Managing Nitrogen from Biosolids

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Managing Nitrogen from Biosolids

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MANAGEMENT
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Foreword

Both the art and the science of biosolids management have evolved rapidly in the last few years. As the business of biosolids management has evolved, so has the recognition that nitrogen management in biosolids and other organic byproducts is a complex proposition.

In 1993, the Washington State Department of Ecology (Ecology) published the first draft of *Biosolids Management Guidelines* (WDOE 93-80). These guidelines provided a much needed approach for determining biosolids application rates. After release of the draft, it was recognized that even more comprehensive information and guidance on biosolids nitrogen management would be useful. A strong and cooperative working relationship between Ecology, the Northwest Biosolids Management Association, and universities in the Pacific Northwest presented an ideal opportunity for compiling existing information on nitrogen in biosolids and combining it with the most current scientific knowledge on the behavior of nitrogen in the environment.

This manual, *Managing Nitrogen from Biosolids,* is the outcome of this collaboration. It is written for professionals and other persons interested in developing a comprehensive understanding of biosolids nitrogen management and learning an exacting approach to determining biosolids application rates. It does not purport to have broad applicability for management of nitrogen in residuals other than biosolids. It is hoped, however, that those managing nitrogen in other materials can find some support for their efforts in this manual. Nor is this manual considered a final and definitive work. It will be updated and improved as our knowledge of nitrogen management grows. For those with a less critical need to manage biosolids nitrogen, Ecology's *Biosolids Management Guidelines* is recommended for those in Washington state; publications approved by appropriate regulatory agencies and academic institutions are recommended for those in other states and in British Columbia.

Managing Nitrogen from Biosolids is the product of a cooperative effort between the states of Washington, Oregon, and Idaho, and the province of British Columbia, Canada. The Washington State Department of Ecology appreciates the cooperation and contributions of Dr. Charles Henry, University of Washington, College of Forest Resources; Dr. Craig Cogger, Washington State University Cooperative Extension Service; Dr. Dan Sullivan, Oregon State University; Dr. Bob Rynk, University of Idaho; Michael Van Ham, University of British Columbia; and Roberta King, King County, Washington. The support and involvement of the Northwest Biosolids Management Association are also acknowledged and appreciated.

Contents

Foreword

Chapter 1: Introduction 1.1

Chapter 2: The Nitrogen Cycle 2.1
The importance of nitrogen as a plant nutrient 2.1
Biosolids as a means to provide nitrogen and other nutrients to soils and plants 2.2
Mechanics of the nitrogen cycle 2.2
  Nitrogen mineralization and immobilization 2.4
  Ammonia volatilization 2.6
  Plant uptake 2.7
  Nitrification 2.7
  Denitrification 2.8

Chapter 3: Overview of the Nitrogen Balance Approach and Guidelines for Reducing Risks of Nitrate Leaching 3.1
Steps in the Nitrogen Balance Approach 3.1
Guidelines for reducing risks of nitrate leaching 3.3

Chapter 4: Using the Nitrogen Balance Approach for Estimating Net Plant-Available Nitrogen from Biosolids 4.1
Components of the plant-available nitrogen calculation 4.1
Mineralization rate of organic N in biosolids 4.1
Volatilization of Ammonia 4.4
Denitrification 4.6
Example plant-available nitrogen calculation 4.7
References 4.8

Chapter 5: Using the Nitrogen Balance Approach for Agricultural Systems
D. SULLIVAN 5.1
Acceptable agronomic rate ranges 5.1
Estimating plant-soil (crop) nitrogen requirement (N_{req}) 5.2
Estimating Nitrogen from Other Sources ($N_{credits}$) 5.5
Example net crop nitrogen requirement calculation 5.9
Uncertainties in estimating net crop nitrogen requirements in agricultural systems 5.9
References 5.13

Chapter 6: Using the Nitrogen Balance Approach for Forest Systems
C. HENRY 6.1
Application of biosolids to forest sites 6.1
Estimating plant nitrogen requirement (N_{req}) 6.1
Estimating nitrogen from other sources ($N_{credits}$) 6.4
Example net nitrogen requirement calculations 6.5
Uncertainties in estimating net nitrogen requirements in forest systems 6.6
References 6.8

Chapter 7: Using the Nitrogen Balance Approach for Rangelands
R. RYNK 7.1
Application of biosolids to rangelands 7.1
Determining biosolids application rates 7.3
Recommended management practices 7.4
References 7.5

Chapter 8: Overview of the Balanced Soil Amendment Approach for Mixtures of Biosolids and Carbon-Rich Residuals
C. HENRY 8.1
Results of studies on carbon-to-nitrogen ratios 8.1
Choosing an initial organic matter content and C:N ratio 8.5
Calculating application rates using the Balanced Soil Amendment Approach 8.7
Summary 8.9
References 8.9

Chapter 9: Analysis of Nitrogen in Soils and Biosolids
K. DORSEY 9.1
Preparing a sampling plan 9.2
Collecting samples 9.2
Preparing and analyzing samples 9.3
Reporting 9.5
References 9.6

Appendices
A. Glossary
B. Abbreviations & Symbols
C. Matrix Tables of Local Research Results
    Pacific Northwest biosolids Research Results: Mineralization
    Pacific Northwest biosolids Research Results: Volatilization
    Pacific Northwest biosolids Research Results: Denitrification
D. Nitrogen Mineralization Study
E. Ammonia Volatilization Study
F. Verifying Biosolids N Availability with Crop Uptake Research
G. Pacific Northwest Agricultural Biosolids Management References

List of Figures

Chapter 1

Figure 1.1. The Nitrogen Balance Approach and the Balanced Soil Amendment Approach for determining biosolids application rates 1.2

Chapter 2

Figure 2.1 Comparison of the chemical composition of a typical soil to a typical biosolids 2.2
Figure 2.2 The nitrogen cycle: inputs to soil, nitrogen transformations, and losses from soil 2.3
Figure 2.3 Nitrogen inputs to soil: atmospheric deposition, nitrogen fixing plants, and fertilization 2.4
Figure 2.4 The processes of nitrogen mineralization and immobilization from biosolids 2.6
Figure 2.5 The process of ammonia volatilization from biosolids 2.7
Figure 2.6 The change in percentage of ammonia versus ammonium in solution as the pH and temperature change 2.7
Figure 2.7 The process of nitrification, which may lead to leaching 2.8
Figure 2.8 The process of denitrification 2.8

Chapter 3

Figure 3.1 Conceptual presentation of the plant-soil nitrogen requirement 3.1
Figure 3.2 Conceptual presentation of net plant-available N 3.2
Figure 3.3 Conceptual presentation of biosolids application rate calculation 3.3

Chapter 5

Figures 5.1 Nitrogen application rates required to reach 95 percent of maximum yield (a) or 100 percent of maximum yield (b). Nitrogen response plotted as a quadratic function. Dryland soft white winter wheat, Ellensburg, WA, 1992 . . . . 5.2
Figures 5.2 Example of nitrogen deficiency, agronomic rate, and excess N ranges as demonstrated by grain N uptake and soil nitrate-N (a) and grain yield and grain N concentration (b). Dryland soft white winter wheat, Ellensburg, WA, 1992 . . . . 5.2
Figure 5.3 Plant-available nitrogen supplied by biosolids and other available nitrogen sources compared with nitrogen uptake by a silage corn crop. The difference between total nitrogen supply and crop nitrogen uptake represents a nitrogen use efficiency of 60 percent 5.12

Chapter 8

Figure 8.1 Types and general fractions of carbon compounds found in plant residues and soils 8.2
Figure 8.2 Conceptualized rate of decomposition of different organic compounds 8.3
Figure 8.3 Comparison in accumulative mass of nitrate leaching between two biosolids/paper mill fine mixtures with 12:1 and 52:1 carbon-to-nitrogen ratios 8.4
Figure 8.4 Percentage loss of organic matter in mixtures and percentage loss of total nitrogen from biosolids/paper mill fine mixtures as a function of initial carbon-to-nitrogen ratios of the mixtures 8.4
Figure 8.5 Delay in the appearance of nitrate leaching from tubes as a function of initial carbon-to-nitrogen ratios of biosolids/paper mill fine mixtures 8.5
Figure 8.6 The conceptual Balanced Soil Amendment Approach 8.5

Figure 8.7 Ideal release curve for nitrogen as a function of carbon-to-nitrogen ratio 8.6

Chapter 9

Figure 9.1 Simplified flowchart for analysis of nitrogen in biosolids and soils 9.4

List of Tables

Chapter 2

Table 2.1 Transformations and chemical reactions in the nitrogen cycle 2.5

Chapter 3

Table 3.1 Factors affecting the relative risk of nitrate leaching 3.4

Chapter 4

Table 4.1 Estimates of N mineralization rate ranges for biosolids treatment methods (percent of initial organic N) 4.3
Table 4.2 Results of field studies of N mineralization rates in Northwest biosolids (percent of initial organic N) 4.3
Table 4.3 Estimates of N mineralization rates for years following application of biosolids (percent of the remaining organic N) 4.4
Table 4.4 Ammonia volatilization rates from Northwest biosolids applied in western Washington (maritime climate) 4.5
Table 4.5 Suggested design values for ammonia loss after biosolids application to agricultural and forest lands 4.6
Table 4.6 Suggested design values for denitrification rates after biosolids application to agricultural and forest lands 4.7
Table 4.7 Example calculation of plant-available N from biosolids 4.8

Chapter 5

Table 5.1 Estimated Nitrogen uptake per unit of above-ground harvested biomass for crops used for biosolids application 5.5
Table 5.2 Worksheet for estimating net crop N requirement for grass silage and winter wheat crops 5.10
Table 5.3 Plant-available nitrogen throughout the growing season (May-September) for a silage corn crop planted May 15 with biosolids applied on April 15 at a rate of 400 lb/ac total nitrogen 5.11

Chapter 6

Table 6.1 Suggested design values for nitrogen uptake for forest trees and understory of fully established and vigorously growing forest ecosystems in Washington 6.3
Table 6.2 Suggested design values for nitrogen immobilization in soils from biosolids applied to forest systems 6.4
Table 6.3 Example estimate of biosolids N to be mineralized in 1996 based on estimated mineralization rates for 3 years prior to 1996 . . . . 6.5
Table 6.4 Example estimate of residual soil nitrate 6.5
Table 6.5 Example of calculation of first-year biosolids application rates for Douglas-fir stands of three different ages 6.7
Table 6.6 Nitrogen requirements and application rates for biosolids application to hybrid poplar and young Douglas-fir plantations 6.8

Chapter 8

Table 8.1 C:N ratios of different kinds of mature compost and their corresponding raw materials 8.3

Table 8.2 Recommended initial carbon-to-nitrogen ratios for mixtures of biosolids and carbon-rich residuals for use as soil amendments 8.7
Table 8.3 Application rates for biosolids/C-rich residual mixtures with initial C:N ratios of 30:1 and 40:1 and a 10 percent initial organic matter content compared with application rates for biosolids only 8.9

Chapter 1

Introduction

Nitrogen (N) has traditionally been considered one of the most important nutrients for plants. It can increase plant growth and crop yield. Because most soils are often deficient in the type of N that plants can readily use, chemical fertilizers or organic "residuals" such as manure or biosolids are added annually to agricultural soils and are increasingly being added to forest soils.

The amount of N in biosolids is relatively high, making it an attractive fertilizer. In fact, biosolids application rates must be carefully calculated to avoid adding too much N, which can leach out of the soil in the form of nitrate and degrade the environment. Seldom have trace applications of biosolids posed problems from trace metals, such as cadmium, copper, nickel, and zinc, whereas such heavy applications will invariably cause nitrate leaching. Many studies have documented this.

Determination of proper biosolids application rates depends on a number of factors. In situations where there are small quantities of biosolids, large amounts of land available for biosolids application, and no goals for maximum crop yields, application rates can be conservative. In situations where there are large quantities of biosolids and limited available application areas, relatively minor adjustments in assumptions about the behavior of N in the environment can determine whether a potentially costly and time-consuming process must be undertaken to identify additional application sites. In situations that include maximum crop yield goals, the determination of an appropriate application rate is critical.

Other aspects of managing N from biosolids must also be considered, including the behavior of N in compost products and the management of excess N in areas where high application rates of biosolids are used in land reclamation.

A great deal of research has focused on N management and the accurate design of biosolids application rates. The purpose of this manual is to present the most current knowledge on the behavior of N in the environment and to provide guidelines on how this knowledge can be used in biosolids application projects. Specific objectives are as follows:

- To increase the understanding of what happens to N after the land application of biosolids, so that the effects of specific biosolids types, management strategies, and site conditions can be better predicted
- To provide methods for designing site-specific biosolids application rates for agricultural, forest, and rangeland systems and for making assumptions based on local research results
- To provide a common tool to assess biosolids application and management designs for those involved in review or approval of biosolids land application projects

This manual presents two basic approaches for determining biosolids application rates (Figure 1.1). The majority of the manual (Chapters 3 through 7) focuses on the Nitrogen Balance Approach, which relies on the processes (transformations and losses) that occur in the nitrogen cycle, as described in Chapter 2. The objective of this approach is to match available N in the biosolids and the soil to the amount of N that plants need. In contrast, the Balanced Soil Amendment Approach (Chapter 8) is concerned more with the soil amendment properties of the biosolids than with their fertilizing properties. Its objective is to increase the organic matter of the soil by adding a mixture of biosolids and a carbon-rich residual (such as sawdust). The excess N added from the biosolids can be immobilized by the carbon-rich residual. Compared to the Nitrogen Balance Approach, the Balanced Soil Amendment Approach is a new concept that requires more fine tuning in the field to verify application rates. The final chapter (Chapter 9) of this manual provides recommended methods for laboratory analysis of N in biosolids and soils.

Just as the nature of N is dynamic—it is constantly changing in form—this manual is a growing document that will change as new information emerges from continuing research.

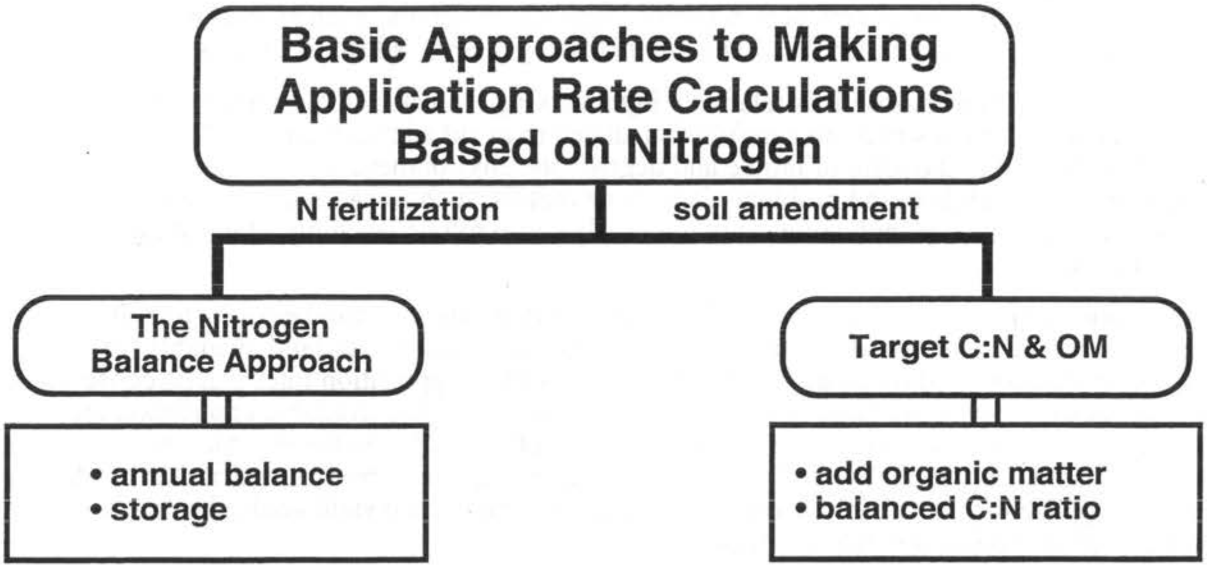


Figure 1.1 The Nitrogen Balance Approach and the Balanced Soil Amendment Approach for determining biosolids application rates.

Chapter 2

The Nitrogen Cycle

Plants need at least seventeen elements to grow. Three of these elements—carbon, oxygen, and hydrogen—are referred to as "building blocks." Plants get these elements from air and water. The other fourteen elements, such as nitrogen, potassium, and phosphorus, are referred to as "nutrients." Plants usually get nutrients from the soil.

Nitrogen has traditionally been considered one of the most important plant nutrients. This chapter describes the importance of nitrogen as a plant nutrient, the role that biosolids can play in providing nitrogen and other nutrients to enhance soils and crop yields, and the mechanics of the naturally occurring nitrogen cycle as they relate to biosolids application.

The importance of nitrogen as a plant nutrient

Nitrogen gas comprises about 78 percent of the earth's atmosphere. Nitrogen (N) in various forms is also found in rocks, soils, sediment, oceans, and living matter. Growing plants, animals, and microbial populations need a continual source of N. It is an essential component of the proteins that build cell material and plant tissue. In addition, it is necessary for the function of other essential biochemical agents, including chlorophyll (which makes photosynthesis possible), many enzymes (which help organisms carry out biochemical processes and assimilate nutrients), and nucleic acids such as DNA, RNA (which are involved in reproduction). Most microorganisms and plants obtain N from the surrounding soil and water. Animals get N from the food they eat. A few organisms obtain N directly from the pool of nitrogen gas (N_2) in the atmosphere, but this requires the organism to expend energy.

Of all the major plant nutrients, N is often the most important determinant of plant growth and crop yield. Plants lacking N show stunted growth and yellowish leaves. Plant growth and crop yield usually increase when N is added, despite the presence of N in soils. This is because most of the N in soils is stored within the soil humus in forms that plants cannot access. Chemical fertilizers add N in forms that plants can use immediately or after a brief conversion. Organic materials such as manure, biosolids, and compost add some readily available N, but most of the N in these materials is contained in organic compounds that must decompose before plants can use the N. Although some of the decomposition occurs relatively quickly (within a year), most of the organic N takes years to change into plant-available forms. In the meantime, microorganisms in the soil assimilate and convert some of the N released through decomposition back into unavailable organic forms that are eventually incorporated and stored within the soil humus.

Just as too little N can cause problems, too much N can also cause problems. These problems can extend to plants, humans, animals, and the environment. For example, in plants, too much N can produce weak stems in grain crops (lodging), reduce quality in fruit such as peaches and apples, and lower sugar content in sugar beets. Excess N can lead to an accumulation of nitrate in the edible foliage of plants such as spinach and forage crops. Ingestion of such high-nitrate foods can pose possible health risks for animals and humans.

The problems posed to the environment occur when excess N in soils is carried away with surface runoff and water moving through soils and then finds its way to water and other ecosystems, which can also receive N from precipitation. Most of this N is in soluble forms, such as nitrate and ammonium. N entering lakes, streams, and other surface water changes the character of the water body and contributes to its accelerated aging, or "eutrophication." In this process, the N increases the growth of algae and aquatic vegetation, which create aesthetic problems and deplete the oxygen content of the water as they eventually die and decompose. Much of the N from the decomposed algae and aquatic vegetation remains in the water to nourish new organisms, thus continuing the cycle of growth, decomposition, and oxygen depletion.

High levels of ammonium are toxic to fish and use up dissolved oxygen in the water as the ammonium converts to nitrate. Nitrate poses a particular environmental concern because of its mobility. Nitrate readily moves with water moving through soils. It can contaminate groundwater to the point at which it becomes a health risk (10 ppm). The primary health concern is methemoglobinemia (called the "blue baby" syndrome). Human infants and some animals are especially susceptible. In this condition, the digestive system reduces nitrate to nitrite, which interferes with the blood's ability to carry oxygen.

Biosolids as a means to provide nitrogen and other nutrients to soils and plants

If appropriate calculations are made and proper management practices are observed, biosolids can provide a viable means to enhance soil and plant N. Biosolids contain N and all of the other nutrients necessary for plants to grow—and in fairly well balanced ratios compared to what plants need. As can be seen in Figure 2.1, the amount of N in biosolids is relatively high compared to the amount of N in the soil.

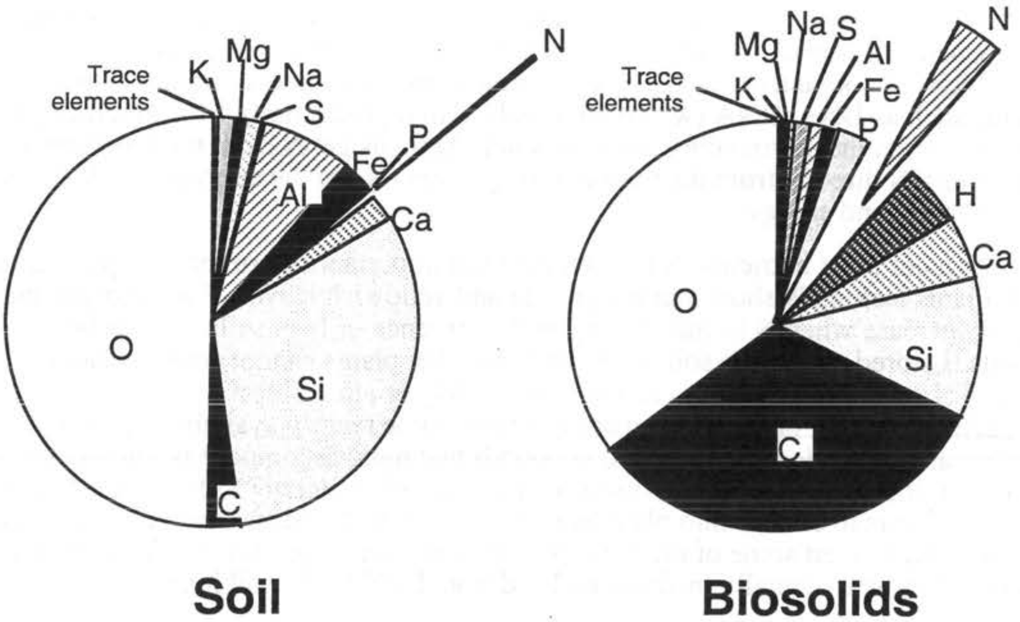


Figure 2.1. Comparison of the chemical composition of a typical soil to a typical biosolids.

Mechanics of the nitrogen cycle

N occurs in several chemical forms, sometimes referred to as "oxidation states." These forms vary greatly not only in their characteristics—from the proteins of solid organic matter to gaseous ammonia—but also in the way they behave. These forms are classified as either organic or inorganic N. Organic forms of N are found in compounds such as amino acids, protein, and more resistant N compounds (ultimately, humus). Inorganic forms include ammonium (NH_4^+), ammonia (NH_3), nitrate (NO_3^-), and nitrite (NO_2^-). Inorganic forms of N are the "available" forms that plants and microorganisms can use or that can move in the soil as water moves through it. Most N in the soil is in the unavailable organic form. This is N that has been taken up by plants or other organisms and then incorporated into soil organic matter when the plants die and decompose. In biosolids, the majority of N added to the soil is in organic forms; the remainder is in inorganic forms (NH_4^+ and NO_3^-).

Many forms of N are present in any environment at any point in time, mainly because N readily shifts from one form to another. NO_3^-, NH_4^+ and N_2 can be converted to organic N (ON) by plants and microorganisms; ON can be converted back to inorganic forms as the organic compounds decompose. N can also shift between inorganic forms (for example, NH_3 to NH_4^+ or NO_3^- to N_2). These shifts occur as nature attempts to establish an equilibrium among the various forms as environmental conditions change. N in the soil interacts with the atmosphere, soil particles, soil solution (the water that surrounds or moves through the soil), microorganisms, and plants. If a new source of N is added to alter the balance or if environmental conditions (such as temperature and moisture) change, N transformations take place. Because environmental conditions are constantly changing, N transformations are constantly occurring. This continual movement of N from one form to another is known as the "nitrogen cycle."

The nitrogen cycle both affects and is affected by living organisms (Figure 2.2). N compounds created by biological activity are eventually available for later use by other organisms. N enters the soil from a variety of sources. Unlike other nutrients, only a small amount of N is contributed from the mineral part of the soil (i.e., rocks). Most naturally occurring N enters the soil either as NO_3^- or NH_4^+ in rainfall (atmospheric deposition) or by special plants, such as alfalfa, ceanothus, and red alder, that are called "nitrogen fixers" (Figure 2.3). Humans also increase the N in soils by fertilizing with either chemical or organic fertilizers. Once in the soil, the N will transform through the processes of mineralization, immobilization, volatilization, nitrification, denitrification, and plant uptake. Two of these transformations—volatilization and denitrification—result in losses of N from the soil. N is also lost through leaching and runoff.

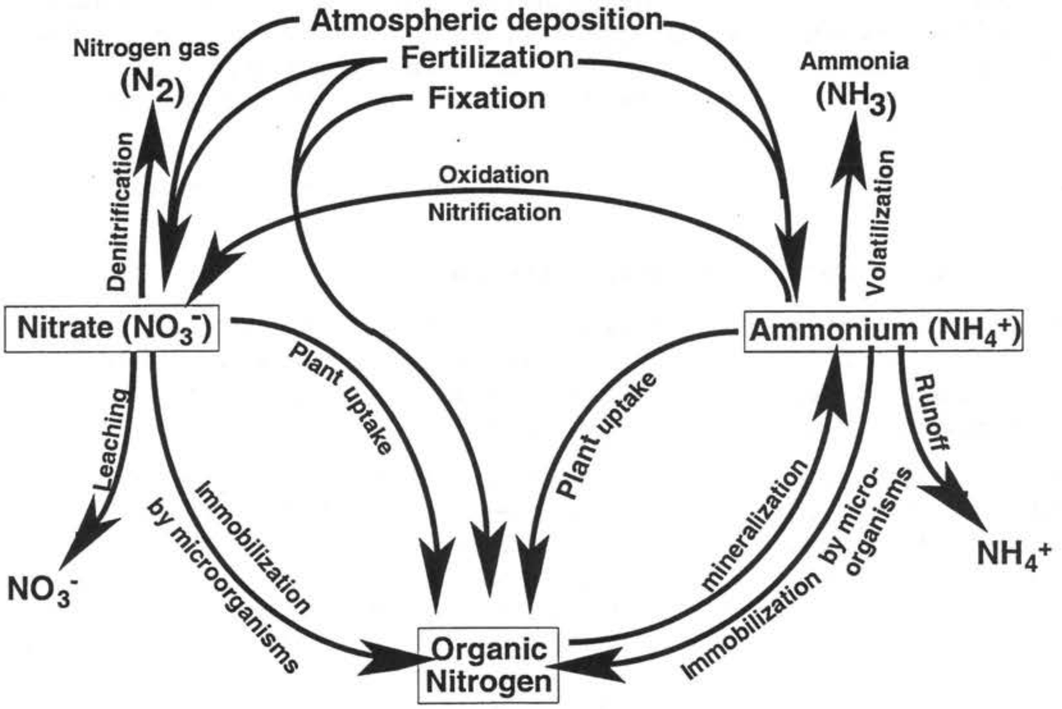


Figure 2.2. The nitrogen cycle: inputs to soil, nitrogen transformations, and losses from soil.

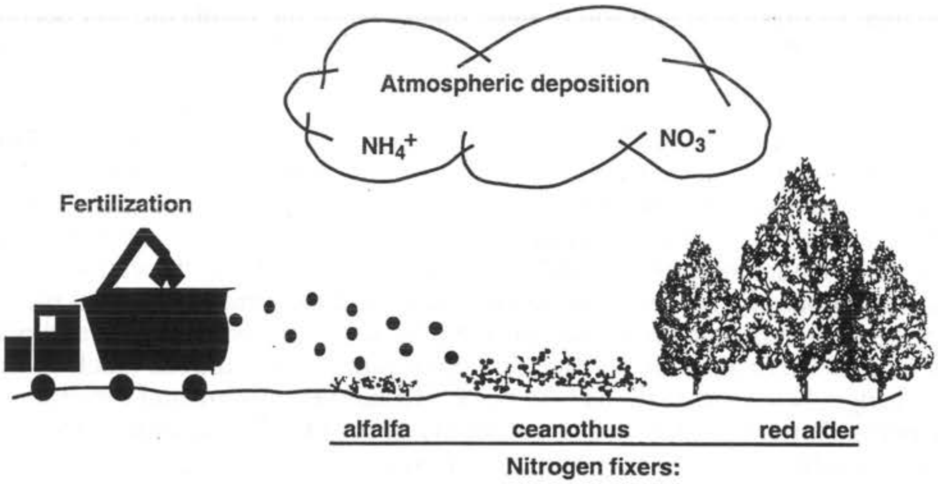


Figure 2.3. Nitrogen inputs to soil: atmospheric deposition, nitrogen fixing plants, and fertilization.

Because most of the transformations and losses are caused by microbial action, all the processes are slowed down considerably when temperatures are low. For example, for each decrease of 18°F in the soil temperature, microbial action decreases by about half. At about 40°F, microbial action is fairly slow. Through much of the winter, the average soil temperature is at or below this temperature, especially under forest stands in Washington; therefore, mineralization, nitrification, and denitrification are very slow. The nutrients from applications made during the winter will essentially be stored in the forest floor and soil layers until temperatures increase. Significant NO_3^- leaching will not occur from winter applications because NO_3^- generally will not be formed. Only NO_3^- present in the soil at the time of application will be lost. Although this inactivity can also be the case in agricultural soils, winter sunshine can warm up the surface of the soil enough for short periods to allow some transformations to occur. If there is no corresponding plant uptake, NO_3^- leaching can occur.

