	17 ¹	5	26	3	13	3	0.09	0.27	0.06		47 ²	80

¹ 13, if corn, buckwheat & sorghum are discounted

² 72, if corn & buckwheat are discounted

Table 6.7: Comparison Of Cow Manure With Hay And Straw *Nutrients in lbs/ton dry weight*

	N	P ₂ O ₅	K ₂ O	S	Ca	Mg	Cu	Mn	Zn	B	Mo	Fe	C/N ratio	Energy index gal/ton
Cow Manure	11	3	9	0.9	6	2	0.02	0.06	0.06	0.04	0.002	0.8	18	20
Legume Hay	50	13	33	5	22	3	0.02	0.2	0.1	5 ¹	0.006	0.2	16	78
Nonlegume hay	25	11	38	4	4	3	0.01	0.1	0.06				32	81
Nonlegume straw	17	5	26	3	13	3	0.009	0.27	0.06				47-72	80
<i>Ratio of nutrients are normalized to unity for nitrogen</i>														
Legume hay/manure	1.0	1.0	0.8	1.2	0.8	0.4	0.2	0.7	0.4	30 ¹	0.6	0.05		
Nonlegume hay/manure	1.0	1.6	1.9	2	0.3	0.7	0.2	0.7	0.4					
Nonlegume straw/manure	1.0	1.1	1.9	2	1.4	1.0	0.3	3	0.6					

¹ Note: The value for the boron content of legume hay was taken from one experiment with alfalfa and may not be typical for all legumes.

Table 6.8: Nitrogen Absorption By Fresh Residues

C/N Ratio Of Residues	Lbs Of Nitrogen Taken Up From Soil By	
	1000 Lbs Air-Dried Residues	10 35-Lb Bales
30	3	0.9
40	6	2
50	8	3
60	9	3
70	10	4
high	16	6

sulfur or silage. Any mulch, especially hay but sometimes even packaged bark chips, will decompose. So smell it to be sure. Chances are that if hay or straw is dried properly, it will last a reasonable time, but even so, if it is to be stored, one suggestion is to compost it [12].

The immediate nutrient content of a mulch is difficult to estimate. Soluble substances will leach into the soil, including potassium and water-soluble organic substances. The portion of the mulch in contact with the soil will break down, and, slowly, the rest of the mulch will follow.

People who mulch continuously can assume a carryover from previous years and that almost all the nutrients are available, except for leaching and nitrogen losses. Nitrogen losses other than through leaching should be small, because the nitrogen tends to become available slowly enough that excesses of soluble nitrogen do not accumulate.

It may be interesting to calculate the fertilizing value of a mulch, assuming that all nutrients eventually move into the soil. As an example we could consider a mulch made by tearing apart bales of hay into one inch layers and placing them

evenly on the ground. A bale of hay or straw is about 14 by 20 by 32 inches and may weigh about 40 lbs. A bale divided into one-inch layers can cover about 62 square feet of soil, and about 700 bales, weighing about 14 tons, would be required to cover an acre.

If each bale is made up of a nonlegume hay of average nutrient value as characterized in table 6.5, the hay would contain about 350 lbs of nitrogen, 150 lbs of phosphate and 530 lbs of potash. So much nitrogen would appear to produce an excess, but table 6.5 shows that such hay will have a C/N ratio of about 32. With this ratio, 11,000 lbs of carbon accompanies the nitrogen. Most of the nitrogen will be tied up by soil organisms attacking the carbon, although after a period of decomposition and oxidation of carbon, some will become available. Some of the phosphorus and potassium will also become absorbed into the soil and be made relatively unavailable, but annual applications of such a mulch is bound to result in a large accumulation of available nutrients.

To produce 14 tons of hay, one might need about 3 acres of orchardgrass, and probably more of timothy. On this assumption, mulching a garden with one-inch layers of baled hay requires a hayfield about 3-5 times the size of the garden.

Lawn clippings are similar to a non-legume hay. They are a good soil activator and fertilizer, even though not enough may be available for a mulch. One problem is that they tend to compact and are best used with a bulking agent, such as a small amount of hay, straw or other residues.

6.4 Other Local Residues

Leaves

Leaves are often easily available, and no doubt they are a good source of nutrients. Their complete fertilizer value, however, can only be inferred, because only the analyses of their macronutrients is available in the literature. The average NPK content of deciduous leaves is about 0.8% nitrogen, 0.15% phosphate and 0.15 - 0.5% potash (0.15% in evergreen needles, 0.5% in deciduous leaves).

The most likely fertilizer value of leaves, however, is in their trace elements and sulfur content. Before a leaf dies and drops from the tree, most of the macronutrients (probably except sulfur) have already drifted back into twigs and branches. Micronutrients, however, are immobile and remain in the leaf. Consequently, leaves can be expected to contain appreciable quantities at least of copper, iron, manganese, and perhaps other trace elements.

Leaves have to be managed carefully in order to realize their maximum benefit. If collected together in a mass, they form a compact, impenetrable mat when wet. To avoid this, they should be either shredded or mixed with coarse materials. Either way they can be spread directly, turned into the soil, or composted.

Leaves can also be rotted alone, to form leaf mold, but no advantage of rotting over composting seems to exist, and rotting can take several years unless the leaves are well shredded. Evergreen needles decompose very slowly and are probably best used as a protective and decorative mulch for ornamentals and trees.

Paper

Paper is useful as a mulch to suppress weeds. It also has value for its cellulose but has little or no nutrient value for plants. It may be used in a new strawberry bed or, for that matter, any garden. To keep the paper from being blown away, staple sheets end to end to form a long roll which, when unrolled, may be held down by stones, branches or hay. Punch holes for planting.

Alternatively, shred the paper and use it as any other mulch.

One potential problem is the possible hazard of heavy metals in the printing inks. According to the USDA, the ink used in newspapers is free of lead and therefore safe to use as a mulch. Also, the Minnesota Pollution Control Agency [9] has found that, if mixed paper is used (such as paper from different magazines), any toxic materials are present in such negligible quantities that no danger exists. Unmixed paper may be satisfactory also, but one would need more information.

Seaweed

Seaweed is a good soil amendment but is usually a practical residue only for gardens of small to moderate size. The nutrient content of seaweed varies with the species and the time of year when gathered, but typical values, on a dry weight basis, are 1.2 - 5% nitrogen, 0.2 - 1.3% phosphate, 2.8 - 10% potash, about 0.02% boron, 0.001% copper, 0.05% iron, 0.05% manganese, 0.002% molybdenum, 0.004% zinc, and numerous additional elements at lower concentrations.

Suppose that a person is able to haul 100 lbs of air-dried seaweed (perhaps five times this amount of fresh seaweed) to a 3000 sq ft garden. According to the above figures, this amount will supply the equivalent of 17 - 70 lbs of nitrogen/acre, 3-18 lbs phosphate/acre, 40 - 140 lbs potash/acre, and about 0.3 lbs boron, 0.01 lbs copper, 0.7 lbs iron and manganese, 0.02 lbs molybdenum, and 0.05 lbs zinc, all per acre.

A comparison of these figures to those in tables 4.1 - 4.3 shows that the quantities of NPK supplied by this amount of seaweed are significant, since the phosphorus, potassium and much of the nitrogen are readily available. Boron seems to have a reasonable presence, and possibly molybdenum, but the quantities of the other trace elements do not seem to be significant. The micronutrients furnished by seaweed are of questionable value despite their impressive diversity.

Where crops such as potatoes are grown directly in seaweed on top of the ground, the trace elements may be more influential.

Perhaps the most important merit of seaweed is its content of assimilable organic materials, in particular the growth hormones. In this respect seaweed is rivalled only by animal manure and compost [78]. On the other hand, research in British Columbia with kelp [11] concludes that even the growth hormones have questionable value. Possibly seaweed is worthwhile only to people living near the coast, where it can be foraged rather than purchased.

The salts in seaweed, which need not be washed off for application to most soils or for composting, may provide additional nutrients, particularly magnesium.

Pond Dredgings

The use of pond dredgings as a fertilizer is practically unknown in the U.S. but is popular in China. Fed by a stream, the pond collects the silt carried by the flowing water and becomes a reservoir of nutrients. The pond may be partitioned into two or more sections, each of which is independently drainable. Then one section can be drained each year and the dredgings transferred to the soil⁶

⁶Scott and Helen Nearing built such a pond at their home in Maine.

Chapter 7

Compost

7.1 Summary

Hot composting is a method for recycling residues rapidly and with the possibility of destroying pathogens and weed seeds. The result is a concentration of plant nutrients and organic byproducts.

Cold composting is a slower alternative which does not kill weed seeds or pathogens but should be more conservative of humus nitrogen.

This chapter manifests more than the others of a possibly irrational personal bias, so I should reveal it now. For those composting for their own use, the best residues are those of especially low nutrient value and inappropriate to spread directly. The use of high quality residues such as manure, hay and straw risks the loss of nutrients and are better managed in other ways. This judgement strongly favors cold over hot composting.

The predicted nutrient value of self-produced compost is possible, based on averages.

7.2 Hot Composting

Conditions and Requirements

Composting is the decomposition of waste products by aerobic means, that is, through microorganisms which require oxygen. It first became popular through the work of Sir Albert Howard [48]. Briefly, raw materials are gathered into a pile and so managed as to generate enough heat to reach an initial temperature somewhere between 100 and 160 degrees F. At this temperature rapid breakdown of organic residues occurs, along with the destruction of weed seeds and parasites. The pile is turned regularly in order to introduce additional oxygen and to bring undecomposed material from the outside into the center¹.

The process was further developed at the University of California at Berkeley as a means of sanitizing municipal wastes [42].

¹For further information on the technology of composting, see [41].

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In the U.S. the process is commonly referred to either as the Berkeley composting method or as hot composting.

The result of the decomposition of organic matter is humus, which is a complex mixture of the byproducts of hundreds of varieties of organisms plus the remains of those which have expired. Furthermore, the byproducts are subject to further attack in order to gain whatever energy they may furnish. There is a continual sequence of stages of decomposition; each stage liberates additional carbon, the carbon/nitrogen ratio drops, and the residues become increasingly resistant to further attack.

Two essential requirements are moisture and air; adequate moisture is necessary for any form of life, and oxygen is needed to release the energy from carbon in the residues. The two threats to adequate oxygen are excessive moisture and compaction of material. Fresh, succulent green residues require particular care in order to avoid compaction; most likely the best way of working with them is with a variety of shapes.

Nitrogen is necessary for the growth of organisms and consequently to maximize the generation of heat. But it is not always necessary to obtain the temperature range for hot composting.

Temperature is a measure of the state existing when the flow of heat away from the pile equals the heat generated within it. The extent of the flow depends on the amount of material and its insulating value. Fallen tree leaves, for example, with a C/N ratio of about 100, constitute a fire hazard if gathered in a sufficiently large pile: they are known to spontaneously catch on fire from the heat generated.

Nitrogen, however, is necessary where only a small amount of material is available. The C/N ratio should be such as to maximize biological activity in order to compensate for the greater heat loss from the larger ratio of surface to volume.

In most situations, the minimum size of a compost pile should be about four feet on each side and 3 - 4 feet high. With a higher pile, the material should vary enough to avoid compaction. The residues should be just wet enough that no excess moisture can be wrung out from a handful. If the pile is too wet, turning will help dry it out. Insulating the surface with hay or leaves should reduce heat loss².

The usual criteria for maximum activity is a C/N ratio in the range of 20 - 30; it seems reasonable inasmuch as it correlates with the C/N ratio of the organisms themselves³.

If left alone, the carbon/nitrogen ratio of a compost pile drops from its initial value to a point somewhere between 15 and 20. But decomposition, although it slows considerably, doesn't stop, as denitrification becomes a major activity⁴.

²For additional suggestions especially applicable to a vegetable compost, see [5].

³For example, the C/N ratio of fungi is about 10. When a fungus attacks an organic substance, some of the carbon is oxidized, releasing energy; some is utilized as body tissue; and the remainder is passed off as a waste product. Approximately 40% of the carbon attacked by fungi is used for tissue development. With these assumptions, the C/N ratio of the organic material must be at least 25 in order that carbon not be limiting.

⁴The possibility of significant denitrification at a C/N ratio near or below 17 was pointed out to me by William Brinton.

Eventually, life ceases as organisms die out for lack of food. The end result is a lot of minerals, a small, stable humus fraction, and a minimal amount of life.

So when should the result of hot composting be spread? Weather permitting, it may be best applied as soon as possible after most of the material has lost its original appearance; as soon as it begins to look like soil. Doing so offers the best opportunity to minimize unnecessary losses, and it gives the soil organisms a chance at the available energy.

Limitations of Hot Composting

The two inevitable losses are nitrogen and humus (through the loss of carbon). Nitrogen is lost by

- leaching of nitrates
- loss of ammonia which is generated too rapidly for incorporation into biomass
- **denitrification.**

Humus is lost by

- oxidation of carbon
- lack of nitrogen for tissue generation.

For municipalities and businesses that produce compost commercially, these losses are either unimportant or limited by advanced technology. For them hot composting is an ideal process for quickly generating large quantities of safe and valuable soil amendments from waste products. For municipalities at least, conservation of nitrogen and humus is not important in processing wastes; nor is it for some commercial producers, who make up losses with fertilizer additions.

But losses are important to most farmers and many gardeners. They should consider other options before doing it themselves: not only does it require time and labor but also the proper equipment to assure that the entire pile reaches the minimum temperature necessary to kill undesirable organisms. Furthermore, it is wasteful, probably of organic matter but certainly of nitrogen.

As discussed in chapter 6 nitrogen losses have three causes: leaching of nitrates, escape of ammonia, and denitrification.

Leaching losses can be prevented by keeping the pile covered; a layer of hay or straw may be enough to cause water to roll off the surface. Ammonia losses are unavoidable in hot composting of a small pile unless its pH is monitored and controlled, not easily done without the proper equipment. Denitrification losses depend on the degree to which oxygen is lacking; without adequate control it is extensive in hot compost owing to the high demand for oxygen.

Furthermore, not only disease organisms are destroyed by the high temperature inherent in hot composting, but beneficial organisms as well, and a period of time is necessary before hot compost achieves the biological diversity already existing

in cold compost. For example, compost produced by hot composting is not as effective as cold compost in preventing damping-off of seedlings [7].

Finally, without knowing the actual C/N ratio of the materials in a small pile, the tendency is to add an excess of nitrogenous material in order to assure that it will heat up. The consequence is an even greater loss of nitrogen.

There is always a price to pay for doing something quickly. In this case it is a loss of nitrogen additional to the loss occurring in a slow process of breakdown; it is also a loss of humus owing to the decreased availability of nitrogen and probably to the less efficient metabolism of those micro-organisms which survive the high temperature.

If rapid production of a concentrated mineral fertilizer with a broad range of trace elements is the primary goal, then hot composting is a good choice; otherwise alternatives are preferable. Whatever the decision, the reward is not worth the risk in composting diseased plants with the expectation that a small home operation will kill all pathogens.

A counter argument is that the price is acceptable: the creation of growth-enhancing humus components is worth the loss of nitrogen and total humus. That may be so, but other methods of composting also produce a variety of components with less loss. Furthermore, alternatives permit the activity of a larger number of organisms during the entire process, not just those that can withstand high temperatures. They include not only a greater range of micro-organisms but also bigger animals such as earthworms and spiders.

Some of these objections may not apply to commercial operations using modern methods. Those methods include an elaborate system for controlling air flow through the pile. The air not only supplies oxygen, but it cools the pile, and by this means, compost can be produced at an optimum temperature range which kills pathogens and weed seeds but nevertheless preserves some beneficial organisms. Furthermore, waste products handled by some businesses are such that disease organisms and weed seeds are unlikely⁵.

7.3 Cold Composting

An obvious alternative to hot composting is cold composting - gather materials into a pile without regard to the C/N ratio, adding to it as materials accumulate, and let it sit. In time, anywhere from a few weeks to a few months (or maybe years with difficult materials), it takes on the appearance of soil and can be spread. Better yet is to add soil in order to absorb excess moisture and improve aeration by reducing compaction.

Nitrogen losses will also occur in cold compost. Leaching of nitrates is probably more extensive than in hot compost because the pile is exposed longer to the environment. Owing to the slow rate of decomposition, however, ammonia loss should be minimal, unless animal manure is a major component. Although the demand for oxygen is much less than it is in hot compost, denitrification is still

⁵A discussion of compost produced commercially for use in plant containers can be found in [17, chapter 12].

likely but to a lesser extent. Demitrification can, however be further reduced by adding soil to increase aeration.

Cold composting has several variations. One is the traditional above-ground pile, but there are at least two possibilities for direct incorporation underground, which may be more effective:

- grow crops in alternate rows and dig in raw compost materials in the unplanted rows; alternate in succeeding years
- sow inoculated legumes over material dug in⁶

Finally, even though cold composting does not destroy disease organisms directly, its results probably help to control them, owing to the ecological balance resulting from the increased diversity of organisms.

A final note illustrates the difference between the two processes. Liming a cold compost pile to a pH near 7 is advisable because it will encourage the development of a greater variety of micro-organisms. Fungi will proliferate at almost any pH, but bacteria tend to prefer a neutral environment.

Never, however, lime a hot compost pile and probably not any pile containing a substantial amount of fresh animal manure: doing so will accelerate the escape of ammonia and subsequent loss of nitrogen.

Figure 7.1 is my view of the expected results of hot and cold composting. It is not meant to support the discussion but only to show the results if you accept it. The first chart shows the percent of carbon remaining if spread when the final C/N ratio is 20 and 30, and the expected loss of nitrogen is 50%. This is intended to represent the effect of hot composting; the expected loss of nitrogen appears to be based on anecdotal evidence but is reasonable considering the various causes.

The second chart is similar, except for an expected nitrogen loss of 30%. This is meant to represent cold compost. It is, however, a guess and could be more or less depending on aeration and the nature of the materials.

The curves are not completely fair; for instance, the loss of nitrogen from a compost pile spread when the C/N ratio is 30 will be less than if it were spread at a C/N ratio of 20; but no one to my knowledge has measured the loss as the C/N ratio drops from 30 to 20. So it may be best to accept the error rather than add another assumption. In any event, the curves come from equations derived in appendix D, so you are free to modify them.

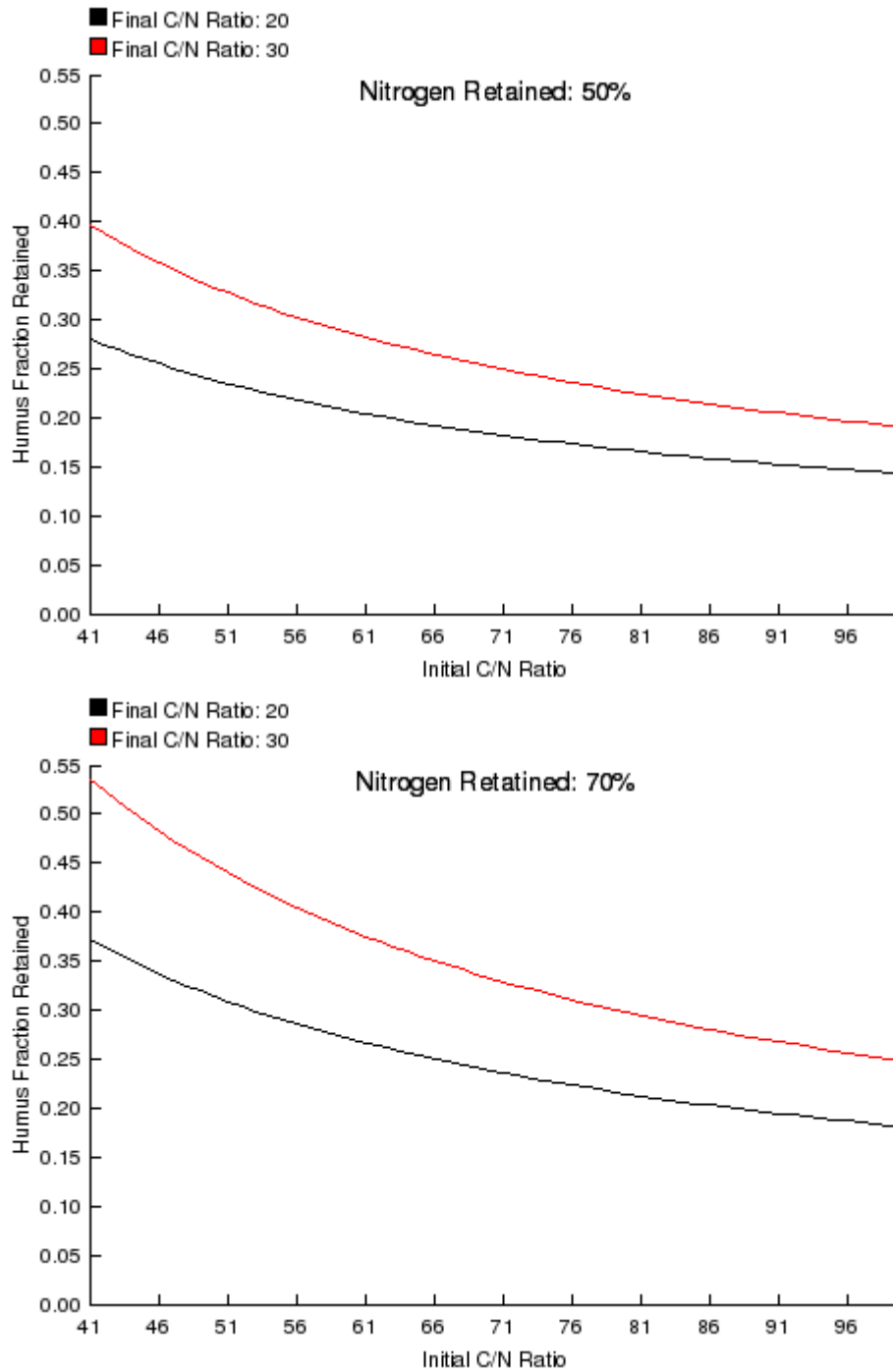
7.4 Manure In Compost

Is there a difference between hot compost made with and without manure? According to followers of Biodynamic agriculture, there is a difference, but no one makes clear what it is. One experiment does show a difference: according to work

⁶This was developed by the Henry Doubleday Research Association, a unique organization which carries out a number of research activities on gardening on its own grounds and among its members. For a subscription, which includes a quarterly newsletter, contact the Henry Doubleday Research Association, Ryton-on-Dunsmore, Coventry, CV8 3LG, England.