The various transformations are shown in Table 2.1 and then described in the following sections.

Nitrogen mineralization and immobilization

Mineralization of N occurs when the organic matter in biosolids decomposes (Figure 2.4). The soil microorganisms break organic bonds to obtain energy. When the organic matter is completely broken down (oxidized), carbon dioxide (CO_2), water (H_2O), and minerals are left. The inorganic (available) form of N resulting from decomposition is NH_4^+.

The rate of decomposition and release of available N depends on the nature of the N compounds, which are greatly influenced by the type of treatment or stabilization process the biosolids receive, the duration of the process, and the type of organic matter in the biosolids. Decomposition is slower when the biosolids are more stable. Typical N mineralization rates for the first year range from 0 to 60 percent of the ON. Decomposition is not complete in the first year. It continues during the next few years at progressively slower rates. Some of the N is retained in stable organic matter (such as humus), which continues to mineralize very slowly. As much as half of the ON in some biosolids may remain stable for decades.

Table 2.1. Transformations and chemical reactions in the nitrogen cycle.

Transformation	Chemical Reaction	Description
N fixation	$0.5N_2 \rightarrow R\text{-}NH_2$	Plants and some microorganisms use N_2 from the air and convert to ON in a symbiotic relationship with microbes
N mineralization	$R\text{-}NH_2 + H_2O + H^+ \rightarrow R\text{-}OH + NH_4^+$	Transformation of organic N to inorganic N (NH_4^+) as microorganisms decompose organic matter.
N immobilization		Transformation of inorganic N to organic N as microorganisms incorporate N into their cell structures or soil humus during the decomposition process
From NO_3^- (first step)	$NO_3^- + 2e \rightarrow NO_2^- + 6e \rightarrow NH_4^+$	
From NH_4^+	$NH_4^+ + R\text{-}OH \rightarrow R\text{-}NH_2 + H_2O + H^+$	
NH_3 volatilization		Loss of ammonia (NH_3) from soil water to air
First stage (in water)	$NH_4^+ \rightarrow NH_{3(aq)} + H^+$	
From water to air	$NH_{3(aq)} \rightarrow NH_{3(air)}$	
Nitrification		Transformation of ammonium (NH_4^+) to nitrite (NO_2^-) nitrate (NO_3^-) by microorganisms
By *Nitrosomonas*	$NH_4^+ + 1.5O_{2(aq)} \rightarrow NO_2^- + H_2O + 2H^+$	
By *Nitrobacter*	$NO_2^- + .5O_{2(aq)} \rightarrow NO_3^-$	
Denitrification		Transformation of nitrate (NO_3^-) to nitrogen gases (N_2 or N_2O)
To N_2	$NO_3^- + 1.25[HCHO] \rightarrow 0.5N_2 + .75H_2O + 1.25CO_2 + OH$	
To N_2O	$NO_3^- + [HCHO] \rightarrow 0.5N_2O + .5H_2O + CO_2 + OH$	

R = organic compound.

Often N released from biosolids organic matter may be taken up by soil microorganisms and converted back to organic forms. This process is called "immobilization" (Figure 2.4). When biosolids are applied, the available N allows microbial populations to expand rapidly and decompose the soil organic matter, temporarily locking up the N in microbial biomass or in long-term stable humus. The N incorporated into the cell structure of the microorganisms will be released gradually as the microorganisms die and decompose. Immobilization generally occurs in nutrient-poor soils, in soils with a lot of matter that is low in N and high in carbon (such as woody material or straw), or in soils where organic amendments (such as sawdust or low-N compost) have been added.

The carbon-to-nitrogen (C:N) ratio is often used as an indication of whether mineralization or immobilization will occur. The C:N ratio is the total concentration of C divided by the total concentration of N. When surface soil layers have a C:N ratio greater than 30:1, then immobilization is highly likely to occur. This is because microorganisms need N to assimilate the available C. When the C:N ratio is below 20:1, N mineralization is likely to occur. When the C:N ratio is between 20-30:1, both mineralization and immobilization may occur but they will generally balance.

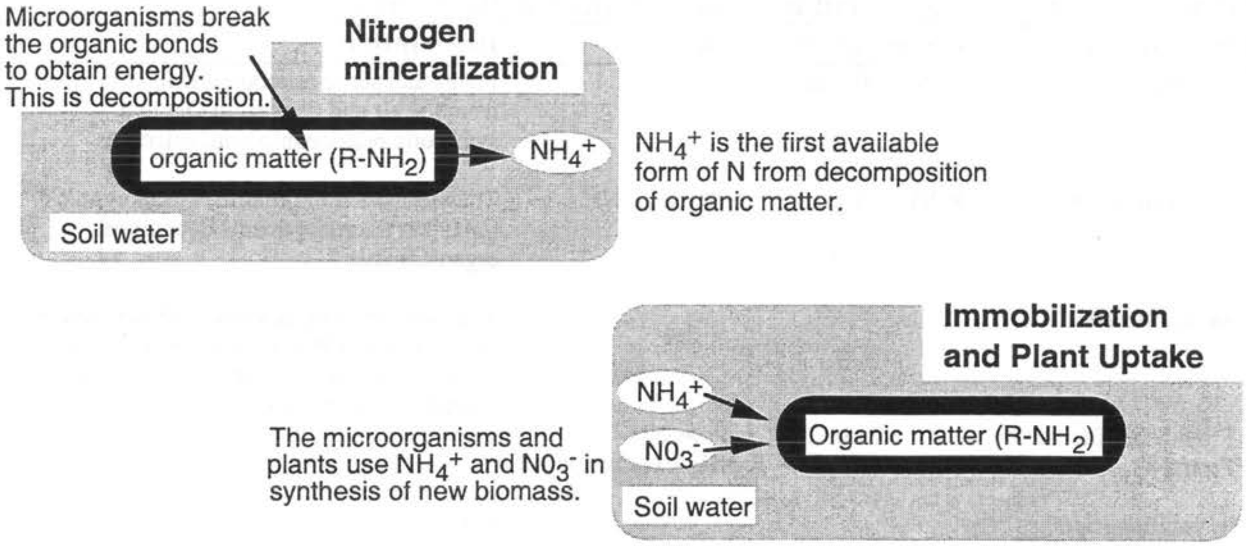


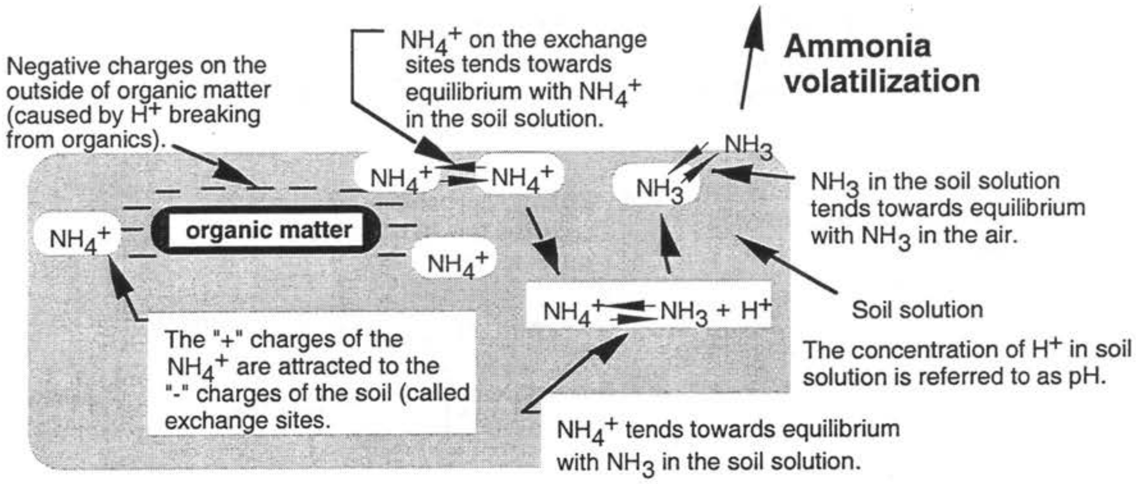
Figure 2.4. The processes of nitrogen mineralization and immobilization from biosolids.

Ammonia volatilization

The potential for loss of ammonia gas (NH_3) to the air depends on several equilibrium relationships in the soil (Figure 2.5). Ammonium (NH_4^+) plays an important role in these relationships. Most of the NH_4^+ is bound to soil surface exchange sites; the remainder is dissolved in soil solution. If some NH_4^+ is removed from the soil solution through plant uptake or other means, NH_4^+ will move from the soil surface sites into the soil solution to reestablish equilibrium.

The NH_4^+ in the soil solution also tries to maintain an equilibrium with the NH_3 in the soil solution. If more NH_3 is needed to maintain the equilibrium in the soil solution, NH_4^+ will transform to NH_3. If more NH_4^+ is needed in the soil solution, NH_4^+ will move from the soil exchange sites. This equilibrium depends on the soil pH (Figure 2.6). At pH 6.0, only 0.1 percent of the total of these two is NH_3; at pH 7.0, 1 percent is NH_3; and at pH 9.0, the ratio is one to one. When a significant amount of NH_3 is present in the soil solution, some will "volatilize" into the air. When this happens, all the relationships try to reestablish. More NH_4^+ transforms to NH_3, and more NH_4^+ comes off the soil exchange sites. When the soil solution evaporates, the concentration of NH_3 increases and the potential for loss increases.

Most volatilization occurs within the first few days of biosolids application. The amount of NH_3 that volatilizes depends on a number of environmental factors and biosolids management techniques. The important ones, in addition to the pH, include temperature and wind speed, and whether the biosolids are incorporated, injected, or surface applied. As much as 100 percent of the initial NH_3 and NH_4^+ in biosolids that are surface applied to agricultural soils can be lost to volatilization. Even when the biosolids have been mixed in with the soil the majority of the NH_3 may volatilize if the soil has a high pH (over 8.0). Little volatilization may occur in sites such as forest environments in western Washington state because of the low pH of the forest floor, the low wind speed in the forest stands, and the low amounts of radiation reaching the forest floor.



2.5. The process of ammonia volatilization from biosolids.

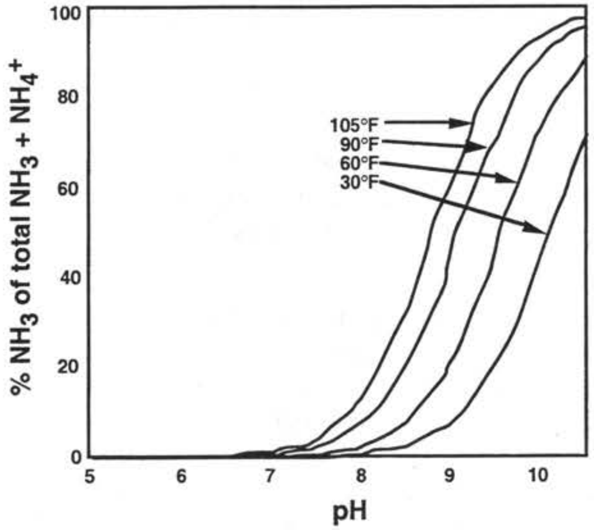


Figure 2.6. The change in percentage of ammonia versus ammonium in solution as the pH and temperature change.

Plant uptake

Plants use inorganic N and convert it to ON. Agricultural crops, trees, and understory use the available N from biosolids to increase growth. Crop N uptake varies widely, depending on crop type, growing conditions (moisture and temperature), and management practices, but can be higher than 300 lb/ac/yr (340 kg-N/ha/yr). N requirements for different forest systems also vary widely, from older stands with little N requirements to rapidly growing hybrid poplar stands with requirements greater than 300 lb/ac/yr (340 kg-N/ha/yr).

Nitrification

Microorganisms oxidize available NH_4^+ to NO_3^- in order to get energy (Figure 2.7). This process is called "nitrification." During the process, the microorganism *Nitrosomonas* oxidizes NH_4^+ to NO_2^-, and the microorganism *Nitrobacter* oxidizes the NO_2^- to NO_3^-. Nitrification rates are highest when soils are warm and moist and the pH is neither strongly acidic nor alkaline. Over-application of inorganic N in arid climates will promote buildup of excess of NO_3^- in the soil. If leaching losses are insignificant, this buildup provides a bank of available nutrients for the next crop. However, in moist climates (where rainfall exceeds evapotranspiration), NO_3^- leaching may occur.

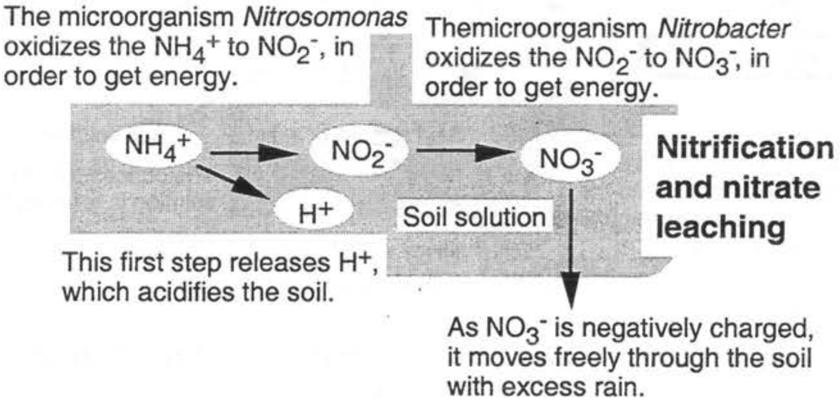


Figure 2.7. The process of nitrification, which may lead to leaching.

Denitrification

Like higher plants and animals, many microorganisms use O_2 as an essential part of their metabolism. If the soil becomes depleted of O_2, some microorganisms can use the oxygen in NO_3^- as an alternative by reducing the NO_3^- to nitrogen gases (N_2 or N_2O). This process is called "denitrification."

The amount of denitrification depends on the availability of NO_3^-, on soil saturation, on soil temperature, and on availability of easily decomposable organic matter. When a site within the soil becomes saturated with water (either an entire soil layer or pockets within a layer), O_2 can no longer diffuse readily into that site. If microorganisms are active within that site, they will deplete the O_2 and then begin using the NO_3^-. If a soil is too cold for microbial activity or if there is too little food (organic matter) available for the microorganisms, the O_2 will not be depleted and denitrification will not occur. (Appendix C shows research results from the Northwest.)

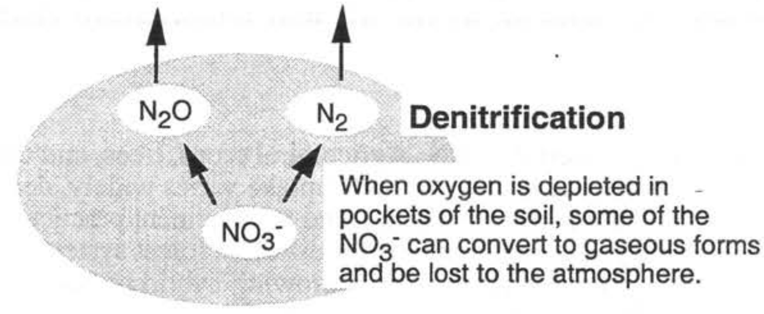


Figure 2.8. The process of denitrification.

Chapter 3

Overview of the Nitrogen Balance Approach and Guidelines for Reducing Risks of Nitrate Leaching

The objective of the Nitrogen Balance Approach for calculating biosolids application rates is to match available inorganic N with the N demand of the plant-soil system. This chapter describes the steps in the Nitrogen Balance Approach and presents guidelines for reducing risks of nitrate leaching when using the approach.

Steps in the Nitrogen Balance Approach

The Nitrogen Balance Approach consists of three steps:

Step 1. Estimate the net N requirement that allows a healthy crop (or trees and understory in a forest system) to grow at the desired yield.

Step 2. Estimate the plant-available N from the biosolids: the pool of N the plant has access to after additions and losses take place.

Step 3. Calculate the annual biosolids application rate by dividing the net plant-soil N requirement by the plant-available N from the biosolids.

Step 1. Estimate the net N requirement

The net N requirement is calculated as follows (Figure 3.1): the amount of inorganic N the plants need (plant uptake), minus the available N in the soil from other sources (N credits) and the amount of N the soil supplies—or plus the amount the soil needs (immobilizes).

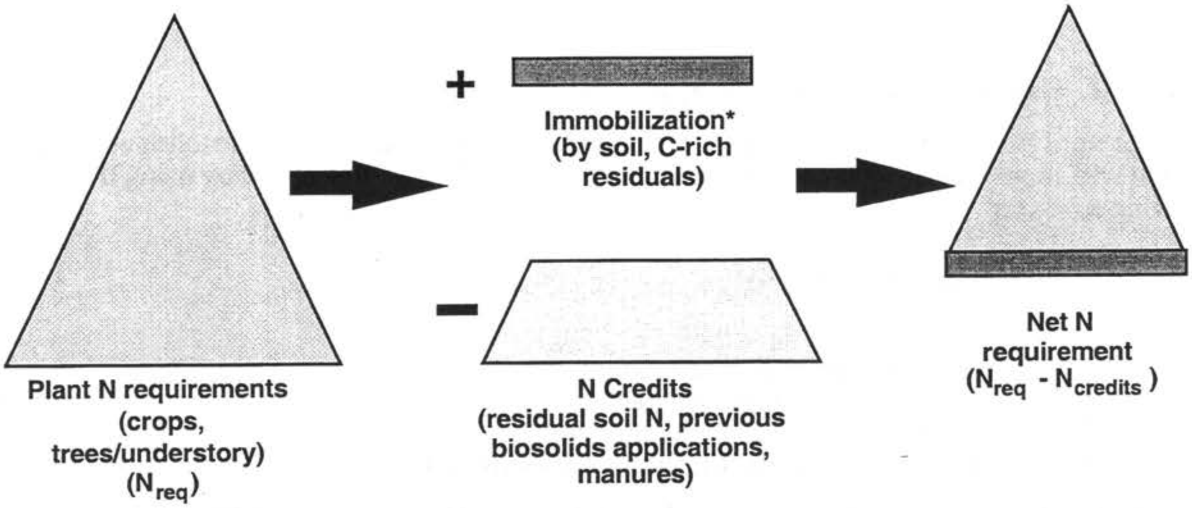


Figure 3.1. Conceptual presentation of the plant-soil nitrogen requirement. (*Immobilization occurs only in special circumstances).

N credits reduce the amount of N needed from a new biosolids application. A soil may have its own "bank of N"—residual soil nitrate, soil organic matter, and N mineralized from previous biosolids applications. The soil may also contain available N from a previous legume crop, manure or other fertilizers, and irrigation water. (See Chapters 5, 6,, and 7 for instructions on how to calculate net N requirements for application to agricultural, forest, and rangeland systems.)

Step 2. Estimate plant-available nitrogen in the biosolids

The second step in the Nitrogen Balance Approach is to estimate how much available N the biosolids will provide. The plant-available N (PAN) is the *net* amount of available inorganic N (NO_3^- and NH_4^+). It is calculated as follows (Figure 3.2): the inorganic N initially in the biosolids as NO_3-N, NH_4-N, plus the ON mineralized during the first year after application, minus the ON lost to the atmosphere by ammonia volatilization and denitrification. (See Chapter 4 for instructions on how to calculate the PAN.)

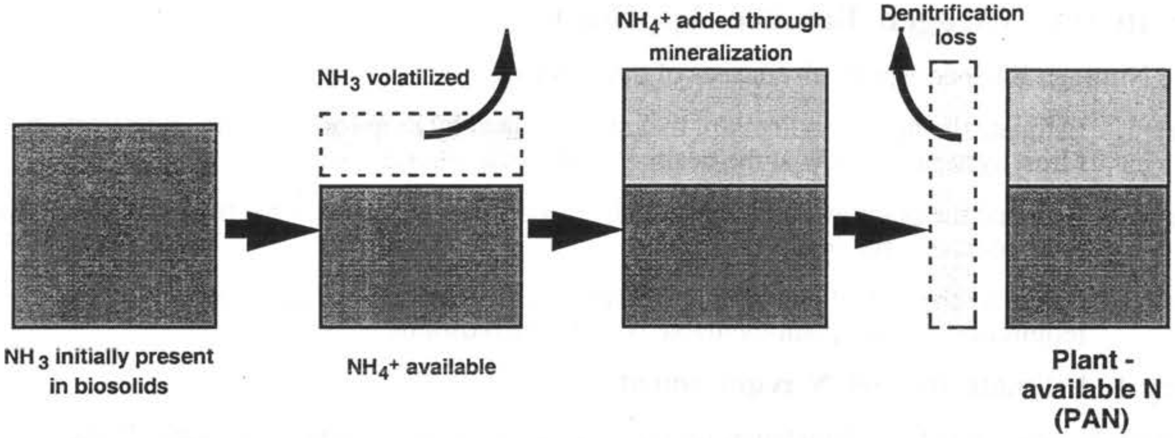


Figure 3.2 Conceptual presentation of net plant-available nitrogen.

Step 3. Calculate the biosolids application rate

In the third step, the results of the first two steps are used to calculate the biosolids application rate that will supply a given year's N requirement (Figure 3.3). It is calculated by using the following equation:

$$B_{app} = (N_{req} - N_{credits})/PAN \tag{3.1}$$

where

B_{app} = Biosolids application rate, dt/ac
N_{req} = Plant-soil N requirement, lb/ac
$N_{credits}$ = N available from other sources, lb/ac
PAN = Net plant-available N from the biosolids, lb/t

Example: The N requirement for annual production of 25 tons of grass silage is 417 lb/ac. Credits for other N sources (soil organic matter mineralization and soil NO_3^- determined via soil testing) are 264 lb/ac. Biosolids will supply 34 lb/t of N after ammonia and denitrification loss.

Variables:

N_{req} = 417 lb/ac
$N_{credits}$ = 264 lb/ac
PAN = 34 lb/t

Result: $B_{app} = (417-264)/34 = 4.5$ dt/ac

(See Chapters 5, 6, and 7 for instructions on how to calculate the biosolids application rates for agricultural, forest, and rangeland systems.)

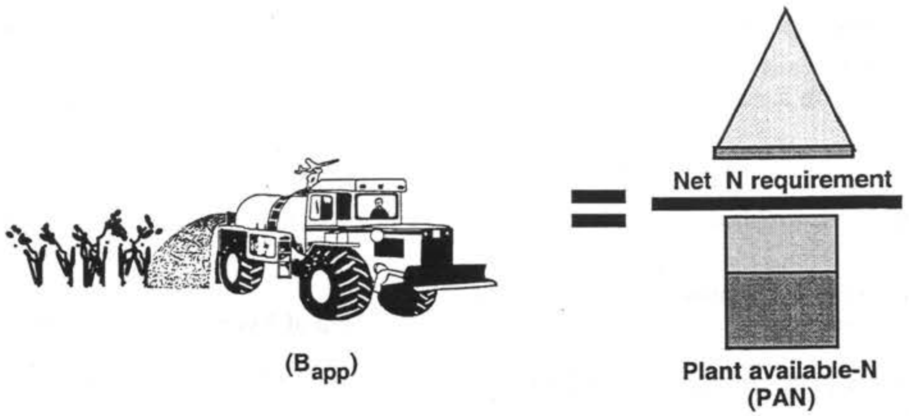


Figure 3.3 Conceptual presentation of biosolids application rate calculation.

Guidelines for reducing risks of nitrate leaching

The risk of nitrate leaching depends on several factors:

- **The site.** For example, the vulnerability of the soil to leaching, history of use of manure and other organic fertilizers, and annual precipitation
- **The crop.** For example, rooting depth and period of active N uptake
- **Quality of N testing and calculation methods.** For example, plant and soil testing, net N requirement calculations, and biosolids application rate calculations
- **Results of N tests and calculations.** For example, results of previous plant and soil tests and estimates of ammonia volatilization

Table 3.1 identifies relative risk factors for nitrate leaching at a site. If several factors are uncertain, the overall risk is compounded. Some of the identified risks can be reduced. For example, if biosolids appear to be of variable quality, more frequent analysis may be needed. If yield goals are uncertain, then harvest data can reduce uncertainty for future applications. Crop and soil N monitoring can reduce the uncertainty for a particular site/crop/management combination. Some situations with high risk may be best to avoid entirely.

Table 3.1. Factors affecting the relative risk of nitrate leaching.

	Relative Risk		
Risk Factor	**Low**	**Medium**	**High**
Crop N uptake efficiency			
Effective crop rooting depth	> 36 in.	12-36 in.	12 in.
Period of active N uptake by crop	> 120 days	60-120 days	< 60 days
Site potential for nitrate leaching			
Soil series vulnerability to leaching loss	Low	Medium	High
Irrigation system	Drip	Sprinkler	Furrow
Annual precipitation (non-irrigated sites)	6-12 in.	12-18 in.	> 18 in.
Impact of previous organic N inputs			
History of organic N input	None	2 out of 5 years	Annual
History of organic N application rate (previous 5 years)	0-100 lb/yr	100-300 lb/yr	Over 300 lb/yr
N testing and calculations for plants and soil			
Crop N requirement calculation	Based on previous site monitoring data and professional agronomist calculations	Based on values in a university fertilizer guide	A standard rate for all crops (for example, 5 dt/ac)
In-season soil testing	Frequent	Occasional	None
In-season plant tissue testing	Frequent	Occasional	None
Results of previous plant and soil tissue testing at the site	Low residual soil nitrate; moderate crop N concentrations	Medium residual soil nitrate; moderate crop N concentrations	High residual soil nitrate; high crop N concentrations
N testing and calculations for biosolids			
Planned vs. actual application rate	± 10% of planned	± 10-20% of planned	> ± 20% of planned
Mineralization rate estimate	Based on incubation test data **and** past site monitoring data	Based on incubation test **or** past site monitoring data	Based on book values—no track record
Ammonia (NH_3) loss estimate	NH_3 is < 5% of Total N	NH_3 is 5-30% of total N	NH_3 is > 30% of total N
Frequency of total solids testing	Daily	Weekly	Annually
Standard deviation in total N analyses (dry weight basis)	± 0.5% N	± 0.5 - 1.5% N	> ± 1.5% N

Chapter 4

Using the Nitrogen Balance Approach for Estimating Net Plant-Available Nitrogen from Biosolids

The Nitrogen Balance Approach (Chapter 3) includes three variables for calculating a biosolids application rate—the amount of N required by plants and soil (N requirement), the amount of N available from biosolids (net plant-available N, or PAN), and the amount of N available from other sources (N credits):

$$B_{app} = (N_{req} - N_{credits})/PAN \tag{3.1}$$

This chapter presents methods for estimating the net plant-available N (PAN) from biosolids to be applied to a site and for estimating the amount of N available from biosolids previously applied to the site (part of the $N_{credits}$ calculation). Chapters 5, 6, and 7 present methods for calculating the net N requirement (N_{req} - $N_{credits}$) for agricultural, forest, and rangeland systems.

Components of the plant-available nitrogen calculation

PAN estimates are based on the chemical characteristics and stability of the biosolids, on site conditions, and on application techniques. The PAN provided by biosolids is the amount of inorganic N that is initially in the biosolids as nitrate and ammonium (NO_3^--N and NH_4^+-N), plus the organic N (ON) mineralized to NH_4^+-N during the year of application, minus the inorganic N lost to the atmosphere by ammonia (NH_3) volatilization and denitrification. Equation 4.1 presents a means to calculate the PAN:

$$PAN = [AN \times (1-V/100) + NN + ON_0 \times K_0/100] \times (1-D/100) \times 20 \tag{4.1}$$

where

PAN = Net plant-available N, lb/t
AN = NH_4^+-N in biosolids as applied, %
NN = NO_3^--N in biosolids as applied, %
ON_0 = ON in biosolids as applied, %
K_0 = Mineralization rate of ON during the year of application, % of initial ON
V = Loss of NH_3 by volatilization, %
D = Loss of NO_3^--N by denitrification, %
20 = Conversion, 2,000 lb/t/100 (to convert from % to a fraction)

The tables in this chapter provide design values that can be used to complete this equation. The values provided are based on a number of assumptions regarding application conditions. If conditions differ from those described, we recommend that site-specific monitoring be conducted to determine appropriate values.

Mineralization rate of organic N in biosolids

Mineralization—the transformation of ON to NH_4^+—occurs when the organics in biosolids decompose. Estimates of ON mineralization rates for a particular biosolids usually rely on the following:

- Incubation studies (field or laboratory)
- Crop N uptake studies (field or greenhouse)

- Average mineralization rates of biosolids treatment (processing/stabilization) methods
- Regression equations based on biosolids ON content

Incubation studies indicate that biosolids contain one or more "pools" of ON with different mineralization rates (Lerch et al., 1992). The "fast" or "rapid" ON pool is made up of amino acids and proteins. These organic compounds degrade rapidly (within 2 to 4 weeks in laboratory-controlled warm, moist soils). The "slow" organic N pool is made up of more resistant N compounds that take months or years for complete decomposition. Freshly digested biosolids usually contain both fast and slow mineralizing ON pools. The fast pool accounts for about half of the N mineralized during the first year. Biosolids that have been stored for greater than 6 months (lagoons or stockpiles) or that have been stabilized in addition to digestion (drying beds or composting) generally have lost much of their fast-pool ON.

Short-term mineralization rates vary with fluctuations in soil temperature and moisture—warm and moist conditions are ideal for rapid mineralization. This might suggest that climate greatly impacts mineralization rates. However, as long as good conditions exist for a reasonable period at some point during the year and extreme dry or cold conditions do not prevail, the amount of N mineralized over 1 year will not vary greatly according to climate. Mineralization will proceed rapidly in ideal conditions until the readily decomposable organics are stabilized, taking around 2 months in good soil conditions. Thereafter, mineralization slows considerably. When either soil moisture or temperature is not ideal, it takes 2 to 6 months for mineralization of the fast-pool ON and stabilization of the readily decomposable organics.

The presence or absence of fast-pool ON in the biosolids can be an important factor in calculating appropriate biosolids application rates and times. For example, a slow-mineralizing biosolids source may not provide enough available N to satisfy crop needs immediately after application. Regardless of type of biosolids, it is assumed that mineralization occurs for 4 years after application. After this period, the remaining ON stays in the soil as stable organic matter.

Estimating mineralization rates for the year of application

Estimated mineralization rate ranges for the year of application for different biosolids sources are shown in Table 4.1. These ranges were developed from many sources and authors' research and experience (see Appendix C). First-year mineralization rates are greatly affected by biosolids type and treatment process, mainly because of the presence or absence of fast-pool ON. The rates range from almost negligible for some composted biosolids and lagooned biosolids with long detention times to remarkably high rates for lime-stabilized biosolids and aerobically digested biosolids with short detention times.

The rate ranges shown in Table 4.1 can be used to estimate N mineralization rates. We recommend the middle of the range unless specific information on the site or the biosolids justifies using a higher or lower value within the range. If higher or lower values are proposed, we recommend mineralization tests or field monitoring to verify assumptions for a particular biosolids source, because the estimated mineralization rate plays such an important role in determining application rates. There are a number of methods to do this, including field and laboratory incubation studies and crop growth studies.

Recent incubation and crop N uptake studies in the Northwest (Cogger et al., 1999; Cowley and Henry, 1997; Sullivan et al., 1997) have identified higher mineralization rates for anaerobically digested biosolids than used in most guidance documents (for example, USEPA, 1995). These rates are shown in Table 4.2; details are provided in Appendix D. It is unclear whether the higher mineralization rates reported in recent studies are due to changes in biosolids treatment processes over time or differences in incubation and plant N uptake study methods.

Table 4.1. Estimates of N mineralization rate ranges for biosolids treatment methods (percent of initial organic N).

Biosolids Treatment Method	Mineralization Rate (% of initial organic N)
Anaerobically digested	
Liquid	20-40
Dewatered	25-45
Heat-dried	25-45
Aerobically digested	30-50
Lagooned	10-30
Lime-stabilized	30-60
Composted	0-30
Drying bed	15-40
Oxidation ditch	30-50

Table 4.2. Results of field studies of N mineralization rates in Northwest biosolids (percent of initial organic N).

Biosolids Treatment Method	Mineralization Rate (% of initial organic N)
Anaerobically digested	
Liquid (2)	26-27
Dewatered (3)	32-44
Aerobically digested	49
Lagooned	19
Lime stabilized	55
Composted (4)	1-27
Drying bed	37
Oxidation ditch	45
Biosolids-soil mix	2

Note: Numbers in "( )" indicate more than one wastewater treatment plant tested.

Source: Cowley and Henry, 1997 (Appendix D).

Calculating mineralization rates for years following application

All ON is not released during the first year. Mineralization essentially continues during the next 3 years at progressively slower rates. If previous applications of biosolids have been made, an N credit must be calculated for them. Equation 4.2 is used for calculating this N credit:

$$\begin{aligned} N_{prev} = {} & [B_1 \times ON_1 \times (1-K_0/100) \times K_1 \\ & + B_2 \times ON_2 \times (1-K_0/100) \times (1-K_1/100) \times K_2 \\ & + B_3 \times ON_3 \times (1-K_0/100) \times (1-K_1/100) \times (1-K_2/100) \times K_3] \times 0.2 \end{aligned} \tag{4.2}$$

where

N_{prev} = Total mineralized ON from biosolids applications in previous years, lb/ac
B_i = Biosolids application rate "i" (1, 2 or 3) years ago, t/ac
ON_i = ON in biosolids "i" (1, 2 or 3) years ago, %
K_0 = Mineralization rate of ON ***during*** the year of application, % of initial ON
K_i = Mineralization rate of ON during the year "i" (1, 2 or 3) years ***after*** application, % of ***remaining*** ON

Equation 4.2 assumes that mineralization will be negligible 4 years after application. A number of long-term field studies have estimated that 20 to 50 percent of biosolids ON remains in soil as stable organic matter (more than 4 years after application). This estimate corresponds to mineralization of 50 to 80 percent of the ON applied (Barbarick et al., 1992; Johnston et al., 1989). This is much greater cumulative N mineralization than calculated using decay series presented in existing guidance documents such as USEPA (1995), due to the low mineralization rate constants recommended in them.

Table 4.3 can be used to determine the "K_i" factors in the equation. We recommend that the middle of each range be used, unless specific information on the site or the biosolids justifies using a higher or lower value within the range (see example in Chapter 6, p. 6.4).

Table 4.3. Estimates of N mineralization rates for years following application of biosolids (percent of the remaining organic N).

Year Following Application	Mineralization Rate (% of remaining organic N)
1	5-12
2	2-6
3	1-2

Volatilization of ammonia

The loss of ammonia gas (NH_3) to the atmosphere after biosolids application reduces the amount of PAN in biosolids. NH_3 in soil solution has an equilibrium relationship with NH_4^+. When a significant amount of NH_3 is present in the soil solution, some will go into the air. This process is called "ammonia volatilization." When this happens, more NH_4^+ transforms to NH_3. When the soil water evaporates, the concentration of NH_3 increases and the potential for NH_3 loss increases. Volatilization occurs rapidly after application (peaking in the first day). Some of the mineralized ON can also volatilize -- a potential total of greater than 100 percent of initial NH_4^+ applied.

Factors that affect volatilization

The percentage of NH_4^+ in biosolids that transforms to NH_3 and volatilizes depends on a number of factors:

- pH of soil and biosolids
- Biosolids treatment processes
- Biosolids application method
  - Incorporation versus surface application
  - Days to biosolids incorporation via tillage
- Moisture content of biosolids
- Air temperature and wind speed

For example, losses from volatilization are close to zero when biosolids are incorporated into the soil, when the soil has a low pH, and when wind and temperature are low. Little volatilization may occur in forest environments in western Washington state because of the low pH of the forest floor, the low wind speed in the forest stands, and the reduced radiation reaching the forest floor. Losses from volatilization are larger when biosolids are applied to the surface of the soil and the soil is dry and warm. Volatilization losses from biosolids surface applied to agricultural soils can be as high as 100 percent of the NH_4^+ initially present during the first few months (Grey and

Henry, 1995). Table 4.4 illustrates the variation in volatilization rates of Northwest biosolids incorporated or surface applied in western Washington; more details are presented in Appendix E.

Table 4.4. Ammonia volatilization rates from Northwest biosolids applied in western Washington (maritime climate).

Biosolids Treatment Method	Volatilization Rate (% of initial ammonia lost)
Anaerobically digested	
Liquid	20-40
Dewatered	
Incorporated	
Agronomic rate	14-50
Double agronomic rate	25-49
Lime-amended	45-134
Reduced pH	12-28
Surface applied	51-127
Aerobically digested	6-12
Lagooned	4-20
Lime-stabilized	14-22
Drying bed	2-5
Oxidation ditch	9-23

Note: All biosolids incorporated, except as noted.
Source: Cowley and Henry, 1997 (Appendix E).

Biosolids treatment processes. Some biosolids treatment processes dramatically affect susceptibility to NH_3 loss:

- Lime stabilization at pH 12.0 results in very rapid NH_3 loss when the biosolids are exposed to the atmosphere (before or after field application).
- Biosolids processed in drying beds lose NH_3 during the treatment process, and commonly have a pH near 7.0 (little potential for NH_3 loss).
- Aerobic composting promotes NH_3 loss, converts inorganic N to organic forms, and reduces pH to near 7.0 (reducing potential for NH_3 loss).

Biosolids application method. Incorporation of biosolids into the soil through tillage reduces NH_3 loss. This management practice moves NH_3 into the soil, where it is held as NH_4^+ on negatively charged soil surfaces. NH_3 loss is most rapid immediately after application. Some NH_3 loss is expected even when application and tillage take place on the same day. Little NH_3 loss is expected with direct injection of biosolids ("immediate tillage"). NH_3 can be lost after shallow incorporation when soil pH is high and the weather is hot (Grey and Henry, 1995). Sommer and Ersboll (1994) provide a discussion of tillage effects on NH_3 loss.

Surface application of biosolids to the soil (not incorporated into the soil through tillage) increases NH_3 loss, but acidification gradually slows the loss. Acidification is a byproduct of NH_3 loss—that is, each molecule of NH_3 lost generates one molecule of H^+ (acidity). Acidity is also generated after biosolids application by the nitrification process (conversion of NH_4^+ to NO_3^-) and by the sulfur oxidation process (conversion of reduced sulfur forms such as sulfides to sulfate). Biosolids that remain on the soil surface will eventually reach a pH near 7.0. After 6 days on the soil surface, NH_3 loss from biosolids is usually very close to zero. Calcium carbonate, present in soils with a pH of 8.0 or above, increases NH_3 loss. Because the carbonate maintains a high soil pH, NH_3 loss from biosolids is expected to continue to occur on calcareous soils as long as the biosolids remain on the soil surface. (Koelliker and Kissel, 1988, discuss the chemical reactions affecting NH_3 loss after N fertilizer application.)

Moisture content of biosolids. Liquid biosolids that are surface applied lose less NH_3 than do dewatered biosolids. Liquid biosolids have lower initial NH_3 concentrations and greater soil contact after application than do dewatered biosolids. Soil contact reduces NH_3 loss by reducing pH and adsorbing NH_4^+. (Sommer and Olesen, 1991, provide additional information on moisture content effects on NH_3 loss.)

Air temperature and wind speed. The rate of NH_3 loss increases with temperature and wind speed. In forests, trees and understory vegetation reduce NH_3 loss by reducing temperature and wind speed at the soil surface (Henry and Zabowski, 1990; Coles et al., 1992).

Design values for volatilization rates

Table 4.5 presents suggested design values for the percentage of NH_4^+ initially present in the biosolids that transforms to NH_3 and volatilizes following application.

Table 4.5. Suggested design values for ammonia loss after biosolids application to agricultural and forest lands.

Application Method	Volatilization Rate (% of ammonia lost)	
	Liquid	Dewatered
Agricultural application		
Incorporation by tillage		
0-2 days to incorporation	20	40
3-6 days to incorporation	30	50
> 6 days to incorporation	40	60
Injected	0	0
Composted or drying bed	0	0
Lime-stabilized [a]	90	90
Forest application [b]		
Open stand	10	25
Closed stand	5	15

[a] Analyzed for ammonium (NH_4^+) before lime addition.
[b] Assumes surface applied, liquid or dewatered.

Denitrification

Factors that affect denitrification

Loss of N through denitrification reduces the amount of inorganic N available for crop uptake. The microorganisms responsible for the denitrification process require three conditions: N in the nitrate (NO_3^-) form, soluble organic carbon, and an anaerobic environment. Warm, moist, fine-textured, high-organic-matter soils promote denitrification. Organic amendments such as biosolids generally accelerate the process by increasing the supply of carbon and NO_3^- and by increasing the probability of anaerobic soil conditions (by increasing soil respiration rates). In the Northwest, denitrification is most likely to occur west of the Cascade mountains in the spring and fall when temperatures are warm and rainfall moistens the soil. Denitrification can also occur east of the Cascades in fine-grained soils that receive irrigation.

Predicting the timing and quantity of denitrification loss in agricultural soils is difficult because of the many variables involved. Moreover, it is difficult to measure denitrification because the temperature, moisture, and NO_3^- concentrations needed for a high rate of denitrification are usually present only for short periods of time. Soil drainage class (an estimate of how fast the water drains from soils) has been routinely used as a predictor of denitrification loss because anaerobic conditions are more likely in poorly drained soils (SCS, 1992; Meisinger and Randall, 1991). However, recent research in the Northwest shows that soil drainage class is a poor predictor of denitrification loss (Paul et al., 1997; Paul and Zebarth, 1997 a&b; Myrold et al., 1992; Myrold, 1988). For example, Myrold et al. (1992) measured N losses on perennial grass pastures in western Oregon as affected by soil drainage. The highest denitrification rate (12 to 15 percent of manure total N applied per year) occurred in the soil with the best drainage, apparently because of its high organic matter content. With inorganic N fertilization in Oregon's Willamette Valley, denitrification loss was very low (0.6 to 1.5 lb/ac/yr) on both a poorly drained and a well-drained soil (Myrold, 1988). Apparently, denitrification loss on these soils was restricted by the supply of NO_3^- and the lack of available carbon.

Design values for denitrification rates

Suggested design values for denitrification rates are shown in Table 4.6. The values given are conservative to reflect the difficulties in measuring and predicting denitrification rates.

Table 4.6. Suggested design values for denitrification rates after biosolids application to agricultural and forest lands in the Pacific Northwest.

Biosolids Application Method	Denitrification Rate (% of inorganic N lost)
Agricultural application	
Non-irrigated	0
Irrigated	0-15
Forest application	
Semi-arid	0
West side of Cascades	
Open stand	20
Closed stand	10

Note: For agricultural applications, the denitrification loss estimate includes only the additional denitrification loss stimulated by the available carbon supplied by the biosolids. Usual denitrification losses for N derived from fertilizer or other sources are included in the crop N efficiency factor (e_f) used to calculate the crop N requirement. (See Chapter 5 for additional information.)

Example plant-available nitrogen calculation

Table 4.7 shows the calculation for the PAN for a typical biosolids. It uses numbers from analysis of the biosolids or from assumptions made in regard to the transformations and losses of N in the biosolids. The other numbers are made by a step-by-step procedure broken down from Equation 4.1, shown here and at the beginning of this chapter.

$$PAN = [AN \times (1\text{-}V/100) + NN + ON_0 \times K_0/100] \times (1\text{-}D/100) \times 20 \qquad (4.1)$$

where

PAN = Net plant-available N, lb/t

AN = NH_4^+-N in biosolids as applied, %
NN = NO_3^--N in biosolids as applied, %
ON_0 = ON in biosolids as applied, %
K_0 = Mineralization rate of ON during the year of application, %
V = Loss of ammonia by volatilization, %
D = Loss of N by denitrification, %
20 = Conversion, 2000 lb/t / 100 (to convert from percent to a fraction)

Table 4.7. Example calculation of plant-available N from biosolids.

Biosolids Treatment Method	Design Value (%)	Calculated Value (lb/t)
Ammonium concentration in biosolids	1.5	
Amount available N per dry ton		30
Percent ammonia volatilization	25	
Amount available N per ton volatilized		-8
Organic N concentration in biosolids	4.5	
Percent organic N mineralized	40	
Amount available N per ton added		36
Percent nitrate denitrification	10	
Amount available N per ton denitrified		-6
Net plant-available nitrogen		**52**

Note: The numbers in the black boxes are from analysis of the biosolids or from assumptions made in regard to the transformations and losses of N in the biosolids. The other numbers are made by a step-by-step procedure broken down from Equation 4.1.

References

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Chapter 5

Using the Nitrogen Balance Approach for Agricultural Systems

The Nitrogen Balance Approach (Chapter 3) includes three variables for calculating a biosolids application rate—the amount of N required by plants and soil (N requirement), the amount of N available from biosolids (net plant-available N, or PAN), and the amount of N available from other sources (N credits):

$$B_{app} = (N_{req} - N_{credits})/PAN \qquad (3.1)$$

This chapter presents a method for calculating the net N requirement for agricultural systems ($N_{req} - N_{credits}$), gives a range of acceptable application rates, and discusses the uncertainties that accompany the calculation of such rates. (The method for estimating the PAN from biosolids is given in Chapter 4.) The calculation method presented can be used for a number of purposes:

- To screen potential sites for their capacity to use N inputs from biosolids
- To assess the possible causes of excess available N at a site
- To fine-tune net N requirements taken from university fertilizer guides
- To develop net N requirements for crops without a published university fertilizer guide

The method is designed for large sites that receive annual biosolids applications. We do not recommend its use for small sites or for sites that receive only occasional biosolids applications. Moreover, use of this calculation method requires regular soil and plant tissue testing and the involvement of a professional agronomist. A simpler calculation method using university fertilizer guides (Cogger and Sullivan, 1999) is sufficient for most sites.

Acceptable agronomic rate ranges

Crops respond to N by the "law of diminishing returns" (Figure 5.1a). The shape of N response curves for chemical fertilizers and for biosolids are generally similar. However, calculations of PAN for biosolids assume that biosolids total N is less available than is chemical fertilizer N. In Figure 5.1a, the total N supplied by biosolids is about 30 percent as available as N supplied by a chemical fertilizer. Without added N, some crop yield is produced from N supplied by soil organic matter, residual inorganic N in the soil, and other non-fertilizer N sources. If N is deficient (limiting yield), the first application of N fertilizer (chemical or biosolids) increases yield the most. Successive increments of applied N continue to increase yield up to a maximum yield imposed by climate, crop genetics, and other factors. As the maximum yield is approached with increasing N rates, less of the applied N is used by the crop.

In the example in Figure 5.1a, biosolids applied at 184 lb/ac N or fertilizer applied at 55 lb/ac N result in 95 percent of maximum yield. But maximum crop N uptake (Figure 5.2a) usually occurs at a higher N application rate than 95 percent of maximum yield, and additional crop N uptake near the maximum yield increases crop N concentration (Figure 5.2b). To reach maximum yield, however, applied N rates would have to increase substantially (over 50 percent) (Figure 5.1b). (Note that this example does not account for unplanned variability due to soil type, weather, and so forth.). To address this difficulty, a range of rates near maximum yield are used (Johnson and Raun, 1995; Raun and Johnson, 1995). It is important to monitor crop and soil N to fine-tune estimated agronomic rates. At N rates above the agronomic rate range shown in Figures 5.2 a & b, the additional applied N is not used by the crop and accumulates as excess soil N. The "excess range" is characterized by high soil nitrate (Figure 5.2a) and very high crop N concentrations (Figure 5.2b).

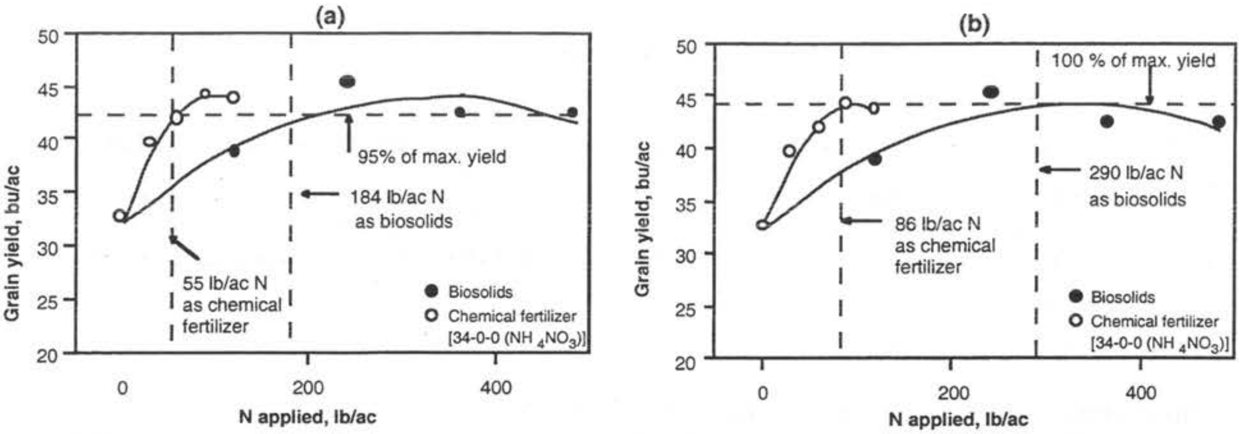

Figure 5.1. Nitrogen application rates required to reach 95 percent of maximum yield (a) or 100 percent of maximum yield (b). Nitrogen response plotted as a quadratic function. Dryland soft white winter wheat, Ellensburg, WA, 1992.

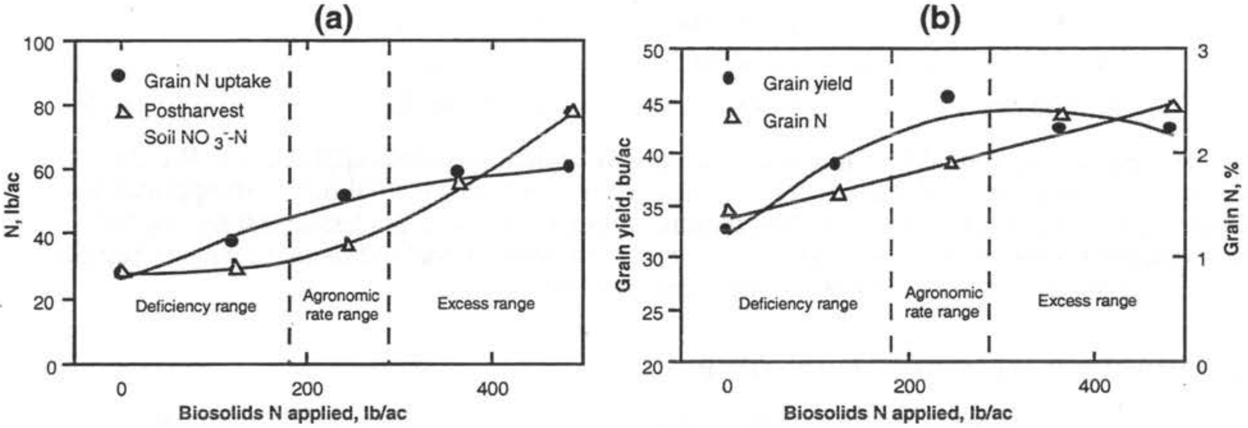

Figure 5.2. Example of nitrogen deficiency, agronomic rate, and excess N ranges as demonstrated by grain N uptake and soil nitrate-N (a) and grain yield and grain N concentration (b). Dryland soft white winter wheat, Ellensburg, WA, 1992.

Estimating plant-soil (crop) nitrogen requirement (N_{req})

Estimates of crop N requirement must consider the N uptake and N uptake efficiency factor for the crop (Bock and Hergert, 1991). The N uptake must be estimated for both the harvested and unharvested portions of the crop. The following is a simplified equation for estimating crop N requirement:

$$N_{req} \quad = \quad N_{uptot}/e_f \qquad (5.1a)$$

where

N_{uptot} = Total above-ground crop N uptake, lb/ac
e_f = Crop N uptake efficiency factor, decimal fraction (see following discussion)

A more detailed equation is used for calculating crop N requirement:

$$N_{req} \quad = \quad [(Y_h \times N_{upunit}) + (Y_{res} \times N_{upunit})]/e_f \qquad (5.1b)$$

where

Y_h = Unit yield goal of harvested above-ground portion of crop (tons, bushels, and so forth)
N_{upunit} = N uptake by harvested or unharvested portions of crop, lb/unit yield
Y_{res} = Unit yield of unharvested above-ground crop residues
e_f = Crop N uptake efficiency factor

Example: For soft white winter wheat in a dryland cropping system, the estimated grain yield is 60 bu/ac, grain N uptake is 0.95 lb/bu, straw yield is 3 t/ac, straw N uptake is 10 lb/t, and crop N uptake efficiency factor is 0.60.

Variables:

Y_h = 60 bu/ac
N_{upunit} for grain = 0.95 lb/bu
Y_{res} = 3 t/ac
N_{upunit} for straw = 10 lb/t
e_f = 0.60

Result: $N_{req} = [(60 \times 0.95) + (3 \times 10)]/0.60 = 145$ lb/ac

N removal from grazed pastures is lower than for forages harvested for hay or silage at the same yield level. With grazing, a portion of the N is returned to the field in the form of animal feces and urine. Estimates of crop N requirements under grazing management should be made by a professional agronomist.

Harvested crop yield goal (Y_h)

A reasonable method for determining a yield goal is to calculate a 5-year average of yields and then to add 5 to 10 percent to that average. Field-by-field records are the best source for crop yields. Proven yields for most grain farms can be obtained from the local U.S. Department of Agriculture Farm Service Agency (FSA) office. For most other crops, grower records are the only available source. A site used repeatedly for biosolids application should have yield data collected each year. This accumulated data can be used for determining crop N requirement. If crop yield data is not kept, additional crop and soil N monitoring may be appropriate.

For high-yielding grain crops, the upper limit on crop N requirement should be used. For example, research in western Oregon has demonstrated that winter wheat has the same crop N requirement (approximately 260 lb/ac) for a 100 bu/ac yield as for a 150 bu/ac yield (Karow, 1995). This amount of N is needed to maximize crop yield potential; actual yields reflect limiting factors other than N (such as plant disease).

Nitrogen uptake per unit of harvested yield (N_{upunit})

The N uptake per unit of harvested yield (N_{upunit}) for common grain, forage, and other crops are shown in Table 5.1. These N uptake values were derived from the crop N concentrations, moisture contents, and unit weights listed in Table 5.1 and then applied to the following equation:

$$N_{upunit} = [N_{conc}/100 \times (100 - Y_m)/100] \times Y_{lbac} \qquad (5.2)$$

where

N_{conc} = Crop N concentration, dry weight basis, %
Y_m = Crop moisture content, %
Y_{lbac} = Crop yield unit, lb/ac

Example: For N uptake per ton of grass silage harvested at the late vegetative stage of growth, the moisture content is 75 percent, the usual dry weight N concentration for this stage of growth is 2.50 percent, and the crop yield unit is 2,000 lb/ac.

Variables:

N_{conc} = 2.50 percent
Y_m = 75 percent
Y_{lbac} = 2,000 lb/ac

Result: $N_{upunit} = [2.5/100 \times (100 - 75)/100] \times 2{,}000 = 12.5$ lb/ac grass silage

For moisture contents other than the "typical" values given in Table 5.1, the N_{upunit} can be calculated by applying the N concentrations for each crop listed in Table 5.1 to equation 5.1. The crop N concentrations listed in Table 5.1 are averages for crops fertilized to near-maximum yield. Crops supplied with excessive N or crops stressed by disease, lack of water, or other factors may have substantially higher N concentrations (over 115 percent of the values in Table 5.1). For forage crops, the stage of maturity has a major effect on harvested N concentrations. N concentrations are highest in young, leafy forages, declining with crop maturity. Matching the projected yield with the appropriate growth stage is critical for accurate estimates of forage crop N removal. Crop N concentrations substantially different than the typical values listed in Table 5.1 should be documented by plant tissue testing.

Crop residue yield (Y_{res})

For some crops, only a portion of the above-ground biomass is harvested. The crop residue per unit of grain production is not listed in Table 5.1 because of the wide range in straw yields for different cereal varieties. If straw is routinely baled after grain harvest, crop residue yield can be estimated from grower records. Otherwise, estimates can be obtained from a professional agronomist.

Nitrogen uptake per unit of crop residue yield (N_{upunit})

Typical crop residue N concentrations are listed in Table 5.1. The N_{upunit} for crop residue can be calculated using Equation 5.2.

Crop N uptake efficiency factor (e_f)

Not all of the PAN present in the root zone is recovered as above-ground crop N uptake. The crop N uptake efficiency factor accounts for the following:

- Available N taken up by roots
- Available N (ammonium and nitrate) that is lost via leaching, immobilization, and denitrification with good crop, fertilizer, and irrigation management
- Available N present as soil ammonium or nitrate at the end of the growing season

Assuming recovery of fertilizer N by above-ground crops under good management practices, we recommend using a crop N uptake efficiency factor of 0.60 to 0.75 (0.60 for annual crops and 0.75 for forage crops with perennial root systems). Perennial forage crops are generally more efficient than are annual crops, because perennial forage crops have deeper root systems that have greater surface area for absorption and that actively take up N for a longer period each year. Bock and Hergert (1991) discuss in more detail the factors involved in estimating crop N uptake efficiency factors.

Table 5.1. Estimated Nitrogen uptake per unit of above-ground harvested biomass for crops used for biosolids application.

Crop	Plant Part	"As-is" (wet weight basis)				Data Source[b] (growing region)
		Moisture Content (Y_m) (%)	Unit Weight	N_{Conc}[a] (% of dry weight)	N Uptake Per Unit (N_{upunit}) (lb/ac)	
Grain crops						
Barley	Grain	12	bu (48 lb)	2.10	0.9	U.S.
Oats	Grain	12	bu (32 lb)	2.20	0.6	U.S.
Spring wheat, soft white	Grain	12	bu (60 lb)	1.80	1.0	W. OR
Winter wheat, hard red	Grain	12	bu (60 lb)	2.10	1.1	U.S.
Winter wheat, soft white	Grain	12	bu (60 lb)	1.80	1.0	W. OR
Barley, oats or wheat	Straw	12	ton	0.55	9.7	U.S.
Grass seed	Seed	12	ton	2.40	42.2	W. OR
Grass seed	Straw	12	ton	0.95	16.7	W. OR
Forage crops						
Alfalfa, late vegetative	Hay	12	ton	3.30	58.1	U.S.
Alfalfa, early/mid bloom	Hay	12	ton	2.90	51.0	U.S.
Alfalfa, full bloom	Hay	12	ton	2.50	44.0	U.S.
Clover, late vegetative	Hay	12	ton	3.40	59.8	U.S.
Clover, full bloom	Hay	12	ton	2.40	42.2	U.S.
Corn	Silage	70	ton	1.35	8.1	W. OR
Grass, late vegetative	Hay	12	ton	2.50	44.0	W. WA
Grass, late vegetative	Silage	75	ton	2.50	12.5	W. WA
Grass, mid-bloom	Hay	12	ton	1.75	30.8	W. OR
Grass, mature	Hay	12	ton	1.10	19.4	W. OR
Specialty crops						
Hops	Cones	5	bale	2.30	4.6	W. OR
Hops	Residue	5	per bale		7.6	W. OR

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[a] Typical range in plant N concentration is ± 15 % of the "common value" given. Actual crop N concentrations will vary depending on climate and crop maturity, variety, and general nutritional status.