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Figure 7.1: Compost Retained as a Function of Nitrogen Retention and C/N Ratios



done in Germany with watery mixtures of compost, that made with manure has a natural fungicide not comparably present in vegetable compost [13].

One advantage of manure in compost is its convenience. It is a natural buffer, supplying whatever may be missing. Otherwise, compared with the two alternatives of managing manure (rotting, direct application in advance of planting), composting, especially hot composting, is likely to cause the most loss⁷.

A decision on whether to compost manure is likely to depend on three factors:

- the convenience compared with the necessity to find alternate sources, especially of nitrogen but perhaps also phosphorus
- the assumption of whether the result has beneficial residues that more than compensate for losses of nitrogen and humus
- the age of the manure; if it is not fresh from the animal, loss of nitrogen in addition to whatever has already occurred may be unimportant.

7.5 Nutrient Value of Compost

Compost concentrates nutrients because of the loss of bulk. This loss depends upon the initial C/N ratio of the residues; the higher the ratio, the greater the loss of bulk and the greater the concentration of nutrients. On the other hand, the loss of bulk means less humus.

The nutrient content of well-prepared compost may be approximately 15 to 30 lbs of nitrogen/ton of compost, about 5 to 10 lbs of phosphate/ton, and about 30 lbs or more of potash/ton. Relative to calcium, magnesium is usually moderate to high, but it may be low compared to potassium. Sulfur and the trace elements should be high. A cubic yard of soil-free compost weighs about 700-1000 lbs.

Approximately half of the compost breaks down in the soil during the first year after application, and so about half of the nitrogen and sulfur should become available the first season. Much of the phosphorus in compost is in inorganic form; although a significant amount should be readily available, depending upon the pH, the actual quantity is impossible to predict.

Most of the calcium, and magnesium in the original residues is no longer in organic form and will become available immediately. Most of the potassium is never in organic form and is always available; indeed leaching losses can be significant.

⁷this may not be so, however, if the urine is treated separately from the solids, because it is the main source of the loss of ammonia.

Chapter 8

Other Organic Fertilizers

8.1 Summary

Green manures offer succulent growth which decomposes easily in the soil, releasing nutrients. Green manures also smother weeds, keep nutrients from leaching, and protect the soil over winter. Permanent cover crops conserve nutrients, support a high biological activity, and produce a superior soil structure. The fertilizer value of green manures is difficult to predict because of the lack of knowledge of their ability to scrounge for nutrients, except in rare cases or with weeds.

The nutrient content of hay and straw can be estimated from tables 6.5 and 6.6, and of weeds, from table 8.1.

Wood ashes are a source of potassium, phosphorus and trace elements in addition to a limited liming capability.

Purchasers of commercial organic products should obtain data on their total organic and nitrogen content.

Soil activators may have value in an unusual situation, but some may further deplete a barren soil.

8.2 Cover Crops

Characteristics of Cover Crops

A cover crop is any plant which improves the soil on which it grows. The actual benefits depend upon whether the plant is a perennial or an annual. Cover crops in pastures, hayfields and orchards consist of grass or mixtures of grasses and legumes. Some legumes, principally clover, are grown for hay for one or two years in rotation with grains and row crops. Hedgerows are effective cover crops, since they protect the soil from erosion. The greatest benefit of perennials to the soil they are grown on is from the activity of their roots.

Annual cover crops are grown before or after a vegetable crop or in preparation for a field crop such as hay. They are usually grown as green manures: turned into

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the soil while still green, normally just before they flower. The greatest value of annual green manures is usually in the topgrowth, but the roots are also beneficial.

Green manures are chosen for their fast, vigorous growth and high production of green, succulent topgrowth. The topgrowth decomposes quickly in the soil and produce a flush of biological activity and a quick release of nutrients, some of which the roots may have accumulated from the subsoil.

Green manures rarely increase the organic content of the soil. The more likely affect is to cause the soil organic content to drop. This is owing to the tillage associated with turning the green crop under and with seed bed preparation. Green manuring establishes a dynamic soil system, where some of the humus is replaced by succulent residues, leading to a temporarily high biological activity and rapid availability of nutrients.

Green manuring is not practiced in dry climates where water is chronically a limiting element to plant growth. Considerable soil water is lost in transpiration from the green manure plant, lowering the water table, and following crops are likely to suffer.

Even in humid areas, however, green manuring is not popular, because it requires that land be left idle for a period of time, an unpopular practice for most market gardens on expensive land. Consequently, except when legumes are used to fix nitrogen, green manures are not usually grown as a fertilizer. Nonlegumes may be grown as smother crops to control weeds, and they are commonly used as a winter cover and catch crop, to protect the soil from erosion and to conserve nutrients otherwise lost by leaching.

Traditional choices for green manures are buckwheat, small grains such as rye and oats, and annual grasses such as sudan grass and annual ryegrass. Other varieties are possible, however; rape, for example, has been used as a green manure occasionally and is an excellent choice, so long as it is not followed by another brassica (which could encourage clubroot disease).

Legumes are also possible; Austrian winter peas are commonly planted in the fall for overwinter growth where winter temperatures are not severe; but they or other field peas may be grown also in cold climates in the spring or late summer. Soybeans were once popular, and sometimes hairy vetch is grown as a winter cover crop.

Most legumes, however, with the possible exception of Austrian peas, are expensive for use as a green manure. Also, with the exception of soybeans, legumes do not have a good leaf coverage, and they are poor smother crops; in fact they encourage weeds, owing to the nitrogen sloughed off their roots. They are best grown in combination with a nonlegume.

Planting a living mulch, or undersowing (or overseeding) a cash crop with a cover crop, is a variation of green manuring. Undersowings have attractive features: they provide a ground cover during the growing season and after harvest of the cash crop, and they compete with weeds. Legumes will fix nitrogen.

The disadvantage of a living mulch is that it also competes with the cash crop for moisture, nutrients and light. To minimize competition it should be sown late enough after seeding the main crop in order to minimize competition with the main

crop but early enough to compete with weeds¹.

Permanent cover crops do not have the vigor of green manures. Nevertheless, biological activity can be high; in fact average biological activity is higher under a good grassland than any other plant system. In contrast to the dynamic transience associated with a green manure, biological activity under grass is stimulated by the attainment of a stable, undisturbed state with a good environment (near-neutral pH, good drainage).

The sod not only feeds soil organisms but also protects the soil from the direct sun and rain for the entire year. Furthermore, the slow release of nutrients from dead roots and topgrowth minimizes leaching losses. Nutrients are strongly conserved and pass back and forth among the plants and soil organisms. The combination of a high biological activity and the extensive root system of grass leads to a superior soil structure and a slow but steady increase in soil humus.

When a sod is plowed under, it has a effect similar to a green manure: a rapid breakdown occurs with a sudden release of nutrients stored over a long period of time. A cultivated crop following a sod is usually successful.

Fertilizing Value of Cover Crops

The fertilizing value of a mulch obtained from a cover crop can be estimated from tables 6.5 and 6.6. An example is in chapter 6.2.

The fertilizing value of a crop turned into the soil in which it was grown, however, is difficult to determine. One can't tell simply by measuring the nutrient content of the plant. There is no way to distinguish between nutrients scavenged from the subsoil in a normally unavailable state and those already available.

Not much is known about scavengers; statements can be found indicating that one crop or another is good at picking up a particular trace element, but such reports are difficult to verify. The best commonly accepted examples of a green manure collecting unavailable nutrients are buckwheat and sweetclover, which have reputations for accumulating phosphorus.

One way of inferring the value of deep-rooted cover crops is to look at weeds, or at least those weeds which grow on depleted soil. If the soil is infertile and the weeds deep-rooted, a reasonable conclusion is that they are getting their nutrients from the subsoil. Table 8.1 [67] shows the nutrient content of some weed varieties. The nutrients are listed in terms of lbs/ton in order to facilitate a comparison with other residues.

Woody plants have a reputation for picking up unavailable minerals. Apples, grapes and blueberries, for example, seem to grow better than one might expect with a meager supply of phosphorus.

8.3 Organic Byproducts

Table 8.2 is a summary of waste materials that have been recycled at one time or another [19], [63], [70], [71]. Depending upon their resistance to decomposition,

¹See articles in New Farm magazine for current information and practices.

Table 8.1: Nitrogen Value Of Assorted Weeds

	Nutrients, Lbs/Ton Dry Weight			
	N	P_2O_5	K_2O	Ca
Carrot, Wild (<i>Daucus carota</i>)	33	12	84	
Chickweed (<i>Stellaria media</i>)	77	34	220	28
Corn flower (<i>Centaurea cyanus</i>)	46	16	39	44
Crab grass (<i>Digitaria sanguinalis</i>)	38	18	93	
Daisy, Ox-eye (<i>Chrysanthemum leucanthemum</i>)	42	9	58	
Dandelion (<i>Taraxieum officinale</i>)	57			
Flax, Toad (<i>Linaria vulgaris</i>)	37	13	46	
Foxtail grass (<i>Setaria glauca</i>)	35	15	90	
Goldenrod (<i>Solidago juncea</i>)	25	8	32	
Lady's Thumb (<i>Polygonum persicaria</i>)	62	23	62	71
Lamb's Quarters (<i>Chenopodium album</i>)	80	27	218	52
Lettuce, Wild (<i>Lactuca canadensis</i>)	21	9	44	
Mallow (<i>Malva rotundifolia</i>)	80			
Morning Glory (<i>Convolvulus arvensis</i>)	72	19	94	27
Mustard (<i>Brassica</i> sp.)	50			
Pigweed (<i>Amaranthus retroflexus</i>)	85			
Purslane (<i>Portulaca oleracca</i>)	84			
Radish, Wild (<i>Raphanus raphanistrum</i>)	37	16	26	26
Ragweed (<i>Ambrosia artemisaefolia</i>)	27	8	36	
Sedge, Broom (<i>Andropogon scoparius</i>)	16	4	14	
Sorrel (<i>Rumex acetosella</i>)	24	4	38	
Stickweed (<i>Aster lateriflorus</i>)	38	12	32	
Thistle, Canada (<i>Carduus arvensis</i>)	54	13	82	76
Thistle, Sow (<i>Sonchus oleraccus</i>)	56	20	126	35
Yarrow (<i>Achillea millefolium</i>)	40	14	61	55
Average	49	15	75	46

they can be turned into the soil directly, composted or used as a mulch. Most are rarely found, except wood ashes, which are common enough to warrant additional remarks.

Wood Ashes

The principal nutrients in woods ashes are potash, usually 3 to 8%, phosphate, usually 1 to 2-1/2%, calcium, 20 to 25%, and magnesium, about 2%. Ashes also contain trace elements immobilized in the woody tissue. Although ashes are commonly recognized as a source of potassium and limestone, in addition phosphorus, though low, is highly available. With these elements present, plus the trace elements, ashes are a good fertilizer for legumes. The liming value of wood ashes is

Table 8.2: Nutrient Content Of Processing Wastes [41]

Table 1: Nutrient Content Of Processing Wastes [41]

	Nutrients, Lbs/Ton Dry Weight			C/N	Energy Index, Gallons/Ton
	N	P_2O_5	K_2O		
Bran					
rice	14	6	4	55	77
wheat	44	52	30	18	81
Chaff & hulls ¹	10-16	3-12	3-28	66	79
Average	12	6	16		
Corn cobs	10	1	12	80	80
Legume shells ²	16-40	3-5	10-72	30	83
Average	28	4	32		
Pomace					
apple	8	0.8	4	21	17
castor	80-130	20-40	8-30	8	93
Average	110	32	15		
Seed cake ³	92-132	32-64	24-36	7	82
Average	112	44	28		
Wood ashes	10-60	40-200			
Average	32	106			
Wood chips					
deciduous ⁴	0.2-1.0	2-3			
old pine	0.1	0.2			

¹ buckwheat, flax, barley, cotton, millet, oats, rice, rye, wheat

² field soy bean, peas, peanuts

³ rape, sesame, soybean, sunflower, linseed

⁴ ash, oak, hickory

about 2/3 lb of lime for each pound of ashes, as estimated in appendix C.

Ashes from a typical household are a practical fertilizer only for a small to moderate garden. A cord of wood may reduce to about 40 lbs of ashes²; this has an liming value equivalent to about 25 lbs of lime and has about 2 lbs of potash. Meeting a 100 lb potash demand for a one acre field with wood ashes, for example, would require ashes from 50 cords of wood.

On the other hand, the ash supply from a house which burns four cords of wood, used on a garden of 3000 sq ft, would add lime at the equivalent rate of about 3/4 ton/acre and potash at the rate of about 120 lbs/acre. Spread every year, such a quantity would meet the potassium requirement of a crop or at least

²According to W. Erhardt, University of Maine, who obtained his information from two sources. One states that the ash content may vary from 50-60 lbs/cord, and the other that a variation of 8-40 lbs/cord is likely.

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Table 8.3: Nutrient Content Of Commercial Organic Products [41]

	Nutrients, Lbs/Ton Dry Weight					Energy Index Gallons/Ton	
	N	P_2O_5	K_2O	S	C/N		
Alfalfa pellets	54 (2.7%)	10 (0.5%)	56 (2.8%)	4 (0.2%)		15	82
Blood meal	260 (13%)	40 (2%)				3	85
Bone meal	60 (3%)	400 (20%)	10 (0.5%)				
Cocoa shells	20 (1%)	20 (1%)	60 (3%)			42	83
Cottonseed meal	120 (6%)	40 (2%)	40 (2%)			7	84
Fish scraps ¹	180 (9%)	140 (7%)				4	80
Hoof & horn meal	140-300	40 (2%)					
Average	220 (11%)					3	69
Linseed meal	100 (5%)	40 (2%)	20 (1%)			8	84
Seaweed, ground	20 (1%)	4 (0.2%)	40 (2%)	60 (3%)			
Soybean meal	120 (6%)	30 (1.4%)	40 (2%)			7	82
Tankage ²	80-180	180-400					
Average	130 (6.5%)	290 (14.5%)				7	85

¹ dried & ground

² rendered, dried & ground

come close, but it might also eventually raise the pH to an excessive level. A seven cord household with a 1000 sq ft garden would be in trouble very soon.

Wood ashes should be handled with care; they are caustic and may injure anyone working with them, and they may injure soil life. Composting ashes might be preferable to spreading them directly. They should be added to a manure compost, however, only after the first stage of breakdown, to avoid unnecessary loss of nitrogen.

Coal ashes are not the same as wood ashes. They have no nutritive value and may contain toxic substances. Coal ashes can improve a heavy soil if they are first screened to select only the finer particles and then soaked to leach out toxic elements.

8.4 Commercial Organic Products

Many organic residues are available commercially as dried and ground preparations. Table 8.4 [19], [63], [70], [71] lists the more common materials. Some will be discussed in more detail in chapter 10.

Commercial compost produced by companies having access to large quantities of waste products is a good alternative for those who are not able to make their own. Unfortunately, a fair appraisal of commercial compost is difficult. Current labeling laws require specification of water-soluble nitrogen and potassium and citrate-soluble phosphorus. In practice, however, knowledge of the organic content and the total nutrient content, or at least the total nitrogen content, is more

useful. Anyone using large amounts of purchased compost should write to the manufacturer for these specifications.

In particular the total nitrogen content gives the best estimate of the available nitrogen. About half of the total nitrogen should become available during the first year of application.

Knowledge of the total phosphorus and potassium content of compost is useful, though not as valuable as nitrogen. Unlike nitrogen, phosphorus and potassium could exist in commercially available compost partly as rock powders; if so, their availability would be impossible to estimate.

Uncomposted commercial blends of organic materials and rock powders are also for sale. Like compost, their value is specified only in terms of the readily available **NPK** content. The organic and total nutrient analysis would be useful, though probably not as valuable as it would be with compost. The actual composition may vary, depending upon the manufacturer's inventory. Also nitrogen availability would be difficult to estimate. The nitrogen from most residues is quickly available, except for leather meal, which is a major ingredient of some blends.

When using any material containing leather waste, one should enquire about the presence of chromium.

8.5 Soil Activators

A completely different category of materials are the various proprietary products sold as soil activators. They are intended to boost biological activity or to use enzymes to increase the availability of soil nutrients. Nitrogen is the usual target.

Whether these activators are useful depends on the soil to which they are applied. If the soil is already fertile, activators are unnecessary. Where they may be most useful is on depleted soils. Some people feel that these products are useless and a waste of money. It seems reasonable, however, to believe that circumstances exist in which they do work, that is, they result in the release of available nitrogen.

A greater concern, however, is the damage they will do if they are successful in a poor soil. The nitrogen that they manage to extract will come from oxidizing the little quantity of organic matter that still is in the soil. They will accelerate the loss of organic matter and leave the soil worse off than before.

Activators which do not exploit the soil organic matter but help plants obtain minerals may be better - if they work. One example is humates, which appear to stimulate biological activity in the root zone. Such biological activity includes mycorrhizae, which are able to increase the availability of minerals, particularly phosphorus. Whether or not humates are effective is still in dispute. If they are, and if the increased biological activity feeds off of carbohydrates produced by the plant roots rather than the soil humus, these activators may have merit. Compost also contains humates and is preferable because it has many additional beneficial elements.

Before choosing any activators, it would be worthwhile to compare them with compost in a field experiment. A conclusion should include an analysis of costs and benefits.

Part III

Nutrients and Fertilizers

Chapter 9

Introduction to Part III

9.1 Summary

Except for this one, each chapter in this part covers one of the major nutrients or, collectively, the micronutrients (or trace elements).

Three major topics in those chapters are:

- the importance of the nutrient to the plant and what happens if the nutrient is deficient or excessive
- the behavior of the nutrient in the soil and what can be done to make the most of the soil reserves
- organic and inorganic fertilizers used to supply the nutrients.

This chapter restricts itself to two auxiliary topics: fertilizer blends and effects of the ionic nature of substances taken up by plants.

9.2 Fertilizer Blends

This book has no discussion of synthesized blends, although the relevant chapters do cover the individual ingredients. The purpose of mentioning them here is to note the convention in specifying their content.

Blends are mixtures of commercial fertilizers, such as urea, triple phosphate and potassium chloride. They are a convenience prepared to supply specified amounts of nitrogen, phosphate (P_2O_5), and potash (K_2O)¹. A 10-10-10 fertilizer contains 10% of each of these components. Potassium chloride alone carries a 0-0-60 analysis, meaning that it contains no nitrogen or phosphate but has 60% potash.

Some blends contain an additional nutrient, such as magnesium. In that case the specification will include its content with a specific identification, such as 10-10-10-5Mg.

¹K is for Kalium, which is Latin and German for potassium

Note that the identification specifies phosphorus and potassium in an oxide form. This convention arose in the early years of analysis. At that time, the procedure was to roast a sample in a standardized process. This oxidized the minerals, which were weighed and reported as such. Procedures have changed but the convention remains, perhaps in order to avoid the reaction from buyers who think they are suddenly receiving less for their purchase. The actual nitrogen-phosphorus-potassium content of a 10-10-10 fertilizer is about 10-5-8.

In order to avoid confusion, the tables in these chapters maintain this same convention: expressing phosphorus in terms of the oxidized form phosphate and potassium as potash.

Some blends such as 10-10-10 are characterized as complete fertilizers, even though they contain no other nutrients. Moreover, the only information usually available on the commercial composts and organic mixtures is their NPK content. So everyone who uses these products should understand the notation.

9.3 Cations and Anions

Nutrients absorbed by plants are in ionic form.

Ions are electrically charged chemical elements or compounds. They are the result of salts dissolved in water. Table salt is sodium chloride and dissolves in water, producing sodium ions and chloride ions. The sodium ions have a positive electrical charge, and the chloride ions a negative charge.

If two electrodes are placed in salted water and connected to a battery, the sodium ions will drift to the negative electrode, or cathode, and the chloride ions to the positive electrode, or anode. Consequently, positively-charged ions are called cations, and negatively-charged ions anions.

The common nutrient cations are nitrogen in ammonium form, calcium, magnesium, potassium, copper, iron, manganese and zinc; common anions are nitrogen in nitrate form, phosphorus, sulfur, boron and molybdenum.

Some of the properties of nutrients depend on whether they are present as cations or anions. Their net movement from the soil to the roots is such that the plant remains electrically neutral with respect to the soil. This requires an equilibrium between the net flow of cations and the net flow of anions. Consequently the total flow of cations is limited by the availability of anions, and vice versa.

The limitation on the total intake of cations limits each one: calcium, magnesium, potassium (and ammonium-nitrogen in acid soils)². Plants, however, have a preference for potassium³ built into their behavior and will absorb as much as is available; the result is often a deficiency in the other cations but more likely magnesium.

Similarly, an interaction exists between nitrogen and phosphorus (except in acid soils). If both are in excess, phosphorus may be deficient, owing to the higher mobility of nitrogen.

²We can ignore the effect on trace elements because the very small quantities required manage to slip in if the supply in the soil is adequate.

³For an explanation why plants favor potassium over other cations, see chapter 12.2

In addition, the nature of the ionic charge determines how, if at all, the soil stores plant nutrients. **Cation exchange**⁴ is the mechanism for storing the major cations (calcium, magnesium and potassium).

Anion exchange also exists, but it does not function as consistently as cation exchange, and it is not beneficial. Nitrate-nitrogen is not held by anion exchange; sulfur is held to some extent; and phosphorus is held so strongly that it is not easily available.

Fortunately, anion exchange is not necessary for the conservation of anions, because anions are a significant component of organic matter. Soil microorganisms have a much greater requirement for anions to produce cell tissue than for cations⁵. As the organisms die and are attacked in turn by other organisms, a portion of these nutrients becomes available to plants.

Nitrogen has a balancing effect, since it can exist in the soil as either a cation (ammonium) or an anion (nitrate). In acid soils, calcium and magnesium are low, and nitrogen tends to be present predominantly in the ammonium form, which can be adsorbed and stored in the **cation exchange** mechanism. As a stored ammonium cation, nitrogen competes less with phosphorus for plant uptake. This is an advantage in an acid soil, where phosphorus may be strongly bound, and plants need all the help they can get to obtain a sufficient quantity. In a mildly acid, neutral or alkaline soil, nitrogen is predominantly in the nitrate form. As an anion it does not compete with calcium and magnesium for adsorption by cation exchange. This favors many plants which have a higher requirement for calcium and magnesium than those more tolerant of acid conditions.