[b] Data sources for typical U.S. crops: Meisinger and Randall (1991) and the National Research Council (1996). Data sources for Oregon and Washington: published and unpublished data from Oregon State and Washington State Universities.

Estimating nitrogen from other sources ($N_{credits}$)

N from other sources contributes to the total quantity of N available for plant uptake. These sources are credited in calculating an agronomic biosolids application rate. Other N sources are as follows:

- Expected N additions
  —Fertilizer N applications
  —Irrigation water
  —Atmospheric deposition
- Available inorganic N present in the soil
- Estimated soil organic N mineralized
- Adjustments to estimated soil organic N mineralization:
  —N mineralized from plowdown of a legume or a cover crop
  —N mineralized from previous biosolids or manure applications

Expected N additions

The following paragraphs describe methods for calculating the credit for expected N additions.

Fertilizer N applications. A small amount of a phosphorus (P) starter fertilizer may be needed for maximum yield of some row crops. Starter P fertilizers are usually ammonium phosphates that contain 10 to 20 percent N (weight basis). Sulfur also may be supplied as ammonium sulfate (21 percent N) or ammonium thiosulfate (12 percent N). N supplied from these sources should be credited.

Irrigation water. Irrigation water is a significant N source when groundwater or reuse water with a high nitrate concentration (over 10 mg/L), such as wastewater effluent, is applied. Irrigation water can be a highly effective N source. Research with irrigated corn in Nebraska showed that the efficiency of N from irrigation water was similar to side-dress N fertilizer (Francis and Schepers, 1994; Ferguson et al., 1991). The N supplied by irrigation water is the product of water applied (inches) and the nitrate concentration of the water (lb/in.). For example, irrigated pasture in the Hermiston area (Oregon) has an annual irrigation requirement of 35 in./yr (Cuenca, 1992). Irrigation water containing 10 mg/L (2.3 lb/ac-in.) of N would supply about 80 lb/ac/yr of N.

Atmospheric deposition. In most areas of the Northwest, the quantity of N supplied by atmospheric deposition is very low (less than 10 lb/ac/yr) and can be ignored as N addition. Zero can be entered for this credit unless site-specific monitoring data show significant deposition.

Available inorganic N present in the soil

Both soil nitrate (NO_3^-) and soil ammonium (NH_4^+) are considered in calculating the credit for inorganic N in the soil.

Soil nitrate. Soil testing is a reliable measure of the current soil NO_3^-. Testing must be conducted before biosolids application. Credits for pre-application soil NO_3^- are widely used in low-precipitation cropping zones (less than 18 in./yr). Early spring NO_3^- testing (February through April) usually is **not** useful in higher precipitation areas (over 18 in./yr) because NO_3^- remaining from the previous year has leached and little spring mineralization has occurred. Pre-application testing later in the year (May through August) is useful in all precipitation zones.

Appropriate sampling depths for soil nitrate-N (NO_3-N) vary with cropping system, soil depth, and other factors. Sampling to a 24-in. depth is suggested for most crops. Soil samples should be composited in 12-in. depth increments. An initial deep sampling (48 to 60 in.) should be considered at new biosolids application sites to document accumulations of NO_3-N below the root zone.

In most soils, a small amount of the NO_3-N (1 to 3 mg /kg) is unavailable to plants because of limited root access. This amount of NO_3-N (about 4 to 12 lb/ac-ft) is insignificant in most cropping systems but becomes important when NO_3-N is credited on the basis of a deep (36- to 72-in.) sampling depth. Soils with higher clay contents have more NO_3-N that is inaccessible for root extraction. A suggested formula for adjusting measured soil NO_3-N for unavailable NO_3^- is based on soil clay content (Schepers and Mosier, 1991):

$$\text{Unavailable } NO_3\text{-N (mg/kg)} = \text{percent clay} \times 0.1 \tag{5.3}$$

Using this formula, a soil with 30 percent clay would have 3 mg/kg NO_3-N that is not available for plant uptake. So, a soil test of 10 mg/kg NO_3-N would be adjusted to 7 mg/kg NO_3-N.

Soil ammonium. Soil NH_4^+ is sometimes included as N credit, particularly for samples collected from the surface soil (12-in. depth). In agricultural soils, NH_4^+ levels are usually low because nitrification (conversion of NH_4^+ to NO_3^-) generally proceeds more rapidly than mineralization (conversion of organic N to NH_4^+). Soil NH_4^+ levels are more difficult to interpret than NO_3^- levels for the following reasons:

- Chemical extraction with 2M KCl (the recommended extractant) displaces some NH_4^+ bound by clay minerals that is not plant-available.
- Drying soils increases extractable NH_4^+ content.

We suggest that soil NH_4^+ (0- to 12-in. depth) be included in N credits **only when** fertilizer or organic N sources have been recently applied (within the last 60 days). Soil samples for NH_4^+ analysis should be air dried at room temperature (approximately 68 to 77°F).

Estimated soil organic N mineralized

Soils contain a large reserve of organic N (ON). For most situations, N mineralized from soil ON ranges from 40 to 200 lb/ac/yr. Annual mineralization rates for soil ON are calculated using the following equation:

$$SON_{yr} = TKN_{soil} \times N_{soilmin}/100 \times BD \times c_{bd} \tag{5.4}$$

where

SON_{yr} = Soil organic N mineralized per year, lb/ac/yr
TKN_{soil} = Soil total N, mg/kg, 0- to 12-in. depth
$N_{soilmin}$ = Estimated annual soil organic N mineralized, %
BD = Soil bulk density at the site, g/cm^3
c_{bd} = 2.72, conversion factor for standard soil bulk density (1 g/cm^3) and standard soil depth (12 in.)

Example:

Variables:

TKN_{soil} = 3,000 mg/kg
$N_{soilmin}$ = 1% of soil organic N mineralized/yr
BD = 1.3 g/cm^3

Result: $SON_{yr} = 3{,}000 \times 1/100 \times 1.3 \times 2.72 = 106$ lb/ac/yr

For purposes of this estimation, the TKN_{soil}, (total Kjeldahl N content of soils) is considered equivalent to total ON, because over 99 percent of total N in soil is present in an organic form. A soil with 3 percent (0 to 12 in. depth) organic matter contains approximately 5,000 lb/ac N.

Estimating the $N_{soilmin}$ in agricultural soils depends on depth of soil, season, and other conditions at the site. Usually only the surface soil (12-in.depth) and only the period from March through October are considered in calculating annual mineralization rates. The small amount of soil ON mineralized during winter months (November through February) is usually ignored in calculating annual mineralization rates. Most soil ON mineralization takes place from March through October, which corresponds roughly with the growing season for perennial grasses. The quantity of soil ON mineralized per acre increases as the following conditions increase:

- Soil ON concentrations
- Tillage
- Soil moisture content (unless soil is saturated)
- Soil temperature
- Artificial (tile) drainage

- Length of cropping cycle (for example, a higher N mineralization for a wheat-fallow cropping system than for an annual cropping system)

Typical $N_{soilmin}$ values range from 1 to 4 percent of the ON present in the surface horizon. Desert soils recently brought under irrigation often have high N mineralization rates (over 4 percent of ON per year). In these soils, a larger proportion of soil organic matter is of recent origin (easier to decompose) and temperature and moisture conditions are near optimum for soil N mineralization. Soils with high organic matter contents (over 5 percent) west of the Cascade mountains often have low N mineralization rates (approximately 1 percent of ON per year), because the organic matter is older (more resistant to mineralization), soil temperatures are lower, and poor drainage often limits oxygen availability.

Adjustments to estimated soil organic N mineralization

Previous ON mineralized from plowdown of a legume or a cover crop and from previous biosolids or manure applications must be factored into the calculation of N from other sources, and the soil N mineralization rates must be adjusted accordingly.

$N_{credits}$ for legume or cover crops. The following information is needed to estimate N contributions from legumes or cover crops:

- Legume or cover crop biomass
- ON content biomass
- Estimated N mineralization rate of the biomass

Mineralization rates usually increase as crop residue N concentrations increase (Vigil and Kissel, 1991). For green residues with high N concentrations (over 2.5 percent N, dry weight), first-year N mineralization rates are usually 20 to 50 percent of N plowed down. For cover crops with low N concentrations (less than 1 percent N), first-year N mineralization rates are usually less than 10 percent of N plowed down. Recommended N fertilizer rates for most crops decrease by about 30 to 100 lb/acre for the year following plowdown of an alfalfa or a legume cover crop.

$N_{credits}$ for previous biosolids or manure applications. Sites with a history of continuous biosolids or manure application have elevated soil ON mineralization rates. Soil testing for organic matter content alone will not detect differences in mineralization rates resulting from previous biosolids or manure applications. The appropriate credit for a site depends on the following factors:

- Previous biosolids/manure application rate
- Biosolids/manure ON content
- Quantity of remaining ON
- Mineralization rate of remaining ON
- Residual effects of previous applications on soil pH and microbial activity

Application records can be used to calculate historical ON inputs. Estimates of residual ON quantity and mineralization rates vary widely. For sites with a history of frequent biosolids or manure applications, N credits for previous applications usually range from 40 to 100 lb/ac/yr. Repeated biosolids or manure applications at a site increase the need for soil and crop N monitoring. The longer the history of biosolids or manure N application, the more uncertain is the proper credit for previous applications. (Chapter 4 gives methods for calculating N credits for previous biosolids applications.)

Example net crop nitrogen requirement calculation

Table 5.2 shows all of the steps described so far in this chapter for calculating the crop N requirement (N_{req}) and credits for N from other sources ($N_{credits}$). The table uses two examples: grass silage and winter wheat.

Uncertainties in estimating net crop nitrogen requirements in agricultural systems

This chapter provides a step-by-step procedure using the Nitrogen Balance Approach for estimating net N requirements for agricultural biosolids applications. In describing the process, we have attempted to point out some major limitations in the approach and to caution that agronomic rates for biosolids application should be regarded with a level of uncertainty (a range of application rates for near-maximum yield).

Monitoring soils and crops and following good crop management practices are essential. Soil and crop N monitoring are valuable tools in biosolids N management. These tools are currently the best available technology for determining if biosolids application rates are appropriate. Protocols for N monitoring are well developed for the major agronomic crops and for some high-value crops. The design and implementation of a high quality crop and soil N monitoring program will require the involvement of a professional agronomist.

A number of agricultural N management models have been developed recently to increase the accuracy of the Nitrogen Balance Approach. These models continue to be adapted and will undoubtedly become a larger part of routine N management in the future. They provide a time scale (daily, weekly, or monthly) that is more meaningful for most cropping systems, where most of the annual crop N uptake takes place over a short 4- to 12-week period. They also can provide site-specific estimates of soil organic N mineralization if soil moisture and temperature data are available. Soil temperature and moisture measurements can now be routinely taken via automated systems, with the data retrieved electronically. We anticipate a merging of our knowledge of N availability from biosolids with models for N cycling and soil water balance. Managing biosolids in the context of such models will be a major step forward.

Critical variables

In general, the most powerful variables affecting net N requirements (N_{req} - $N_{credits}$) in agricultural systems are as follows:

- Crop N uptake efficiency factor (e_f), which needs further research on N losses (leaching, immobilization, denitrification, volatilization) for specific cropping systems
- Estimated soil ON mineralized (SON_{yr}), especially for soils that have a history of manure, biosolids, or cover crop inputs

Unfortunately, regional estimates for these variables are usually not very accurate. This problem is not exclusive to biosolids management. It is a challenge for all organic waste management plans. However, we have a higher confidence in our ability to estimate the available N supplied by biosolids. This is the result of recent research on biosolids in the Northwest (Appendixes C, D and E).

Table 5.2. Worksheet for estimating net crop N requirement for grass silage and winter wheat crops.

	Symbol	Units	Examples			
			Grass Silage[a] (tons)		Winter Wheat[b] (bushels)	
		Crop N Requirement				
$N_{req} = N_{uptot}/e_f$	$N_{uptot} = (Y_h * N_{upunit}) + (Y_{res} * N_{upunit})$		$N_{upunit} = [N_{conc}/100 * (100 - Y_m)/100] * Y_{lbac}$			
Harvested portion						
Yield goal	Y_h		25		60	
Moisture content	Y_m	%	75		12	
N concentration	N_{conc}	% of dry wt.	2.5		1.8	
Unit N uptake	N_{upunit}	lb/unit yield	12.5		1.0	
N uptake (harvested)		lb/ac		313		57
Unharvested portion						
Yield	Y_{res}	tons			3	
Unit N uptake	N_{upunit}	lb/unit yield			10	
N uptake (unharvested)		lb/ac		0		30
Combined N uptake	N_{uptot}	lb/ac		313		87
N uptake efficiency factor	E_f	Fraction, 0-1	0.75		0.60	
Total crop N requirement	N_{req}	**lb/ac**		**417**		**145**
		N from Other Sources				
Expected N additions						
Fertilizer N		lb/ac	0		0	
Irrigation water		lb/ac	10		0	
Atmospheric deposition		lb/ac	0		0	
Total N additions				10		
Residual soil nitrate		lb/ac		80		60
Annual soil organic N mineralized ($SON_{yr} = TKN_{soil} * N_{soilmin}/100 * BD * c_{bd}$)						
Soil organic N (0-12 in.)	TKN_{soil}	mg/kg	1900		400	
Soil bulk density (0-12 in.)	BD	g/cm^3	1.30		1.30	
Estimated annual N mineralization rate	$N_{soilmin}$	% of TKN_{soil}	2.00		2.00	
Total annual N mineralized	SON_{yr}	lb/ac		134		28
Mineralization adjustments						
Legume or cover crop		lb/ac	0			0
Previous biosolids application		lb/ac	0			0
Previous manure application		lb/ac	0			0
Total mineralization adjustments				0		
Total N from other sources	$N_{credits}$	**lb/ac**		**224**		**88**
Net N requirement ($N_{req} - N_{credits}$)				**193**		**57**

Note: The numbers in the black boxes were derived from research studies on grass silage and winter wheat.

[a] Reflects the usual values for tall fescue grown on a sandy loam soil in western Washington.

[b] Reflects the usual values for soft white winter wheat grown on a silt loam soil in a wheat/fallow rotation in central Washington (10 to 14 inches of annual precipitation).

Keeping the following cautions in mind can help refine these estimates:

- The net N requirement (N_{req} - $N_{credits}$) calculated in this chapter is roughly comparable to a N fertilizer recommendation from a university fertilizer guide. It is critical to remember that university fertilizer recommendations will not be comparable to the N requirement (N_{req}) as calculated in this chapter.
- Credits for soil organic matter mineralization must be included for **all sites.** Failure to do so will result in an excessive net N requirement.
- Crop N uptake and crop N requirement do not mean the same thing, nor are they interchangeable. Crop N requirement is always greater than crop uptake because it includes an efficiency factor that accounts for N not taken up by the plant or stored in plant roots.
- The suggested values given here for N from other sources ($N_{credits}$) may seem high to those accustomed to reviewing N budgets. This is because our N credits represent the available N supplied by an N source (for example, soil organic matter), not the net N uptake by the crop. For example, if soil organic matter supplies 100 lb/ac N and a crop N uptake efficiency factor (e_f) of 60 percent is used for calculating crop N requirement (N_{req}), then net crop N uptake from soil organic matter mineralization is estimated at 60 lb/ac.

The importance of timing in matching nitrogen supply with crop demand

The method for calculating net N requirement presented in this chapter implicitly assumes that N can be accurately managed with the Nitrogen Balance Approach. This is a big assumption, because it assumes that N supply from a variety of sources will match crop N needs throughout the growing season, ensuring the desired yield without accumulating excess N that can be leached as nitrate. Timing, crop management practices, and monitoring are vital. Table 5.3 shows a sample estimate of the PAN from biosolids and other sources throughout the growing season for a silage corn crop. Figure 5.3 plots this PAN against the plant uptake for the same crop.

Table 5.3. Plant-available nitrogen throughout the growing season (May-September) for a silage corn crop planted May 15 with biosolids applied on April 15 at a rate of 400 lb/ac total nitrogen.

N Sources	Unavailable N	Available N
From other sources		Soil nitrate 60 lb/ac N, as tested April 15 Soil organic N mineralized at 1 lb/ac/day
From biosolids		
Inorganic N	10 percent of total N (40 lb/ac) in ammonium form lost by volatilization	10 percent of total N (40 lb/ac) in ammonium form
Organic N	60 percent of total N (240 lb/ac)	20 percent of total N (80 lb/ac) mineralizes: • 10 percent is fast-pool organic N that mineralizes at a rate of 2 lb/ac/day in the first 20 days (40 lb/ac total) • 10 percent is slow-pool organic N that mineralizes at a rate of 0.6 to 0.3 lb/ac/day during the remainder of the growing season (approximately 90 days at an average of 0.45 lb/ac/day = 40 lb/ac)
Total plant-available N from biosolids		30 percent of 400 lb/ac, or 120 lb/ac

Note: The crop has no cultural problems such as disease, insects, or irrigation failure.

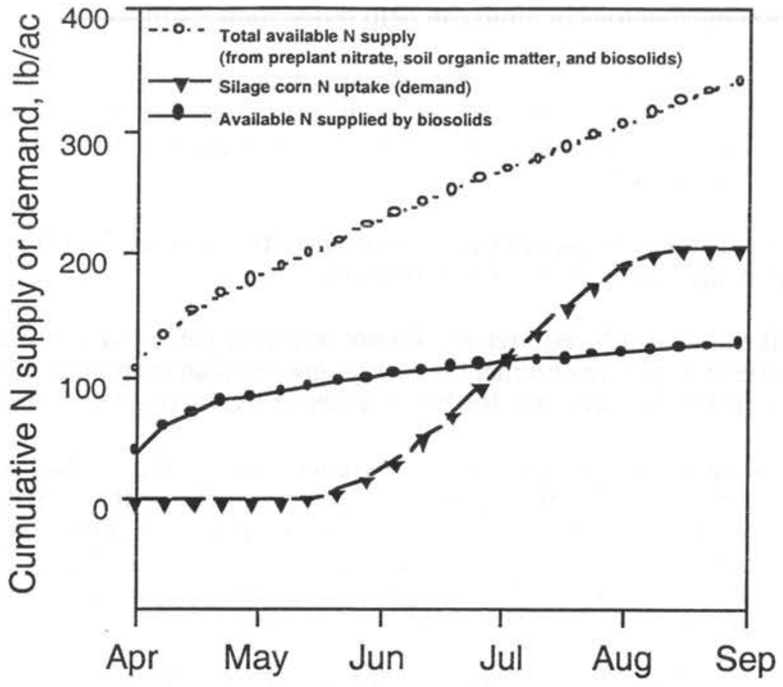

Figure 5.3. Plant-available nitrogen supplied by biosolids and other available nitrogen sources compared with nitrogen uptake by a silage corn crop. The difference between total nitrogen supply and crop nitrogen uptake represents a nitrogen use efficiency of 60 percent.

As can be seen in Figure 5.3, the total soil inorganic N supply is much greater than crop demand early in the growing season, which provides an opportunity for nitrate leaching. The total soil inorganic N supply is large (180 lb/ac) at planting; an additional 160 lb/ac is predicted from biosolids organic N mineralization and soil organic matter mineralization during the growing season. Cumulative crop N uptake (demand) follows an s-shaped curve over the course of the growing season. Uptake is minimal (less than 30 lb/ac) until mid-June, when the corn begins rapid growth (stem elongation). For the next 8 weeks (mid-June to mid-August), the crop N uptake rate is nearly linear (2 to 3 lb/ac/day). After mid-August there is little additional crop N uptake. Thus, an adequate PAN supply is critical for crop performance during the rapid growth period (mid-June to mid-August).

The key N management practice in this example is irrigation management (proper scheduling and application methods to minimize leaching). The inorganic N present in the root zone in May could be leached out before the crop is capable of taking it up. N mineralized from biosolids and soil organic matter after early August will not be taken up by the plants and will be susceptible to leaching by winter precipitation. Fall cover crops planted after corn harvest would reduce fall nitrate leaching.

To reduce risk, the total PAN could be determined in early June by soil testing, prior to the period of high N demand by the corn crop. If N supply is inadequate in June, additional fertilizer N could be applied. If N supply in June is excessive, lower biosolids application rates could be applied next year.

Other examples of the timing and quantity of N uptake for a variety of Pacific Northwest crops are provided in Sullivan et al. (1999), and additional references are included in Appendix G.

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Chapter 6

Using the Nitrogen Balance Approach for Forest Systems

The Nitrogen Balance Approach (Chapter 3) includes three variables for calculating a biosolids application rate—the amount of N required by plants and soil (N requirement), the amount of N available from biosolids (net plant-available N, or PAN), and the amount of N available from other sources (N credits):

$$B_{app} = (N_{req} - N_{credits})/PAN \qquad (3.1)$$

This chapter presents a method for calculating the net N requirement for forest systems (N_{req} - $N_{credits}$). (The method for estimating the PAN from biosolids is given in Chapter 4.)

Application of biosolids to forest sites

Calculating net N requirements for forest systems can be complicated. The plant-soil N requirement (N_{req}) must be determined for two components—the trees and the understory, both of which are perennial. In addition, the dynamics of forest systems are such that there is no annual harvest (removal of N from the site) and there is a great degree of recycling of nutrients in decaying vegetation, litterfall, twigs, and branches.

Moreover, forest sites are often nutrient deficient at the start of a biosolids application program because they have not received repeated fertilizations of N. This N deficiency can promote immobilization of N in the soil, which must be considered in the calculation of biosolids application rates. Further, when biosolids are applied to nutrient-deficient soils, the availability and cycling of N in forest systems can dramatically change. The N cycling is changed both with initial and repeated applications of fertilizers and biosolids. For example, both the amount of litterfall (foliage and branches that fall off the trees) and the N concentrations in litterfall are changed by biosolids fertilizations. The availability of or demand for N by the soil also changes as the soil moves from a nutrient-deficient status to a nutrient-rich status.

Because of the tremendous number of native plants—all with different N accumulation rates—and because of the different growth stages of trees and the variability in soil productivity of the wide variety of forests that exists in the Northwest, we do not have the comprehensive research database to guide us to accurate application rates in all cases.

Despite these uncertainties, biosolids can be applied with confidence to forest systems as long as initial estimates are conservative and a monitoring program is carried out to fine-tune application rates during the first few years of application to a new site.

Estimating plant nitrogen requirement (N_{req})

Plant nitrogen uptake

Table 6.1 provides estimates of annual N uptake by the tress and understory of fully established and vigorously growing forest ecosystems in Washington state.

Plant uptake and accumulation of N by forest systems vary according to the age and species of tree stands, the type and coverage of vegetative understory on the forest floor, the amount of litterfall, and the practice of management activities such as thinning and pruning. N uptake and accumulation can range from relatively small amounts in old stands that have little ability to assimilate additional N to relatively large amounts (over 300 lb/ac/yr) in systems that are properly managed and where species (such as hybrid poplars) are selected that respond to biosolids.

The trees and understory use the available N from biosolids, resulting in an increase in growth. The majority of the annual N accumulation occurs in the foliage of both trees and understory; however, accumulations continue in the woody biomass throughout the lifecycle of the stand. There are marked differences between tree species and different growth stages of tree stands in their accumulations of available N. N accumulations in seedlings differ from those in juvenile trees where tree canopies are greatly increasing (the largest component of N accumulations), and N accumulations in juvenile trees differ from those in mature trees. (Dyck et al., 1984, found that N uptake can be up to 110 lb/ac/yr in young Douglas-fir when the trees fully occupy the site, but as low as 25 lb/ac/yr in old Douglas-fir stands.)

A recently planted or open stand will have the highest N accumulation rates, but this rate varies with the type of understory. Annual uptake will be the highest on sites where herbaceous plants such as grasses, berries, ferns, or elderberry have established. Growth rates are slow and annual N uptake is low on sites where woody understory species such as salal or Oregon grape have established. It has been found, however, that with repeated applications of biosolids the understory species composition will gradually change to herbaceous plants.

Litterfall adds a complexity to N cycling. We do not have a good database on the contribution that litterfall makes to the variety of forest systems, especially following biosolids applications. We have seen longer needle retention for a number of years following an application, but assume that eventually more litterfall will occur. The numbers shown in Table 6.1 are assumed to be "net" uptake values: gross N uptake minus N supplied by decomposition of litterfall.

Management activities, such as thinning and pruning, that affect the N dynamics are similar to litterfall in their effects, except to a far greater extent. These activities will temporarily increase the cycling of N from the foliage that decomposes. An estimate of this contribution must be made in these situations, and the N uptake rates in Table 6.1 must be adjusted accordingly.

Soil immobilization rates

Soil immobilization, or long-term soil storage of N, is the transformation of inorganic (available) N in the form of ammonium (NH_4^+) or nitrate (NO_3^-) into organic N by soil microbes. Because forest soils are often deficient in N, there may be excess organic matter in the surface soil horizons. When biosolids are applied, the available N allows microbial populations to expand rapidly and to decompose the soil organic carbon, temporarily locking up the N in microbial biomass or in long-term stable humic acids. The N incorporated into the cell structure of the microorganisms can eventually be re-released (mineralized) at a very slow rate as microorganisms die off.

The carbon-to-nitrogen ratio (C:N) of the forest floor and surface mineral horizons can serve as an indicator of the potential for soil immobilization of N from biosolids applied to forest sites. As a rule, when the C:N ratio is greater than 30:1, immobilization will generally occur. This indicator does not apply to sites with large woody debris, due to their small surface to mass ratio. Thus, large woody materials give a high C:N, yet are not greatly involved in decomposition.

Table 6.2 gives recommended N immobilization design values for some forest sites. Depending on the amount of carbon and whether the site has been fertilized before, immobilization can be up to 1,000 lb/ac (Henry, 1991). However, sites with a young stand, soil with medium to low productivity, and a good forest floor probably will immobilize in the neighborhood of 175 lb/ac. In contrast, on sites with high soil productivity, little N immobilization will occur. In an old stand (over 40 years) that has had a closed canopy for a long time, the forest floor will usually build up. Since temperatures are low, decomposition (and subsequent nutrient cycling) will be reduced. In these situations, a "priming effect" occurs, where the biosolids accelerate the decomposition of this built-up forest floor and release (mineralize) N. This effect most likely will provide the N for any soil immobilization that would otherwise be supplied by the biosolids. Thus, no additional soil immobilization is assumed.

Table 6.1. Suggested design values for nitrogen uptake for forest trees and understory of fully established and vigorously growing forest ecosystems in Washington.

Trees and Understory	N Uptake (lb/ac/yr)
Trees	
Hybrid cottonwood	
Year 1	50
Year 2	120
Year 3	200
Year 4	220
Year 5-10	240
Douglas-fir	
Planted 2 years ago or less	0
Juvenile plantations (age 3-25 years)	
Canopy covers 100% of site	110
Canopy covers 50% of site	55
Older stands	
Age 25-40 years	45
Age over 40 years	25
Pine (semi-arid climate)	
Planted 2 years ago or less	0
Juvenile plantations (age 3-25)	
Canopy covers 100% of site	80
Canopy covers 50% of site	40
Older stands	
Age over 25 years	30
Red alder	
All ages (fixes N)	0
Understory	
Herbaceous vegetation	
First application (adjust by % of site covered)	100
Annual reapplications	0
Reapplications over 2 years apart	40
Woody vegetation (salal, Oregon grape)	
First application (adjust by % of site covered)	40
Annual reapplications	0
Reapplications over 2 years apart	20

When biosolids are re-applied, little additional N will be immobilized unless the previous application was made more than about 2 years before. Overestimation of N immobilization at forest sites can result in biosolids application rates that significantly exceed tree N requirements. Consequently, estimates of immobilization should either be set very conservatively or be based on biosolids field studies that document the increase of soil organic N from different soil horizons.

Table 6.2. Suggested design values for nitrogen immobilization in soils from biosolids applied to forest systems.

	Soil Immobilization Rate (lb/ac)
Highly productive site	0
Medium to poor site productivity	
First application	175
Reapplications (less than 3 years apart)	0
Reapplications (3-4 years apart)	50
Reapplications (over 5 years apart)	100
Old stand (over 40 years, closed canopy)	0

Estimating nitrogen from other sources ($N_{credits}$)

N mineralized from prior applications of biosolids

The N credits that must be included when biosolids have been previously applied to a site are calculated using Equation 4.2, described in Chapter 4 and shown again here:

$$\begin{aligned} N_{prev} = \; & [B_1 \times ON_1 \times (1\text{-}K_0/100) \times K_1 \\ & + B_2 \times ON_2 \times (1\text{-}K_0/100) \times (1\text{-}K_1/100) \times K_2 \\ & + B_3 \times ON_3 \times (1\text{-}K_0/100) \times (1\text{-}K_1/100) \times (1\text{-}K_2/100) \times K_3] \times 0.2 \end{aligned} \tag{4.2}$$

where

N_{prev} = Total mineralized ON from biosolids applications in previous years, lb/ac
B_i = Biosolids application rate *i* years ago, t/ac
ON_i = ON in biosolids *i* years ago, %
K_0 = Mineralization rate of ON during the year of application, % of initial ON
K_i = Mineralization rate of ON during the year *i* years after application, % of remaining ON

Table 6.3 provides an example of the N credit calculated for previous biosolids applications.