Cation exchange is not important for the trace elements. Trace element cations are held by chelation, discussed in chapter 16. The anion trace elements do not chelate but are bound to a small extent, perhaps by anion exchange, and they are present in the organic matter. Their storage in the soil, however, is less efficient than that of other nutrients. Molybdenum is rarely affected by the lack of a good storage mechanism, because it is required in such a small amount. But Nature seems to have forgotten boron, for the soil has no adequate mechanism for holding it; it is the most common trace element to be deficient.

⁴Cation exchange is discussed in chapters 14 and 15

⁵This tendency to absorb anions preferentially over cations may appear to violate the principle of electrical neutrality. It doesn't, because the microorganisms can release carbonate anions to compensate for absorbed mineral anions. A similar situation occurs in plants, which could release either carbonate anions or hydrogen cations to balance any difference in absorbed electrical charges. This compensation is the reason for the broad statements above inferring a relationship between the flow of cations and anions, but not an equality. The number of absorbed cations need not equal the number of absorbed anions, but the difference between them is approximately constant.

Chapter 10

Nitrogen

10.1 Summary

Nitrogen is an essential element of all proteins; it affects the growth of a plant and the quantity and quality of produce. The most obvious manifestation of an adequate supply is a luxuriance of leaf color and growth.

It is, however, the one nutrient most likely to be deficient.

Nitrogen is subject to losses in a greater variety of ways than any other nutrient: volatilization of ammonia, leaching and denitrification of nitrates.

Nitrogen fixation by soil organisms is the only significant way to maintain the soil supply in a sustainable system.

Table 10.1 compares nitrogen fertilizers; table 10.2 lists typical application rates.

10.2 Nitrogen In The Plant

Nitrogen represents Life. It is an ingredient of proteins and distinguishes them from carbohydrates. Carbohydrates are passive, storing energy or providing physical structure, but proteins control the movement of energy and materials and the growth of the plant. Sugars, starches and cellulose are carbohydrates; chlorophyll, enzymes, and hormones are proteins.

Inasmuch as proteins influence food quality as well as quantity, nitrogen has a predominant role among the soil nutrients. Nevertheless, to the casual observer the obvious effect of nitrogen is on leaf growth and color. Nitrogen fertilizer produces a luxurious growth of lush green leaves, essential for capturing the sun's energy and converting it into sugars. Nitrogen is necessary for the production of sugars and, subsequently, of sweet, ripe fruit.

If nitrogen is low, growth is stunted, and all plant functions are disturbed. Nitrogen is mobile and, when in short supply it will drift from older leaves to younger ones. Deprived of nitrogen, the older leaves will often turn light green, yellow, or in some cases pink.

A stunted plant with such discolored leaves is a good sign of a protein deficiency in the plant, and it may indicate a nitrogen deficiency in the soil, but it also may

Table 10.1: Comparison Of Nitrogen Fertilizers

	Characteristics			Value Of Fertilizer, \$/Ton ¹				Typical Cost \$/Ton ²
	Nitrogen %	Energy Index Gal/Ton	C/N Ratio	Value Of Nitrogen	Value Of Potash & Phosphate	Value Of Energy	Total Value	
Organic Fertilizers								
Fresh manure								
Cow	0.5	20	18	\$3	\$2	\$21	\$26	\$5
Horse	0.6	25	22	\$4	\$3	\$26	\$33	
Pig	0.6	18	14	\$4	\$3	\$19	\$26	
Sheep	1.0	32	16	\$6	\$5	\$33	\$44	
Poultry								
Cage layer	1.5	20	7	\$9	\$7	\$21	\$37	\$7
Broiler	1.3	64	25	\$8	\$6	\$66	\$80	
Compost	1.2	40	17	\$8	\$12	\$41	\$61	
Hay								
Legume	2.5	78	16	\$16	\$9	\$80	\$105	
Nonlegume	1.25	81	32	\$8	\$9	\$83	\$100	\$62
Seed cake, castor pomace	5.6	88	8	\$35	\$14	\$91	\$140	
Ground meal								
Blood meal	13	85	3	\$82	\$15	\$88	\$184	\$2000
Seed meals	6	83	7	\$38	\$14	\$86	\$138	
Cottonseed meal	420							
Soybean meal	300							
Alfalfa pellets	2.7	82	15	\$16	\$12	\$86	\$114	\$244
Tankage	6.5	85	7	\$41	\$71	\$88	\$199	
Fish meal, 9-3-0	9	80	4	\$57	\$15	\$82	\$154	\$640
Nitro-10	10	85	4	\$63	\$88	\$150	\$480	
Fertrell Super N, 4-2-4	4	≤ 50	≥ 6	\$25	\$23	≤ \$52	≤ \$100	\$360
Inorganic Fertilizers								
Urea (organic, synthetic)	43			\$13.50			\$13.50	\$13.50
Sodium nitrate								
16-0-0	16			\$5.02			\$5.02	
15-0-14	15			\$4.71	\$2.34		\$7.05	
Ammonium nitrate	33			\$10.36			\$10.36	
Ammonium sulfate	20			\$6.28			\$6.28	

¹ Nitrogen is valued at \$0.31/lb, phosphate at \$0.25/lb, potash at \$0.17/lb and energy at \$1.03/gal for #2 fuel oil

² Costs are based on the following prices: hay, \$1.25/40 lb bale; blood meal, \$25/25 lb bag; cottonseed meal, \$10.50/50 lb bag; soybean meal, \$14.80/100 lb bag; fish meal, \$16/50 lb bag; Nitro-10, \$12/50 lb bag; Fertrell Super N, \$9/50 lb bag; urea, \$10.80/80 lb bag; 0-46-0, \$9/80 lb bag; 0-0-60, \$8/80 lb bag; alfalfa pellets, \$6.10/50 lb bag

Table 10.2: Application Of Nitrogen Fertilizers

	To add 10 lbs nitrogen/acre				To add 30 lbs nitrogen/acre			
	Qty (Lbs) Needed For 1 acre	Qty (Lb/A) added 1000 sq ft	P_2O_5	K_2O	Qty (Lbs) needed for 1 acre	Qty (Lb/A) added 1000 sq ft	P_2O_5	K_2O
Organic								
Fresh manure								
cow, horse, pig	2000	50	4	9	6000	130	10	30
sheep	1000	20	4	10	3000	70	10	30
Poultry	800	30	8	5	2000	50	20	10
Compost	800	20	3	30	2500 Lb	60	10	80
Hay								
Legume	400	9	2.5	7	1200	30	7	20
Nonlegume	800	18	5	15	2400	60	14	50
Seed cake								
castor pomace	180	4	3	2	540	12	10	6
Ground meal								
Blood meal	80	2	5		230	5	15	
Seed meals	170	4	3	3	500	11	9	8
Tankage	150	3.5	22		460	11	7	
Fish meal,	9-3-0	110	2.5	3		330	8	10
Nitro-10	100	2.5			300	7		
Fertrell Super N, 4-2-4	250	6	4	10	750	17	12	30
Inorganic								
Urea (synthetic)	23	0.5			70	1.6		
Sodium nitrate								
16-0-0	62	1.4			190	4		
15-0-14	67	1.5		9	200	5	28	
Ammonium nitrate	30	0.7			91	2		
Ammonium sulfate	50	1.2			150	3		

mean that the soil is too cold or too wet or too dry, or that the plant is under attack by an insect or disease.

All soil life requires nitrogen in substantial amounts, and because supplies are usually limited, competition is vigorous. Perhaps for this reason, plants evolved to render the metabolism of nitrogen first in priority among all other processes.

This priority may mean survival under natural conditions, but it can be disastrous if the nitrogen supply is unusually high. In the presence of excess nitrogen, a plant's response is to divert energy, carbohydrates, water and minerals in order to metabolize it.

Consequently everything is thrown out of balance:

- sugars and starches are unavailable
- the plant is overly succulent

- tubers accumulate water and rot
- plants are weak and fall over
- flowering and fruiting is delayed
- fruits ripen unevenly
- trace elements, such as boron and copper are deficient.

If sunlight is insufficient to provide enough energy for nitrogen metabolism, the plant accumulates nitrates and free amino acids, the latter of which may attract insects.

Stimulation of plants in a winter greenhouse, by heating the soil and fertilizing, is especially hazardous in combination with the low light conditions, because of the possible accumulation of nitrates. Vegetables harvested from a greenhouse in the afternoon of a sunny day contain fewer nitrates than those picked after a cloudy day [10].

10.3 Nitrogen In The Soil

Nitrogen Fixation

Unlike other soil nutrients, nitrogen does not originate from the soil but from the air. Some nitrogen accumulates when rainfall absorbs nitrates in the atmosphere. Some nitrogen is fixed by soil organisms associated with legumes, such as clover, alfalfa, peas, beans and a few trees (locust and acacia, for example). Some is fixed by organisms associated with non-legumes such as alder, various olive bushes (Autumn olive, Russian olive), bayberry and New Jersey tea. And some is fixed by free-living organisms (such as blue-green algae) not associated with plants.

So far as is known, the primary source of nitrogen is associated with legumes, with production in the range of 50-200 lbs per acre per year. The amount contributed by rainfall and fixation by free-living organisms rarely exceeds about 10 lbs per acre per year; an outstanding exception is the blue-green algae which inhabit flooded fields and can supply all the nitrogen needed for growing rice.

Fixation by organisms allied with non-legumes is unknown but is likely to be less than the amount associated with legumes. Such plants are pioneers, surviving in acidic soils with low nutrient availability.

Not much is known about optimizing the nitrogen-fixing capability of trees and nonlegumes. Indigenous species seem to do well by themselves. Annual and perennial legumes, however, are more demanding, and an awareness of the following points should help in assuring successful results:

1. Nitrogen fixation by legumes takes place as a result of the attachment of specific bacteria (rhizobia) to the plant roots. The bacteria penetrate the roots and form small nodules on the root surface. The carbohydrates extracted from the roots by the bacteria supply enough energy for the bacteria to utilize their ability to convert nitrogen from the atmosphere into nitrates.

2. The soil that supports a legume should have a sufficient quantity of all minerals other than nitrogen. In particular, rhizobia require phosphorus, iron, molybdenum and cobalt.

Secondly, the rhizobia obtain their carbohydrates from the plant, so the plant must be healthy and vigorous, well supplied with minerals, in order to provide the bacteria with a supply of carbohydrates in addition to its own needs.

In most cases a pH above 6 is necessary for the maximum availability of minerals and therefore for growing agricultural legumes. An exception is lupines, most varieties of which are best adapted to acid conditions. Also, in sandy soils of the Atlantic coast and southeast, where organic matter is low, the pH should not be much above 6.0, otherwise trace elements may be deficient.

3. Legume seed should be treated with an appropriate bacterial inoculant (unless the same legume has been grown successfully in the soil within the past few years), in order to assure rapid nodule formation and fixation capability. An inoculant is not absolutely necessary; the plant will attract the necessary bacteria spontaneously, but the delay in doing so may be unacceptable, and the particular rhizobia present may be an inferior variety.

Inoculant sold for alfalfa and clover is also suitable for sweetclover; garden inoculant is satisfactory for field peas and vetch; but soybeans, lupines and cowpeas require specific inoculants.

There is a benefit to inoculating clayey soils after planting, rather than inoculating the seed, because it results in a better distribution of the nodules along the root system [6].

4. Nitrogen is only fixed as the plant requires it. If the plant receives enough nitrogen, its production of carbohydrates is diverted to manufacturing proteins, and the supply to the root nodules is cut off. If nitrogen is low, carbohydrate production increases, and more becomes available to the root nodules. This feedback mechanism gives legumes an extra competitive edge, because the production of carbohydrates requires energy, which is better utilized for other purposes if the plant has no need for additional nitrogen.

So alfalfa does not respond to applications of nitrogen; it simply fixes less. Clover often does respond to manure, but any response is due to minerals in the manure, particularly potassium. Also, early spring peas may respond to nitrogen if the soil is too cold for nitrogen-fixation to be effective.

5. Legumes can contribute nitrogen to the soil before the plant is tilled under, because various portions of the roots die during the year and are sloughed off along with their nodules. The nodules decay rapidly and release nitrogen. Legume roots may die when stressed, for example by a local exhaustion of nutrients or a drought. Grasses growing with the legumes will utilize nitrogen released from these decaying roots and nodules.

Consequently, one of the best ways to maximize nitrogen fixation is to grow a non-legume as a companion crop. The non-legume sops up excess nitrogen in the soil and forces the legume to continue fixing nitrogen.

As an anecdotal example, I once saw a butternut tree planted alongside a nitrogen-fixing autumn olive shrub, which towered over neighboring butternuts planted at the same time.

During a drought, nitrogen fixation ceases, but soon after, new roots develop fresh nodules, and fixation resumes.

6. Annual legumes (such as peas, beans and soybeans), which are harvested for the pods, will not contribute nitrogen to the soil. This is because all of the fixed nitrogen is in the seed. They grow well in soil poor in nitrogen but leave little if any behind. In fact, some beans are very inefficient and require fertilizer nitrogen for optimum yield. Possibly some nitrogen is added to the soil from sloughed nodules, but most annuals make a great demand on soil nitrogen; so any net improvement owing to sloughing off of dead roots is small. To improve the nitrogen status of the soil with annual legumes, it is necessary to either:

- turn them under as a green manure before they are in full bloom;
- cut them before full bloom and let them regrow; or
- use the harvest for feed and recycle the manure.

Perennial forages, such as alfalfa, clover and trefoil, do not divert all of the nitrogen to the seed but retain a considerable amount for continued growth. Even if cut for hay, perennial legumes will add nitrogen to the soil, through the sloughing off of dead roots and nodules. Perennials, however, are slow to start fixing nitrogen and should be left to grow for at least a year before turning under.

In summary, the best way to maximize the fixation of nitrogen is to minimize available soil nitrogen, grow vigorous, healthy legumes, and keep the legumes in the vegetative stage. Where feasible, harvested seed from annuals should be used as animal feed and the manure recycled.

Immobilization Of Nitrogen

The fact that carbonaceous residues added to soil will cause the immobilization of nitrogen during decay was discussed earlier in chapter 2, but four conclusions are worth noting here:

1. if the residues are succulent or easily decomposed, nitrogen immobilization is only temporary
2. adding nitrogen will not help speed up decay, because soil organisms can usually find the nitrogen they need locally. Adding organic nitrogen, however, should lead to a higher accumulation of humus (because more carbon is used for growth)
3. nitrogen losses from denitrification are inevitable.
4. Nitrogen fertilizer should be added before planting a crop rather than while turning residues into the soil.

Nitrogen Losses

Usually, the more one tries to force nitrogen into the soil, the greater are the chances of losses. If the soil is overfertilized, it may find a way to get rid of the nitrogen almost as fast as the farmer puts it on. If the nitrogen is spread in ammonium form, the soil may either cause it to be volatilized or to be rapidly nitrified (converted to nitrate form) and soon afterward lost as a gas by denitrification. If the nitrogen is initially in nitrate form, it may be denitrified or leach into the groundwater.

Loss of Ammonia

Volatilization of ammonia has already been discussed in relation to manure handling (chapter 6.2). It can occur in the soil after heavy applications of manure and when urea or ammonia fertilizer is used if the soil pH is high. Recent research, however, has shown that losses can be reduced by adding calcium or potassium salts to the soil¹.

Nitrate Leaching

Leaching of nitrogen occurs in climates with moderate to high rainfall. Whenever excess water percolates through the soil, it carries with it any dissolved nitrogen. The principal nitrogenous constituents of soil water are nitrate salts and soluble organic substances. Ammonium salts rarely leach, because the soil has mechanisms for absorbing excesses².

The leaching of dissolved organic materials carries away not only nitrogen but also sulfur and trace elements. To minimize leaching, the soil pH should be maintained near neutral. This maximizes biological activity, which aids in the stabilization of soluble organic substances. Also the calcium in the lime is a good binding agent and reduces the instability and solubility of organic residues.

On the other hand, some instability of organic matter is desirable, because unstable organic substances are easily attacked and will release nitrogen, phosphorus and sulfur, which then become available to plants. Unstable organic matter is also responsible for the soil's ability to keep trace elements in an available form. So the pH should not be too high; ideally it should be near neutral, and organic residues should be continually added to the soil.

Denitrification

The concept of denitrification is new to many people, but it can account for substantial losses of available nitrogen. Denitrification is likely to occur in the presence

¹For further information, see a series of articles, the latest of which is [38].

²One of the mechanisms is **cation exchange** (see chapter 14 for a discussion), which keeps ammonium from leaching but maintains it in an available state. Another is the trapping of ammonium ions by crystal minerals in the soil. Such trapped ammonium is tightly bound and generally unavailable, but some is released at a slow rate. Potassium can be trapped similarly, as discussed in chapter 12.

of nitrates and organic matter whenever free oxygen is low³. In the absence of air, many soil organisms can extract oxygen from nitrates, using organic matter for **carbohydrates**; the nitrates are converted to gaseous nitrogen or nitrous oxide. Even the best-drained soil may have anaerobic pockets at some time.

Denitrification is half of a nitrogen buffering action in the soil, the other half being nitrogen fixation by free-living organisms. Both function best in an anaerobic atmosphere and require organic matter for carbohydrates. However, if nitrates are low, nitrogen will be fixed, but if high, it will be denitrified.

Too much organic matter can encourage denitrification, because an excess produces enough biological activity to use up all of the available oxygen. The critical amount of organic matter depends upon the coarseness of the organic residues and the texture of the soil as they affect oxygen supply; an open sandy soil can handle a greater amount of compact residues than a clay soil.

Denitrification is a hazard not only in the soil but also in the hot composting process, where biological activity can be very high indeed, especially during the initial stage. Perhaps because of the diversity of organisms that can denitrify nitrates, denitrification continues even at the high range of temperatures reached by a pile.

To some extent, denitrification is influenced by the nature as well as the quantity of the organic matter. Stabilized humus is more resistant to attack than fresh residues, and it has less energy to offer. Denitrification is more likely under acid than under neutral conditions, perhaps because organic matter is not as well stabilized in an acid soil.

Therefore, to minimize the likelihood of denitrification, the soil structure should assure good aeration, and the pH should be near neutral. Organic matter is important in maintaining good structure, but unstabilized organic residues should be added slowly enough so that the soil has the opportunity to stabilize them and to maintain sufficient aeration. Organic residues should not be tilled under too deeply, otherwise they will exhaust the limited oxygen supply; usually it is best to keep residues within the top 2-3 inches of the soil.

Most important in minimizing denitrification is the necessity of keeping the nitrate level down. If soluble fertilizers are applied, they are best spread frequently in small amounts. One should never mix soluble fertilizer with fresh carbonaceous residues; the biological activity stimulated by the residues will exhaust the oxygen supply, and most if not all the fertilizer will be lost.

(At this point I am unable to resolve a conflict between these remarks and experience regarding the spreading of manure. On the one hand, the need to minimize denitrification loss leads to the following conclusion: Since fresh manure containing the urine has a high content of unstable nitrogen, light applications are more conservative of nitrogen than heavy applications. Farmers with a limited supply of manure, however, have found that manure is better utilized as measured by average crop yield, by concentrating the manure in a restricted area.

³Recent evidence, however, is that denitrification can sometimes occur even in the presence of free oxygen

Resolution of this conflict is possible: perhaps the miscellaneous value of the manure more than compensates for nitrogen loss. Or perhaps the manure has already lost much of its volatile nitrogen before spreading, and further loss is minimal. But I don't know and leave the question to the reader.)

Summary of Losses

In determining fertilizer use, some account has to be taken of these possible losses. There is no simple rule, because nitrogen losses depend upon the particular situation. Heavy applications of soluble or otherwise unstable forms of nitrogen could result in high losses. Poorly aerated soils will probably produce greater losses than well-aerated soils. Leaching losses are more likely with soils having a coarse texture, a low organic content, low biological activity or a lack of growing crops.

Other things being equal, losses probably depend upon the **C/N ratio** of the fertilizer. Where the C/N ratio is low, nitrogen is readily released with less chance of being used profitably; but where it is high, nitrogen is released more slowly and excesses are unlikely. According to table 10.1, nitrogen losses from blood meal should be greater than losses from animal manure or from alfalfa pellets, while soybean or cottonseed meal should result in intermediate losses. Nitrogen losses from fresh hay should be less than losses from manure.

10.4 Nitrogen Fertilizers

Comparisons

Table 10.1 is a comparison of various nitrogen fertilizers. The first three columns list the nitrogen content, the **energy index** and the **C/N ratio**. The next four columns show the value in dollars of individual components and the total value. The last column indicates typical prices for some fertilizers⁴.

All of the organic fertilizers except the last three were discussed in chapter 8.3. Of these three, Nitro-10 and Fertrell Super N are typical commercial organic fertilizers. Nitro-10 is made from untanned animal hides, and Fertrell Super N is a blend of organic and inorganic materials, the exact composition of which depends upon the materials available to the manufacturer. Fertrell specifications, however, indicate that the organic content may be up to 50%. Urea is a synthetic fertilizer. It is chemically the same as the urea in animal urine, and the nitrogen has the same high availability and low stability.

Table 10.1 includes four inorganic fertilizers. Sodium nitrate mined from Chile is a natural product and is available in two forms, one with potassium nitrate and one without. Both also contain significant amounts of boron (0.2 - 0.4 lbs/ton) and iodine. The latter is probably not important for plants but is essential for

⁴Prices are those found in Maine in 1984. They represent the lowest prices from the following sources: the Agway distribution depot in Pittsfield, Maine; Organic Growers Supply (associated with the Maine Organic Farmers and Gardeners Association); and the mail order price list from the Necessary Trading Company, New Castle, Virginia.

human and animal nutrition. Ammonium nitrate and ammonium sulfate are typical synthetic fertilizers.

With the energy content of organic fertilizers included in the determination of their value, table 10.1 shows that animal manure is the best buy wherever it can be obtained locally, since its cost is usually less than its value. To the purchase price must be added the cost of hauling and spreading it. In 1979 the cost of spreading manure in Maine was about \$1.50 per ton, and even at several times that, it is a good investment.

Hay is reasonably priced anywhere that it is grown, especially if it can be bought as mulch hay at a lower cost. Nonleguminous hay, however, is not a good source of immediately available nitrogen, because the C/N ratio is too high, so its greatest value is as a mulch or in compost, where the nitrogen has a more long-term benefit. If alfalfa or clover or any leguminous hay can be obtained at a good price and turned under, much of its nitrogen will be available quickly.

Commercial organic nitrogen fertilizers (excluding urea) are not fairly priced, especially blood meal selling at more than ten times its value. The two most equitable commercial organic products in Maine appear to be soybean meal and alfalfa pellets, both available at feed stores in 50- or 100-lb bags. In Maine, the price of either is about twice the value. It would be worth the time required to compare costs of different organic fertilizers before purchasing sizeable quantities.

Other Considerations

With commercial organic fertilizers selling at an unjustifiable premium, why should anyone choose them over synthetic or inorganic fertilizers? There is probably no justification for choosing blood meal except for small gardens; it is expensive, and its nitrogen is available much too quickly to be used efficiently. In its action it is closer to soluble fertilizers than to organic residues.

On the other hand, alfalfa pellets have a good C/N ratio and are well balanced, with numerous other nutrients. They are easy on the soil and are the best buy among organic fertilizers. One might choose them for the same reason that a person will take out a whole life insurance policy or join a Christmas club. These return less on an investment than alternatives which may be equally safe, but the forced savings reduces the possibility that surplus funds will be squandered. Similarly, the use of commercial organic fertilizers insures that some organic residues will be added, but at a premium. For a garden or if the fertilizer is used only as a supplementary dressing, the premium may be small.

An added value of a product like alfalfa pellets is its trace elements.

The seed meals (cottonseed and soybean) fall somewhere between the extremes of blood meal and alfalfa pellets.

Naturally occurring Chilean nitrate bridges the gap between organic residues and synthetic fertilizers. It has no organic value, and the nitrogen is soluble and subject to leaching losses and denitrification. Chilean nitrate does, however, contain trace elements, and it has a liming value equivalent to about 1/2 pound of lime for each pound of Chilean nitrate, according to the approximate calculation in appendix C; it is a suitable fertilizer for acid soils.

Chilean nitrate is a good choice when making a transition to the use of organic residues and cover crops, and it is probably the best choice for market gardeners who cannot obtain enough organic residues or afford the cost of commercial organic fertilizers. Owing to its sodium content, however, Chilean nitrate is not good on alkaline soils.

This brings us to fertilizers containing ammonia or ammonium (and include urea). Like urea, liquid ammonia is subject to volatilization in alkaline soils, but it is also caustic and destructive of soil life. Ammonium salts are not caustic, but they tend to acidify the soil⁵.

The application of these fertilizers has to be timed carefully and placed properly to avoid burning leaves and roots. Moreover they require that the soil be treated with nitrate inhibitors; these retard biological activity in order to minimize the loss of nitrogen by denitrification.

In addition, ammonium salts tend to inhibit the release of non-exchangeable potassium, which is an important source of nutrients in some soils⁶.

Finally, they are also the most concentrated of nitrogen fertilizers and impossible to spread in small quantities. They exist with no regard for adverse effects on the soil or nutrient imbalances. Probably nowhere is the conflict between the mass production of food and the maintenance of soil life and activity - and, most likely, the quality of the harvest - more obvious than in the use of these fertilizers.

Determining Fertilizer Application Rates

In any soil of reasonable fertility, the only value of a nitrogen fertilizer is to supplement whatever amount that biological activity releases from the organic matter in its need for energy. In most cases the annual release falls within a range of 1 - 4% of the total nitrogen, depending on the climate and the degree to which the organic matter is subject to attack. Furthermore the success of a crop depends not only on how much nitrogen is released but when it is available.

Soil tests at best can only predict an average result of these variables. The simplest test evaluates soluble nitrates, but this depends on when the soil is tested. A test for organic matter is a valuable supplement, but that states nothing about its composition.

Most likely the best procedure is to start with an estimate and keep records. They should include information on the plant varieties, fertilizer rates and timing, the weather, and the results. They should be taken every year to see the effects of weather conditions.

There are several possibilities for an estimate:

- a soil test
- advice from a neighbor
- tables of fertilizer use in this book or elsewhere

⁵For example, see appendix C.3 for a calculation of the acidifying tendency of ammonium sulfate

⁶Chapter 12.3

- a conservative guess, perhaps somewhere in the range of 20-50 lbs of available nitrogen/acre (1/2 to 1-1/4 lbs/1000 sq ft).

The best time to apply is at the beginning of the season, when biological activity is sluggish.

Fertilizer Rates and Nitrogen Availability

Table 10.1 lists the amount of fertilizer required to add either 10 lbs or 30 lbs of nitrogen per acre. Twenty lbs are often added as a side dressing, and any amount from 10 to 100 lbs has been used as a starter fertilizer. In addition, table 10.1 shows the amount of phosphorus and potassium which are also added when organic fertilizers are spread.

Nitrogen from soluble fertilizers is available immediately. Most commercial organic products are about 85% as effective as soluble fertilizers during the year of application, probably because their C/N ratio is so low; the nitrogen is not released as quickly as it is from soluble fertilizers, but it is quick enough to be effective in the first year. Leather meal is an exception, however, with a nitrogen availability of about 15 - 20% in the first year of application.

Nitrogen release from the above-ground portions of leguminous cover crops is also rapid. Release from the decaying roots is difficult to predict, but probably about half becomes available during the first year. Release from the tops or roots of green nonleguminous crops may be slow during the first few weeks after incorporation, but it should pick up afterward.

Nitrogen is released from animal manure at varying rates during the first year, from about 50% for cow manure to about 90% for poultry manure. About half the nitrogen from compost is released the first year.

Nitrogen release from all organic substances, however, depends upon biological activity; if the environment is unfavorable, the nitrogen will remain unavailable. Adequate moisture, aeration and a warm soil are necessary. A cold spring or a dry summer will inhibit availability, and wet conditions may promote denitrification. Consequently one always has to be aware of the weather when planning for supplemental topdressings.

Chapter 11

Phosphorus

11.1 Summary

The primary function of phosphorus is the transfer of energy from plant leaves to its storage in sugars and starches. Its observable effect is to enhance root development, seed size and flower development.

Once in the soil, it is so active that it is almost completely immobile. A plant needs a good root structure to find it; on the other hand phosphorus is not subject to leaching losses,

Both the pH and biological activity affect the availability of phosphorus to plants.

The value of fertilizer depends on how it is spread and the availability of water. Table 11.1 is a comparison of fertilizers.

11.2 Phosphorus In The Plant

Phosphorus is the Power Broker. It controls and distributes the energy trapped by photosynthesis preparatory to storing that energy in sugars and starches.

It is also an essential element in every metabolic process. It is a constituent of DNA and RNA and necessary in protein synthesis. Root nodules associated with the fixation of nitrogen require an ample supply of phosphorus.

But the role phosphorus plays in energy transfer is its most important activity and the one which is most affected by a deficiency.

Seeds contain a large amount of phosphorus. A phosphorus deficiency reduces the number and size of seeds. Larger seeds can germinate from deeper into the soil, and the sprouting plants have more resistance to drought.

Phosphorus is a stimulus to root development. Roots branch out and root hairs form profusely in the vicinity of a source of phosphorus. Owing to its effect on roots, phosphorus is a major factor in determining the early growth of a plant and its vigor throughout the season.

Nitrogen and phosphorus have complementary tendencies. Nitrogen enables the plant to trap energy from sunlight, and phosphorus facilitates the actual use

Table 11.1: Comparison Of Phosphorus Fertilizers

	Characteristics		Value Of Fertilizer, \$/Ton				Typical Cost ¹ \$/Ton	For 30 Lbs P_2O_5 /Acre		
	P_2O_5 %	Energy Index Gal/Ton	P_2O_5 \$	Plus N \$	Energy \$	Total \$		Quantities Needed		N Added
							Tons/Acre	Lbs/1000 Sq Ft	Lb/Acre	
Organic										
Poultrymanure										
Cage layer	1	20	5	11	21	37	7	2	70	50
Broiler	0.7	64	4	10	66	80		2	90	50
Compost	0.4	40	2	18	41	61		4	80	100
Bone meal										
3-30-0	30		147	19		166	758	100	2	2
Tankage	14.5	85	71	41	99	199		210	5	14
Fertrell Gold SS										
2-4-2	4	≤ 50	20	19	≤ 52	≤ 91		750	17	15
Inorganic										
Hard rock phosphate	30		147			147	147	100	2	
Colloidal phosphate	18		88			88	150	170	4	
Superphosphate										
0-20-0	20		98			980	150	3		
Triple phosphate										
0-46-0	46		226			226	226	65	1.5	
Monoammonium										
phosphate 10-53-0	53		260	62		322		57	1.3	6
Diammonium										
phosphate 18-46-0	46		226	114		340		65	1.5	12

¹ Costs are based on the following prices: bone meal, \$18.95/50 lb bag; rock phosphate, \$175/ton; colloidal phosphate, \$150/ton; Fertrell 2-4-2, \$9.50/50 lb bag; triple phosphate, \$9/80 lb bag

of the energy. Nitrogen is a necessary component of proteins, but phosphorus manages the synthesis of proteins.

In field crops, nitrogen encourages grasses, while phosphorus encourages legumes.

However, nitrogen in the nitrate form (slightly acid to alkaline soils) competes with phosphorus for takeup by the plant roots. But it is much more mobile, and phosphorus can be overwhelmed by an excess of nitrogen even if it is adequate otherwise.

A deficiency of phosphorus also, like nitrogen, produces stunted growth. On some plants the underside of leaves may be purplish, owing to the accumulation of underutilized sugars. A phosphorus deficiency delays the growth of new shoots and the development of flowers.

11.3 Phosphorus In The Soil

Limitations On Phosphorus Mobility

Owing to its high reactivity with almost anything which it contacts, phosphorus has a lower mobility than any other nutrient. It can be bound up by soil organisms, by mineral elements (particularly aluminum, calcium and iron), and by clay minerals containing aluminum or iron. Consequently phosphorus does not remain in a free state for long, and any amount taken up by plants usually comes from an area within a fraction of an inch around the roots.

One of the few agricultural benefits of a temporarily anaerobic condition is that it causes iron phosphate to change from ferric phosphate to ferrous phosphate, which is more soluble.

Otherwise phosphorus is only slowly available to plants. Furthermore, in cool weather, particularly in the spring, biological activity is low, and phosphorus availability may be low even if a soil test indicates an adequate amount.

An advantage of this immobility is that it limits leaching losses to such low levels as to be measurable only over periods of 50-100 years¹. Water pollution from phosphates is caused not by leaching of phosphorus through the soil but by runoff of phosphorus-containing fertilizers from the surface.

Factors Affecting Phosphorus Mobility

Soil pH

The pH affects the limitation on phosphorus availability in several ways:

- a low pH reduces biological activity and diversity, which limits the effectiveness of soil organisms in promoting the release of phosphorus
- in weathered soils - particularly in humid areas of the east, south and north-west - a low pH increases available aluminum, which ties up phosphorus.
- a high pH limits mobility by precipitation with calcium

The net effect is to create a window - in most cases in the pH range from 6.5 to 6.8 - where these tendencies to immobilize phosphorus drop off.

On most acid soils the pH can be adjusted with lime, but on alkaline soils pH control is not easy. Where it is high because of arid conditions, constant irrigation to leach the salts may help, although excess irrigation washes away some of the important nutrient salts in the process. Gypsum may help by dissolving insoluble sodium carbonates. Where the soil is on top of a limestone bed, or in dry conditions, peat moss and finely ground mined sulfur are common natural materials for increasing acidity; but they may be expensive. Aluminum sulfate and sulfuric acid are synthetic alternatives.

¹Under extreme conditions, leaching of phosphorus can be significant, for example in very coarse soils with little organic matter or clay, or in peat soils with little aluminum or clay. Some loss also occurs from the leaching of soluble organic substances containing phosphorus.

Fortunately, biological activity reduces the damage from alkaline soils. The production of organic acids as a metabolic byproduct creates a separate environment with a reduced pH around plant roots, where activity is strongest.

Phosphorus And Water

The major mechanism for plant roots to absorb phosphorus - as well as other anion nutrients (nitrogen, sulfur, boron, molybdenum, and silicon) - is by solution in soil water. Although the solubility of phosphorus in water is low, it is adequate for plant growth if water flow is steady throughout the growing season.

The reverse is also true. Phosphorus is important in good root development, and good root development is necessary to enable the plant to find water. Consequently, an adequate supply of phosphorus is essential at the beginning of the season.

Moreover, the placement of phosphorus fertilizers affects its availability. Phosphorus fertilizer topdressed or banded results in high growth within a small volume of the soil. In dry weather, the lack of well-spaced roots limits the plant's ability to take up water. Dry weather will also cause root development downward in search of moisture, away from the fertilized zone. More care than usual is necessary in order to assure a satisfactory supply of water.

Consequently, if an irrigation system is in place to assure a sufficient supply of water throughout the season, topdressing or banding is probably the most efficient way to utilize fertilizer. Otherwise a better procedure is to broadcast the fertilizer and thoroughly till it under.

Saturation of the Phosphorus Reservoir

One way to overcome the tendency of the soil to absorb phosphorus is to load it down with fertilizer to such an extent that all the mechanisms which can tie up phosphorus are overpowered. This is one rationale for banding phosphorus fertilizer.

The strategy often works, but it can be dangerous. Phosphorus may be present at such excessive levels as to have a harmful effect on crop growth. The major hazard of a phosphorus overload is the reduction of trace element availability, particularly of iron, manganese and zinc. Phosphorus must be unusually high to be so detrimental, but occasionally it is.

The role of organic matter And biological activity

Organic matter and the activity of soil organisms have a strong influence on the availability of phosphorus. Any which is released by decaying residues is readily available.

Phosphorus picked up by fungi is distributed throughout the innumerable extensions of their microscopic threads (mycelia). Upon death of the fungi, the released phosphorus is apportioned more evenly throughout the soil. A consequence is that phosphorus broadcast onto a pasture is soon well distributed. This reduces the need for irrigation, stated earlier, in soils topdressed with phosphorus fertilizer.

Organic matter can break up the aluminum-phosphate bond in an acid soil, because aluminum has a stronger affinity for organic matter than it does for phosphorus.

Soil organisms cause the production of organic acids as waste products of their metabolism. These acids are effective in dissolving inorganic phosphorus. The particularly high activity surrounding plant roots produces a high concentration of acids, which is especially favorable to phosphorus availability.

Some fungi invade the roots of plants for the purpose of extracting carbohydrates. The value of these fungi - mycorrhizae - is that they accumulate minerals, including phosphorus, which they pass on to the roots. Fungi assisting the plant in obtaining phosphorus is analogous to nodule-forming bacteria which provide nitrogen to legumes.

As is true with nitrogen fixation, however, this exchange and cooperation between plant and microorganism is an agent of last resort. If the plant can obtain phosphorus (or other minerals) by an easier route with less expenditure of carbohydrates, it will do so in order to divert its energy elsewhere. Mycorrhizae are useful only when available phosphorus is low. They are probably responsible for the success of trees in soils poor in phosphorus and may be most useful to perennials.

Organic matter and biological activity are often the predominant sources of phosphorus, especially in alkaline soils. Plowed sods produce a good crop the first year because of the phosphorus released by the decaying residues.

Root activity

By a straightforward but technical chemical process, the roots of plants facilitate the breakdown of insoluble calcium phosphates, releasing the phosphorus. This process may occur with any plant having a high calcium requirement. It has been demonstrated with squash and undoubtedly is a factor in the ability of many calcium-loving legumes to make direct use of rock phosphate.

11.4 Phosphorus Fertilizers

Fertilizers

Table 11.1 lists only those organic materials which offer a generous supply of phosphorus. Others, such as cow manure, hay and seed meals are good for maintaining phosphorus, and possibly they might supply enough to growing plants even though soil phosphorus is low. But their value is questionable for building up soil phosphorus where the phosphorus/nitrogen balance is low.

Of the inorganic materials listed, two natural products are hard rock and colloidal rock phosphate - also called soft rock phosphate. The alternative name for hard rock phosphate from Florida is pebble phosphate. The usual use for these is in the production of commercial phosphorus fertilizers, four of which are listed in table 11.1.

Colloidal rock phosphate is the variety commonly available to organic agriculture. When rock phosphate from Florida is mined, a very finely-divided low-grade

ore is removed by washing it away to a settling basin. After the water has evaporated, any sediment which has a phosphate content of 20% or more is sold as an animal feed supplement; the rest is marketed as colloidal phosphate for fertilizer use.

Of the four synthetic fertilizers listed in table 11.1, superphosphate is the oldest. It was first manufactured in England in the middle of the nineteenth century by dissolving bone meal in sulfuric acid. The new product became so popular among farmers that bones soon became scarce. Englishmen scoured Europe looking for them and earned a reputation as "the Ghouls of Europe". Eventually, the industry was rescued when rock phosphate was discovered in North Africa, and production of superphosphate increased steadily up to recent years.

Today, however, superphosphate is considered inefficient because of its relatively low phosphorus content and has been superseded by triple phosphate and by mono-ammonium phosphate and di-ammonium phosphate. Owing to its sulfuric acid parentage, superphosphate is a combination of calcium phosphate and calcium sulfate, or gypsum, while triple phosphate contains no sulfate. The two ammonium phosphate fertilizers are a mixture of ammonia and phosphoric acid and are now the most popular phosphorus fertilizers in the world.

Comparisons

The ideal fertilizer appears to be poultry manure; it is cheap and loaded with nitrogen and phosphorus. However, **cage layer manure**, the strongest, is difficult to deal with nonprofessionally and should be used carefully for several reasons:

- it is messy, hard to clean up, and leaves an odor for days or weeks
- it can inhibit germination and injure seedlings because of its high ammonia and salt content
- it can pollute groundwater faster than other manures
- it is comparatively low in potassium but usually has a high lime content; heavy or constant applications can drive the pH to an excessive level.

Applications of cage layer manure on most soils should not exceed 5 tons/acre, or 250 lbs/1000 sq ft. It is not a pleasant material, but no soil which regularly receives it is acid or low in phosphorus.

Bone meal is the oldest phosphorus fertilizer. Owing to its high cost, it is popular today principally among caretakers of small gardens. Its nutrient content is usually specified by available NPK content, typically 1-11-0, rather than the total content referred to in table 11.1.

At one time, farmers manufactured their own bone meal by roasting the bones of slaughtered livestock or by soaking bones in urine or water and allowing them to ferment. Bones have also been composted by mixing them with wood ashes or quicklime and covering them with soil for several weeks.

In terms of the cost per pound of phosphorus, hard and colloidal rock phosphates is less expensive than bone meal; but the availability of the phosphorus is

much lower. Rock phosphates are the skeletal remnants of marine animals, which have a similar composition to the bones of land animals, namely a combination of calcium phosphate and lime. Over long periods of time, however, while the deposits were still under water, the carbonates in the lime were slowly replaced by fluorides, resulting in a much more stable material. Colloidal phosphate has about 2% immediately available phosphate compared to 11% for bone meal; hard rock phosphate may have 3% immediately available phosphate.

Experimental results comparing hard and colloidal rock phosphate do not seem to exist, but in any event available phosphorus is low in both products. The choice of one or the other on the basis of a miniscule availability misses the point of using rock phosphate. Rock powders are applied either because they are cheap or because of the decision to use fertilizers whose nutrients are released by the biological activity of the soil.

Colloidal rock phosphate particles are so fine that they are hazardous to lungs and should be handled with the use of a respirator.

Rock phosphate does have a high availability in acid soils. It has been used with great success in the black soils of Illinois.

Despite its high cost, bone meal is often preferred to rock phosphate, particularly on small gardens, for three reasons:

1. it is easier to obtain
2. its higher availability is significant
3. it is easier to spread.

Where immediate effect on plant take-up is essential, the limited availability of phosphorus in rock phosphate is the major impediment to its widespread use. Where the soil pH is above 6, usually optimum for other reasons, phosphorus availability in either rock phosphate or colloidal phosphate is low without the help of biological activity. Bone meal offers a higher initial availability and is more suitable in a near-neutral soil, but that portion which is not initially available is slow to dissolve. Rock and colloidal phosphate, and bone meal to a lesser extent, are useful mainly for their long-term benefits.

Rock phosphate, as well as other rock powders, are reputed to become more available when spread with animal manure. Although the evidence for this belief is weak, I have sometimes recommended the combination as a desperate measure. Some studies conclude that the mixture is effective, and others that it is not. The effectiveness may depend on the state of the manure. In theory, the organic acids of manure are said to dissolve the rock phosphate. But fresh manure tends to have a high pH, which may cancel the effectiveness of the acids. Rotted manure, however, is somewhat acid and may be more efficient.

An alternative to increasing the near-term usefulness of rock powders is to spread them before turning under a planting of green manures. The decay of the vegetation stimulates a high biological activity and the production of organic acids; this will hasten the availability of the rock powders.

Despite its limited availability, rock phosphate can be efficiently utilized by some plants. There is little universal agreement on what those plants are, but on everybody's list are buckwheat, sweetclover and mustard; other recommendations are Indian corn and rape. Most legumes are better than average at picking up rock phosphate, and most grasses and small grains are worse than average.

For a philosophical comparison of rock phosphate and the synthetic, acidulated fertilizers, see chapter 1. Where organic certification standards forbidding the use of synthetic phosphorus fertilizers are in force for philosophical reasons or marketing purposes, rock or colloidal phosphate has to be the preference. Otherwise, the synthetics are worth considering, especially if they are less costly and their use is restricted to an initial period of building up phosphorus reserves. Among the synthetics, triple phosphate or superphosphate should be the choices².

Before any inorganic phosphorus fertilizer is used, one should determine that phosphorus is indeed deficient. Organic residues contain more phosphorus than most people realize and are often sufficient for maintaining the soil supply. Most of the phosphorus in residues is inorganic, but both the organic and inorganic forms have a high availability. One exception is starting a crop in a cold Spring; this may warrant supplemental phosphorus even if the soil reserve is adequate.

Spreading Rates

The phosphorus test differs from tests for other major nutrients in that the result does not state how much phosphorus the soil contains, but only whether or not adding fertilizer is warranted. Consequently a low test result does not by itself indicate how much fertilizer is likely to be necessary.

The amount that is necessary depends upon the fixing power of the soil, that is, the power of the soil to lock up fertilizer phosphorus. The fixing power depends upon the nature of the soil and upon the soil pH. Several states have developed tests to measure this fixing power, or they have successfully correlated the phosphorus test with the fixing power. The University of Vermont, for example, bases a fertilizer recommendation on phosphorus and aluminum tests, on the assumption that aluminum is responsible for locking up phosphorus. This method works very well for acid soils in Vermont and possibly in other states in New England but not for soils with a low aluminum content.

In a state where recommendations are based upon the fixing power of the soil, and where the soil and pH are characteristic for that state, then the fertilizer recommendation may be very good. Otherwise one has to make a choice based on other, usually average considerations.