Residual soil nitrate

A pool of plant-available inorganic soil N may exist from prior applications of either chemical or organic fertilizers, from excessive atmospheric deposition, and from other sources identified in Chapters 2 and 5. Generally, when this occurs, the inorganic N will have been transformed to nitrate (NO_3^-). This supply of available N in the soil reduces the amount of PAN that the biosolids must supply. To take this into account, soil samples are taken from different soil layers throughout the rooting zone and analyzed for NO_3^--N. The quantity of N available to the plants is then calculated using the following equation (example in Table 6.4):

$$RN = (NN_{s1} \cdot SD_{s1} + NN_{s2} \cdot SD_{s2} + NN_{s3} \cdot SD_{s3} + \ldots) \cdot 0.29 \tag{6.1}$$

where

RN = Residual soil NO_3^-, lb/ac
NN_{si} = Soil NO_3^- concentration for *i* sampling depth, mg/kg
SD_{si} = Depth of soil sampling layer, for *i* sampling depth, in.
0.29 = Conversion factor (there is about 150 t/ac of soil per in. depth)

Table 6.3. Example estimate of biosolids N to be mineralized in 1996 based on estimated mineralization rates for 3 years prior to 1996.

Year	Starting Organic N (lb/ac)	Mineralization Rate (%)	Mineralized N (lb/ac)	Remaining Organic N (lb/ac)
Biosolids Applied in 1993 at a Rate of 3.5 dt/ac and 4.5 % Organic N				
1993	315	40	126	189
1994	189	5	9	180
1995	180	2	4	178
1996	178	1	2	176
Biosolids Applied in 1994 at a Rate of 2.7 dt/ac and 4.5 % Organic N				
1994	243	40	97	146
1995	146	5	7	139
1996	139	2	3	137
1997	137	1	1	136
Biosolids Applied in 1995 at a Rate of 4.5 dt/ac and 5.2 % Organic N				
1995	468	40	187	281
1996	281	5	14	267
1997	267	2	3	264
1998	264	1	3	261
Total organic N from prior applications to be mineralized in 1996				**19 lb/ac**

Note: Application rates, original organic N concentrations, and estimated yearly mineralization rates are taken from records of biosolids applied in prior years. The other numbers are derived from application of Equation 4.2.

Table 6.4 shows an example of an estimate of plant-available soil NO_3^--N before biosolids are applied.

Table 6.4. Example estimate of residual soil nitrate.

Depth of Sample* (in.)	Soil Nitrate Concentration (mg/kg)	Conversion factor (0.29)	Residual Soil Nitrate (lb/ac)
1	32	0.29	10
4	16	0.29	19
6	10	0.29	18
6	1	0.29	2
Total residual soil nitrate			**49**

Note: The numbers in the black boxes identify the depth of the soil sampled and the corresponding NO_3^--N concentrations. (*Sampling depths will vary for different soils.) Column 3 is the conversion factor. Column 4 is the product of Columns 1 x 2 x 3 (numbers are rounded off to nearest whole number).

Example net nitrogen requirement calculations

Douglas-fir stands

Table 6.5 presents the assumptions and calculations for determining biosolids application rates for three different Douglas-fir stands. The characteristics of these stands and of the biosolids were taken from a study conducted in the early 1980s. Note the great range of calculated application rates—from 1.5 dt/ac for the old stand to 15 dt/ac for the 15-year-old stand—had the Nitrogen Balance Approach been used and the stand differences been taken into account. The range is caused by three conditions: (1) the varied uptake rates in the three stands by both the understory and the trees, (2) the higher immobilization in the soils in the younger stands and a "priming effect" in the older stand, and (3) the higher losses of N to the atmosphere in the younger stands because of higher amounts of radiation hitting the forest floor and greater potential wind speed.

The actual biosolids application rate to each plot (21 dt/ac) caused considerable NO_3^--N leaching. Average calculated quantities of NO_3^--N leached during the first year were 100, 63, and 413 lb/ac for the 1-, 15-, and 55-year-old stands, respectively, compared to 3 lb/ac for the control plots. The effect of the difference between the actual application rates and N balance application rates compare well with the research results in terms of loss of NO_3^--N through leaching.

Example calculation for a series of years

Table 6.6 presents an example of how tree N uptake may change over time (for hybrid poplar) and how re-applications of biosolids affect application rates (for both hybrid poplar and Douglas-fir).

For a site that is to receive a series of annual applications at intervals over a number of years, the basic approach is the same for any year's application. However, numbers chosen for each variable will be different depending on whether it is an initial application and whether subsequent applications are done annually or at less frequent intervals.

A key consideration for an initial application is the assumed amount of N in the biosolids that will be immobilized by the soil. Biosolids additions will build up the soil N pools to the point that an equilibrium will eventually exist between soil N mineralization and immobilization. Thus, for subsequent **annual** applications, it should be assumed that there will be no additional soil immobilization.

Factors, such as residual soil NO_3^--N, mineralization of N from previous applications, and the fact that understory may cycle its N, will decrease the amount of N needed from a new biosolids application. Ideally, all the NO_3^--N will be used up during the growing season or may be relatively low west of the Cascade mountains where much of the excess NO_3^- leaches out annually. Any carry over should be accounted for in soil sampling and analysis for residual soil NO_3^-.

Uncertainties in estimating net nitrogen requirements in forest systems

As mentioned earlier, not all the N dynamics of forest systems can be approached with certainty because of the recycling of nutrients in decaying litterfall, the potential for soil immobilization, and the strong influence of stand characteristics and the year of application. In some cases, we have simplified the N dynamics. For example, we have not included quantity and quality of litterfall in the calculations, because we do not have the expertise to do so. However, litterfall is indirectly included in the calculations. Plant N requirements are assumed to be "net" uptake values; that is, gross N uptake minus N supplied by decomposition of litterfall. Also, soil immobilization and residual soil NO_3^- somewhat account for litterfall.

These uncertainties can be mitigated if initial estimates are conservative and a monitoring program is carried out to fine-tune application rates during the first few years of application to a new site. Many of the concepts and estimates presented in this chapter reflect an intensive monitoring that has enabled the development of this practice for a number of forest systems. New projects in different forest stands will continue to improve the predictive capability of calculating an N balance in forestry. Especially helpful will be projects at a broad range of sites with different tree species, climates, and soil conditions, because the majority of our information comes from the Douglas-fir forests of western Washington. As new information is developed, this chapter will improve in its utility.

Table 6.5. Example of calculation of first-year biosolids application rates for Douglas-fir stands of three different ages.

	1-Year-Old Stand		15-Year-Old Stand		55-Year-Old Stand	
Plant N requirements (lb/ac)						
Uptake for understory	100		100		20	
Uptake for trees	0		110		25	
Estimated soil N immobilized	175		175		0	
Total		275		385		45
N available from other sources (lb/ac)						
N from previous applications	0		0		0	
Residual soil nitrate	0		0		0	
Other	0		0		0	
Total		0		0		0
Net N requirement		275		385		45
Plant available nitrogen from biosolids (lb/t)						
Percent ammonium concentration in biosolids	0.7		0.7		0.7	
Amount available N per ton		14				14
Percent ammonia volatilization	35		35		10	
Amount ammonium per ton volatilized		-5		-5		-1
Percent organic N concentration in biosolids	3.9		3.9		3.9	
Percent organic N mineralized	25		25		25	
Amount organic N per ton added		20		20		20
Percent denitrification	10		10		5	
Amount nitrate per ton denitrified		-3		-3		-2
Net plant-available nitrogen		26		26		30
Application Rate (t/ac)		**10.7**		**15.0**		**1.5**

Notes: The numbers in the black boxes were assumed from characteristics of the different stands or from analysis of the biosolids (Tables 6.1 and 6.2).
The calculation assumes no prior biosolids application (thus no N mineralized from previous applications) and no residual soil nitrate.

Table 6.6. Nitrogen requirements and application rates for biosolids application to hybrid poplar and young Douglas-fir plantations.

	Plant N Requirements (lb/ac)						
Year	Trees	Understory	Soil N Immobilized	N Min. From Previous Applications (lb/ac)	Net N Requirement (lb/ac)	Plant-Available N in Biosolids (lb/t)	Application Rate (t/ac)
				Hybrid Poplar			
1	50	100	0	0	150	53	2.8
2	120	50	0	-8	162	53	3.1
3	200	0	0	-10	190	53	3.6
4	220	0	0	-13	207	53	3.9
5	240	0	0	-14	226	53	4.3
				Douglas-Fir			
1	100	100	175	0	375	53	7.1
2	100	0	0	-19	81	53	1.5
3	100	0	0	-8	92	53	1.8
4	100	0	0	-9	91	53	1.7
5	100	0	0	-6	94	53	1.8

Note: For simplicity, the following assumptions were made:

- The plant-available N from biosolids is the same (53 lb/t) throughout the 5 years of application. (In actual conditions, plant-available N may vary through the years and as stand conditions change.)
- All available soil N is used during the year (no residual soil NO_3^--N).
- The poplar plantation was converted from a fertilized agricultural field, and the soil has no capacity to immobilize N.

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Chapter 7

Using the Nitrogen Balance Approach for Rangelands

The Nitrogen Balance Approach (Chapter 3) includes three variables for calculating a biosolids application rate—the amount of N required by plants and soil (N requirement), the amount of N available from biosolids (net plant-available N, or PAN), and the amount of N available from other sources (N credits):

$$B_{app} = (N_{req} - N_{credits})/PAN \qquad (3.1)$$

This chapter presents a method for calculating the net N requirement for rangeland systems ($N_{req} - N_{credits}$). (The method for estimating the PAN from biosolids is given in Chapter 4.).

Unlike agricultural systems, rangelands do not involve the harvest of a specific crop with an expected yield and well-document N requirements. The concept of an "agronomic" application rate loses significance in rangeland situations, especially if single applications are intended to produce multi-year effects. Therefore, other approaches are used to determine biosolids application rates to rangelands. Two such approaches are as follows:

- Use of fertilizer guidelines for rangelands as a substitute for the net N requirement
- Use of biosolids application rates determined from research findings or from careful experimentation coupled with site monitoring

This chapter discusses the possible reasons for applying biosolids to rangelands and then discusses these two approaches for determining appropriate application rates for particular sites.

Application of biosolids to rangelands

Application of biosolids to rangelands is of great interest because of the vast area of range that occupies western North America. Rangelands offer a potential place for management of a large amount of biosolids. In many cases, suitable range sites are more accessible than agricultural areas yet are more isolated from houses and other sensitive land uses. More importantly, biosolids can improve the productivity and ecology of rangelands.

Rangeland is a type of natural land area that supports vegetation but is neither forested (in large proportion) nor cultivated for crop production. It is commonly managed for grazing livestock, principally cattle and sheep, but it also provides habitat and forage for wildlife and outdoor recreation for people. Rangelands are typified by the open arid expanse of grassy and shrub-covered terrain seen in cowboy movies. Most of the rangeland in western North America is public land, and much of it fits the Hollywood image. The rangeland that is privately owned still represents a large amount of land. They are often fenced and intensively managed for grazing.

In contrast to agriculture, rangeland is characterized by a mixed assortment of mostly perennial plants, by reliance on seasonal natural precipitation, and by no harvest, tillage, or cultivation. Range conditions tend to be harsh. The climate of rangelands in the inland Northwest is predominantly arid or semiarid with cold winters and hot summers. Precipitation is seasonal and inconsistent from year to year. Lack of water usually limits plant growth. Vegetative growth fluctuates through the year and from year to year, depending on temperatures and the amount of moisture available from precipitation. When water is abundant, availability of nutrients, particularly N and P, determine plant growth. Well-adapted native vegetation (grasses, forbs, and shrubs) survives these conditions and supplies forage for livestock and wildlife. However, rangeland ecology is fragile and environmental changes can alter its character and quality. During the late nineteenth and early twentieth centuries, unrestricted grazing degraded much of the range in the western United States. The resulting effects—reduced forage value, undesired plant species, and erosion—still persist in many areas today.

Although it is not a common practice, fertilization has long been recognized as a way to enhance the quantity and quality of range forage. Organic sources of nutrients, such as biosolids, provide fertility for several years through the gradual release of nutrients as organic matter decomposes. In addition, biosolids serve as a soil amendment, improving the soil and water conditions. To minimize disturbance to the soil and plants, biosolids are surface applied to range soils without incorporation.

Benefits of biosolids application

Research studies have shown that surface applications of biosolids to arid and semiarid rangelands can yield the following benefits:

- Increase water infiltration and soil moisture retention, thereby decreasing runoff and erosion (Loftin and Aguilar, 1995; McMurry, 1995; Moffet et al., 1995)
- Increase vegetative growth and cover (Loftin et al., 1995; Wester et al., 1995)
- Reduce wind erosion (Harris, 1995)
- Improve forage quality and palatability with higher concentrations of nutrients in plant tissues (Loftin et al., 1995; Fresquez et al., 1990b)
- Promote specific desired plant species (Redente et al., 1995; Benton and Wester, 1998) or inhibit unwanted species (Fresquez et al., 1990a)
- Lower concentrations of potentially toxic elements (such as Mo and Se) in plant tissues (Pierce et. al., 1995)
- Help restore degraded rangelands (Loftin et al., 1995; Fresquez et. al., 1990a)

The application of biosolids to rangelands also has possible drawbacks, such as accumulation of salts in soils and plants, undesired changes in plant species composition, movement of nitrate and other compounds with soil water, and overgrazing of areas fertilized with biosolids. However, research indicates that these drawbacks present little risk or can be avoided with appropriate management. On balance, therefore, application of biosolids to rangelands is a beneficial and safe practice.

Recommended application practices

The fertilization and soil-amending properties of biosolids will last for several years. Research suggests that the effects of biosolids continue for 5 years or more after an application to rangeland. Given the long-term benefits and the variable growth of range vegetation, it may be more practical to make one biosolids application every several years, rather than apply biosolids annually.

If possible, applications should be made in the fall or winter. Studies conducted in western Texas found that plants responded better to biosolids applied in the dormant season compared to applications made just prior to and during the growing season (Wester et. al., 1995). With spring applications, biosolids may act as a mulch and interfere with water movement into the soil after light rains. Leaching of nitrate from biosolids over the winter and early spring is less of a concern in range environments because of the limited amount and movement of water in the soil.

Because range plant species respond differently to biosolids-altered conditions, applications can affect the botanical composition of the site. Generally, biosolids application favors grasses and forbs (non-grass herbaceous plants) over legumes. Shrub response is species-specific. In addition, research has shown that biosolids applications can encourage growth of certain desired plants, depending on the nature and status of the site. Given that biosolids can alter the composition of the plant species, a range specialist should be consulted in evaluation of the biosolids application site, rate, and procedures.

Determining biosolids application rates

The following sections describe two approaches to determining biosolids application rates for rangelands:

- Use of fertilizer guidelines for rangelands as a substitute for the net N requirement
- Use of biosolids application rates determined from research findings or from careful experimentation coupled with site monitoring

Using fertilizer guidelines for local rangelands

If available, recommended application rates for fertilizing rangelands can provide the basis for calculating a "surrogate" biosolids application rate. The fertilizer recommendation represents the net N requirement ($N_{req} - N_{credits}$) for the rangeland plants. The biosolids application rate (B_{app}) can be determined by dividing the N requirement (fertilizer recommendation) by the amount of plant-available N (PAN) from the biosolids for the first year of the application (Chapters 4 and 5).

$$B_{app} = \text{(fertilizer recommendation)/PAN}$$

The N fertilization recommendation used should be specific to local range conditions. Nutrient requirements depend to a great extent on climate and plant species. As a result, suggested range fertilizer rates found in publications vary greatly, from roughly 20 to 200 lb/ac. If local range fertilizer guidelines are not available, a range specialist should be consulted or a safe target application rate should be used (as described in the following section).

Once a guideline is selected, it is important to take into account the distinctions between this procedure and the Nitrogen Balance Approach (Chapter 3). One distinction is that a fertilizer recommendation is not strictly equivalent to the N requirements of the plants. It is an umbrella value determined from research data or judged from previous experience. It assumes that the site does not have a large reserve of available soil N, which is usually the case for rangelands. Therefore, no subtraction of N credits is included in the calculation. If biosolids or manure may have been applied to the site in the recent past, a soil sample should be collected and analyzed and/or the amount of N provided by previous applications of biosolids or manure should be estimated (Chapter 4).

In addition, the calculation of PAN in the biosolids must take into account that range conditions are not conducive to N losses through denitrification but are very conducive to N losses through ammonia volatilization. Volatilization losses can be relatively large because of the hot, dry conditions and because biosolids are surface applied without soil incorporation. The conventional assumption is that 50 percent of the ammonia present is volatilized if the biosolids are applied during the cool, wet season and that 100 percent is volatilized if biosolids are applied in the hot, dry season.

Using target application rates

If fertilizer guidelines are not available, a safe "target" biosolids application rate can be assumed, followed by site monitoring to assess the effects of the application. Depending on range management goals (increased forage quality or range restoration), the site can be monitored for a number of variables, including forage production, changes in plant species composition, amount of soil organic matter, concentrations of nitrate and metals at various soil depths, volume and quality of runoff, and chemical composition of plant tissues. The rate for subsequent applications can be adjusted up or down according to site monitoring results.

Research findings can form the basis for selecting a target biosolids application rate that improves range productivity and conditions as much as possible without potentially causing environmental damage. Several research studies have applied biosolids to rangelands at various rates and then monitored the effects on forage production and environmental conditions. Application rates of up to 40 dt/ac have been investigated. The studies have shown that benefits result even from low application rates, as low as 2 dt/ac. Generally, plant growth and nutrient concentrations increase as application rate increases. However, in some studies, growth was reduced at application rates approaching 40 dt/ac. Potential environmental impacts also tend to increase as application rate increases, although runoff volume may actually decrease as the rate increases. In interpreting research findings, differences in the nature of the biosolids, climate, and range ecology should be taken into account.

Selected examples of research findings are as follows:

- Based on research in degraded rangeland in north central New Mexico, Loftin et. al. (1995) recommend an application rate of 20 dt/ac, which appears to keep trace metal concentrations in the soil and plants at safe levels.
- In a Texas desert grassland, Wester et. al. (1995) found that production of selected grasses generally improves at biosolids application rates up to 8 dt/ac and, in most cases, higher rates lead to further improvements.
- Studying biosolids application in a semiarid sagebrush ecosystem in Colorado, Pierce et al. (1995) found that an application rate of 5 dt/ac effectively supplies essential plant nutrients. They suggest that application rates greater than 9 dt/ac may pose the potential for movement of nitrate to surface water in the first year following application.

Experience of non-researchers can also help in choosing a target application rate. On ranches that apply biosolids to rangelands, application rates of 2 to 5 dt/ac are common (Gallier et al., 1993). These are lower than the rates that research has generally found to be effective and environmentally safe. Because low application rates appear to be beneficial and because range acreage is abundant, it seems prudent and reasonable to initially set a low target application rate (about 2 to 5 dt/ac).

Recommended management practices

Again, because the status and ecology of the site can be altered, it is very important that a range specialist be involved with the planning, management, and evaluation of the application. The application of biosolids should complement the management goals for the range, rather than using the range simply as an outlet for biosolids. Rangeland sites that are already in peak condition or that include critical wildlife and plant habitats may not be good candidates for biosolids applications. As with any biosolids application, conditions that may lead to contamination of groundwater and surface water should be avoided. This includes application of biosolids to steep slopes, riparian areas, wetlands, and snow covered ground near surface water.

Grazing restrictions must be observed if biosolids do not meet pathogen and vector reduction criteria. In the United States, a 30-day waiting period for grazing is required for Class B biosolids. In general, grazing should be monitored on range fertilized with biosolids. It is possible that animals will overgraze fertilized areas because of the improved forage quality and palatability.

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Chapter 8

Overview of the Balanced Soil Amendment Approach for Mixtures of Biosolids and Carbon-Rich Residuals

Biosolids provide more than just N to soils. The value of the organic matter in biosolids as a soil amendment (conditioner) is as important as, if not more important than, its value as a fertilizer. Soils that can benefit most from the conditioning properties of biosolids are soils that have been recently disrupted by either human activity or natural disturbances, soils whose original soil characteristics are poor (sandy or gravelly soils), or soils that are used to manufacture topsoil.

The organic matter in biosolids can influence most of the processes that occur in soils: (1) storage of nutrients and water, (2) immobilization of trace elements, (3) support of plants, (4) aeration of plant roots, and (5) transport of excess water. Short-term soil productivity can be improved both by nutrient addition and by changing the moisture holding capacity of the soil. Long-term soil productivity can be improved by a continual slow release of nutrients as the organic matter decomposes.

As other chapters in this manual have emphasized, the amount of N that will be available to plants must be taken into consideration when determining biosolids application rates. Too much N may transform to nitrate and leach into groundwater; too little available N will reduce plant growth. Compared with some other residuals, biosolids are lower in organic matter and higher in N. Biosolids application rates must be calculated so that inorganic N does not exceed plant N requirements. A carbon-rich residual—such as wood chips, paper fines, or straw—could be used as an alternative to biosolids to achieve the desired organic matter content of the soil. However, such residuals will generally immobilize (store) N in organic forms that are not available to the plants.

One possible solution is to mix biosolids with a carbon-rich residual in order to achieve a balanced carbon-to-nitrogen ratio (C:N). This approach—called the Balanced Soil Amendment Approach—is still in the early stages of development. The remainder of this chapter presents results of studies conducted on the C:N ratio and provides methods for calculating appropriate application rates for such a mixture.

Results of studies on carbon-to-nitrogen ratios

Mineralization and immobilization of N are governed by C:N ratios. Traditionally, it has been suggested that a C:N ratio greater than 30:1 will immobilize N, a ratio less than 20:1 will mineralize N, and a ratio between 20:1 and 30:1 will produce no net changes in N availability. These ratios have been used as a "rule of thumb" for agricultural systems where C and N sources are fairly consistent in nature and degradability. A number of studies using various residuals suggest that decomposition dynamics may be too complex to solely rely on the C:N rule of thumb (Chandler et al., 1980; Hatiori and Mukai, 1986; Henry, 1991). Release or demand for N depends not only on the C:N ratio but also on the types of organic compounds in the residual and how long breakdown of these compounds has been occurring. Different residuals have different stability in terms of organic decomposition rates and thus have different impacts on the mineralization or immobilization of N. If the carbon is in a form that is difficult to decompose or if the majority of the carbon sources are large in particle size (thus decreasing the surface-area-to-mass ratio and restricting access by the decomposing microorganisms), net mineralization may occur when the C:N ratio is considerably higher than 20:1, and, in the same sense, the average C:N ratio for net immobilization to occur may have to be much higher than 30:1.

Decomposition rates of organic compounds

Residuals consist of many different kinds of compounds (Figure 8.1a). As decomposition occurs, both the quantities and characteristics of C change to resemble those found in soil (Figure 8.1b). Organic compounds decompose at different rates, loosely defined by stages (Figure 8.2). Compounds such as sugars, starches, fats, and proteins are broken down by bacteria during the rapid decomposition period in the first few weeks. Hemicellulose and cellulose are broken down by actinomycetes and fungi over a period of months to years. Lignin and lignocellulose are fairly recalcitrant, similar to humus, and are decomposed by fungi over a period of tens to hundreds of years.

Studies support this concept of differing decomposition rates depending on the type of C compound. For example, Chandler et al. (1980) found that decomposition was strongly related to lignin content during fermentation of different plant parts and manures. As lignin content increased, decomposition decreased. Similarly, Hatiori and Mukai (1986) found that as the inorganic and lignin fractions in different biosolids increased, the amount of C in biosolids that mineralized decreased. Lerch et al. (1992) found that the mineralization of C in biosolids was strongly related to biosolids proteins.

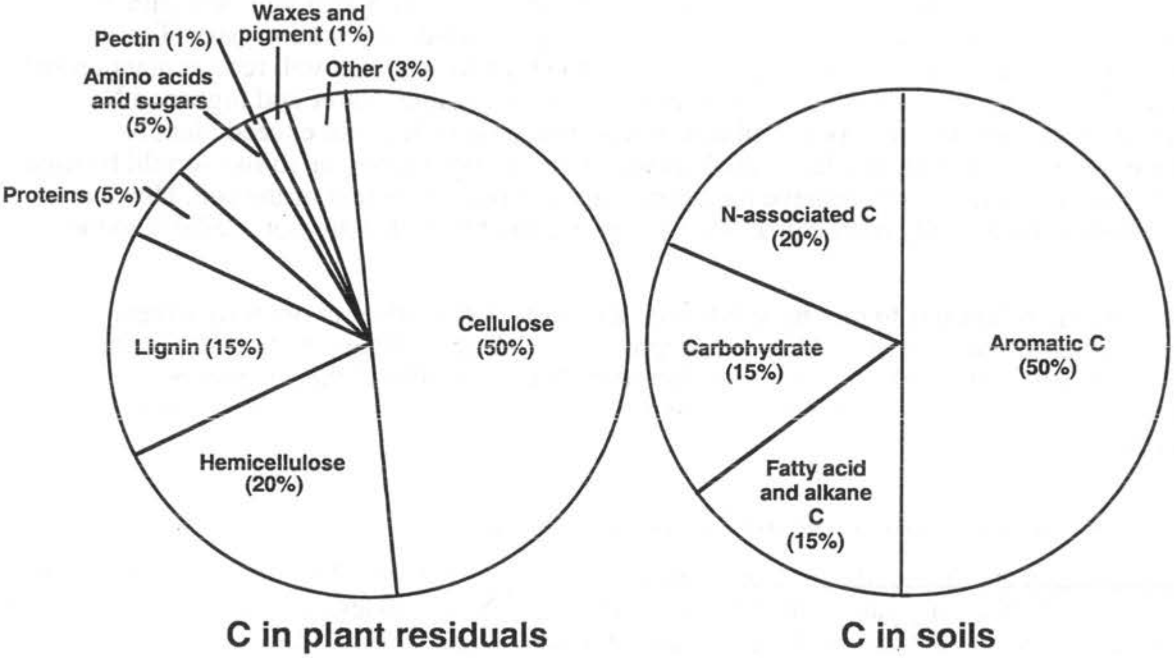

Figure 8.1. Types and general fractions of carbon compounds found in plant residues and soils (modified from Brady, 1997).

Influence of time on carbon-to-nitrogen ratios and nitrate leaching

C:N ratios change with time. Complete decomposition of organic matter produces carbon dioxide (CO_2), water, and minerals. The CO_2 releases to the atmosphere, while the N usually gets reincorporated into organic compounds. The net effect is to reduce the C:N ratio. If this ratio moves to below 15:1, excessive N will volatilize in the form of NH_3. Compost piles provide good examples of the changes that take place as residuals decompose (Table 8.1). Often mixtures of materials in compost piles start at C:N ratios greater than 30:1 and drop to below 15:1 after stability is reached.

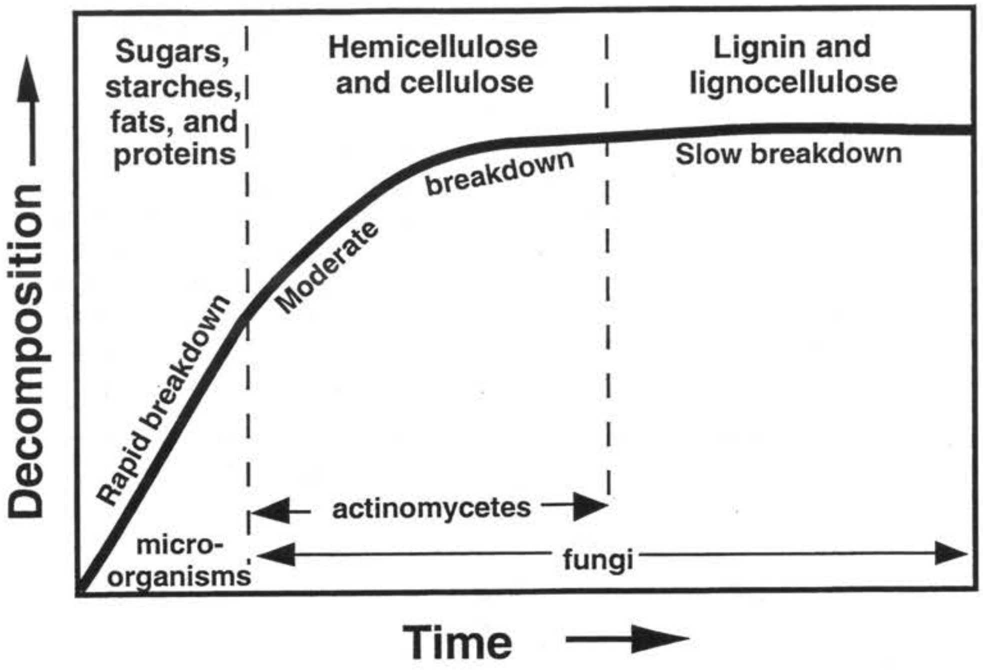

Figure 8.2. Conceptualized rate of decomposition of different organic compounds (modified from Henry, 1996).

Table 8. C:N ratios of different kinds of mature compost and their corresponding raw materials.

	C:N Ratio	
	Raw Material	Compost
Biosolids	8.7	11.2
Biosolids + sawdust	21.5	17.9
Biosolids + rice hulls	14.9	14.2
Garbage + bark	21.6	16.1
Garbage	16.0	15.8
Municipal refuse	20.7	14.9
Cow Manure	22.0	11.3
Cow manure + pig manure + straw	-	12.7
Chicken manure	5.3	8.2
Leaves	33.4	12.1

Source: Modified from Chanyasak et al., 1983a.