One rule of thumb, when planning to use a soluble phosphorus fertilizer, is to determine the amount of phosphorus needed for growing the crop and then increase this by about 50%. Tables 4.1 and 4.3, for example, can be used to make an estimate of the amount required.

²see chapter 10.4 for an argument against the use of ammonium phosphate or any fertilizer containing ammonia or an ammonium salt

11.4. Phosphorus Fertilizers

The rock phosphate choices are usually used for long-term benefits rather than to meet an immediate demand. A rate of approximately 1 ton/A is customary. This application is based upon the notion that such a quantity will supply crops for 4 years, which is about as long as one can plan in advance. But the amount is arbitrary, and more or less could be spread with the same results, unless, of course, that 2% immediate availability is essential.

Bone meal is intermediate between rock phosphate and the soluble synthetics, and so intermediate rates are appropriate.

Table 11.1 also shows how much of each of the fertilizers is needed to supply a given amount of phosphorus.

Chapter 12

Potassium

12.1 Summary

Potassium's unique function is as a regulator of metabolic activities. It is the only nutrient which remains in the plant fluids in a soluble state. In some plants, more is required than any other soil nutrient.

Potassium is highly mobile in the soil, but leaching is minimized by **cation exchange** and by trapping within clay crystals.

Table 12.1 compares potassium fertilizers. Constant use of plant residues and animal manure, which contain significant potassium, will assure a satisfactory supply, sometimes an excess.

12.2 Potassium In The Plant

Potassium is the Great Regulator. It is active in numerous enzyme systems which control metabolic reactions, particularly in the synthesis of proteins and starches. Micronutrients, which have similar functions, are required only in minute amounts. In contrast, potassium must be present in large quantities, although it seems to be completely unsuited for its role¹. As tables 4.1, 4.2 and 4.3 show, some plants require more potassium than any other soil nutrient, even nitrogen.

Since potassium functions as a regulator, it is not a constituent of the plant tissue, but rather of the fluids which flood the tissue. Consequently it affects the balance in water pressure inside and outside the plant cells. When potassium is deficient, water fills the plant cells and they become flabby. A potassium deficiency also causes plants to be more sensitive to drought, frost and a high salt content. Sometimes winter hardiness can be increased by adding potassium in the fall.

¹Many metals and enzymes are co-regulators, and they function by means of chelation, wherein the metal attaches itself to a specific site on the enzyme. Chelation normally requires a multivalent metal. All of the trace elements are multivalent, but potassium is monovalent, and a mechanism had to evolve in which a monovalent ion could also function as a co-regulator. The reason for such an inefficient adaptation, contrary to the usual tendency for frugality in nature, is not understood; perhaps it is simply that a lot of potassium is needed anyway to balance sodium in establishing the osmotic pressure across cell membranes.

Table 12.1: Comparison Of Potassium Fertilizers

	Characteristics		Value Of Fertilizer				Typical Cost ¹ \$/Ton	To Add 30 Lbs K_2O Quantities Needed	
	K_2O %	Energy Index Gal/Ton	K_2O \$/Ton	P_2O_5 Plus N \$/Ton	Energy \$/Ton	Total \$/Ton		Tons/Acre	Lbs/1000 Sq Ft
Organic									
Fresh manure									
Cow	0.5	20	2	4	21	26	5	6	250
Horse	0.5	25	2	5	26	33		5	230
Pig	0.4	18	1	6	19	26		7	300
Sheep	1	32	3	8	33	44		3	120
Poultry manure									
Cage layer	0.5	20	2	14	21	37	7	5	230
Broiler	0.7	64	2	12	66	80		4	170
Compost	3	40	10	10	41	61		1700	40
Hay	1.8	80	6	12	82	100	62	2800	60
Straw	1.3	80	4	7	82	93		4000	90
Cocoa shells	3	83	10	11	86	107		1700	40
Fertrell Super N 4-2-4	4	≤ 50	13	35	≤ 52	≤ 87	360	2250	30
Inorganic									
Wood ashes	5		18	7		25		1000	23
Granite dust	5		17			17	85	1000	23
Greensand	7		23			23	125	700	17
Basalt	2-10								
Sul-po-mag, K-mag 0-0-21-11 Mg	21		70	(Mg) 90		160	205	240	6
Potassium chloride 0-0-60	60		200			200	200	83	2
Potassium sulfate 0-0-50	50		168			168		100	2

¹ Basis of costs: hay, \$1.25/40 lb bale; Fertrell Super N, \$9/50 lb bag; greensand, \$170/ton; sul-po-mag, \$9/80 lb bag; 0-0-60 bag. Magnesium is valued at \$0.41/lb, based on the cost of magox at \$19/80 lb bag

The connection with both protein and starch formation puts potassium in a central role. Potassium is involved in photosynthesis and protein synthesis in leaves, cellular structure of the stalks, and starch synthesis in the roots. A potassium deficiency will lead to an excessive accumulation of simple sugars and free amino acids, photosynthesis will be retarded, and cereal plants will be weak and subject to lodging. In addition, a deficient plant is susceptible to attack by pests and disease organisms [65].

Biennials and perennials especially require a sufficient supply of potassium in order to synthesize the starches necessary to carry the plants through winter.

The complementary effects between nitrogen and potassium are analogous to those between nitrogen and phosphorus. The disturbances brought about by a potassium deficiency will also occur with a nitrogen excess. In either case the high priority in the metabolism of nitrogen uses the available supply of potassium, and not enough remains for other essential functions.

Unfortunately, the importance of potassium does not immunize the plant against the effects of an excess; a plant will absorb as much as is available. The loser is usually magnesium - but sometimes calcium in an acid soil. Magnesium is necessary for proper utilization of phosphorus, and a magnesium deficiency can produce effects similar to a phosphorus deficiency.

12.3 Potassium In The Soil

Both nitrogen and phosphorus are constituents of the soil organic matter, but potassium is not. Soil organisms have a much lower requirement for potassium than plants do. Consequently, as organic residues decompose, most of the potassium is quickly released. The behavior of potassium in the soil is determined more by physical than by chemical or biological processes.

Two mechanisms limit the leaching of potassium from the soil. One is that the potassium ion is small and may be trapped inside crevices within clay particles, where it is held by crystalline forces. This happens also to ammonium ions. Both are trapped and become unavailable, although they are released slowly if the amount in solution drops. Potassium so held is sometimes called fixed or non-exchangeable potassium.

The second soil mechanism for conserving potassium is cation exchange, which comes about because small clay and humus particles develop a negative electrical charge. The negatively charged particles attract positively charged ions, or cations, which include potassium. Cation exchange is discussed in chapter 14.4 in relating soil pH to the calcium content. It is sufficient now only to state that exchangeable potassium associated with cation exchange usually is much greater than the quantity dissolved in the soil water - the only exceptions are those soils low in both clay and organic content.

Soluble and exchangeable and non-exchangeable potassium make up the pool of available potassium. Unfortunately, commonly available soil tests do not evaluate the non-exchangeable component. Plants grown in clay soils may be receiving enough potassium even when soil tests indicate a deficiency.

Some plants, either with the help of soil bacteria or where roots create a local acid environment, are able to extract potassium directly from rock powders. According to a survey of the literature [24], tobacco, oats, rye, alfalfa, clover, sweetclover and tomatoes are good at doing so, while soybeans, cow peas, corn and buckwheat are not.

12.4 Potassium Fertilizers

Fertilizers

The potassium content of several common materials is shown in table 12.1. In summary, all animal manures and most plant residues are good potassium fertilizers. Hay and straw are representative of such plant residues, but other materials would do as well. Cocoa shells, commonly available commercially for use as a mulch, supply a significant amount of potassium.

In practice, the liberal use of organic residues of almost any kind supplies enough potassium with no need for an additional inorganic fertilizer. Indeed, with heavy applications of residues, the potential for an excess of potassium exists, especially in many soils of the eastern U.S., where magnesium is often low.

Where inorganic potassium is necessary, wood ashes are popular, and they also contain lime and a small but highly available amount of phosphorus.

Rock powders which contain significant amounts of potassium are granite dust and greensand. They are popular among organic enthusiasts because, like rock phosphate, nutrients become slowly available via the soil's biological activity. Basalt is not available commercially, but it can sometimes be obtained locally. Its potassium content is highly variable, but basalt weathers more quickly than granite dust or greensand, and its potassium is more readily available [24].

Sulfate of potash magnesia (often sold under the trade names of sul-po-mag and K-mag) is a naturally occurring crystalline material known as langbeinite. Potassium chloride is also found as a natural crystal, sylvite, although chemical means are usually used to purify it. Potassium sulfate is currently produced by a number of methods, most of which involve the use of potassium chloride.

Comparisons

With a steady program of recycling organic residues, potassium is unlikely to be deficient, except when the residues are predominantly nitrogenous with a poor balance in potassium, as in poultry manure, blood meal and cottonseed meal. Usually if the C/N ratio is high, the potassium/nitrogen ratio will also be high.

Wood ashes are a good source of potassium and are probably the only fertilizer necessary for growing clover. Three limitations are:

1. they are caustic
2. they may cause the soil pH to rise excessively

3. it is difficult to obtain enough to add significant amounts of potassium to moderate or large areas.

The usual practice with rock powders such as granite dust and greensand is to spread quantities of the order of 3-5 tons per acre, which should suffice for about 3-4 years, probably more if other sources of potassium are used.

Granite dust has an approximately neutral pH, but greensand is acidic, with pH levels of 1.0 to 3.5 possible. However, this low pH figure is misleading, and the amount of lime required to neutralize the acidity is low. The soil may be temporarily disturbed locally by the acidity of greensand, but the long-term effect should be negligible with normal applications.

Three advantages of potassium rock powders over soluble fertilizers are:

- In mimicking the natural tendency of the soil minerals to release their potassium slowly, rock powders eliminate luxury consumption by the plants if no other significant source of potassium is present;
- Potassium rock powders contain trace elements, to varying degrees;
- Potassium rock powders require less energy to produce, but this saving is partially offset by the greater amount of energy required for transportation.

Whether the above features warrant the high price of potassium rock powders is a question being considered by an increasing number of farmers and gardeners. The traditional justification for the use of potassium rock powders is their slow release of potassium. In this respect, rock powders certainly do mimic the soil minerals; but they do not mimic organic residues, the potassium of which is soluble and released rapidly.

Three options among the soluble commercial fertilizers are potassium chloride, Potassium sulfate, and sulfate of potash magnesia. The first, also known as muriate of potash, is the most common, accounting for 95% of all potassium fertilizers used in the world. Following is a brief summary of the virtues of chlorides vs. sulfates:

- Some crops have a low tolerance to chlorides, mainly tobacco, fruit trees, potatoes and some beans; and others cannot tolerate a high amount of chlorides, (strawberries, alfalfa, some beans, grapes, tomatoes, cucumbers and onions). On the other hand, chlorides have no discernible effect on many plants, such as most field crops, and they seem to be beneficial to some, for example asparagus, beets and buckwheat.
- Chlorides have little nutrient value, and the small amount that is required is easily met by the normal chloride concentrations in the soil. The sulfur in potassium sulfate, however, is an important plant nutrient.
- Potassium chloride acidifies the soil, because chlorides leach out calcium and magnesium. Potassium sulfate also has an acidifying effect, but not so strongly; this is because calcium sulfate is less soluble than calcium chloride.

- Chlorides appear to inhibit nitrifying organisms (those which convert soil ammonium to nitrates). This is desirable with the use of ammonium fertilizers, because it slows down nitrification of the ammonium and thus minimizes the chances of denitrification. If one is depending on the natural soil processes, however, then potassium sulfate is preferable.
- Potassium chloride is the least expensive of the three options, and potassium sulfate the most expensive.
- sulfate of potash magnesia also supplies magnesium and is the best balanced of the three.

Potassium Availability

The potassium in organic fertilizers is highly available, because potassium is not organically bound; when the plant dies and decomposes, potassium is released immediately. Among the inorganic fertilizers, granite dust and greensand (and basalt to a lesser extent) are the only slow-release fertilizers. The others are soluble.

Fertilizer Rates

Unless the history of the soil is known well enough to be able to predict that potassium is deficient, additions of soluble inorganic potassium fertilizer are not wise without a soil test, particularly if organic residues are recycled. The only possible exception might be if a large quantity of nitrogen is about to be spread or if the soil is already known to be high in magnesium. One of the most common examples of an imbalance is an overlimed soil, heavily fertilized, with no regard paid to magnesium. Little can be done in such a situation until the excesses are either leached or used up.

Wood ashes add lime as well as potassium, but they contain little magnesium. The major problem with wood ashes is the danger of overliming, and without a soil test, application rates should not exceed about 1-1/2 lb/100 sq ft. This would only add the equivalent of about 20 lbs of potash per acre, but a higher rate of application could result eventually in an excessive pH.

If the soil is known to be low in potassium, then a rate of 50-100 lbs of commercial potash/acre may be reasonable. If nitrogen is also to be supplied, then the amount of applied potash should be about the same as the amount of nitrogen or slightly more.

If a high potassium application is planned for soils naturally low in magnesium, fertilizer is better spread frequently at low rates.

Table 12.1 also indicates the amount of fertilizer necessary to add a given amount of potash.

Chapter 13

Sulfur

13.1 Summary

Sulfur is an essential ingredient in some amino acids. A deficiency results in a lower production of proteins and an enlarged pool of free amino acids.

The use of most organic residues or any sulfur-containing fertilizer in an amount necessary to satisfy other nutrient requirements will suffice also for sulfur.

Tables 4.1, 4.2 and 4.3 list quantities of sulfur removed by crops.

13.2 Sulfur In The Plant

Sulfur is the Junior Partner to nitrogen; it is an essential ingredient in some amino acids, but not all. However, amino acids which contain sulfur are necessary for all proteins, and a deficiency of sulfur will block the synthesis of proteins. The result will be an accumulation of free amino acids and a decrease in plant activities.

Sulfur is not as mobile in plant tissue as nitrogen. The result is that a deficiency affects a plant in a different way. Both cause leaves to turn yellow. The difference is that a nitrogen deficiency first affects the older leaves and a sulfur deficiency the younger leaves.

A deficiency of sulfur is unusual but possible in an acid soil with low organic content

13.3 Available Sulfur

Sulfur is available to the plant either from the air or from organic or inorganic sources. The only component that is easy to test is the inorganic supply. Assessing the total sulfur supply requires an estimate of the likely amount available from the air and organic matter.

At one time, all sulfur came from animal manure. Then, in the early days of synthetic fertilizers, superphosphate and ammonium sulfate supplied whatever a crop needed. When these sources lost favor after the development of concentrated, sulfur-free fertilizers, industrial pollution came to the rescue. Now with the drive

for clean air, this last resort is vanishing, or at least we hope it is, and concern for sulfur nutrition of plants is growing.

There will always be some sulfur in the air from natural sources, such as volcanic activity, sea spray, and the release of hydrogen sulfide gas from swamps and bogs. Atmospheric sulfur can be absorbed by the soil, but it can also be taken up directly by plant leaves. Owing to the variable nature of the causes of atmospheric sulfur, however, the quantity actually deposited is unpredictable.

In some respects, the properties of sulfur in the soil are intermediate between those of the other major nutrient anions, phosphorus and nitrogen. Sulfur, like phosphorus but unlike nitrogen, is found in soil minerals, and, as the soil weathers, it becomes available in the form of sulfate ions. Sulfate sulfur is subject to leaching, like nitrate nitrogen, but to some extent it can be bound by clay minerals, as phosphorus is. Sulfate is not as strongly held by clay minerals, and adding phosphorus to the soil can displace sulfur and make it available.

Like nitrogen and phosphorus, sulfur is needed by soil organisms. The organic matter in an average soil contains about 1/8 as much sulfur as nitrogen. A soil that can be expected to release about 50 lbs of nitrogen/acre should release about 6 lbs of sulfur/acre.

Alkaline soils are usually dry, and leaching of sulfur (or any nutrient) is minimal. Consequently, chances are good that sulfur is not low on an alkaline soil, nor on any soil with a moderate organic content. But an acid, leached soil with a low organic content and which is not downwind from an industrial center is likely to be deficient.

13.4 Sulfur Fertilizers

Choices

Animal manures are an excellent source of sulfur and are well-balanced with respect to nitrogen. Crop residues such as hay and straw are also good. Among the inorganic fertilizers, sulfate of potash magnesia is a natural fertilizer, langbeinite. Gypsum is calcium sulfate.

Pure sulfur for agricultural purposes is obtained from naturally-occurring deposits in the southern U.S. or as a byproduct of the desulfurization of various gases and coal. It can be purchased either as a fine dust, often called flowers of sulfur, or granulated sulfur. Sulfur dust is an explosion hazard, so it should be handled with care; the granulated form is safer to use. Epsom salts are magnesium sulfate, either crystallized from natural deposits or synthesized. Potassium sulfate and ammonium sulfate are synthesized products.

Sulfur is rarely deficient in the soil so long as some sulfur-containing materials are spread. Deficiencies occur when the use of concentrated, sulfur-free fertilizers stimulate plant growth and cause the removal of soil sulfur without compensation.

Gypsum applied to an alkaline soil will often improve the soil structure by dissolving sodium carbonate when the soil is moist.

Gypsum also improves plant growth in an acid soil. The reason is not clear, but some acid soils are highly leached and possibly low in sulfur.

Table 13.1: **Fertilizers For Supplying Sulfur**

	Sulfur Content		Quantity
	In %	In Lb/Ton	Needed To Add 10 Lbs Sulfur
Organic			
Manure			Tons
Cow	0.05	0.9	10
Horse	0.06	1.1	9
Pig	0.08	1.6	6
Sheep	0.08	1.5	7
Poultry			
Cage Layer	0.2	4	3
Hay	0.2	4	2
Straw	0.15	3	3
Inorganic			
Potassium magnesium sulfate	19	380	53
Gypsum	19	380	53
Pure sulfur ¹	100	2000	10
Epsom salts	13	260	77
Potassium sulfate	17	340	59
Ammonium sulfate	24	480	42

¹ sulfur dust (flowers of sulfur) or granulated sulfur

Pure sulfur is used to acidify an alkaline soil. Sulfur-loving bacteria oxidize it, at which point it combines with water to form sulfuric acid. Sulfur is sometimes applied to make phosphorus more available in alkaline soils, perhaps the microbial equivalent of superphosphate.

Application Rates

Tables 4.1, 4.2 and 4.3 state that crops remove about 15-30 lbs of sulfur per acre. Where rainfall is high, we might increase that amount by about 50% to estimate the need. The soil and air together should furnish about 50 lbs of sulfur per acre. Table 13.1 shows the amount of various fertilizers needed to supply an additional 10 lbs of sulfur.

Chapter 14

Calcium And Soil PH

14.1 Summary

Calcium is necessary in cell membranes and in the growing points of plant roots and tops; a deficiency causes them to wither and die.

It also helps to neutralize toxic materials in a plant.

Calcium assists in the development of soil structure. It also acts as a filler to maintain balance among cation nutrients and to limit the influence of acid cations

Retention of calcium in the soil and its function as a balancing agent depends upon the **cation exchange** properties of the soil.

Soil pH has no direct effect on plants; it is important only in its influence on biological activity and the availability of phosphorus and trace elements.

Table 14.1 lists calcium amendments.

14.2 Calcium In The Plant

Calcium is the Servant, opening and closing doors and keeping out unwelcome intruders. It exists at all interfaces. It is part of cell walls and controls movement into and out of the cell. It is in the growing tips of the roots and tops and is part of the sticky substance that surrounds the roots and binds them to the soil.

It also reacts with waste products, either precipitating them or chelating with them, rendering them harmless to the plant.

Plant roots are inefficient at absorbing calcium from the soil, about 10 times less efficient than they are at absorbing potassium. Consequently the actual amount of calcium taken up by the plant is small, despite the large quantity that may be present in the soil.

A deficiency of calcium causes dieback of growing tips, in both roots and tops, and causes cell membranes to lose their impermeability and to disintegrate. Roots are short, thick and bulbous, also symptomatic of aluminum toxicity.

14.3 Calcium In The Soil

The low ability of the plant to take up calcium coincides with the large amount in most soils. Its presence is usually in the range of thousands of pounds/acre, at least an order of magnitude greater than that of other nutrients. Except under conditions of severe calcium deficiency, no relation exists between the amount of calcium in the soil and the amount in a plant. Furthermore, like potassium, soil organisms require little calcium.

Calcium has two major effects in the soil. One is as a bonding agent in the aggregation of soil particles, wherein it helps to bind organic and inorganic substances. It is important in the development of a good soil structure¹.

Secondly, it acts as a nutrient filler, to maintain balance among nutrients and occupy space which otherwise would be taken up by acid elements.

The value of lime as a neutralizer is not in the calcium it contains, otherwise gypsum would be as good in raising the pH. The carbonate in lime is the neutralizing agent. Other carbonates would raise the pH as well, and some would do it faster, but they would throw the soil out of balance. Potassium carbonate would produce such a high level of potassium that plants might not survive the lack of other nutrients.

Carbonates² are necessary to control the pH in an acid soil, but maintaining a nutrient balance requires calcium.

The role of calcium as a filler exists because the soil contains a reservoir of mobile cations. The flow of cations in and out of the reservoir is known as **cation exchange**. It has four effects:

1. limits leaching losses
2. establishes the availability of the major cations to plants
3. influences the soil pH
4. determines the quantity of lime needed to change the pH.

14.4 Soil PH And Cation Exchange

Cation Exchange

Cation exchange is due to the presence of either very fine clay or humus particles; these have a negative electric charge. They attract cations, which have a positive charge, and the result is a collection of cations floating around the particles. The particles are called **micelles** (short for microcells).

Cations are not chemically bound to the micelles but rather held loosely as a collection. They constantly drift back and forth between the micelles and the soil solution. Those associated with the micelles form the pool of exchangeable

¹Chapter 2.2 has a discussion of soil structure.

²or oxides, which are more expensive.

cations and those in solution the pool of soluble cations. In equilibrium, a balance is reached between exchangeable and soluble cations; this balance determines the soil pH.

In most soils, the exchangeable cations dwarf the soluble cations. Soluble cations taken up by plants or those lost by leaching are replaced by exchangeable cations. The application of lime produces cations that first enter the soil solution and then drift onto the micelles.

The principal exchangeable cations are calcium, magnesium, potassium, hydrogen, in many areas aluminum, and in acid soils ammonium. In a soil containing mostly calcium, the majority of the exchangeable cations are calcium ions.

Exchangeable calcium, magnesium, potassium and ammonium are directly available to plants. A plant root in the immediate vicinity of a micelle can take up one of these nutrients and substitute an equivalent amount of hydrogen ions.

The cation exchange reservoir is determined by the number of micelles. A measure of this number is the cation exchange capacity, or CEC³. The larger the exchange capacity, the larger is the number of exchangeable cations.

A large exchange capacity, however, does not assure a fertile soil but only that the soil contains a large number of exchangeable cations. The CEC does not indicate whether the cations are nutrients. The purpose of adding lime is to replace acid with alkaline ions. Plants are less sensitive to the calcium concentration than to the other major cation nutrients in the soil, and calcium plays the major role in this process.

Soil PH

Soil pH is an imperfect and limited concept. A discussion of why this is so may help in interpreting soil test results.

The term pH is chemical in origin. Its intended purpose is to indicate the hydrogen ion concentration, converted to logarithmic units, in a water solution. The conversion is such that a neutral solution has pH 7; a lower pH means that the solution is acid and a higher pH that it is alkaline. The pH can be estimated with the help of paper strips coated with chemicals whose color depends upon the acidity of the water solution. A more accurate measurement is with a pH probe; it measures the hydrogen ion concentration in solution.

The consequence is that pH refers to the water in a soil rather than the soil itself. The concept of pH has no meaning for a solid.

People who first tried measuring the pH of soil simply plunged a probe into a soil sample; but the results were erratic, because the probe did not make intimate contact with the soil water. More reliable results were obtained with a paste, adding just enough water to the soil to saturate it, just before it becomes shiny with excess water.

³This definition is simplistic, but it gives a good image of the concept of the exchange capacity. More accurately, the cation exchange capacity is a measure of the number of positive electrical charges that can be attracted to the micelles. Some cations in the soil are associated with one positive charge, some with two charges, and some with three or more. In chemical terminology, these charges denote the ionic valence of the cation.

This procedure, however, is laborious. Eventually the test was standardized by combining soil and water in a predetermined proportion, commonly but not always equal quantities by weight.

The problem is the distinction between the hydrogen ion concentration actually in solution in the soil and the concentration in a laboratory test. The relation between the two depends upon the amount of water used and its purity. The more water, the greater the dilution, the lower the concentration of soluble hydrogen ions and the higher the pH.

Salts in the water will replace some of the exchangeable acidity. Salty water will result in a higher soluble hydrogen ion concentration, or a lower pH. Moreover, during a dry season salts will accumulate in the soil, and when the rains come, these salts are leached out.

If the pH is tested during the dry part of a season, the soil salts will dissolve in the water used to measure the pH. But they will not during the wet season, having already leached out. The pH measured during a drought will be lower than the pH measured after a rainstorm.

So a pH meter does not measure soil pH nor even the pH of the soil water, but rather the pH of the water mixed with the soil by a technician or by a machine. Secondly, this distinction produces results which depend upon the amount of water used and its saltiness.

Different testing laboratories may give different results. Some laboratories use salted water in order to swamp out the effect of varying salt content in the soil; this produces more uniform results, but the pH is lower, by an amount which may vary between a tenth and more than a whole pH unit, depending upon the extent to which the soil has a high salt content on the one hand or is leached out on the other; the average drop in pH is about half a unit.

Unfortunately, most charts and tables showing the best pH for growing specific crops are based on the pH measured in pure water, although states that measure pH in salt solution have accumulated their own data.

Furthermore, the pH is not uniform throughout the soil; it is lower in the area around plant roots, owing to a higher biological activity.

However, it is the best that can be done at a reasonable cost, and soil pH is still the most important of the simple tests. Owing partly to the variations in pH that can occur, people who test their soils regularly should take samples at the same time of year and during typical weather conditions.

Importance Of Soil PH

Plants are not sensitive to soil acidity; rather they are sensitive to the effect of the acidity on the availability and form of plant nutrients. An acid soil inhibits the conversion of nitrogen from the ammonium to the nitrate form, and plants have evolved accordingly.

Most plants prefer nitrogen in the nitrate form, but grasses and grains do best with a mixture, and blueberries require nitrogen in the ammonium form. In an acid soil, levels of aluminum and available manganese can rise to the point where they become toxic to plants, while molybdenum may be deficient. In an alkaline

soil, the availability of most trace elements may be too low for some crops. The availability of soil phosphorus drops in an acid or alkaline soil.

The soil pH is also a significant factor in determining the quantity and diversity of soil organisms; a neutral pH encourages a greater and more diverse population than an acid soil.

Exceptions do occur, because some plants have unique trace element requirements. Blueberries evolved in acid soils containing large amounts of iron and ammonium-nitrogen. Grasses and other monocotyledons have a requirement and a tolerance for moderately high amounts of manganese and zinc; these are most available in acid soils.

Exceptions also occur with soils. Some soils have a high aluminum content, and a higher pH may be warranted for the sake of improving the status of available phosphorus. Sandy, highly weathered and poorly buffered soils are typical of many areas of the Atlantic coast and the southeast. These soils require more acidity for satisfactory availability of some trace elements, notably manganese; the pH of those soils should not rise above 6.0 - 6.2.

On the other hand, these tendencies to favor a departure from a biologically optimum pH can be reduced or eliminated by the presence of organic matter, which can tie up aluminum and chelate many trace elements. Soil pH is not as important to plant growth when the organic content is satisfactory.

In the southwest and most of the west, soils are low in aluminum. In addition, organic soils (with an organic content of 50% or more) contain little aluminum. In these soils there is no chance of aluminum toxicity; raising the pH to avoid it is unnecessary. It is most necessary in the weathered, high aluminum soils of New England and in the coastal Northwest.

Soil PH And Calcium

Lime serves to increase the pH, by modifying the balance between acidity and alkalinity. The predominant sources of acidity are the acid-forming cations, hydrogen and, where it is significant, aluminum⁴. The sources of alkalinity are the base

⁴The reason for the influence of aluminum on soil acidity is discussed in [61], but for convenience the following is a brief summary of the argument.

Aluminum is a cation, like calcium, magnesium and potassium, but it differs from them in that it can combine with water in a process called hydrolysis. Water splits into hydrogen and hydroxide ions, and the aluminum combines with the hydroxide to become aluminum hydroxide. This leaves the hydrogen ions in solution.

Initially in a very acid soil, aluminum is without hydroxide ions, and hydrogen ions are numerous. If the soil is limed, some of the hydrogen ions are neutralized. This causes the aluminum to hydrolyze some water, releasing additional hydrogen ions into solution and tending to maintain the soil acidity. This continues until the aluminum in solution has hydrolyzed all the water it can. However, the calcium in the lime replaces exchangeable aluminum at the soil micelles, and this aluminum goes into solution and represents an additional source of hydrogen. So still more lime must be added until the exchangeable aluminum is consumed.

In the reverse process, the presence of increasing amounts of hydrogen ions causes some of the aluminum hydroxide to give up its hydroxide, which combines with the hydrogen to form water. With the increasing presence of hydrogen, increasing amounts of aluminum are freed and can become exchangeable, replacing exchangeable nutrient cations.

cations, principally calcium, magnesium and potassium. The equilibrium between exchangeable acid and base cations determines the amount of hydrogen ions and the pH of the soil solution.

Accordingly, soil acidity can be neutralized with anything that supplies alkalinity. Wood ashes are excellent for neutralizing soil acidity, but only in moderately quantities; otherwise they would add too much potassium. The only substances that can effectively neutralize a soil without impractically disturbing the cation balance are alkaline materials containing calcium alone or calcium plus magnesium. The choice between these two should depend upon the magnesium status of the soil.

The pH as a measure of the equilibrium between the cation reservoir and the soil solution is only a flag. It may state that the soil is too acid but not how excessive the acidity is. A soil in Delaware with a pH of 5 will require much less lime to neutralize it than a typical soil in California at pH 5. The amount of lime required is dependent on the CEC. A Delaware soil typically has a low CEC and fewer acid cations; it requires less lime to neutralize than a young California soil at the same pH but with a high CEC.

The advantage of a high CEC well balanced in nutrient cations is that it constitutes a reservoir against the natural acidifying tendency of the soil. A soil with a higher CEC is more strongly buffered⁵. This buffering capability counteracts the detrimental effect of acid rain on most soils⁶.

14.5 Calcium Fertilizers

Fertilizers

Table 14.1 is a list of calcium fertilizers. Poultry manure, wood ashes and seashells or lobster shells are the only common organic sources of enough calcium to be useful when spread in typical amounts.

Animal manures also contain a large quantity of carbonates and have a liming value. The actual carbonate content, however, is variable, and the liming value of manure is unpredictable. Much of the calcium in poultry manure comes from the lime in poultry feed, most of which passes through the animal. With overuse of poultry manure, there is a danger of driving the pH too high.

Legume hay contains calcium, but the calcium has no liming value because the hay has no carbonates.

Two popular waste materials for liming are clam shells and wood ashes. Clam shells are almost pure calcium carbonate, and wood ashes comprise a variety of carbonates and oxides. The lime equivalent of wood ashes shown in table 14.1 takes into account the total carbonate and oxide content, not just calcium alone⁷. Clam shells have a low solubility and require several years to be effective. They should

⁵although it can be a problem in rejuvenating an abandoned soil, particularly where organic matter accumulates, as in the northeast.

⁶see appendix C.3.

⁷see appendix C.2 for details.

Table 14.1: Fertilizers For Supplying Calcium

	Calcium Content		Lime Equivalent Lb/Ton
	%	Lb/Ton	
Organic			
Manure			
Poultry manure - cage layer	≤ 4	≤ 80	
Other manures	0.2-0.4	4-8	
Legume Hay	1.4	28	
Inorganic			
Clam & oyster shells (approximate)	34	680	1700
Wood ashes (approximate)	35	700	1750
Calcitic limestone (approximate)	38	760	1900
Dolomitic limestone (approximate)	25	500	1900
Rock phosphate			
Colloidal	21	420	800
Hard rock	33	660	1200
Gypsum	23	460	

be ground as finely as possible for the quickest results. Wood ashes are effective almost immediately. But they are also caustic and require care in spreading.

Agricultural limestone is the most common method for adjusting the soil pH. Two kinds of limestone are available, one being primarily calcium carbonate, or calcitic limestone, and the other a mixture of calcium and magnesium carbonate, often called dolomitic or simply high magnesium limestone. Both have approximately the same liming capability.

At one time, other more soluble forms of lime were used. Burned lime, or quicklime, is calcitic limestone which has been heated in a furnace to drive out carbon dioxide, leaving calcium oxide. It is soluble and caustic. It is also difficult to spread effectively, because it tends to form flakes in the soil, which become insoluble owing to the formation of a crust of calcium carbonate on the surface.

Hydrated lime, or slaked lime, is burned lime to which water has been added. It is soluble and even more caustic than burned lime. It is also unstable and eventually changes to insoluble calcium carbonate upon exposure to air.

Rock phosphate and bone meal raise the pH to a modest extent⁸; this adds to their value in an acid soil. They act more slowly than limestone, however, because of their lower solubility.

Gypsum, sometimes called land plaster, has no liming capability. It improves the growth of clover in an acid soil, but not as well as lime. Its most likely value is in its sulfur. It is, however, useful in improving the soil structure of alkaline soils, by facilitating the removal of excessive amounts of sodium⁹.

⁸Appendix C.2 derives quantitative estimates.

⁹To learn how gypsum improves alkaline soils, see, for example, [21].

Gypsum may possibly be helpful in acid soils with a low cation exchange capacity, by supplying calcium without raising the pH. It can counter the toxic effects of aluminum in plants; it has been used effectively in growing cranberries and on some soils in the southeast. Why it works is not clear, although the fact that it does illustrates the point made earlier that plants are not sensitive to the pH but rather to its effect on the environment.

Calcium chloride is another source of calcium which does not raise the pH. It has been used as a foliar spray for fruit trees in an acid soil having an excess of potassium.

Lime Rates

As noted earlier, the **cation exchange capacity** depends upon the clay and organic content. In arid and semi-arid soils, the clay content is more important, but most of these soils need little or no lime. Where lime is most important, organic content is the predominant factor determining the exchange capacity. Some popular recommendations in articles and handbooks base the lime requirement only on whether the soil is sandy, silty or clayey. This may be satisfactory in some areas, but it is an oversimplification and least applicable to those soils most likely to need liming.

A reliable soil test offers a lime recommendation that takes into account the **CEC** of the soil. Most state laboratories have developed accurate correlations that reflect this dependence either directly or indirectly. Many private laboratories have done so also, but some universally apply results to all states which are valid only in a few.

A defect of a soil test kit is the lack of an adequate lime recommendation, and people who use one must develop their own correlations. To start, it is best to be conservative. If, for example, the pH goal is 6.8, then no lime should be necessary if the pH is above 6. If it is below 6, then one ton of lime per acre, or 5 lbs/100 sq ft is reasonable; it can be doubled if the organic content is known to be high. If the pH is below 5.0, two tons/acre, or 10 lbs/100 sq ft are more likely to be needed.

More than two tons/acre should not be added in one year, otherwise trace elements - particularly boron - could be tied up temporarily. Where magnesium is low, at least the first ton of lime per acre should contain magnesium.

Lime should be thoroughly tilled into the soil. If it is simply topdressed, it will take a long time to move down into the soil, at a rate of about one inch/year in New England¹⁰.

The quantity of gypsum needed to neutralize sodium in an alkaline soil depends upon the sodium content, but typical amounts are of the order of several tons/acre.

¹⁰According to Winston Way, extension agronomist, University of Vermont.

Chapter 15

Magnesium

15.1 Summary

Magnesium is a constituent of chlorophyll. It is also active in the metabolism of phosphorus. A deficiency rarely affects yield but can reduce the nutritional quality of crops.

Cation exchange is the only means of holding magnesium against losses in the soil.

Fertilizing for magnesium in soils naturally low in magnesium requires an inorganic amendment. It is especially difficult if both calcium and potassium are high.

Table 15.1 lists the magnesium content of typical fertilizers.

15.2 Magnesium In The Plant

Magnesium puts the Green in green plants. It is the only metal which is a constituent of chlorophyll. Chlorophyll is identical to the hemoglobin in blood, except that chlorophyll contains magnesium instead of iron. It is not too excessive to claim that a lack of magnesium produces anemic plants.

Only about 20% of the magnesium in plants, however, is in chlorophyll. The rest functions as a regulator for various metabolic processes. Magnesium is necessary in every operation involving phosphorus; an apparent phosphorus deficiency can sometimes be tempered with magnesium fertilizer. In addition, magnesium influences nitrogen metabolism and is important in the assimilation of carbon dioxide during photosynthesis.

Magnesium and sulfur are the most neglected of the major nutrients, sulfur no doubt because until recently fertilizers contained enough to satisfy plant requirements. In the case of magnesium, nothing short of a gross deficiency seems to affect yields, unless phosphorus is also low.

This masks, however, the effect of magnesium on the nutritional value of crops. Like sulfur, some amino acids contain magnesium; a deficiency will result in an insufficient supply of true proteins requiring those amino acids and an enlarged

pool of free amino acids. The missing proteins reduce the quality of produce for both animal and human consumption.

An antagonistic relationship exists among calcium, magnesium and potassium: all three are cations, and the total absorption of cations by plant roots is limited. Plants, however, have a built-in preference for potassium, the soil supply of which is usually adequate to excessive; and calcium is the predominant component of lime. Magnesium is rarely prominent in a soil amendment, and it often ends up short.

There are no characteristic symptoms of a mild magnesium deficiency - a moderate deficiency may result in a yellowing of leaves between the leaf veins - perhaps only an awareness that the plant is not functioning or producing well. Owing to the reduced assimilation of carbon dioxide, growth is stunted, and ripe fruit lacks sweetness. A deficiency retards phosphorus metabolism and protein production.

15.3 Magnesium In The Soil

Magnesium behaves much like calcium in the soil. Both are easily leached in humid areas. Conservation of either depends upon the **cation exchange** properties of the soil.

The age of the soil and weather conditions influence the cation exchange capacity and the presence of magnesium. Owing to the particular clays in many of the young unweathered western soils, the exchange capacity is usually high. In addition, these soils are also high in magnesium. Not all soils in the west are so blessed, but many of them are natural cation reserves and very well filled.

Older, weathered soils in the humid areas of the east and south, however, are less favored. Except for some soils (in Pennsylvania for example), old soils are especially leached of magnesium, and the clays are poor at contributing to the **cation exchange capacity**. Organic matter is the predominant influence in determining the exchange capacity. Moreover leaching has left these soils acid, and so the exchange reservoir is filled mainly with non-nutritive acid ions.

Magnesium Balance

The following discussion is relevant only where magnesium is low in the soil. Cation balance is not critical where magnesium is moderate to high, unless it begins to approach levels of the order of 70% of the cation reservoir. And where that extreme situation does exist, I have no help to offer.

Almost all soils in humid areas must be limed periodically. The question then arises, what kind of lime is appropriate. It is reasonable to suppose that a balance should exist among the nutrient cations (calcium, magnesium and potassium).

We do know that excessive potassium can lead to a magnesium deficiency and sometimes a calcium deficiency. An excess of calcium has been responsible for deficiencies in both magnesium and potassium. Experiments have led to the

conclusion that, for many crops, the soil should contain at least as many magnesium ions as potassium ions¹.

Recently, one criterion for cation balance has been adopted by several soil testing laboratories. According to this criterion, 60-70% of the soil reservoir should be filled with calcium, 10-15% with magnesium, 2-5% with potassium and the remainder with acid ions. Within the last few years, however, the hypothesis of cation balance has been challenged, and experiments have shown that yields are substantially independent of these or any similar guidelines based upon the percentage of ions in the cation reservoir. A controversy still exists on the issue.

One issue is that experiments used to test this criterion are set up so that all other nutrients are well supplied. This masks the relationship between phosphorus and magnesium, because magnesium has less importance if phosphorus is high.

Furthermore, tests based on yield alone is an additional bias against magnesium, which is more important in determining the quality of a harvest rather than its quantity².

The concept of an appropriate distribution of the nutrients which make up the cation reservoir does have two uses. One is to determine the amount of lime required to raise the pH to a desired point, and the other is to set a minimum level for magnesium. Tentatively, the following may be a useful guide: In terms of lbs/acre, the soil should contain at least one tenth as much magnesium as calcium, and at least 60% as much magnesium as potassium³.

A guideline for setting minimum levels of potassium should take into account the need to balance nitrogen but not so high as to overwhelm magnesium or calcium. The proper nitrogen/potassium balance is determined by the crop requirements; tables 4.1 - 4.3 may be useful for the purpose.

In practice, a conflict between balancing nitrogen and not overpowering magnesium should occur only with a depleted, weathered soil possessing a low organic content; such a soil has a low **cation exchange capacity** and little ability to store magnesium. In order to preserve the proper magnesium/potassium balance in that case, potassium and consequently nitrogen should be limited; which of course affects the yield. However, table 3.2 has examples where heavy fertilization with

¹that is, the total number in solution and in the **cation exchange** reservoir

²This argument depends on a definition of quality to include not only the appearance of produce but also the nutritional value.

³These suggestions are based upon the following reasoning: The conversion factor between the pounds of a nutrient and the number of atoms, or ions, varies with the nutrient. So a magnesium/calcium ratio of 10/100 in terms of lbs/acre is equivalent to a ratio of 10/60 in terms of ions/acre. This idealized 10/60 ratio is an extrapolation from the earlier criterion (10% magnesium and 60% calcium). Similarly, a magnesium/potassium ratio of 60/100 in terms of lbs/acre is equivalent to a ratio of 1 in terms of ions/acre. As noted earlier, the relation between magnesium and potassium does have an experimental basis for some crops.

The term ions/acre is not a standard unit of measure. The customary measure in soil science is milliequivalents/100 grams of soil, abbreviated as meq/100 g (although this unit is now being replaced in some technical journals). Exchangeable cations and the cation exchange capacity are reported in terms of this unit. The conversion between lbs/acre and meq/100 g is given by the formula, $(\text{lbs}/\text{A}) = F * (\text{meq}/100 \text{ g})$, where $F = 20 * (\text{FW})/(\text{V})$ (FW is the formula weight, and V is the valence of the ion). The idealized magnesium/calcium ratio stated above is the same in either case, but a magnesium/potassium ratio of 1/1 in terms of ions/acre is 2/1 in terms of meq/100 g.

Table 15.1: Fertilizers For Supplying Magnesium

Fertilizer	Magnesium %	Content lb/ton
Organic		
Manure		
Poultry manure-cage layer	0.3	6
Other manures	0.08-0.2	1.6-4
Hay	0.15	3
Straw	0.1	2
Corn, oats, wheat	0.09	2
Soybeans	3.9	78
Inorganic		
Dolomitic limestone		
Average	6-14	
Potassium magnesium sulfate	11	220
Epsom salts	10	200
Magnesia	56	1120

potassium fertilizers without taking into account the necessity of balancing magnesium and calcium affects the appearance of fruit and vegetable crops.

One reason why the relationship among calcium, magnesium and potassium can be so loose is that, within a wide range of values, excessive magnesium is not a concern. Some soils in California have enough magnesium to fill 40% of the cation reserve and yet produce high yields. To be sure, soils with 70% magnesium can not grow crops, but this still leaves room for variation.

15.4 Magnesium Fertilizers

Table 15.1 lists the magnesium content of typical organic materials and of the principal fertilizers.

Most organic residues have a small but significant amount of magnesium. About 20 - 30 lbs of magnesium/acre can be supplied by fresh poultry manure spread at a rate of 5 tons/acre and the other manures at 10 tons/acre, or a hay mulch made from bales split up into one-inch layers⁴. This quantity is enough to supply most crops with sufficient magnesium, although some of the magnesium is likely to be lost by leaching. Compost is an excellent source of magnesium, but not enough information is available to indicate typical amounts.

These residues, however, would add a much greater amount of potassium than magnesium. For example, table 15.1 suggests an application of 10 tons/acre of

⁴Assuming a bale size 11 by 18 by 30 inches weighing 35 lbs, we would find that one bale split up into one-inch layers will occupy a space of about 56 sq. ft. Thus 774 bales would be required to cover one acre, and the total weight of the bales would be about 13-1/2 tons. If each ton supplies two lbs of magnesium, the mulch would add about 27 lbs of magnesium/acre.

non-poultry manure for about 25 lbs of magnesium. However, table 6.3 shows that nonpoultry manure may contain about 10 lbs of potash/ton; so a rate of 10 tons/acre will add 100 lbs of potash, or four times as much potassium as magnesium. Similarly, a hay mulch will add more than ten times as much potassium as magnesium.