The complex and time-dependent relationships of C and N influence the amount of NO_3^- that leaches from the soil. A 1995 study illustrates this relationship (Van Ham and Henry, 1995). The study investigated the relationship between the C:N ratio of mixtures of biosolids and paper mill fines. Paper mill fines (C:N ratio = 82:1) are C-rich, small, particle-sized rejects from paper making. In the study, soil columns filled with soil amended with different ratios of biosolids and paper mill fines were subjected to a short-term laboratory incubation; leachings of water were taken weekly to quantify release of N.

Figure 8.3 presents the weekly accumulative NO_3^- leaching results for two of the mixtures with C:N ratios of 12:1 and 52:1 to contrast the effect of greatly differing C:N ratios. The results indicate a far greater release of NO_3^- with the 12:1 C:N ratio treatment (note that the scales are also different). Surprisingly, *NO_3^- was also released from the mixture with a 52:1 C:N ratio,* but with a far greater *delay* in the appearance of the NO_3^-.

Further interpretation of the study results shows that N loss does not correspond to decomposition; in fact, in this experiment, the opposite was true. The study showed that the higher the C:N ratio, the higher the percentage of organic matter that decomposed and the lower the percentage of N that leached (Figure 8.4). In both cases, there was a very good linear relationship. This supports the concept that as decomposition progresses in high C:N ratio materials, CO_2 releases while N gets reincorporated into the organic mass. It appears that there is a continued loss of CO_2 without corresponding loss of NO_3^- until the C:N ratio is reduced to some critical point, which results in a delay of the appearance of NO_3^- depending on the initial C:N ratio (Figure 8.5).

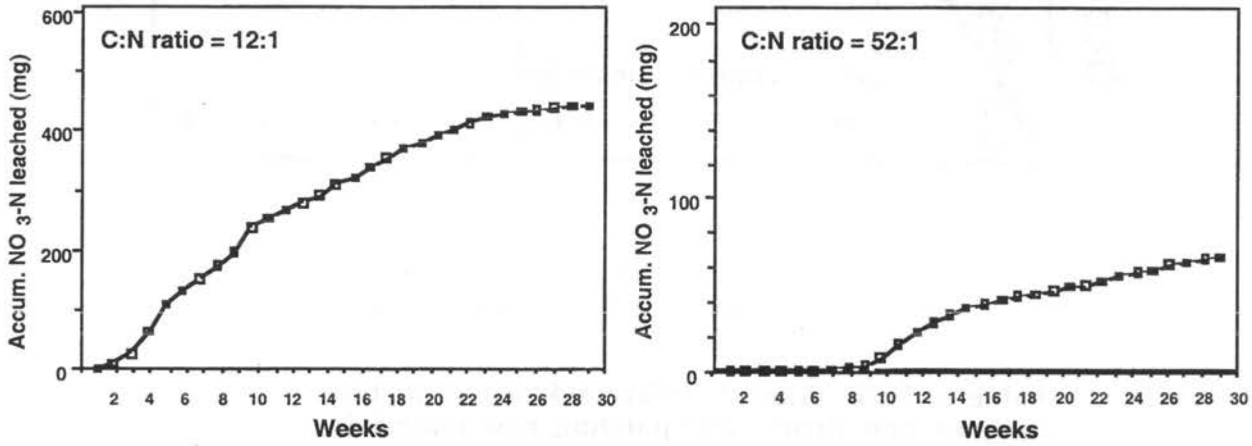

Figure 8.3. Comparison in accumulative mass of nitrate leaching between two biosolids/paper mill fine mixtures with 12:1 and 52:1 carbon-to-nitrogen ratios.

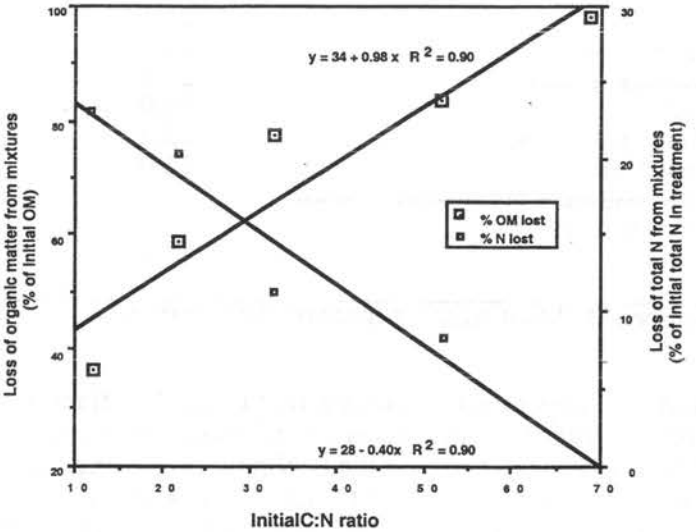

Figure 8.4. Percentage loss of organic matter in mixtures and percentage loss of total nitrogen from biosolids/paper mill fine mixtures as a function of initial carbon-to-nitrogen ratios of the mixtures.

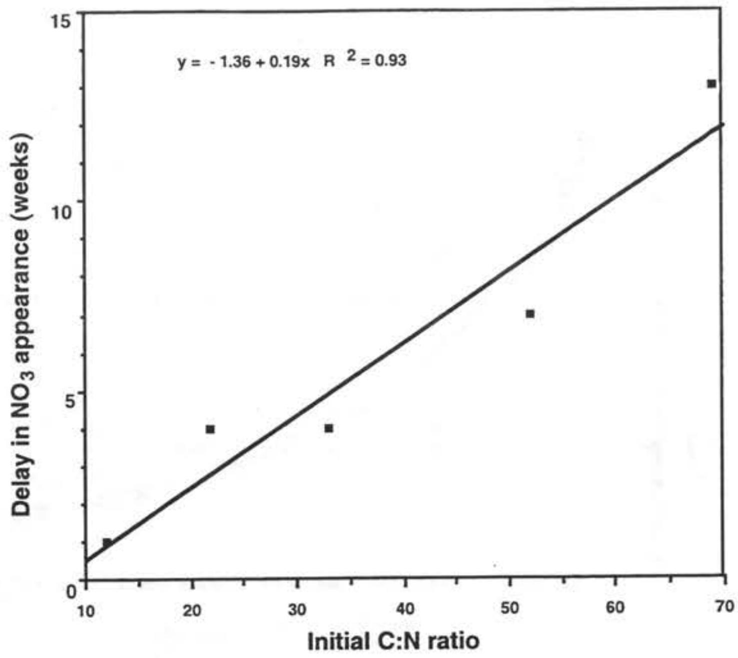

Figure 8.5. Delay in the appearance of nitrate leaching from tubes as a function of initial carbon-to-nitrogen ratios of biosolids/paper mill fine mixtures.

Choosing an initial organic matter content and C:N ratio

Figure 8.6 shows a conceptualization of the Balanced Soil Amendment Approach. The goal is to make N available so that plants have adequate nutrition throughout the course of a treatment and to achieve a balance between C and N. To achieve this goal, the appropriate initial organic matter content and C:N ratio must be selected (Figure 8.7) in order to reach a long-term stable organic matter content at a balanced C:N ratio.

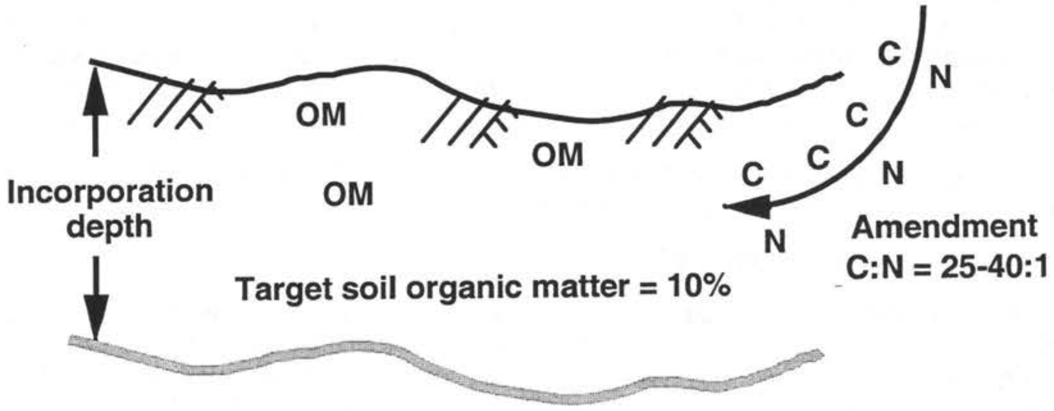

Figure 8.6. The conceptual Balanced Soil Amendment Approach.

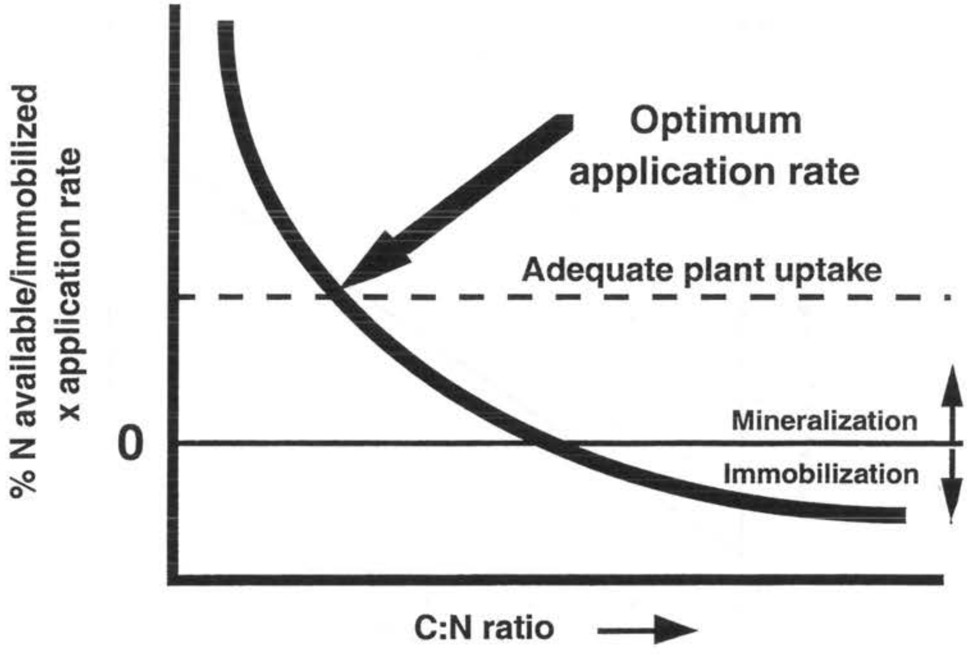

Figure 8.7. Ideal release curve for nitrogen as a function of carbon-to-nitrogen ratio.

Initial organic matter content

A topsoil that has a stable organic matter of 5 percent is usually considered productive. This amount of organic matter gives the soil desirable chemical, biological, and physical properties. In the Balanced Soil Amendment Approach the goal is to achieve a long-lasting productive topsoil by altering the organic matter and nutrient content of the top foot—the rooting zone—of the soil. Because the organic compounds in the residuals (biosolids and other organic matter) added to soil do not have the same stability as humus, a significant portion of the compounds will decompose in the soil within a few years following application. For most residuals, we can assume that about 50 percent of the organic compounds will decompose in the soil in 1 to 2 years. This assumption is only an rough approximation. Some organics such as straw will decompose much faster (and in our biosolids/paper mill fines study where far more than 50 percent loss occurred in 30 weeks), and some organics, such as wood that has a lot of lignin, will decompose much slower.

So if the long-term goal is to have 5 percent organic matter, then a 10 percent initial organic matter content would account for variable decomposition rates.

Initial carbon-to-nitrogen ratio

As discussed earlier, excess N added from biosolids can be immobilized by excess C added as C-rich residuals (such as wood chips, paper fines, and straw) that will be released later for plant use as decomposition continues. The type and stability of the C-rich residual must be taken into account when deciding on an initial C:N ratio for the amendment. If fresh carbon-rich residuals are used, a beginning C:N ratio of 30-40:1 for the mixture is appropriate. If a stable compost is used, then a beginning C:N ratio of 20-30:1 is appropriate.

Table 8.2 lists recommended C:N ratios for different C-rich residuals.

Table 8.2. Recommended initial carbon-to-nitrogen ratios for mixtures of biosolids and carbon-rich residuals for use as soil amendments.

	C:N Ratio
Faster decomposing materials	
Hardwood leaves	40:1
Yard waste	40:1
Pulp and paper sludge	40:1
Straw	40:1
Slower decomposing materials	
Stable compost	25:1
Sawdust	35:1
Wood chips[a]	45:1

[a] Wood chips have smaller surface-area-to-weight ratios than sawdust and are not as effective in immobilizing N.

Calculating application rates using the Balanced Soil Amendment Approach

Calculation of application rates using the Balanced Soil Amendment Approach consists of three steps:

Step 1. Analyze the soil, biosolids, and C-rich residual to determine the C and N concentrations and bulk density of each.

Step 2. Determine the ratio of the mass of the soil and C-rich residual to the mass of the biosolids.

Step 3. Translate the ratios into application rates, using the bulk densities.

For the sake of example, some values for depth of incorporation (1 ft.) and initial target soil organic matter content (10%) have been selected. As experience is obtained for specific sites, different depth or organic matter content may be justified.

Step 1: Analyze the soil, biosolids, and C-rich residual

The first step is to analyze the soil, biosolids, and C-rich residual. It is important to determine the C and N concentrations and bulk density of each. Some organic residuals, such as yard waste that is high in grass content, may not classify as a C-rich residual, because the C:N ratio may already be below the target C:N ratio.

Step 2: Determine the ratio of the mass of the soil and C-rich residual to the mass of the biosolids

The second step is to determine the ratio of the mass of the soil and C-rich residual to the mass of the biosolids. This ratio is determined by solving the following equations for calculating the weighted average of C:N and organic matter. These equations include two unknowns: the mass of biosolids per unit mass of soil and the mass of C-rich residual per unit mass of soil.

$$\frac{M_b C_b + M_c C_c}{M_b N_b + M_c N_c} = \text{C:N (target)}$$

and

$$\frac{M_sOM_s + M_bOM_b + M_cOM_c}{M_s + M_b + M_c} = \%\text{ OM (target)}$$

where

M_b = Unit mass of biosolids (set = 1)
M_s = Mass of soil
M_c = Mass of C-rich material
C_i = C concentration of biosolids and C-rich residual
N_i = N concentration of biosolids and C-rich residual
OM_i = Percent organic matter of soil, biosolids, and C-rich residual (about 1.73 times the % C)

Then, Equation 8.1 is used to solve for the mass of C-rich residual per mass unit biosolids:

$$M_c = \frac{C{:}N \times N_b - C_b}{C_c - C{:}N \times N_c} \tag{8.1}$$

Then, Equation 8.2 is used to solve for the mass of soil per mass unit of biosolids:

$$M_s = \frac{OM_b + M_c(OM_c - \%\text{ OM}) - \%\text{OM}}{\%\text{ OM} - OM_s} \tag{8.2}$$

The final step is to use the bulk densities to translate the ratios into application rates. Equations 8.1 and 8.2 simplify into Equation 8.3:

$$BAR = \frac{21.8 \times D}{\frac{M_s}{Bd_s} + \frac{1}{Bd_b} + \frac{M_c}{Bd_c}} \tag{8.3}$$

and

$$CR = BAR \times M_c \tag{8.4}$$

where

BAR = Biosolids application rate, t/ac
D = Incorporation depth, ft.
CR = C-rich residual application rate, t/ac
Bd_i = Bulk density of biosolids, C-rich residual, and soil, lb/ft^3
21.8 = Conversion factor (43,560 ft^2/ac/2,000 lb/t)

Table 8.3 compares biosolids-only application rates with application rates of biosolids/C-rich residual mixtures with two different C:N ratios.

Table 8.3. Application rates for biosolids/C-rich residual mixtures with initial C:N ratios of 30:1 and 40:1 and a 10 percent initial organic matter content compared with application rates for biosolids only.

	Biosolids	C-Rich Residual	Soil
Assumed N content (%)	5.2	0.8	0.1
Assumed C content (%)	43	45	1
Application rates (t/ac)			
Biosolids only, calculated with the N Balance approach	5		
Biolsolids only, calculated to provide 10 % organic matter (C:N = 9:1)	181		
Biosolids/C-rich residual mixture, C:N = 30:1	23	125	
Biosolids/C-rich residual mixture, C:N = 40:1	11	135	

Summary

This chapter presents the Balanced Soil Amendment Approach to achieving a long-lasting productive topsoil by changing the organic matter content and the nutrient status of the soil. This approach is still being developed, but early lab and field studies have yielded encouraging results. Field studies have been conducted with compost, pulp mill fines, and wood waste (Henry, 1995). As comprehensive data and experience grow, the approach promises to be a valuable tool if used correctly.

The Balanced Soil Amendment Approach provides general guidance for designing an application rate for a mixture of biosolids and a C-rich organic material. A number of C-rich materials can be used. Each of these materials has different characteristics of nutrient content and decomposition, and each must be studied before embarking on a major application program using this approach. In addition, small-scale studies should be conducted to determine the right mixture of biosolids and C-rich residual. The goal is to reach a long-term stable organic matter content of 5 percent at a balanced C:N ratio of between 20-30:1. This amount of organic matter at this C:N ratio normally gives the soil desirable chemical, biological, and physical properties. Because of the changes that take place with decomposition once the mixture is incorporated into the soil, both the initial organic matter and C:N ratio targets are higher than the long-term goal.

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Chapter 9

Analysis of Nitrogen in Soils and Biosolids

The reliability of a biosolids application rate depends on many factors, not the least of which is the accuracy of the analytical information on which the calculations are based. Knowing the amount of residual N in the soil and the amount and form of N in the biosolids—and being able to rely on that information—are critical links in the chain of N management.

Biosolids managers must know the concentrations of the forms of N in the biosolids and soil that are or can become available to plants. Although there are other forms of N in soils and biosolids, the only ones of concern here are organic and inorganic forms including nitrate (NO_3^--N), ammonia (NH_3-N), and ammonium (NH_4^+-N). During analysis, NH_4^+-N is often converted to NH_3-N and analytical results are then reported as NH_3-N. Because both forms are considered to be plant available, this combined analysis does not diminish the quality of the result.

Whenever N values are reported for biosolids samples, it is important to also include values for total solids and volatile solids content. The percent total solids value is used as a component of application rate determinations. The total solids value is also used to derive a dry weight value from a wet weight result and to verify the dry weight values reported. The volatile solids value (expressed as a percent of total solids) is used to draw inferences about expected and reported N values.

The analysis of soils and biosolids for N presents challenges to both the chemist and the biosolids manager:

- Both soils and biosolids may contain compounds capable of interfering with a chosen analytical methodology.
- The concentration of N in biosolids can be high relative to the effective range of some methods of analysis.
- Dilution of the sample may be required, which can lead to errors in analysis.
- Methods of sample processing and preparation can have an impact on analysis results.
- The high organic matter content of some biosolids can complicate sample digestion and some analytical methods.
- Biological activity can result in transformations and/or loss of nitrogen between the time of sampling and analysis.
- Analytical methods may not be precise enough to cleanly separate available and unavailable forms of N.

Ultimately, the best approach to managing these challenges is the consistent use of proper sampling, analytical, and reporting methods. This chapter addresses preparation of a sampling plan; collection, preparation, and analysis of samples; and reporting of results. Each of these steps includes many critical elements. It is beyond the scope of this chapter to present a detailed discussion of each element, but the major points are covered and good references are provided.

Preparing a sampling plan

A sampling plan—even a rudimentary plan—is an important tool in assuring that samples are properly collected, handled, and processed. For complex sampling projects, the assistance of a person experienced in designing sampling plans and programs may be required. A basic sampling plan should identify the medium to be sampled, the equipment and supplies needed for sampling (including forms, labels, and containers), the sample locations, and the methods for collecting, handling, storing, and transporting the samples. For soil sampling (or for large piles of biosolids), a map identifying specific sites to be sampled is important. If sampling at different depths is necessary, this should also be discussed. In some cases, many discrete samples may be needed. In other cases, composite samples (which are then subsampled) may be just as informative and less expensive.

Collecting samples

Sample collection is the first step in the process. If sample collection technique is poor, if samples are not representative, or if sample handling is careless, then the reliability of the data will be questionable and any decisions or conclusions based on the data will be suspect.

For biosolids, samples must be taken at the end point of the treatment process. If the biosolids are going directly from a digester to the application site, then samples should be taken from the digester. If the biosolids are going to a drying bed before being applied to the site, samples should be taken from the drying bed. If biosolids are going to be stored prior to use, then samples may need to be collected from the storage site.

For soils, the season of sampling may be most important. NO_3^- in soil may be measured after harvest (report card sampling) to determine whether the amount of N applied to the last crop was appropriate. Both NH_4^+ and NO_3^- may be measured before planting in dryland cropping and low rainfall areas; such sampling is not as necessary in higher rainfall zones because residual soil N may be leached from the soil during the winter. In some cases, soil N may be measured during the growing season to determine the possible need for additional fertilization.

Soil samples should be taken directly from the application site and should be representative of the soils on which the biosolids will be applied. This may require sampling at different depths in the soil profile and at different areas of the site, depending on soils and past management practices. Guidance on soil sampling can be found in the Washington State Department of Ecology's *Biosolids Management Guidelines* (WDOE 93-80) and the University of Idaho Cooperative Extension's *Soil Sampling Bulletin 704 (1994).*

Whether sampling biosolids or soils, the time between sampling and analysis and between analysis and use of biosolids should be kept to a minimum. For more stable types of biosolids, such as aged biosolids that have been sitting in a drying bed or lagoon for many years, an additional period of time after analysis may make little difference. For other types of biosolids, delays between analysis and use can compromise the reliability of the determination of the biosolids application rate because of transformations and losses of N from the sample or the source.

Collected samples must be preserved and stored. Preservation and storage requirements will vary with the sample matrix, the analytes targeted, and the methods of analysis chosen. There may be specific regulatory requirements related to sample preservation, holding time, and chain of custody that must be followed. The best way to determine requirements is to review any available discussion of the analytical methods to be used and consult with the laboratory that will be doing the analysis.

Preparing and analyzing samples

The way a sample is analyzed depends to a certain extent on the preferences of the chemist and the laboratory, and the way a sample is prepared depends on the selected method of analysis. Generally, preparation involves some type of extraction, digestion, or distillation. The resulting products are then analyzed quantitatively for the selected form of N. Laboratories should be prepared to justify the use of the methods in terms of meeting permit and other regulatory requirements. Biosolids managers may use less exacting methods of analysis as a "litmus test" but not as a substitute for meeting regulations. For example, an in-house laboratory may have limited capabilities to analyze biosolids or soils that can serve as a quick and relatively inexpensive periodic indicator of compliance.

The preparatory process may have effects on the final N content of the sample. For example, drying and grinding processes may lead to a loss of NH_3 and some acid digestion processes may liberate forms of N for analysis that are not plant available. Therefore, it is important to have knowledge of the biosolids or soil matrix being sampled and of the potential sources of interference from the specific method of sample preparation or analysis. Most analytical methods provide information on such interference.

This section lists four documents that contain methods for analysis of N that are directly or indirectly applicable to biosolids. For purposes of analysis, biosolids fall somewhere between the realm of water and waste. The final use for biosolids is either agricultural, or closely related to agricultural use, and biosolids often more closely approximate soil than either waste or water, especially when biosolids have been dewatered.

The four documents are as follows:

- *Test Methods for Evaluation of Solid Waste, Physical/Chemical Methods* (U.S. EPA). This document is cited in the federal biosolids rule for the analysis of inorganic pollutants (40 CFR 503.8). It is used primarily by those concerned with analyzing and managing solid wastes and contains limited methodologies for the analysis of N in soils or biosolids.

- *Standard Methods for the Examination of Water and Wastewater* (American Public Health Association, 1992). This document is also cited in 40 CFR 503.8, but for purposes other than the analysis of N. It is used primarily by those working in water quality and wastewater analysis. It describes a number of analytical methods that are acceptable for the analysis of N in soils and biosolids. **It is a recommended reference.**

- *Methods of Soil Analysis, Part 2—Chemical and Microbiological Properties* (American Society of Agronomy and Soil Science Society of America, 1982). This extensive document is specifically designed to address laboratory methods for the chemical and microbiological analysis of soils. The procedures described may also be applicable for the analysis of biosolids. **It is a recommended reference.**

- *Plant, Soil, and Water Reference Methods for the Western Region* (Gavlak et al., 1994). This is a collaborative effort specifically written with the agricultural community in mind. **It is a recommended reference.**

Figure 9.1 presents a simplified flowchart that shows the general methods for preparation and analysis of samples for inorganic and organic N in soils and biosolids. The figure is followed by descriptions of specific methods listed in the three recommended reference documents.

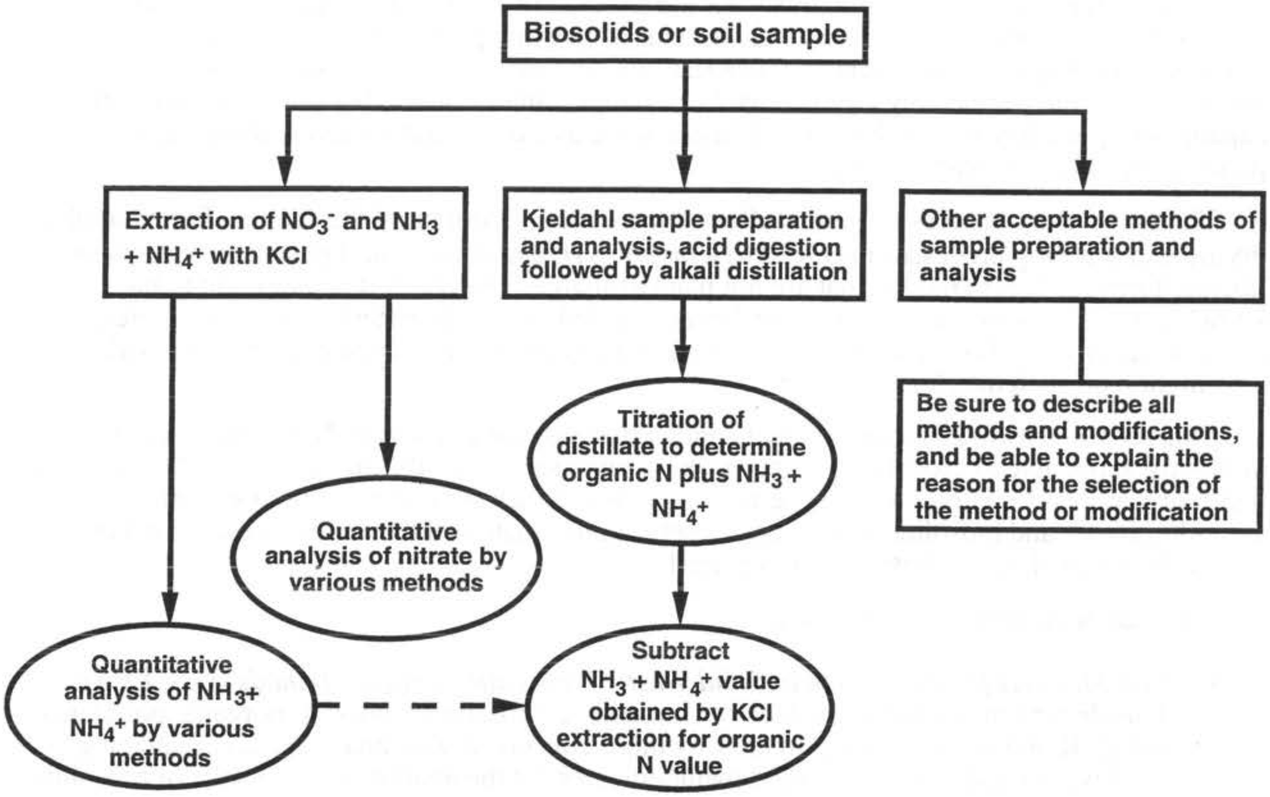

Figure 9.1 Simplified flowchart for analysis of nitrogen in biosolids and soils.

Inorganic nitrogen

Standard Methods for the Examination of Water and Wastewater addresses N in the NH_3, NH_4^+, and NO_3^- forms. It includes Method 4500 for analysis of NH_3 and NH_4^+. Method 4500-NH3 - B describes a preliminary distillation procedure, after which methods 4500-NH3 - C (Nesslerization), D (phenate), E (titrimetric), and H (automated phenate) can be used for quantitative analysis. Methods F and G rely on the use of electrodes and are not recommended for the analysis of soil or biosolids N. Several methods are described under 4500-NO3- for NO_3^-. Methods 4500-NO3 - E (cadmium reduction) and F (automated cadmium reduction) are in common use. Method 4500-NO3 - B is for screening only and is not accurate in other than relatively clean water samples. Some labs have reportedly found methods 4500-NO3 - C and D, which use chromatography and electrodes, to be difficult or unreliable.

Methods of Soil Analysis (Chapter 33) also addresses N in the NH_3, NH_4^+, and NO_3^- forms. Method 33-3 discusses the use of potassium chloride to prepare an extract of exchangeable NH_4^+ and NO_3^- that can then be quantitatively analyzed by various methods. The potassium chloride extraction method is in common use. Method 33-4 discusses steam distillation methods for exchangeable NH_4^+ and NO_3^- with many possible variations. Anecdotal information suggests that there can be significant differences in the results obtained by steam distillation, and it is therefore not recommended. Methods 33-7, 8, and 9 provide for quantitative colorimetric analysis of NH_4^+ and NO_3^-. These methods are used after samples are prepared by extraction or distillation. The methods discussed in 33-10 are not applicable because they deal with non-exchangeable NH_4^+ that is not considered to be plant available.