Soybean meal (and probably cottonseed meal and seedcake residues) is a good source of magnesium, but it is likely to contain about four times as much potassium as magnesium. Only poultry manure seems to have a reasonable balance, supplying a bit less than twice as much potassium as magnesium.

Most organic residues are better sources of magnesium than of calcium, but they are not an ideal magnesium fertilizer. If a soil has a low ratio of magnesium to potassium, most organic residues will not improve the ratio, and they may make it worse.

The two most common inorganic fertilizers for magnesium are dolomitic limestone and sulfate of potash magnesia. Dolomitic limestone is the cheapest of inorganic magnesium fertilizers and is the logical choice for acid soils. But sulfate of potash magnesia is useful if potassium is also low.

Often, however, owing perhaps to a mistake in fertilizer usage, a soil may be high in both calcium and potassium, in which case neither of these amendments is appropriate. The two alternatives are **epsom salts** and **magnesia**, both soluble. Neither one is satisfactory, for reasons to be given presently, and they are both customarily used in small quantities, perhaps enough for temporary relief of a magnesium deficiency, but not enough to raise the soil reserve. They are best used only in an emergency or after a test trial to determine their effectiveness.

Epsom salts are a natural mineral, although they are also synthesized. Magnesia is usually made by heating magnesite, a naturally occurring magnesium carbonate, to drive off the carbon dioxide, a process similar to that used in the production of burned lime from calcitic limestone. Magnesia is a common constituent of commercial fertilizers fortified with magnesium.

Epsom salts are expensive and impractical to spread in large amounts; quantities of the order of 150-200 lbs/acre are common, but this supplies only a small amount of magnesium. An alternative is to apply epsom salts as a foliar spray several times during the season, at a rate of about 10 - 15 lbs/100 gallons of water, saturating the plants [51].

Magnesia is cheaper to add in larger quantities, but it will raise the pH. Spreading magnesia might be feasible in small amounts where a slight pH rise is tolerable. The maximum permissible rate of application varies with individual soils, because it depends upon the permissible rise in the pH and the **cation exchange capacity**. The liming value of magnesia is calculated in appendix C.2. Another disadvantage to magnesia is that it is a dehydrating agent and might affect soil life.

In summary, supplying sufficient magnesium while maintaining a good balance with calcium and potassium is difficult in magnesium-deficient soils with a low organic content. It requires sufficient planning.

Chapter 16

Micronutrients

16.1 Summary

Micronutrients have various functions, some not yet understood. Most of those that are known involve metabolic activities.

Micronutrients are required in small amounts and only in small amounts.

Soil pH and organic content are two important factors affecting their availability in soil.

Several possibilities for inorganic micronutrient fertilizers exist, but organic materials offer a double advantage: a diversity of micronutrients and a natural **chelate** capability.

Table **16.1** lists sensitivity of crops to a micronutrient deficiency. Table **16.2** lists the micronutrient content of organic residues. Table **16.3** contains typical fertilizer application rates.

16.2 Micronutrients In Plants

Most of the discussion in this chapter is from [50].

Some minerals are important to plants only in small amounts; large quantities can be toxic. Most likely not all such minerals been recognized yet, and the functions of those which are known are not well understood. These minerals constitute the trace elements or micronutrients.

This chapter describes those six which have received the most attention. However, there are others. Two whose function is at the borderline of our knowledge are chlorine, which is essential in one phase of photosynthesis; and silicon, which gives plants a mechanical strength, minimizes water loss, and resists disease.

In addition, others are important in various unrelated or indirect ways. Cobalt is necessary to bacteria that fix nitrogen; vanadium is necessary to soil organisms in an as yet unknown way. Trace amounts of cobalt, iodine, selenium and chromium are essential to human and animal health.

The six which are discussed here are boron, copper, iron, manganese, molybdenum and zinc. All except boron control metabolic reactions, together with specific

plant enzymes. Copper, manganese and zinc are involved in a variety of activities. Molybdenum and iron are important in nitrogen fixation and in reducing nitrate to ammonia for the synthesis of proteins. The pink color associated with healthy legume root nodules is due to the existence of an essential iron-molybdenum-enzyme combination. In addition iron is necessary for the production of chlorophyll.

The importance of molybdenum in nitrate metabolism has been confirmed by research with potatoes showing that additions of sodium molybdate can reduce nitrates and toxic glycoalkaloids [8]. This presents a conflict. Potatoes are traditionally grown in acid soils in order to reduce the onset of potato scab; but the availability of molybdenum is low in these soils. Although there may be an alternate way to avoid scab¹, and even though scab is only a cosmetic defect, it is a dilemma for market gardeners.

Boron exists in cell membranes, and, in some as yet unknown way, it is influential in tissue production. It is also important in nitrogen fixation. Boron seems to have a common function with calcium, and a deficiency of either can inhibit the growing points of the plant and disrupt cells. Boron is thought to contribute more than any other micronutrient to the quality of produce.

Our lack of knowledge about the effects of trace elements in plants is due partly to two problems. One is the minute quantity needed in plants and the effect of increasing amounts on plant functions. The usual behavior with major nutrients is that, within a reasonably wide range of fertilizer application rates, plant growth increases with increasing application rates.

The response of plants to micronutrients, however, is an all-or-nothing affair. Within a narrow range of application rates, a plant grows well, indifferent to the precise rate; but outside this range it manages poorly or dies. Boron is deficient for some crops at less than 1 part per million (ppm) in the soil and toxic for others at more than 3 ppm.

The second problem is the complexity of the interactions with each other and with the major nutrients, in both plants and soil. Iron, copper, manganese and zinc are mutually antagonistic. Excess potassium or magnesium may lead to a manganese deficiency. Sulfur or copper may cause a molybdenum deficiency, but phosphorus has a beneficial effect with molybdenum. Phosphorus and iron together may affect zinc. Nitrogen fertilization may lead to deficiencies in iron, copper, or boron, and prolonged phosphorus fertilization may cause a copper deficiency. Zinc availability requires a well-aerated soil, but iron needs some period without oxygen. It is difficult to keep track of these conflicts.

Table 16.1 [50], [57], [51], [22] lists the degree of sensitivity of a variety of crops to a micronutrient deficiency.

16.3 Micronutrients In The Soil

Some soils are extreme in their micronutrient content. Quartz and sandstone soils are low in zinc, while igneous soils can be high. Boron is higher in sedimentary

¹for example a cover crop of soybeans[16], [54]

Table 16.1: **Sensitivity Of Plants To A Micronutrient Deficiency**

	Degree of Sensitivity to a Deficiency		
	High	Medium	Low
Boron	asparagus, beet, brassicas, celery, spinach, sunflower, alfalfa, clover, sweetclover, apple, grape, pear	carrot, lettuce, onion, spinach, sweet potato, cotton, cherry, olive, peach, pear, raspberry, strawberry	beans, corn, cucumber, peas, white potato; buckwheat, cereals, grasses, sorghum, soybean, citrus, blueberry
Copper	beet, carrot, corn, lettuce, onion, spinach, alfalfa, most grains & grasses, most large fruits	brassicas, celery, cucumber, parsnip, pea, clover, cotton, sorghum, blueberry, strawberry	asparagus, bean, potato, rice, rye, soybean
Iron	most crops	asparagus, cabbage, corn, alfalfa, oat	wheat
Manganese	beet, bean, cucumber, lettuce, onion, pea, potato, spinach, radish, oat, sorghum, soybean, sudangrass, wheat, apple, cherry, citrus, grape, peach, raspberry, strawberry	broccoli, cabbage, carrot, cauliflower, celery, corn, cucumber, tomato, turnip, alfalfa, barley, clover, rice.	asparagus, parsnip, field corn, most grasses, rye, blueberry
Molybdenum	beet, brassicas, lettuce, onion, spinach, tomato; alfalfa, clover, sweetclover, citrus	bean, pea; alfalfa, oat, soybean	asparagus, carrot, celery, corn, potato, cotton, most grains & grasses, sorghum; most fruit
Zinc	bean, corn, onion, tomato; cotton, flax, hops, sorghum, sudan grass, soybean, most large fruits	beet, potato; alfalfa, barley, clover, rice	asparagus, carrot, pea, most grasses, oat, rye, wheat

than in igneous rocks. Boron is often high in arid or semi-arid soils, but boron, copper, manganese, molybdenum and zinc may be low in leached sandy soils.

In most cases, however, the total content of micronutrients is adequate, and the two most important factors controlling their availability are the pH and the organic content.

Iron, manganese and zinc are often unavailable in soils of high pH, but molybdenum tends to be unavailable in acid soils. Boron is not as sensitive to pH as it is to the presence of lime, to which it becomes strongly attached, and recently limed soils may develop a temporary boron deficiency.

For most soils, the best compromise between the availability of molybdenum and the other micronutrients occurs when the pH lies somewhere between 6 and 7. Along the Atlantic coast and in the southeast, soils of low organic content may be deficient in total manganese; their pH should not be much above 6.

Organic matter is often essential to maintaining the availability of micronutrients; without it, micronutrients tend to be bound to inorganic minerals so strongly that their release during the growing season is low.

The importance of fresh organic residues is due to their ability to **chelate** the cation trace elements (copper, zinc, iron, manganese)².

Not only does chelation provide a source of micronutrients, but it also buffers the soil against an excess, because only a fraction of the chelated material is released. Tests have shown organic matter in orchard soils to hold as much as 1,000 ppm of the copper that had accumulated from the use of copper-based fungicides. Organic matter is also capable of chelating lead, chromium and other toxic metals. As a buffer, moreover, organic matter decreases the effect of the soil pH. It furnishes micronutrients if the pH is too high, and it inhibits toxicity if the pH is too low.

The alternative of supplying trace elements with inorganic fertilizers while trying to keep track of the antagonisms that exist among them is a nuisance. Also, trace elements from inorganic fertilizers often remain available for too short a time to be useful.

In the U.S. and Canada, the micronutrient most likely to be deficient is boron: its availability is less influenced by organic matter than other trace elements, it leaches easily, and it may be locked up by fresh lime. Boron is often particularly low in subsoils. Consequently, in dry weather it may be deficient as plant roots grow downward in their search for water.

16.4 Sources Of Micronutrients

Organic Matter

It is difficult to find information on the micronutrient content of organic fertilizers, because more attention has been given to determining the NPK content. This

²Molybdenum and boron are anions. They are not chelated, but soil organisms require molybdenum and boron, so they are present in residues. Molybdenum is required by plants in such small amounts that the quantity released by decomposition should be sufficient for plant needs if the pH is satisfactory

is unfortunate, because in our times, with the availability of purified commercial fertilizers, the micronutrients in organic residues may be more important than the major nutrients.

Table 16.2 lists the micronutrient content of those residues which have been tested. Owing to the small amounts of trace elements present, large fluctuations can exist. The values illustrated are useful only in showing the possible magnitude of the micronutrient content. The high value for the boron content of legume hay was taken from a single test of alfalfa and should be suspect.

Table 16.2 also shows the micronutrient content of an average crop. For example, approximately 7 tons of fresh cow manure should, without help from the soil, supply enough boron and molybdenum for 1 ton of crops (dry weight), more than enough copper, iron and zinc, but not enough manganese. Two tons of fresh cage layer manure should furnish enough of all of the trace elements for 1 ton of crops. Two tons of dried seaweed should provide nearly enough, although enough fresh seaweed to supply this much dried seaweed would be difficult to accumulate and haul to the field.

Straw should have approximately the same micronutrient content as hay; most of the trace elements remain in the mature plant tissue, owing to their low mobility. Similar castoffs, such as leaves, should also be high in trace elements. Wood ashes, one of the few materials on which information does exist, contains many trace elements.

As the data for poultry manure infers, seeds have a high content of micronutrients. Commercial products such as cottonseed meal and soybean meal should, therefore, be a good source.

Inorganic Fertilizers

Inorganic micronutrients can be applied in accurately measured amounts in three ways:

- by inorganic salts
- by a complex with a synthetic chelating agent
- by means of glass frits.

Inorganic salts are the easiest to locate and usually the cheapest. Sulfates and oxides are common. Borax supplies boron, and ammonium molybdate and sodium molybdate furnish molybdenum. These can either be added to the soil or sprayed on the foliage. Borax dissolves slowly in water, so a more soluble, proprietary chemical may be preferable.

Synthetic chelating agents mimic the chelating properties of organic matter. Like the inorganic salts, they can be applied to the soil or the foliage.

Glass frits are microscopic glass particles containing micronutrients. Borosilicate glass was one of the first used. Frits have a very large surface area and are slowly dissolved in the soil, after which their nutrients become available. They are not sold directly to the public, however, but only through fertilizer manufacturers,

Table 16.2: **Micronutrient Content Of Various Materials**¹

	Quantities In Lb/Ton					
	Fresh weight basis for manure					
	Dry weight basis for others					
	Boron	Copper	iron	manganese	molybdenum	zinc
Organic						
Manure						
Cow	0.03	0.01	0.27	0.02	0.002	0.03
Horse	0.03	0.01	0.08	0.02	0.002	0.03
Sheep	0.02	0.01	0.32	0.02	0.002	0.05
Pig	0.08	0.01	0.56	0.04	0.002	0.12
Poultry						
Cage layer	0.12	0.03	0.93	0.18	0.011	0.18
Broiler	0.08	0.06	2.0	0.46	0.007	0.25
Hay						
Legume	≤ 5	0.02	0.2	0.2	0.006	0.1
Nonlegume		0.01		0.14		0.06
Straw	0.009	0.27	0.06			
Average	0.2	0.01	0.2	0.4	0.01-0.001	0.05
Alfalfa pellets	0.09	0.02	0.6	0.06		0.03
Seaweed	0.1	0.01	0.04	0.1	0.002	0.02
Inorganic						
Wood ashes	0.6	0.1	40	16		1
Sodium nitrate from Chile	0.8					

¹ Most of the data in table 16.2 comes from [21], [19], [90], [26], [33], [2], [69], [43], [44], [47], [70], [81], [85], [61], [79], [92], [93], [88], [94], [55], [50], [71], [72], [1]. The data on alfalfa pellets was taken from the label attached to bags of pellets sold at the Farmers Union in Farmington, Maine.

who mix them in predetermined proportions for specific crops. They are applied only to the soil. Compared to the inorganic fertilizers and synthetic chelates, they appear to have promise, but not much information is available from independent sources³.

For acid, highly leached sandy soils naturally low in micronutrients, inorganic salts are satisfactory when applied to the soil and are sometimes suitable in alkaline soils. The major difficulties are with copper, iron and manganese. Copper sulfate dissolves very fast and is soon locked up, but before this happens, it may be present in toxic concentrations. the toxicity problem is partly overcome by using copper oxide or copper dust, which dissolve more slowly. Iron and manganese salts are usually useless in alkaline soils.

³For a list of manufacturers of glass frits as well as other trace elements, see [2].

Chelants are finding increasing use, especially in supplying iron, but they are expensive. Manganese chelants are often unsatisfactory, because the manganese can be replaced by other metals before it reaches the plants.

Foliar sprays - either inorganic salts or chelants - are more efficient than fertilizers applied to the soil, and less is necessary. Exceptions are some salts: ferrous sulfate produces mixed results, and copper sulfate may scorch the leaves.

Inorganic salts are satisfactory for supplying boron and molybdenum either to the soil or foliage, although seed treatment is the preferred approach for molybdenum. No chelants exist for either.

Typical application rates for the more common fertilizers are given in table 16.3 [50], [57], [51], [22]. No micronutrient fertilizers, however, should be used without good reason; inorganic fertilizers are not buffered, and they are concentrated. The necessary quantities to apply are so small that uniform spreading is critical.

If these conditions are difficult to keep in mind, reconsider organic residues.

Table 16.3: **Typical Application Rates Of Micronutrient Fertilizers**

Typical Fertilizers	Application Rates	
Boron: Borax (10.6% B)	Soil application	0.5 - 1 lb boron/acre for most crops; up to 2.5 lb/acre for heavy feeders, e.g., alfalfa, beets, turnips
	Foliar spray Perennials annuals	0.2 lbs boron/100 gal water one to three weeks after petal fall spray regularly, e.g., 0.1 lb boron/100 gal water weekly for eight weeks.
Copper: Copper sulfate (25-35% Cu), copper oxide (75% Cu)	Soil application	2 - 6 lbs copper/acre; double this or more for muck soils.
	Foliar spray	0.8 lbs copper/100 gal water
Iron: ferrous sulfate (19% Fe), NaFe-EDDHA (6% Fe), NaFe-EDTA (5-14% Fe)	Foliar spray	3% solution of ferrous sulfate, possibly including a wetting agent, at a rate of 120 - 180 gal/acre, started when deficiency symptoms begin and continued at 2-week intervals until they disappear
Manganese: manganous sulfate (26-28% Mn), Mn-EDTA (12% Mn)	Soil application	5 - 10 lbs inorganic manganese/acre, banded; broadcast application is much less effective
	Foliar spray	0.5 - 1 lb manganese/100 gal water, either inorganic or chelated, repeated two or three times.
Molybdenum: Ammonium or sodium molybdate	Seed treatment	0.25 - 0.5 lbs molybdenum/acre.
	Soil application	lime usually helps; 0.02 - 0.4 lbs molybdenum/acre.
Zinc: Zinc sulfate (23-35% Zn)	Soil application	2 - 20 lb zinc/acre
	Foliar spray (rare)	0.125 - 2.2 lbs zinc/100 gal water, sprayed regularly until the deficiency symptoms disappear

Part IV
Appendices

Appendix A

Conversion Factors

Approximate Densities

Animal manure

Horse: 40 lb/bu, or 800 lb/cubic yard

Broiler: 50 lb/bu, or 1000 lb/cubic yard

Other manures: 80 lb/bu, or 1700 lb/cubic yard

Compost: about 50 lb/bu, or 1000 lb/cubic yard

Hay: a bale 14 inches by 20 inches by 32 inches weighs about 40 lbs

Sawdust: 15 lb/bu, or 300 lb/cubic yard

Wood ashes: 30 lb/bu, or 600 lb/cubic yard

Peat moss (compressed): 25 lb/bu, or 500 lb/cubic yard

Soil, 6-8 inches deep (plowdepth layer): 1000 tons/acre, or 50 lb/sq ft

Fertilizer Units

1 cubic yard = 21.7 bushels

1 bushel = 8 gallons (dry) = 9.3 gallons (liquid)

1 acre = 43,500 sq ft

To convert from percent nutrient content to lbs/ton, multiply by 20

example: 1% = 20 lbs/ton.

To convert from percent to ppm (parts per million), multiply by 10,000

example: 0.01% = 100 ppm.

To convert from ppm to lbs/ton, divide by 500

example: 10 ppm = 0.02 lbs/ton.

To convert from ppm to lbs/acre, multiply by 2 (for soil of average density)

example: 50 ppm = 100 lbs/acre.

1 lb Calcium (Ca) = 1.40 lbs calcium oxide (CaO)

1 lb Calcitic limestone ($CaCO_3$) = 0.56 lbs calcium oxide

1 lb Magnesium (Mg) = 1.66 lbs magnesium oxide (MgO)

1 lb Phosphorus (P) = 2.23 lbs phosphate (P_2O_5)

1 lb Potassium (K) = 1.20 lbs potash (K_2O)

Appendix B

The Energy Index

Most of the energy in organic residues is associated with the carbon. It is released when the carbon is oxidized:



This energy amounts to about 370 BTU/mole of carbon (The heat of formation of CO_2 is -94,000 gram calories/mole, and each BTU of energy is equivalent to 252 gram calories).

The organic component of residues is approximately half carbon. Since a ton is equal to 2000 lbs, each 1% of organic matter is equivalent to 10 lbs of carbon per ton of residues. One pound is equal to 454 grams. The formula weight of carbon is 12, so 10 lbs of carbon is 4540 grams, or $4540/12 = 378$ moles of carbon. Thus the energy from the carbon in each 1% of organic matter contains (378 moles) X (370 BTU/mole), or about 140,000 BTU per ton of residues. This is also the energy in one gallon of #2 heating oil. So each 1% of organic matter in organic residues contains the same energy as one gallon of heating oil/ton of residue.

Humus contains about 58% carbon, more than the organic matter of fresh residues. Consequently each 1% of humus contains as much energy as about 1.2 gallons of fuel oil/ton of soil. One acre of soil of thickness about 6 - 8 inches (a plowdepth layer) weighs about 1000 tons. Hence the energy in each 1% of humus in a plowdepth layer contains as much energy as about 1200 gallons of fuel oil/acre.

Appendix C

Acid And Basic Fertilizers

Fertilizers may alter the soil pH by either adding or removing acidity in the soil. The degree to which the pH changes is determined by **cation exchange**, in which an equivalent amount of one cation is exchanged for an equivalent amount of another.

C.1 Cation Equivalents

Cation exchange is an electrostatic phenomenon. It arises from an attraction between positively charged cations and negatively charged soil particles, or micelles. The soil particles may be either clay or organic matter. Exchange occurs in the displacement of cations of one species by those of another. Of the major cations, hydrogen and potassium have a charge or valence of +1, calcium and magnesium a valence of +2, and aluminum a valence of +3. A micelle has a high negative charge and attracts many cations. A calcium ion will neutralize two of those negative charges, potassium only one. Hence if the calcium drifts away from the micelle, its place can be occupied by two potassium ions or two hydrogen ions or one magnesium ion.

A mole is a unit of measure denoting a fixed number of ions, about 0.6 trillion trillion (known as Avogadro's number). A mole of potassium ions has the same number of ions as a mole of magnesium ions. The conversion factor that relates the weight of a cation to the number of moles is the formula weight, which is the same as the atomic weight for chemical elements. The number of moles of a cation is equal to the actual weight divided by the formula weight. Calcium has a formula weight of 40, and so the conversion factor for calcium is 40 gm/mole. Thus, 1000 grams of calcium contains $(1000 \text{ gms}) / (40 \text{ gms/mole}) = 25$ moles.

A mole, however, is not a good unit of measure. In **cation exchange**, a mole of potassium ions will not displace a mole of calcium ions; since it has only half as much electrostatic charge of calcium, the potassium will only displace half a mole of calcium. A better unit of measure is an equivalent. One equivalent of potassium ions will displace one equivalent of calcium ions. The number of equivalents of a cation is the number of moles multiplied by the ionic valence. So 1000 grams of calcium is 25 moles, or 50 equivalents.

C. ACID AND BASIC FERTILIZERS

If a fertilizer has a liming effect, it is able to neutralize some of the acidity in the soil. We can determine the liming value by calculating the number of equivalents of hydrogen which are neutralized. If the fertilizer has an acidifying effect, we can calculate the number of equivalents of hydrogen which the fertilizer adds to the soil.

C.2 Liming Fertilizers

Limestone

Since calcitic limestone is the most common material for neutralizing acid soil, it will be the reference. The calculations are easier with negligible error by assuming that it is pure calcium carbonate.

In neutralizing acidity, the carbonate in limestone reacts with hydrogen:



The calcium replaces the hydrogen at a **micelle**. Since one molecule of limestone reacts with two of hydrogen, and since a mole of limestone and a mole of hydrogen ions contains the same number (Avogadro's number), it follows that one mole of limestone neutralizes two moles of hydrogen.

The formula weight of calcium carbonate is 100 grams/mole. One pound of limestone, or 454 grams, contains 4.54 moles. One pound of limestone will then neutralize 4.54×2 , or about 9 equivalents of acidity.

Wood Ashes

The liming value of wood ashes is in its oxides and carbonates. Since this is only an estimate, we can assume that all of the calcium, magnesium and potassium exist as oxides.

Most ashes contain 30-35% calcium oxide, 3-4% magnesium oxide, and 3-8% potassium oxide. Assume average values: 32.5% calcium oxide, 3.5% magnesium oxide, and 5% potassium oxide. From the conversion factors in appendix A, the ashes have 23.2% calcium ions, 2.1% magnesium ions, and 4.1% potassium ions.

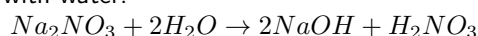
One pound of wood ashes, or 454 grams, then contains 105 grams of calcium ions, 9.5 grams of magnesium ions, and 18.6 grams of potassium ions. The formula weights of calcium, magnesium and potassium are 40, 24 and 78 grams/mole, respectively, and their ionic valences are +2, +2, and +1, respectively. The liming equivalents of one pound of average ashes is then, approximately:

$$\begin{array}{l} \text{Calcium: } (105 \text{ gms}) * (2 \text{ equiv/mole}) / (40 \text{ gms/mole}) = 5.3 \text{ equivalents} \\ \text{Magnesium: } (9.5 \text{ gms}) * (2 \text{ equiv/mole}) / (24 \text{ gms/mole}) = 0.8 \text{ equivalents} \\ \text{Potassium: } (18.6 \text{ gms}) * (1 \text{ equiv/mole}) / (78 \text{ gms/mole}) = 0.1 \text{ equivalents} \\ \hline \text{Total} = 6.2 \text{ equivalents} \end{array}$$

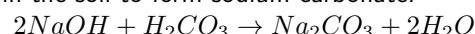
One pound of wood ashes neutralizes about 6 equivalents of acidity. Since one pound of limestone neutralizes 9 equivalents of acidity, a pound of ashes has the same liming value as about $2/3$ pounds of limestone.

Sodium Nitrate

Experience shows that sodium nitrate has a liming effect, but the reason is not clear, because sodium nitrate is a neutral salt. Sodium ions have an alkaline effect, forming sodium hydroxide with water, and nitrate ions have an acidifying effect, forming nitric acid with water:

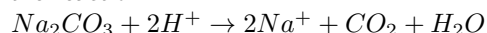


One possible explanation for an imbalance is that the sodium hydroxide reacts with carbonic acid in the soil to form sodium carbonate:



Sodium carbonate has a low solubility. What may be happening is that while the nitrate ions are taken up by plants or organisms or lost by leaching or denitrification, the associated hydrogen ions leach from the soil, and the sodium carbonate remains behind [94, page 340].

If this does occur, the sodium carbonate eventually dissolves and has a liming effect according to the reaction:

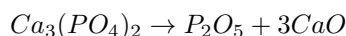


Each mole of sodium ions replaces one mole of hydrogen ions. Since sodium nitrate contains one sodium ion, a mole of sodium nitrate should lead to the neutralization of one mole of hydrogen ions. Sodium nitrate has a formula weight of 85, and so a pound (454 gms) contains about 5.3 moles, and it can neutralize 5.3 equivalents of acidity. Since one pound of limestone neutralizes about 9 equivalents of hydrogen ions, one pound of sodium nitrate should have a liming capacity somewhat more than 1/2 pound of limestone.

According to the official method for determining the acidifying effect of fertilizers, the liming value of sodium nitrate is actually about 1/3 pound of limestone for each pound of sodium nitrate [61, page 178]. In the absence of any other plausible hypothesis to explain the liming effect of sodium nitrate, this model gives a reasonable explanation, except perhaps that a significant fraction of the nitrate and hydrogen ions remain in the soil.

Bone Meal and Rock Phosphate

The claim sometimes made for the liming capability of rock phosphate is exaggerated. It is based on an artificial chemical reaction splitting tricalcium phosphate into two products:



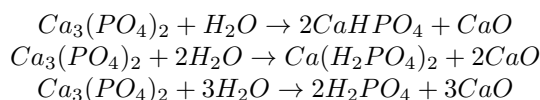
There are several problems with this:

- rock phosphate is not tricalcium phosphate but rather a complex mixture which includes either fluoride, chloride or hydroxyl; in order to account for these variations, the chemical formula may be written as $Ca_5(PO_4)_3(F, Cl, OH)$.
- tricalcium phosphate is stable and doesn't split spontaneously
- P_2O_5 is not part of any normally occurring reaction: it is prepared by igniting pure phosphorus, which doesn't exist naturally by itself.

C. ACID AND BASIC FERTILIZERS

Nevertheless, in an effort to at least estimate an upper bound to the liming capability of rock phosphate, it may be worthwhile to assume that it is indeed tricalcium phosphate.

Tricalcium phosphate can react with water in three different ways to produce calcium oxide:



The first reaction produces dicalcium phosphate, whereby one of the calcium moles has a liming effect; the second produces monocalcium phosphate with two moles of calcium having a liming effect; and the third phosphoric acid with all three moles of calcium having a liming effect.

In practice, all three reactions should take place to some extent. But the degree to which they occur depends on the soil pH. Dicalcium phosphate predominates when the soil is alkaline, monocalcium phosphate when the soil is acidic, and phosphoric acid only when the soil is extremely acidic. The last condition is unlikely in agricultural soils, and we shall ignore the phosphoric acid option.

At a pH of 7, monocalcium and dicalcium phosphate exist in approximately equal amounts. If liming were necessary at a pH of 7, the net liming capability of one mole of the combination would be equivalent to about 1-1/2 moles of lime. So at a pH where lime is advisable, the liming value of the mixture of phosphates should lie in the range between 1-1/2 and 2 moles of lime; maybe a reasonable value is the average, or 1-3/4 moles.

Since a mole of tricalcium phosphate contains three moles of calcium, the portion of calcium contributing to a liming effect is 1-3/4 / 3, or about 60%.

Colloidal rock phosphate has a stated CaO content of about 20%. From Appendix A, the actual calcium content is 20 / 1.4, or about 14%. Of this, 60%, or about 8% of the calcium, should be associated with a lime value. A pound of colloidal phosphate then contains 454 X 0.08, or about 36 grams of calcium having a liming value. Since the formula weight of calcium is 40 and its ionic valence 2, one pound of colloidal rock phosphate neutralizes 36 X 2 / 40 = 1.8 equivalents of acidity. Thus a pound of colloidal phosphate has a liming value of almost 1/5 pound of limestone. A normal application rate of 1 ton/acre will supply the equivalent of about 400 lbs of limestone/acre. As stated above, however, this is an upper limit; some of the calcium is associated with one or more of the variables in apatite - most likely fluoride, which is common in colloidal phosphate from Florida, a principal source in the U.S.

Hard rock phosphate may have a stated CaO content of about 35%. A similar calculation predicts a liming value - also an upper limit - of about 1/3 pound of limestone.

Bone meal does contain limestone. Theoretically, 1/4 of its calcium is in limestone and 3/4 in tricalcium phosphate. If bone meal has a specified CaO content of 28%, 7% should be in the form of limestone and 21% of tricalcium phosphate. With this division, one pound of bone meal has a liming value similar to that of hard rock phosphate, or about 1/3 pound of limestone.

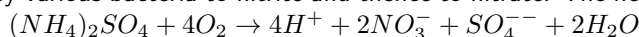
Magnesia

Magnesia is magnesium oxide. We can determine its liming value using the same reasoning as we did for wood ashes, because in that example we assumed that wood ashes contain 3.5% magnesium oxide. Now consider a pound of magnesium oxide, or 454 grams. The number of equivalents in a pound is $454 \text{ gms} \times 2 \text{ equiv/mole} / 24 \text{ gm/mole}$, or 38 equivalents. Then one pound of magnesia should have the same liming value as approximately 4 pounds of limestone.

C.3 Acidifying Fertilizers

Ammonium Sulfate

Chemically, ammonium sulfate is a neutral salt. In soil, however, the ammonium is oxidized by various bacteria to nitrite and thence to nitrate. The net reaction is:



One mole of ammonium sulfate produces 4 moles of hydrogen ions.

The formula weight of ammonium sulfate is 132 gm/mole. One pound of ammonium sulfate contains 3.44 moles. Since each mole of ammonium sulfate produces 4 moles of hydrogen ions, one pound of ammonium sulfate will produce $3.44 \times 4 = 13.8$ equivalents of acidity. So each pound of ammonium sulfate theoretically requires about 1-1/2 pounds of limestone to neutralize its acidity.

According to the official method used to determine the acidifying effect of fertilizers, one pound of ammonium sulfate requires only 1.1 pounds of limestone to neutralize it [61, page 178]. So something else is also occurring which remains unknown (at least to me; maybe the oxidation of nitrite is more complex than is assumed in the above chemical reaction).

Muriate of Potash (Potassium Chloride)

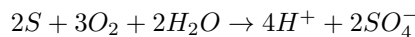
Theoretically, potassium chloride is a neutral salt; it should not affect the soil pH. Whether it actually does is a matter of opinion. The official method used to determine the acidity of fertilizers predicts that potassium chloride has no acidifying effect, but in the field an effect has been noticed.

Potassium chloride has a potential to acidify a soil wherever leaching is prominent. The potassium is absorbed by the plant or fixed in the soil, and the chloride leaches out, taking with it any available cations, principally calcium and magnesium. Their place at the **cation exchange micelle** is taken up by hydrogen and aluminum; the result is a drop in the soil pH. This activity is, in fact, the predominant way in which soils in humid areas become acid, so it is a reasonable model for estimating the acidifying effect of muriate of potash.

Potassium chloride has a formula weight of about 75 grams/mole. One pound of potassium chloride then contains about 6 moles, and each mole produces one equivalent of acidity. So a pound of muriate of potash has a potential acidity which can be neutralized by about 2/3 pounds of limestone.

Sulfur

Soil bacteria oxidize sulfur with a net reaction:



The result is a release of two hydrogen ions for each sulfur atom.

The formula weight of sulfur is 32. One pound contains 454 / 32, or about 14 moles, and produces 28 equivalents of acidity. The only reason for adding sulfur to the soil in substantial quantities is to neutralize excessive quantities of limestone. Sulfur is sometimes dusted on trees as a fungicide, but the amount usually used is too small to have a significant effect on soil acidity. One pound of sulfur will neutralize 28 / 9, or about 3 pounds of limestone.

Acid Rain

Although it may supply nitrogen and sulfur, acid rain is not usually considered as a fertilizer. Its influence on our environment, however, is of great interest, and estimating its effect on the soil should be worth the effort.

The calculation is based upon the assumption that rain is unbuffered. This means that there is no reservoir of acidity: it is all in solution. Consequently, the acidity is the hydrogen ion concentration in solution. It is related to the pH by the equation:

$$\text{acidity} = (10)^{-pH} \text{ moles/liter}$$

A neutral solution having a pH of 7 will then contain 10^{-7} , or 1/10,000,000 moles of hydrogen ions/liter. For our purpose we want to know the hydrogen ion concentration in terms of equivalents/gm of water. This can be determined, since we know that the density of water is 1 gm/ml, and one mole of hydrogen ions is equal to an equivalent of hydrogen. The result is that the hydrogen ion concentration is given by:

$$\text{acidity} = (10)^{-pH-3} \text{ equivalents/gm}$$

Consider one inch of rain. Its weight over an acre is:

$$W = 1\text{gm/cm}^3 * 2.54\text{cm/inch} * 43560\text{ft}^2/\text{acre} * (30.5\text{cm/ft})^2$$

or

$$W = 103,000,000 \text{ gm/acre per inch of rain}$$

Consequently the acidity of 1 inch of rain falling on an acre is:

$$\text{acidity} = 103 * 10^6 * (10)^{-pH-3}$$

As a reference, the liming value of limestone is 9 equivalents/pound. The limestone requirement (L.R.) to neutralize 1 inch of acid rain is

$$\text{L.R.} = 103 * 10^3 * (10)^{-pH} / 9$$

$$\text{L.R.} = 11000 * (10)^{-pH} \text{ lbs limestone/acre per inch of rain.}$$

For example, the lime requirement to neutralize rain with a pH of 4 is about 1 lb/acre/inch of rain. A season of 100 inches of this rain will need about 100 lbs of limestone/acre to neutralize it. So much acid rain is rare, but even then the resulting acidity is not much when we are accustomed to spreading a ton of limestone every few years.

The prediction that acid rain has a negligible effect on soil is due to the assumption that rain is unbuffered. It should, however, be reasonable, because otherwise the rain would contain a high content of buffering chemicals, which is unlikely.

This is not meant to infer that acid rain is not influencing our environment. There is little doubt of its impact on unbuffered lakes and streams, and it appears to affect plant foliage by direct contact. But its influence on agricultural soils should be insignificant.

Superphosphate and Triple Phosphate

In principle the acidifying tendency of synthetic phosphates can be calculated. In practice the effort is not worthwhile. Phosphate fertilizers contain several forms of calcium phosphate, each with its own chemical behavior. An experimental determination seem more feasible. I did this with a single sample of superphosphate and triple phosphate, by measuring the amount of alkali needed to neutralize a water mixture. The results were as follows:

- One pound of the superphosphate sample required about 1/5 pound of limestone to neutralize its acidity
- One pound of the triple phosphate sample required about 5 pounds of limestone to neutralize its acidity.

Apparently the triple phosphate was treated with a large excess of acid in order to increase its solubility. Note that this test was done with only one sample of each fertilizer, and the results may be not valid for all samples.

Appendix D

Compost Losses

Assume that organic matter has three components: carbon, nitrogen, and a residue:

$$O = C + N + R$$

The residue is hydrogen and oxygen (maybe also sulfur), which disappear along with the carbon; and minerals, most of which remain, except for what may leach out (such as potassium).

The presence of the minerals requires an additional parameter and complicates the calculation. Since they constitute a small part of the residues, a convenient solution is simply to ignore them. This introduces an error, but the goal is to obtain only an estimate of the loss of organic matter.

What then remains of the organic matter is:

$$O = C(1 + \gamma) + N$$
$$O = N\left[\frac{C}{N}(1 + \gamma) + 1\right]$$

where $\gamma = R / C$ is the ratio of the volatiles to carbon.

Define the initial and final carbon/nitrogen ratios:

$$\eta_0 = (C/N)_0$$
$$\eta_1 = (C/N)_1$$

The ratio of the final to initial quantity of organic matter is then:

$$\frac{O_1}{O_0} = \frac{N_1[\eta_1(1+\gamma)+1]}{N_0[\eta_0(1+\gamma)+1]}$$

Set $\beta = N_1/N_0$ (the fraction of nitrogen remaining),

$$\frac{O_1}{O_0} = \beta * \frac{\eta_1(1+\gamma)+1}{\eta_0(1+\gamma)+1}$$

Since both carbon/nitrogen ratios are much larger than 1:

$$\frac{O_1}{O_0} \approx \beta * \frac{\eta_1}{\eta_0}$$

The total amount of material in the compost pile is

$$T = M + O$$

where M is the soil (and mineral) content.

The ratio of the final to initial material is:

$$\frac{T_1}{T_0} = \frac{M+O_1}{M+O_0}$$

Let $\alpha = M / O$, the ratio of soil to the initial quantity of organic matter. Then,

$$\frac{T_1}{T_0} = \frac{\alpha * O_0 + O_1}{\alpha * O_0 + O_0}$$
$$\frac{T_1}{T_0} = \frac{\alpha + O_1/O_0}{\alpha + 1}$$

D. COMPOST LOSSES

$$\frac{T_1}{T_0} \approx \frac{\alpha + \beta * \eta_1 / \eta_0}{\alpha + 1}$$

To summarize:

- T: the total weight of the pile
- α : the ratio of the combined soil and organic mineral component to the initial organic matter - negligible in hot composting, perhaps 30 - 60% in cold
- β : the fraction of remaining nitrogen (nitrogen not lost by loss of ammonia or denitrification - probably 50% in hot composting perhaps 75 - 85% in cold composting
- η : the carbon/nitrogen ratio - usually in the range 40 - 100 initially, 15 - 30 when spread.
- the fraction of organic matter remaining: $\frac{O_1}{O_0} \approx \beta * \frac{\eta_1}{\eta_0}$

The last statement is perhaps trivial, since it does no more than confirm what we might expect intuitively: the fraction of remaining organic matter is proportional to the fraction of remaining nitrogen. But it does lend credibility to the graphs in figure 7.1.

Glossary

Glossary

aggregates Units of minerals and organic material cemented together by various actions: carbohydrates produced by bacteria, entanglement by fungal hyphae, electrostatic attraction. The result is a distribution over a wide range of sizes; small particles promote water movement by capillary action, and large sizes facilitate root growth and air flow.. [21](#), [22](#)

amino acids The building blocks of proteins. They are made up primarily from nitrogen and carbohydrates, but many also contain sulfur, phosphorus, and other minerals.. [34](#), [35](#), [117](#), [121](#)

anaerobic Without oxygen. Anaerobic conditions in the soil permit only those organisms which can use chemically bound oxygen. For example, many organisms can remove oxygen from nitrates, resulting in denitrification. Although generally undesirable, an anaerobic environment is occasionally helpful. Some nutrients, such as iron and manganese, are made more available under anaerobic conditions. Anaerobic decomposition is less efficient than aerobic, but anaerobic organisms can attack residues which are too resistant for aerobic organisms. Nitrogen fixation by free-living organisms usually occurs under anaerobic conditions; this is because the enzyme used to aid the process is sensitive to oxygen.. [61](#)

borax Sodium borate. It is available in food stores and is a suitable fertilizer for supplying boron.. [143](#)

broiler manure Manure from chickens raised to become broilers. It is usually mixed with wood chips and is drier and not as strong as cage layer manure.. [59](#)

C/N ratio An abbreviation for carbon/nitrogen ratio.. [15](#), [18](#), [19](#), [68](#), [101](#), [102](#), [118](#)

cage layer manure The unadulterated droppings from confined egg-laying hens.. [58](#), [110](#), [143](#)

carbohydrates Stabilized structures of sugars. Carbohydrates form the skeleton of the plant, and they are a means for storing energy for a long period of time.. 15, 21, 23, 56, 93, 96, 100

cation exchange A process in which the small number of cations dissolved in the soil water (soluble cations) change place with the much larger number of cations associated the soil micelles (exchangeable cations). This constant interchange establishes an equilibrium between soluble and exchangeable cations which, for example, controls the pH of the soil solution and, to some extent the availability of nutrient cations.. 17, 91, 99, 115, 117, 125, 126, 133–135, 153, 157

cation exchange capacity A measure of the ability of the soil micelles to attract cations and keep them in exchangeable form. The exchange capacity depends upon the amount of clay, the type of clay, the organic content and the degree of humification of the organic matter.. 127, 132, 134, 135, 137

CEC An abbreviation for cation exchange capacity.. 127, 130, 132

chelate The process by which an organic substance binds a cation having more than one electrical charge. Chelation is similar to cation exchange, with two differences: (1) A chelating organic substance is highly reactive and often water-soluble, while a soil micelle is unreactive and stable; (2) Chelating substances cannot bind cations with a single electrical charge, such as potassium and sodium. In practice, cation exchange holds the majority of the major cation nutrients (calcium, magnesium, potassium), while chelation holds the cation trace elements (copper, iron, manganese, zinc).. 17, 139, 142

colloidal rock phosphate A low grade form of rock phosphate, consisting primarily of a fine clay powder. It is the most commonly available rock phosphate for small farmers and gardeners.. 8, 62, 109, 156

denitrification A process by which bacteria obtain oxygen from nitrates rather than air, during which the nitrogen in the nitrates becomes volatile and escapes; see chapter 10.3 for details. 15, 18, 55, 73

energy index A term coined in chapter 2 to denote the energy equivalence, in terms of #2 fuel oil, of an organic substance. It is expressed as gallons of fuel oil per ton of an organic substance.. 101

epsom salts Magnesium sulfate. It is used as an emergency source of magnesium.. 136, 137

granular soil structure A well-structured soil, consisting of soil aggregates of varying size.. 12

humus The state of organic residues plus the remains of soil organisms at and beyond the point where the residues are no longer distinguishable as such; the agricultural benefits vary from biological and chemical (nutrient enhancements, pest and disease control) to physical (air and moisture control through a superior soil structure), depending upon the degree of decomposition and consequent stability.. 14–16, 19, 20

lignins organic residues characterized by extraordinarily strong chemical bonds among the carbon molecules; they are difficult to decompose; they can be broken down, but at a slower rate and by fewer soil organisms - mostly fungi - than other substances. 15, 16

magnesia Magnesium oxide, used as an emergency source of magnesium.. 136, 137

micelle Shorthand for micro-cell, it refers to a colloidal clay or humus particle with a large number of negative electrical charges. It attracts positively charged cations, and the collection of micelles and associated cations are the source of cation exchange.. 126, 127, 154, 157

NPK A short-hand notation for Nitrogen-Phosphate-Potash.. 25, 34, 85

pH A measure of the acidity of a liquid in logarithmic units. A neutral solution has a pH of 7. An alkaline solution has a pH greater than 7, and an acid solution a pH less than 7. The pH in soil is the pH of the water in soil; it controls the availability of phosphorus and trace elements and the diversity of soil organisms; the soil pH for most soils is in the range 5.0 to 9.0. 17, 19, 137

rotted manure Fermented manure which has been stored in a sufficiently compacted state to exclude air. 63

superphosphate The first manufactured phosphorus fertilizer, prepared originally by dissolving bones in sulfuric acid. 4

triple phosphate Rock phosphate dissolved in phosphoric acid. 4

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