Plant, Soil, and Water Reference Methods for the Western Region is conveniently separated into matrix-specific sections. The potassium chloride extraction method, discussed in the preceding paragraph on Me*thods of Soil Analysis,* is recommended for NH_4^+ and NO_3^- analysis.

Organic nitrogen

The Kjeldahl method is the most common method in use for determining mineralizable organic N (ON) in biosolids, and is appropriate for soils (although measure of soil ON is typically only done for research purposes). The standard Kjeldahl method involves a two-step process. First, the sample undergoes a sulfuric acid digestion that converts ON compounds to NH_4^+. Second, the converted NH_4^+, along with any NH_4^+ that was originally present, is further converted to NH_3 in an alkali distillation process. The NH_3 liberated in this process is then quantified to determine the total N in the original digest. A separately determined value for NH_3 and NH_4^+ is then subtracted from the value obtained by the Kjeldahl method, and the difference is considered to be the mineralizable, or potentially plant-available, ON.

The Kjeldahl method does not strictly account for all forms of N in a sample, including NO_3^- and nitrite or other compounds with direct N-to-N bonding. The method may recover some of the NO_3^- and other forms of N that are not specifically intended for quantification. The amount accounted for by this incidental recovery is variable. In any case, the Kjeldahl method accounts for the greatest majority of nitrogenous compounds, and the result therefore is often referred to as "Total Kjeldahl Nitrogen" (TKN), or sometimes simply (and less correctly) as "total nitrogen."

The Kjeldahl method can be modified to recover NO_3^- and other forms of N. Although some of these modifications may yield better results, others are not appropriate for the purposes of biosolids application rate determinations because they may liberate forms of N that are not considered to be plant available. Generally, modifications should not be necessary. Any modifications used should be specifically noted on the laboratory report form. The term "total nitrogen" should not be used with the standard Kjeldahl method unless the Kjeldahl method has been deliberately modified in an effort to recover all nitrogenous forms present.

Standard Methods for the Examination of Water and Wastewater describes two variations of the Kjeldahl method. Either method 4500-Norg B (Macro-Kjeldahl) or 4500 Norg C (Semi-Micro Kjeldahl) may be used. Because the concentration of N in most biosolids samples is expected to be relatively high, the macro method is recommended. For highly liquid biosolids samples and soils expected to be low in N, either method is recommended. Soils with high quantities of ON, such as those where large amounts of manure or other organic materials have been applied, may require the macro method.

Methods of Soil Analysis describes the Kjeldahl method (Chapter 31) and two other methods. The electrode method discussed in Section 31-4 is not recommended; the hydrofluoric acid modification in Section 31-5 should also be avoided because it will liberate N that is not considered to be plant available.

Plant, Soil, and Water Reference Methods for the Western Region also relies on the Kjeldahl method. It should be noted that the total nitrogen method described in this reference is different from the Kjeldahl method, and is not recommended.

Reporting

It is important to keep good records of all sampling and analytical events. The records can be used for later reference, as evidence of regulatory compliance, and to ensure proper interpretation of the data. Inadequate or unclear reporting reflects on the laboratory and chemist and can jeopardize a project or result by inviting additional regulatory scrutiny because of suspect application rate calculations. Leave no doubt!

The following items should be reported:

- Dates of sampling events and sample analysis
- Sample numbers (tied to results)
- Origin of sample (field, digester, pile)
- A brief sample description (liquid, solid, semi-solid; clear, dark, gritty)
- Methods of preparation and analysis, including any modifications
- Results reported on both wet and dry weight basis and the units used (mg/kg, mg/L)
- Percent of total solids of the sample and volatile solids content as a percent of total solids
- Name of the technician or other contact person in case of questions

When reporting the various forms of N, the following terms or notations should be used (the form followed by "-N" means that the results are reported as mass of N instead of the entire compound):

- Total Kjeldahl Nitrogen or TKN
- Organic nitrogen or (ON-N)
- Nitrate nitrogen or (NO_3^--N)
- Ammonia nitrogen or (NH_3-N)
- Ammonium nitrogen or (NH_4^+-N)

References

American Public Health Association. 1992. Standard Methods for the Examination of Water and Wastewater. 18th ed.

American Society of Agronomy and Soil Science Society of America. Methods of Soil Analysis, Part 2—Chemical and Microbiological Properties.

Gavlak, R.G., Horneck, D.A., and Miller, R.O. 1994. Plant, Soil, and Water Reference Methods for the Western Region.

Mahler, R.L. and Tindall, T.A. 1994. Soil Sampling. Bulletin 704 (Revised). University of Idaho Cooperative Extension System, Moscow, ID.

U.S. Environmental Protection Agency (U.S. EPA). Test Methods for Evaluation of Solid Waste, Physical/Chemical Methods. EPA Publication SW-846 (various editions and revisions).

Appendix A

Glossary

Appendix A

Glossary

Acid soil: A soil with a pH < 6.5.

Adsorption: A physical or chemical mechanism in which a compound is temporarily attached to a surface.

Aerobic: Conditions having a continuous supply of free oxygen.

Alkaline soil: A soil with pH >7.3.

Agriculture: The production of crops or livestock on a farm.

Amendment: A material with beneficial properties that is added to a soil.

Ammonia (NH_3): A gaseous compound in the soil water that is in equilibrium with NH_4^+. This is the form that will leave the soil and soil water as a gas.

Ammonium (NH_4^+): An inorganic (available) form of N, formed during the **mineralization** of **ON.** NH_4^+ is a **cation** that is soluble in water and available for **plant uptake**.

Anaerobic: Conditions that lack molecular oxygen. In soils, this condition is usually caused by excessive wetness.

Anion: An ion having a negative charge.

Arid: A climate in which potential **evapotranspiration** greatly exceeds precipitation for most of the year, and little water **percolates** through the soil.

Atmospheric nitrogen (N_2): A gaseous form or N not generally available to plants (except N fixers), that makes up about 79% of the atmosphere.

Available elements: The elements in soil solution that can readily be taken up by plant roots.

Available nutrients: See **available elements.**

Cation: An ion having a positive electrical charge.

Cation exchange: The transfer of **cations** in soil solution and **cations** held by soil particles on the exchange sites of inorganic and organic matter.

Cation exchange capacity (CEC): The total potential of soils for **adsorbing cations**. Determined values depend somewhat on the method used.

Chlorosis: The formation of pale green or yellow leaves in plants resulting in the failure of chlorophyll to develop. It is often caused by a deficiency in an **essential element.**

Compost: Organic residues (usually plant or animal) that are arranged into piles and allowed to decompose under controlled conditions of air, temperature, nutrients, and moisture.

Coniferous forest: A forest consisting of predominantly cone-bearing trees with needle shaped leaves (usually evergreen). These are the most common types of forests in the Pacific Northwest.

Continuously anaerobic (*very poorly drained*) soil: A **soil horizon** that is saturated with water throughout the year; it is blue, olive, or gray.

Deciduous forest: A forest composed of trees that shed their leaves at some season of the year.

Denitrification: The biological reduction of N to N gas or oxides of N, resulting in the loss of N into the atmosphere.

Dryland-farming: A moisture-conserving method of farming in arid and semi-arid areas without using irrigation. The technique consists of growing a crop in alternate years, allowing moisture to be stored in the **fallow** year.

Essential elements: Elements that are needed by plants. These include: C, O, H, N, P, K, S, Ca, Mg, Fe, Mn, B, Cl, Zn, Cu, Co, Mo, and Ni,.

Evapotranspiration: The combined processes of evaporation and transpiration.

Excessively drained soil: A soil that loses water very rapidly because of rapid **percolation**.

Fallow: Land that has not been planted with crops for a period of time in order to accumulate moisture, control weeds, control pests, or induce **mineralization** of a nutrient.

Fertilizer: A material that is added to the soil to supply one or more plant nutrients in a readily available form.

Freely drained soil: A soil that allows water to **percolate** freely.

Humus: The well-decomposed, relatively stable part of the organic matter found in soils.

Immobilization: The process by which biological transformations convert inorganic N (NH_4^+ or NO_3^-) into **ON.**

Inorganic nitrogen: Forms of N that are available for plant uptake.

Leaching: The washing out of material (particularly ions) downward through the soil.

Legumes: A group of crops that have the ability to fix N_2 from the air (see **nitrogen fixation**).

Lime: Compounds of calcium used to neutralize soil acidity.

Lysimeter: Apparatus installed in the soil for measuring **percolation** and **leaching**.

Manure: Animal excreta with or without a mixture of bedding or litter.

Mineralization: The processes by which **ON** is biologically broken down and NH_4^+ is released (also called ammonification).

Neutral soil: A soil with pH 6.5-7.3.

Nitrate (NO_3^-): A mineral form of N formed by nitrification of NH_4^+. It is an **anion** that is soluble in water, available to plants, and subject to **leaching**.

Nitrate leaching: Movement of NO_3^- with water from rainfall or irrigation downward through the soil or laterally along impermeable layers in the soil. Because NO_3^- is an **anion,** it is not held by the soil **CEC** and easily **leaches**.

Nitrification: The oxidation of ammonium to NO_2^- and of NO_2^- to NO_3^- by microorganisms. NH_4^+ is used as an energy source by the bacteria *Nitrosomonas* to produce NO_2^-; the NO_2^- is then used as an energy source usually by the bacteria *Nitrobacter* to produce NO_3^-.

Nitrite (NO_2^-): A mineral form of N formed by nitrification of NH_4^+, usually a short-lived intermediate between NH_4^+ and NO_3^-.

Nitrogen (N): An element (atomic number = 7, atomic weight = 14) that exists in every living organism and that makes up 78 percent of the atmosphere. N exists in one of three basic forms: gaseous, inorganic, or organic.

Nitrogen fixation: Conversion of N_2 to **ON** by the symbiotic association between specific plants and bacteria.

Organic nitrogen (ON): N that is incorporated into organic molecules such as amino acids, proteins, chlorophyll, and DNA.

Percolation: Passage of water through the soil by gravity.

pH: A scale that measures the acidity and alkalinity of a solution; the negative logarithm of the hydrogen ion concentration of a solution. pH near 7 is neutral, pH < 6.5 is **acid**, and pH > 7.3 is **alkaline.**

Soil pH: The pH measured in a soil-water mixture.

Plant-available nitrogen (PAN): The amount of inorganic N available to the plant from fertilization. This includes NH_4^+ and NO_3^- forms, plus the N that **mineralizes** from **ON** and minus the N lost by **volatilization, denitrification, and immobilization.**

Plant uptake: The amount of an element that is taken from the soil (soil water) by the plants. It is usually measured in the above-ground portion of the plant.

Rangeland: A type of agricultural land usually used for grazing cattle or other domestic animals that is not planted with a specific crop; often associated with arid soils. Applications of biosolids to these lands are normally to the surface, but sometimes can be incorporated.

Residual soil nitrogen: The **inorganic N** (usually in the form of NO_3^-) that exists in the soil at the time of application of an **amendment** such as biosolids. An application rate will be reduced if there is significant residual soil N.

Soil: A thin, weathered, and biologically active layer of inorganic and organic material occurring at the surface of the earth and supporting plant life.

Soil horizon: A layer in a soil **profile** consisting of relatively uniform materials that runs approximately parallel to the surface of the ground.

Soil profile: A vertical section (usually < 10 feet deep) through a soil exposing all the **soil horizons** from the surface to the relatively unaltered underlying material.

Soil reclamation: The practice of increasing the productivity (ability of the soil to grow plants well) of a disturbed or otherwise unproductive soil by the use of soil **amendments**, such as biosolids.

Soil solution: The water surrounding soil particles.

Soil survey: The systematic examination and mapping of soil.

Soil structure: The aggregation of individual soil particles into larger units with planes of weakness (usually pores) between them. Good structure improves the movement of water and air through the soil.

Soil texture: The coarseness or fineness of a soil; the relative proportions of sand, silt, and clay in a soil. Coarse-textured soils contain mostly sand, while fine textured soils contain mostly silt and clay.

Tilth: The physical state of the soil that determines its suitability for plant growth, taking into account texture, structure, consistence, and pore space. It is a subjective estimation and is judged by experience.

Unavailable nutrients: Plant nutrients that are present in the soil but cannot be taken up by the roots because they have not been released from the rock or minerals by weathering or from organic matter by decomposition.

Volatilization: Loss of gaseous NH_3 to the atmosphere.

Appendix B

Abbreviations & Symbols

Appendix B

Abbreviations

Elements and compounds

C = carbon
C:N = carbon-to-nitrogen (ratio)
CO_2 = carbon dioxide
N = nitrogen
N_2 = nitrogen gas
N_2O = nitrous oxide
NH_3 = ammonia
NH_4^+ = ammonium
NO_2^- = nitrite
NO_3^- = nitrate
O = oxygen
O_2 = oxygen gas
ON = organic nitrogen
R = organic compound

Units of measurement

ac = acre
bu = bushel
cm = centimeter
dt = dry ton
g = gram
ha = hectare
kg = kilogram
lb = pound
mg = milligram
ppm = part per million
t = ton
yr = year

Variables in equations

AN = Percent NH_4^+ in biosolids as applied (%)
B_{app} = Biosolids application rate (dt/ac)
BD = Soil bulk density at the site (g/cm$^{3)}$
B_i = Biosolids application rate "i" years ago (dt/ac)
c_{bd} = 2.72; conversion factor for standard bulk density (1 g/cm^3) and standard soil depth (12 in.)
D = Loss of mineral N by denitrification (%)
e_f = Crop N uptake efficiency factor (0-1)
K_0 = Mineralization rate of ON during the year of application (%)
K_i = Mineralization rate of ON "i" years after the year of application (%)
N_{conc} = Crop N concentration, dry matter basis (%)
$N_{credits}$ = Credits for N from other sources (lb/ac)
NN = Percent NO_3^- in biosolids as applied (%)
N_{prev} = Total mineralized N from biosolids applications in previous years (lb/ac)
N_{req} = N supply required by plants and soil (lb/ac)
$N_{soilmin}$ = Estimated annual soil ON mineralized (lb/ac)
N_{uptot} = Total above-ground crop N uptake (lb/ac)
N_{upunit} = N uptake by crop per unit of yield (bushel, ton, etc.) (lb/unit yield)
ON_0 = Percent ON in biosolids as applied (%)
ON_i = Percent N in biosolids "i" years ago (%)
SI = N immobilization in soil from initial biosolids application (lb/ac)
SON_{yr} = Soil ON mineralized per year (0-12 in. depth) (%)
TKN_{soil} = Soil total (or organic) N (mg/kg)
T_{rem} = Decimal fraction of year remaining (0-1)
V = Loss of NH_3 by volatilization (%)
Y_h = Yield of harvested above-ground portion of crop (bushels, etc.)
Y_{lbac} = Crop yield (lb/ac)
Y_m = Crop moisture content (%)
Y_{res} = Yield of unharvested above-ground crop residue (lb/ac)

Appendix C

Matrix Tables of Local Research Results

Pacific Northwest Biosolids Research Results: Nitrogen Mineralization

Author	Report	Biosolids Type	Biosolids Appl. Rate	Location	Season of Application	Mineralization rate over period in months.										
						2	3	4	5	6	7	8	9	12	21	24
Grey, M. and Henry, C.	Boulder Park Dryland Wheat Biosolids Nitrogen Dynamics 1994 Research Summary	Anaerobic digested from Renton WWTP.	5 dry tons/ac	Boulder Park, near Mansfield, in E. WA	Fall (Sept 1994)		11%				16%					
		"	5 dry tons/ac	"	Spring (May 1995)		35%									
Grey, M. and Henry, C.	Prosser Poplar Plantation Biosolids Nitrogen Dynamics 1994 Reaearch Summary	Anaerobic digested from Renton WWTP. dewatered.	5 dry tons/ac	WSU's Irrigated Agriculture Research Station at Prosser in E. WA	Summer (August 1994)			Drip 25% Micro 26%				Drip 28% Micro 27%				
		"	5 dry tons/ac	"	Spring (April 1995)	Drip 33% Micro 34%										
Grey, M. and Henry, C.	Emerald Farms Biosolids Nitrogen Dynamics 1993-94 Research Summary	Anaerobic digested from Renton WWTP. - dewatered	5 dry tons/ac	Emerald Farms at Sunnyside in E. WA	Spring (May 1994)	39%				55%				48%		
		"	"	"	Fall (Sept 1994)	33%										
		Anaerobic digested from Renton WWTP. -Heat dried	5-20 g per chamber	Emerald Farms at Sunnyside in E. WA	Spring (May 1994)	25%				42%						

Author	Report	Biosolids Type	Biosolids Appl. Rate	Location	Season of Application	Mineralization rate over period in months.										
						2	3	4	5	6	7	8	9	12	21	24
Grey, M. and Henry, C.	Heat Dried Biosolids Organic Nitrogen Mineralization1993-94 Research Summary	Anaerobic digested from Renton WWTP. Heat Dried	4 g /chamber	Pack Forest, W. WA	Fall (Oct 1993)	22%				31%				39%		
		"	"	WSU Puyallup, E. WA	Fall (Oct 1993)	29%				34%				42%		
		"	"	Emerald Farms at Sunnyside in E. WA	Fall (Oct 1993)	5%				23%				30%		
Henry, C.L	Nitrogen Dynamics of pulp and paper sludge amendment to forest soils	Primary P&P Sludge (25% solids)	67 Mg/ha	UW Pack Forest near Eatonville in W. WA					Sand -28.2% Clay -16.2%				Sand - 17.9% Clay - 24.5%	Sand -12.0% Clay -20.9%	Sand -12.3% Clay -31.5%	
		1:2 sec/prim sludge mixture	22Mg/ha (2°) & 45 Mg/ha (1°)	"					Sand 49.2% Clay 48.6%				Sand 67.8% Clay 63.6%	Sand 69% Clay 70.7%	Sand 71.5% Clay 74.3%	
		2:1 sec/prim sludge mixture	45Mg/ha (2°) & 22 Mg/ha (1°)	"					Sand 43.8% Clay soil 48.3%				Sand 56.5% Clay 58.8%	Sand 63.6% Clay 68.0%	Sand 72.9% Clay 73.8%	
		Scondary P&P Sludge (8% Solids)	45 Mg/ha	"					Sand 47.4% Clay 43.2%				Sand 65.0% Clay70.4%	Sand 67.6% Clay 73.9%	Sand 75.0% Clay 79.2%	

Author	Report	Biosolids Type	Biosolids Appl. Rate	Location	Season of Application	Mineralization rate over period in months.										
						2	3	4	5	6	7	8	9	12	21	24
Henry, C.L; Haub , A; Harrison R.B.	Mineralization of Biosolids Nitrogen from Six Oregon Cities	Eugene	22 dt/ha	silt loam in container		13%				28%				31%		
		Salem	22 dt/ha	silt loam in container		43%				60%				64%		
		Gresham	22 dt/ha	silt loam in container		28%				34%				65%		
		United Sewerage Agency	22 dt/ha	silt loam in container		13%				19%				20%		
		United Sewerage Agency	22 dt/ha	silt loam in container		18%				26%				27%		
		Portland	22 dt/ha	silt loam in container		34%				56%				62%		
		Portland	22 dt/ha	coarse sand in container		27%				34%				40%		
		United Sewerage Agency	22 dt/ha	silt loam in container		38%				38%				51%		
		Corvallis	22 dt/ha	silt loam in container		-1%				11%				19%		
		Portland	22 dt/ha	silt loam in container		-21%				7%				15%		
		Portland	22 dt/ha	coarse sand in container		-3%				22%				36%		
Henry, C.L; Coles J; Harrison R.B	Nitrogen Status of Two Douglas - fir Stands and Transformations and Losses following reapplication of Biosolids.	Anaerobically digested primary biosolids from West Point WWTP	47 dt/ha for either 0,1,2 or 3 years, 25 dt/ha 10 years later.	UW Pack Forest near Eatonville in E. WA	Winter	14%										

Author	Report	Biosolids Type	Biosolids Appl. Rate	Location	Season of Application	Mineralization rate over period in months.										
						2	3	4	5	6	7	8	9	12	21	24
Henry, C.L	Dellchem Treatment Process. Evaluation of Sludge reuse impacts for Metro waterwater Treatment Plants.	Dellchem	21 dt/acre			17.7-19.6%										
		Conventional	21 dt/acre			12.8-21.2%										

Pacific Northwest Biosolids Research Results: Ammonia Volatilization

Author	Report	Biosolids Type	Application Rate	Form (& pH if avail)	Location	Soil pH	Application Season	Init. NH_4^+-N	1	2	3	8	15	30	60
									% of NH4+-N remaining after these days						
Grey, M. and Henry, C.	Boulder Park Dryland Wheat Biosolids Nitrogen Dynamics 1994 Research Summary.	Anaerobic digested from Renton WWTP.	5 dry tons/ac	Dewatered	Boulder Park, near Mansfield, E. WA	approx 6.0	Fall (Sept 1994)	194 lbs/ac	89%	88%	87%		78%	76%	
									% of NH4+-N remaining after these days						
Grey, M. and Henry, C.	Prosser Poplar Plantation Biosolids Nitrogen Dynamics 1994 Reaearch Results Summary	Anaerobic digested from Renton WWTP.	5 dry tons/ac	Dewatered	WSU's Irrigated Agriculture Research Station at Prosser, E.WA	>8.0	Summer (July 1994)	79 lbs/ac	89%	87%	83%	71%	64%	61%	54%
									% of NH4+-N remaining after these days						
Grey, M. and Henry, C.	Emerald Farms Biosolids Nitrogen Dynamics 93-94 Research Summary	Anaerobic digested from Renton WWTP.	5 dry tons/ac	Dewatered fresh (8.21)	Emerald Farms at Sunnyside, E. Washington.	7	Fall (Sept. 1993)	74 lbs/ac	57%	39%	31%	21%	0%	0%	0%
		.	.	Dewatered fresh (8.61)	Emerald Farms at Sunnyside, E. Washington.	.	Spring (April 1994)	58 lbs/ac	26%	0%	0%	0%	0%	0%	0%
									Loss of NH4+-N (kg/ha/day)						
Henry, C.L; Coles J; Harrison R.B	Nitrogen Status of Two Douglas - fir Stands and Transformations and Losses following reapplication of Biosolids	Anaerobic digested primary from West Point WWTP.	47 dt/ha for either 0,1,2 or 3 years, 25 dt/ha 10 years later.	Liquid.	12 & 65 year old stands at UW Pack Forest, Eatonville in W. WA		Summer (last application August 1992)	n/a	17	10	5	3	1	1	
									Loss of NH4+-N (kg/ha/day)						
Henry,C.L; and Zabowski D.	Volatile Losses of Nitrogen Following fertilization of Ponderosa Pine	Domestic biosolids from the City of Wenatchee	11.4 Mg/ha	Liquid	Mature ponderosa stand on the eastern slopes of the Cascade Mountains.	4.1-4.9	Spring (April 1989)		3	1.5		0.3	0.3	0.3	30 day total 12.5 kg N/ha (10%)

Pacific Northwest Biosolids Research Results: Denitrification

Author	Report	Biosolids Type	Application Rate	Form (& pH if avail)	Location	Soil pH	Application Season	Denitrification at day after application (kg/ha/day)						
								1	2	3	8	15	30	60
Henry, C.L; Coles J; Harrison R.B	Nitrogen Status of Two Douglas - fir Stands and Transformations and Losses following reapplication of Biosolids	Anaerobic digested primary from West Point WWTP.	47 dt/ha for either 0,1,2 or 3 years, 25 dt/ha 10 years later.	Liquid.	12 & 65 year old stands at UW Pack Forest, Eatonville in W. WA		Summer (last application August 1992)	0.05			0.1	0.6	0.75	0.2
Henry,C.L; and Zabowski D.	Volatile Losses of Nitrogen Following fertilization of Ponderosa Pine	Domestic biosolids from the City of Wenatchee	11.4 Mg/ha	Liquid	Mature ponderosa stand on the eastern slopes of the Cascade Mountains.	4.1-4.9	Spring (April 1989)		0.012	0.016	0.015		0.018	0.012

Appendix D

Nitrogen Mineralization Study

Appendix D

Nitrogen Mineralization Study: Biosolids, Manures, Composts

Neil Cowley, Daniel Thompson , and Charles Henry

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Abstract

A study of the yearly nitrogen mineralization rates of various products derived from municipal wastewater treatment plants, composting facilities and farms in Washington State was conducted. Results indicated that manures and uncomposted biosolids products had greater mineralization rates and lower variability than composts. Additionally, aerobically treated biosolids showed higher mineralization rates than anaerobically treated biosolids; this result is attributed to the more complete stabilization of carbon-nitrogen organic complexes by the anaerobic digestion process. It is suggested that the greater variability of the composts was likely due to the varying levels of maturity and varying types of carbonaceous materials present. It is further suggested that the lower mineralization rate of composted products was due to the existence of greater levels of woody, high carbon materials as well as the greater level of stabilization achieved by the composting process relative to other treatment methods.

Introduction

This report summarizes an examination of the nitrogen (N) mineralization rates of various biosolids, manures and composts. In 1995 an investigation of the yearly mineralization rates of different biosolids, manures and compost products from Washington State wastewater treatment facilities, farms and composting facilities was begun. The research was conducted at Washington State University's Research and Extension Center in Puyallup, WA (Puyallup). The objectives of the study were to determine the mineralization rates of the various products to gain a more thorough understanding of N mineralization dynamics and to develop a more comprehensive knowledge of the most appropriate utilization of the various product types.

Methods and Materials

Study Initiation

Initial installations were made in October 1995. Additional biosolids and composts received from Tacoma, Pierce County Utilities and Cowlitz County treatment plants after the trial was commenced were applied in late November 1995; these chambers were removed 11 months later in late October—at the same time as the initial chambers.

Organic N Mineralization Method

The standard residual technique was used for determination of the organic N mineralization rate. The residuals method used ceramic tubes with 5 grams of biosolids, manure or compost. Biosolids and compost products were oven dried at 70° C. Initial N concentration and mineral N concentration of dried product were analyzed. The chambers were inoculated, capped and then buried. Chambers were removed after either 11 or 12 months—depending on the installation time. After removal, the chambers were oven-dried, weighed, and the samples were removed for total and mineral N analysis.

The percent organic N mineralized was calculated as follows:

$$\frac{(\text{Initial organic N concentration} * \text{Initial wt.}) - (\text{Final organic N concentration} * \text{Final wt.})}{(\text{Initial organic N concentration} * \text{Initial wt.})} * 100$$

Biosolids, Manures and Compost Characteristics

Biosolids, manures and composts examined are summarized by type in Table 1. Specific carbon (C) and N characteristics of the product samples utilized are summarized in Table 2.

Table 1. Biosolids, manures and composts used in mineralization study and treatment type.

Product	*Treatment Type*
Birch Bay	Aerobic
Brewster	Lime-stabilized
Centralia	Drying Bed
Centralia Digested	Anaerobic
Centralia Liquid	Anaerobic (liquid)
Cowlitz County 1	CoCompost
Cowlitz County 2	CoCompost
Cowlitz County 3	CoCompost
GroCo	CoCompost
Kennewick	Lagooned
Land Recovery, Inc.	Yard Compost
Northwest Cascade	CoCompost
Pierce County Utilities	Anaerobic
Port Townsend	CoCompost
Renton	Anaerobic
Smith Brothers-Dairy	Manure
Tacoma	Anaerobic
Tacoma Liquid	Anaerobic (liquid)
Tagro	Soil Mix
Vashon	Oxidation Ditch
Wilcox Farm-Chicken	Manure

Table 2. Carbon and organic nitrogen of biosolids, manures and composts used in mineralization study.

Product	*C%*	*Organic N%*
Birch Bay	30	5.3
Birch Bay	33	4.2
Brewster	31	3.9
Centralia Digested	34	3.6
Centralia Drying Bed	12	1.6
Centralia Drying Bed	11	1.4
Centralia Liquid	28	3.6
Cowlitz County 1	44	2.3
Cowlitz County 1	27	1.8
Cowlitz County 2	31	1.4
Cowlitz County 3	32	1.1
GroCo-Fine	43	0.84
Kennewick	19	1.9
Land Recovery, Inc.	21	1.6
NW Cascade	32	1.3
Pierce County Utilities	35	4.7
Port Townsend	20	1.6
Renton 6/27/95	33	5.1
Renton 9/5/95	33	5.2
Smith Brothers-Dairy	na	na
Tacoma Cake	31	3.3
Tacoma Liquid	29	3.2
Tagro	6.2	0.34
Vashon	43	6.7
Vashon	37	5.0
Wilcox Farm-Chicken	34	3.0

Results

Yearly N mineralization rates of the various products showed that biosolids products and manures had less variability and higher mineralization rates than composts. Some of the chambers containing composts even indicated N immobilization. Annual mean mineralization rates are shown in Table 3 and Figure 1.

Table 3. Average N mineralization of biosolids, composts and manure types.

Soil Amendment	*Average N Mineralization Rate (St.Dev.)*
Soil Mixes, e.g. Tagro	2% (15%)
Yard Compost, e.g. Land Recovery, Inc.	10% (9%)
Cocomposts, e.g. GroCo, Cowlitz	11% (12%)
Lagooned Biosolids, e.g. Kennewick	20% (3%)
Anaerobic Liquid, e.g. Centralia, Tacoma	27% (4%)
Drying Bed, e.g. Centralia	37% (8%)
Anaerobic, e.g. Renton, Pierce, Tacoma	39% (7%)
Oxidation Ditch, e.g. Vashon	45% (1%)
Aerobic, e.g. Birch Bay	49% (7%)
Lime-stabilized, e.g. Brewster	55% (3%)
Manure, e.g. Dairy Cows, Chicken	62% (6%)

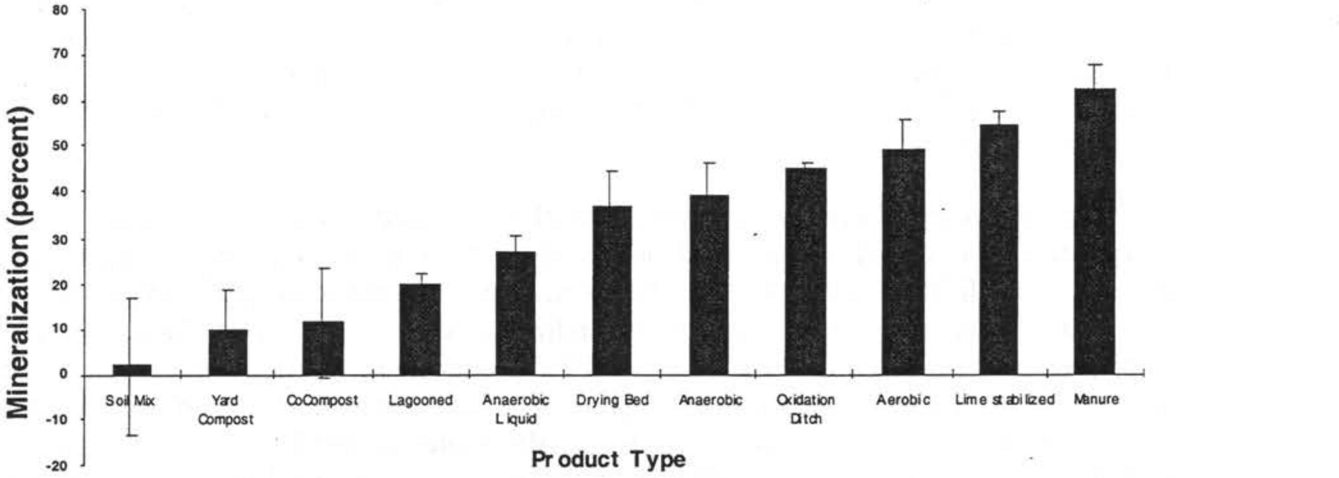

Figure 1. Average N mineralization rate of biosolids, composts and manure types.

Biosolids and Manures

The two manures had the highest average mineralization rates of approximately 60 percent. The aerobically treated product from Birch Bay and the lime-stabilized aerobically treated product from Brewster were next highest, ranging between 49 and 55 percent. The Vashon oxidation ditch (which had the highest concentration of organic N for all samples) mineralized 45 percent in the year. The dewatered anaerobic biosolids from Pierce County Utilities, Renton, Centralia and Tacoma had mineralization rates ranging between 32 and 43 percent. The drying bed product from Centralia had a mineralization rate of approximately 37 percent. The anaerobic liquid biosolids from Tacoma and Centralia had rates ranging between 26 and 27 percent. The lowest mineralization rate among biosolids and manures, 19 percent, was from the Kennewick lagooned material.

Composts

Composts were much more variable in results and generally had much lower N mineralization rates than the manures or biosolids products. The co-composts, had an average yearly mineralization rate of approximately 11 percent, but the standard deviation for this rate was 12 percent, so it may range greatly according the results of this study. The yard compost (produced by the Land Recovery, Inc.) had an average rate of 10 percent (SD =9 percent). The soil mix (produced by Tagro) had the lowest average yearly mineralization rate among all the product types examined, but also the greatest variability; it's mineralization rate was <2 percent ± 15 percent.

Discussion

Previous work has indicated that the rate of organic N mineralization depends upon all of the following: 1) the nature of the initial N compounds (for example, the percentage of initial organic N), 2) the type of treatment or stabilization method, 3) the length of the stabilization period and 4) the type of organics. The results of this study suggested that each of the four factors—individually and/or in combination—likely played some role in determining the annual N mineralization rates of the products tested.

The results indicated that mineralization was likely affected by the initial organic N concentration. The soil mix (Tagro) had the lowest level of organic N and showed the lowest annual N mineralization rate. Likewise, the cocomposts and yard waste compost possessed low levels of initial organic N, and this N was mineralized at relatively low rates. The aerobically treated product from Birch Bay, the lime-stabilized product from Brewster and the oxidation ditch product from Vashon had relatively high levels of initial organic N and showed very high rates of N mineralization. Similarly, the anaerobically treated biosolids products all began with moderate to high organic N levels, and moderate to high rates of mineralization occurred over the course of the study.

The N-mineralization rate also appeared to be significantly impacted by the treatment/stabilization method. The manures received no treatment after production, and it was theorized that the organic fraction thus had a higher concentration of more easily mineralized organic C and N complexes. Given the very high N mineralization rates for the manures, the results provide evidence that, indeed, this was correct. Aerobic digestion (typically performed at smaller treatment plants) is generally not as complete as the anaerobic digestion typical of larger treatment plant operations. The aerobically treated biosolids showed a higher mineralization rate relative to the anaerobically treated biosolids. This was likely the case due to the greater level of more easily decomposed C-N organic complexes present in the aerobically treated products. The composting process generally stabilizes the C-N organic complexes beyond that of other treatment methods, and the results of this study clearly showed that composting decreased the mineralization rate.

Figure 2 shows the decomposition rate. The decomposition rate of the products provides further evidence that those products containing higher concentrations of the more recalcitrant C-fractions (the more stabilized products), have slower decomposition rates with a resulting reduction of the N mineralization rate. With only three exceptions (the lime-stabilized biosolids, the drying bed biosolids and the lagooned biosolids) the decomposition rate indicated the N mineralization rate. Compared to the other biosolids products, the three exceptions were thought to possess relatively more stable organic matter (OM), and, thus, one would not expect the materials to decompose rapidly. Among these three, the lime-stabilized biosolids had a very high N mineralization rate, the drying bed biosolids had a moderate rate, and the lagooned biosolids showed a relatively low N mineralization rate. The lagooned and the drying bed biosolids had the lowest percentage of organic C of all the products examined except for the Tagro soil mix product. With such a low organic C percentage and stable OM, it wasn't expected that these products would decompose rapidly. It was expected that the N mineralization rate for these two product types would be lower than the results indicated. That the N mineralization rate of these two product types was not lower may be the result of the initial low carbon:nitrogen (C:N) ratios of the products. A low C:N tends to lead to greater mineralization of N. The lime-stabilized product was not expected to show such a high N mineralization rate either. However, this product possessed a high initial organic N concentration and, this may account for its high N mineralization rate despite the low decomposition rate.

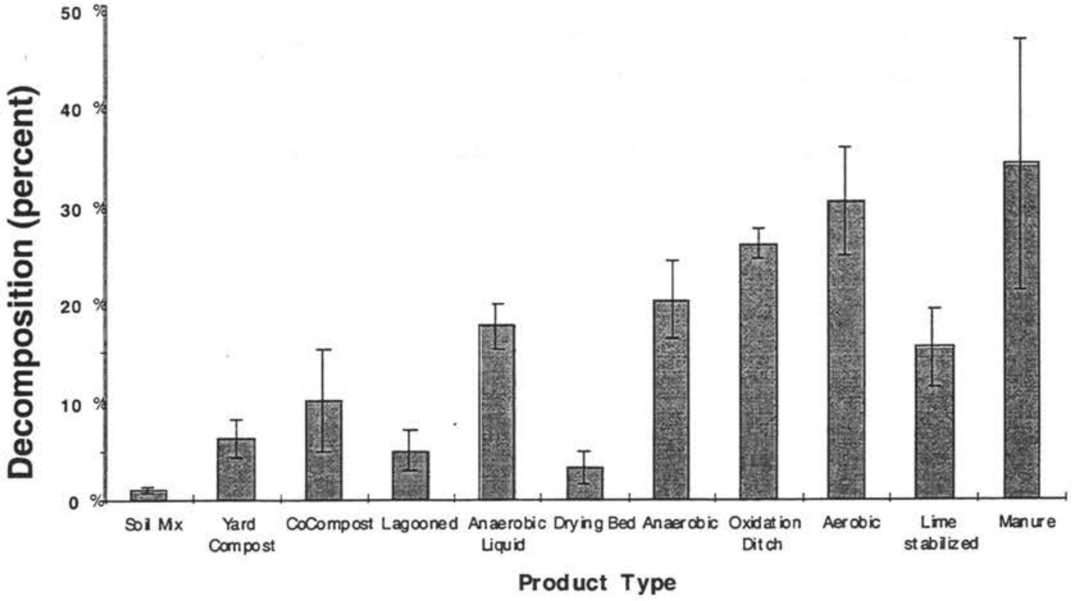

Figure 2. Average decomposition rate of biosolids, composts and manure types.

The length of the stabilization period and the type of organic material likely resulted in the great variability associated with the composted products samples. Specifically, the variability of the compost products was likely due to the variable ages and types of material as well as the heterogeneity within the product; this heterogeneity was due to the variable particle size of woody materials in the composts. The fact that some chambers with composts actually indicated N immobilization provided further evidence that the type of C material and maturity of the compost is very important; an immature compost with difficult to decompose woody material may lead to N immobilization.

Conclusions

Initial product characteristics, treatment/stabilization technique, length of treatment/stabilization, and type of carbonaceous material present all affected the yearly N mineralization rate.

Specifically:

- The higher the initial concentration of organic N, the greater the N mineralization rate.
- The more thorough and lengthy the treatment/stabilization method, the lower the N mineralization rate.
- The more recalcitrant the carbonaceous materials, the lower the N mineralization rate—unless offset by a high initial organic N concentration.
- The following N mineralization rate trends were found: soil mix < yard compost < co-compost < lagooned biosolids < anaerobically treated liquid biosolids < drying bed biosolids < anaerobically treated dewatered biosolids < oxidation ditch biosolids < aerobically treated biosolids < lime-stabilized biosolids<manure.

Appendix E

Ammonia Volatilization Study

Appendix E

Ammonia Volatilization Study

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Introduction:

This report summarizes the results of studies concerning nitrogen (N) volatilization following the application of various organic amendments to soils. Three studies were begun in December 1995 and completed in September 1996. The studies were performed at Washington State University's Research and Extension Center in Puyallup, WA (Puyallup).

Ammonia-nitrogen (NH_3) and ammonium-nitrogen (NH_4^+) ions are added to the soil with biosolids applications or are produced during biological mineralization of organic N in biosolids. The concentration of NH_4^+ in solution and on exchange sites tends toward an equilibrium. Similarly, the concentration of NH_3 and NH_4^+ in solution tends toward an equilibrium. And, according to Henry's Law, the concentration of NH_3 tends toward an equilibrium relationship between its liquid (in solution) and its gaseous (in the atmosphere) phases. Because NH_3 is a gas at normal atmospheric temperatures and pressures, evolution of NH_3 into the atmosphere is a potential major loss of N under certain conditions. The primary factors known to contribute to NH_3 volatilization are:

- **Temperature**: As temperature increases, the constant in Henry's Law changes to favor greater volatilization. Secondly, as temperature increases the percentage of NH_3/NH_4^+ increases. Both of these increase the partial pressure differences and encourage volatilization.
- **Air turbulence**: Movement of air (such as wind speed) is very important in affecting NH_3 volatilization. Turbulence reduces the concentration of NH_3 in the atmosphere above the water (or soil water), thus increasing the driving force from liquid to gaseous. The extent of incorporation of biosolids affects the level of turbulence and gaseous dissipation from the biosolids.
- **Soil Moisture Levels**: Typically, all other things being equal, the lower the moisture level, the higher the volatilization rate. This is the case because as soil solution evaporates, the concentration of NH_3 in solution is increased relative to gaseous NH_3, and the equilibrium must be reestablished by losses of solution NH_3.
- **pH**: As pH increases the equilibrium ratio of NH_3:NH_4^+ in solution increases, and volatilization is more likely to occur because an increase in NH_3 in solution results in an inequilibrium between liquid NH_3 and gaseous NH_3.

The two primary objectives of the studies were: 1) to examine the N volatilization rate of a specific biosolids receiving various treatments, and 2) to determine the N volatilization rate of various biosolids receiving typical application techniques and rates.

Materials and Methods:

The research was conducted in three studies:

1. An investigation of the progressive NH_3 volatilization loss at Puyallup for biosolids from the Renton Wastewater Treatment Plant in King County, WA, (Renton) over a 71 day period. Applications were made both in summer and winter, and used several treatments.

2. An investigation of the 71 day NH_3 volatilization rate of different biosolids at Puyallup utilizing typical application techniques and rates.

Plots established at Puyallup were chosen to represent typical application sites for the west side of the Cascades mountain range in Washington State. The results reported in this study may not be representative of those on eastern side of the Cascades, as the east side experiences harsher extremes in both summer and winter temperatures than experienced on the western side of the mountain range, and typically has much higher pH.

Biosolids and Characteristics

Biosolids characteristics and application rates (in terms of NH_4^+-N) are summarized in Table 1.

Table 1. Initial characteristics of the biosolids examined.

Location	*Biosolids Type*	*Percent Solids*	*NH_4^+-N ($\mu g\ g^{-1}$)*	*NH_4^+-N applied ($kg\ ha^{-1}$)*
Kennewick	Lagooned	6.9	5500	14
Centralia liquid	Anaerobic liquid	6.5	2600	34
Birch bay	Aerobic	2.9	4000	57
Brewster	Lime stabilized	1.6	6600	74
Centralia	Drying Bed	40.5	3050	87
Vashon	Oxidation Ditch	14	15000	106
Renton	Anaerobic dewatered	21	11900	125

Treatments

For all studies, applications of biosolids were made to small plots laid out in a randomized block design.

Renton Biosolids

Applications of Renton biosolids were made on 07/16/96 (excluding the winter application). The site received no irrigation in winter. However, during summer, all plots received irrigation when the adjoining corn crops were watered. The following treatments were explored:

- "Normal": tilled the biosolids into the top 5 cm of the soil; applied at the agronomic rate
- "Acid Added": 150 ml of hydrochloric acid (HCl) was added (intended to decrease the pH by one unit) to 5 kg of biosolids; a "normal" incorporation technique and application rate was utilized

- "Buried": all biosolids buried beneath the upper 5 cm of soil—no biosolids left upon the surface; a "normal" application rate was utilized
- "Double Application": 2x the agronomic rate was applied; a "normal" incorporation technique was utilized
- "Lime-stabilized": the biosolids was applied with a similar weight of lime; a "normal" incorporation technique and application rate was utilized
- "No Incorporation": all biosolids left upon the surface; a "normal" application rate was utilized
- "Winter Application": applications were made on 12/14/96; a "normal" incorporation technique and application rate was utilized

Various Biosolids

Applications of the various biosolids products were made on 07/16/96. The biosolids were applied at agronomic rates and tilled into the top 5 cm of the soil. The site received no irrigation in winter. However, during summer, all plots received irrigation when the adjoining corn crops were watered.

Volatilization Method

Semi static sorption technique volatilization chambers were installed to capture NH_3 volatilized in the control and treatment plots. The 10 cm diameter PVC volatilization chambers had two foam pads soaked with a 2.2 *N* solution of phosphoric acid, glycerol and distilled water. The bottom pad collected NH_3 volatilized from the biosolids-treated soil, while the upper pad removed ambient NH_3 on the site. Only the lower pads were analyzed for treatment effects. Pads were changed after 24 hours in the field. Measurements were made at approximately 1, 3, 4, 7, 14, 28 and 71 days following application. Pads were individually bagged after removal from the chamber and returned to the laboratory in ice. Pads were rinsed repeatedly with distilled water then brought to 500 ml, and tested for NH_3 concentration using the idophyenol blue method.

Volatilization losses were calculated by subtracting measured volatilized NH_3 mass from the initial mass of NH_3 present in the biosolids contained under the chamber. Three chambers measured volatilization loss per day for each treatment.

Results & Discussion

Renton Biosolids

Application technique for the biosolids from the Renton WWTP was investigated in this portion of the study. Application rate, interaction with the soil, irrigation scenario, and season of application was investigated. Average daily loss rates of ammonia from Renton biosolids treated in these different ways at Puyallup over 71 days are shown in Figure 1. Average initial NH_3 loss totals from these treatments are listed in Table 2.

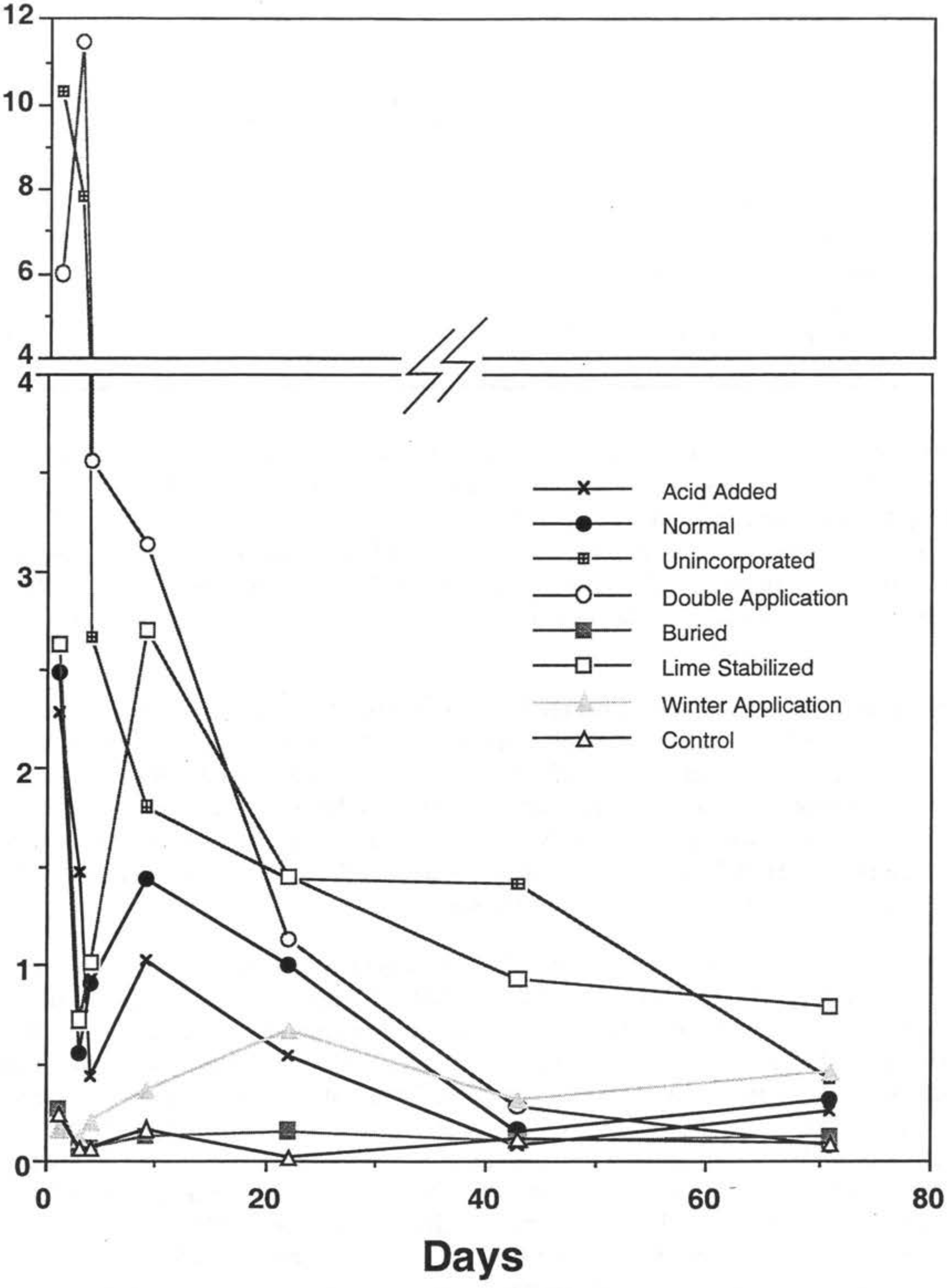

Figure 1: Average daily loss rate of ammonia (in kg/ha/d) from Renton biosolids treated in different ways at Puyallup over 71 days.

Table 2. Renton biosolids with various application treatments applied at Puyallup (percent of initial NH_3 loss totals after 71 days).

Treatment	*% of the initial NH_3 lost after 71 days*
Lime Stabilized	86%
Unincorporated biosolids	94%
Double application	43%
Normal incorporated	37%
Acid added	25%
Winter application	22%
Buried	7%

Effect of season: The volatilization rate was higher in summer than in winter. After 71 days, Renton biosolids incorporated into the soil had an average 37 percent of initial NH_3 loss following the summer application compared with 22 percent of NH_3 for biosolids applied in winter. Given the known effect of temperature on volatilization rates, this was an expected result. However, as summer and winter temperatures at Puyallup are not vastly different, it might be expected that sites with larger seasonal temperature differences would result in larger differences in volatilization rates.

Interaction with the soil: The most readily apparent result is that the unincorporated treatment produced vastly greater volatilization rates relative to the other treatments. Given the known effect of air movement on the volatilization rate, it was expected that loss patterns would follow: unincorporated treatment > normal incorporated > buried. This was true; loss rates were 94%, 37% and 7% respectively. Secondly, when biosolids are mixed into the soil, there is far more potential for pH of the matrix to change; lowered by the soil. Contact with the soil also allows NH_4^+ to to be retained on soil exchange sites.

Effect of pH: Renton biosolids were pH 8.2, whereas the pH of the upper 7.5 cm of soil was 6.2. At this soil pH, NH_4^+ is greatly favored over NH_3. Addition of acid to the biosolids would change the also lower the ratio of NH_3/NH_4^+. In contrast, adding lime and increasing the pH would increase the ratio of NH_3/NH_4^+. Thus the expected result was lime stabilized > normal > acid added. The acid treatment showed a somewhat lower rate of volatilization relative to the normal treatment and a significantly lower rate relative to the lime-stabilized treatment. Since this treatment was applied to a slightly acidic soil, there would be a combined effect on lowering the pH of the biosolids/soil matrix. The lime-stabilized treatment resulted in a significantly greater volatilization rate relative to all other treatments. Such an increase in pH moves the NH_3/NH_4^+ equilibrium relationship such that as the pH increases, the percent NH_3 of the total $NH_3 + NH_4^+$ increases; with this increase in NH_3 in solution, liquid NH_3 becomes out of equilibrium with gaseous NH_3 and is eventually lost from solution as the equilibrium of solution and gaseous NH_3 is reestablished. Such transformations clearly were occurring during this study.

Application rate: The double application treatment had slightly higher volatilization rates than normal application rate. However, the difference was not great. It was expected that the total volatilization loss would be less, as there was a reduced surface area to mass ratio.

Various Products

Average daily loss rates of ammonia from various products examined at Puyallup over 71 days are shown in Figure 2. Average initial NH_3 loss totals from these products are listed in Table 3.

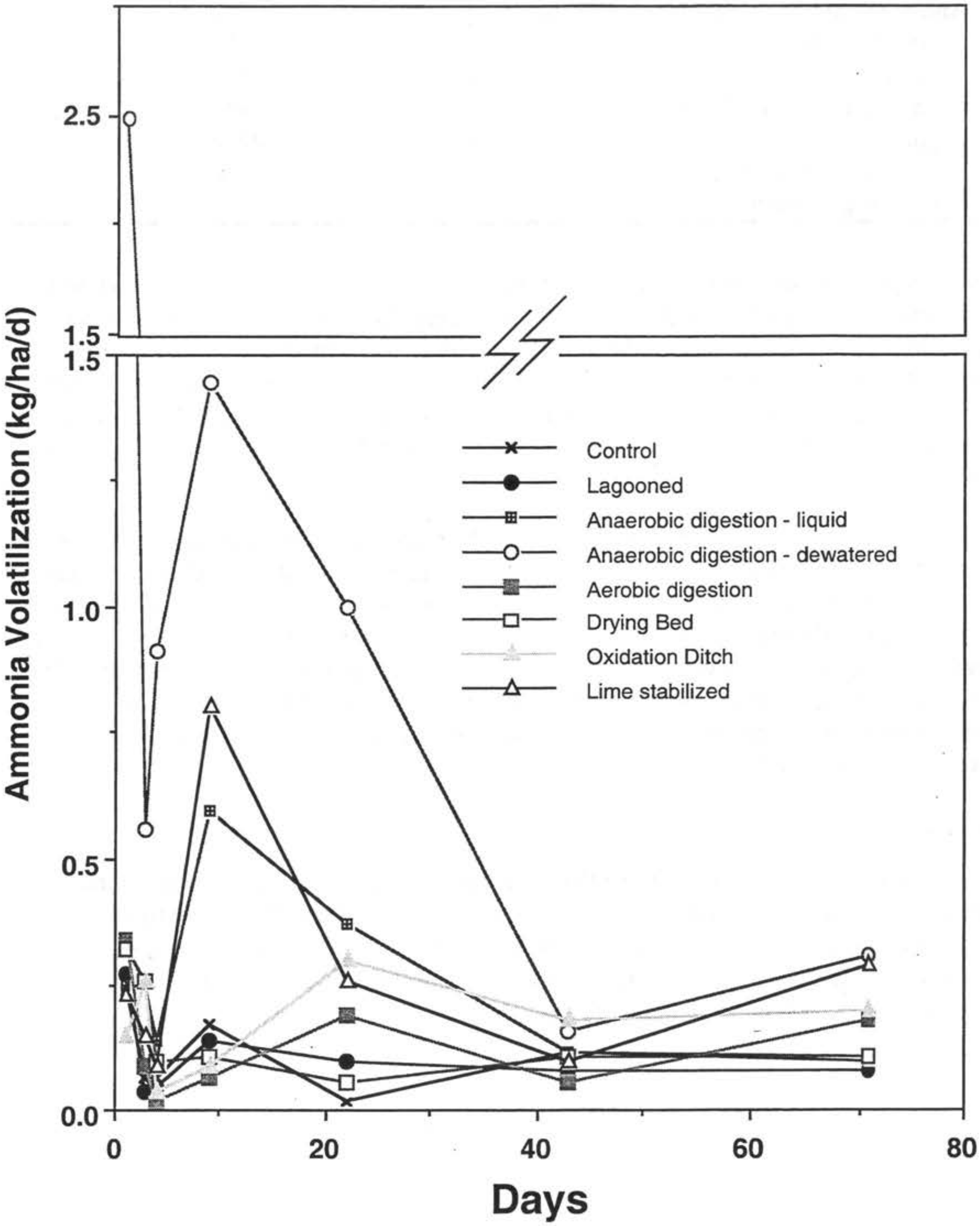

Figure 2. Average daily loss rate of ammonia from biosolids produced at different treatment plants using different biosolids management techniques.

Table 3. Various biosolids with normal application treatment applied at Puyallup (percent of initial NH_3 loss totals after 71 days).

Biosolids Product	*% of the initial NH_3 lost after 71 days*
Anaerobic digestion - dewatered (Renton)	37%
Anaerobic digestion - liquid (Centralia)	51%
Lime stabilized (Brewster)	26%
Oxidation Ditch (Vashon)	24%
Lagooned (Kennewick)	48%
Aerobic digestion (Birch Bay)	15%
Drying Bed (Centralia)	12%

Effect of pH: The lime-stabilized product from Brewster presumably had the highest pH of all the products tested. This biosolids product would likely show the greatest losses of NH_3 volatilization. Such was the case in the study where lime was added to Renton biosolids. However, Brewster's lime-stabilized product did not have a higher volatilization rate than either anaerobically-treated biosolids. This result and the effect of initial NH_3/NH_4^+ levels discussed below suggest that there likely was another factor significantly affecting the NH_3 volatilization rates in this study.

Effect of initial NH_3/NH_4^+ applications: Table 1 presents the total amount of NH_4^+ applied, in the order of: anaerobic dewatered, oxidation ditch, drying bed, lime stabilized, aerobic, anaerobic liquid, and lagooned. However, percent loss of NH_4^+ did not follow this pattern. Overall, the two anaerobically-digested and the lagooned biosolids had the highest rates of volatilization, and the drying bed biosolids showed the lowest rate. The results in this study in addition to the results from the other studies (discussed above) suggests that the initial NH_4^+ levels may be a less significant factor in determining the volatilization rate following the application of biosolids products than other potential factors.

Conclusion

The results of these studies suggest that NH_3 volatilization is affected by temperature, pH, air turbulence, more so than initial NH_3/NH_4^+ levels and the treatment and stabilization processes/techniques utilized. The widely and somewhat unexpected variability of the results suggest strongly that different biosolids with different characteristics be tested before a large-scale application program is embarked on.

Appendix F

Verifying Biosolids N Availability with Crop Uptake Research

Appendix F

Verifying biosolids N availability with grass N uptake research

Nitrogen uptake by a perennial grass crop provides an indirect estimate of the plant-available N supplied by biosolids. We have conducted research at a number of field sites to verify the performance of agronomic rate calculations. Perennial grasses are an ideal test crop for this research because :

- They are highly-efficient in taking up available N from the soil (low nitrate leaching losses)
- They are active in N uptake almost all year in western Oregon and Washington
- They exhibit consistent N uptake responses over a wide range of biosolids application rates (200 to 800 lb N/acre/yr).

Field Research Method. At each experimental location, we applied biosolids and measured the increase in above-ground N uptake (apparent N recovery) by the grass. At each site, grass N uptake was measured for the following treatments (3 to 4 replications per site):

- biosolids only (three application rates per site)
- N fertilizer only (urea or ammonium nitrate)
- no N fertilizer (unfertilized control)

Calculation of N availability. Biosolids N availability was estimated using grass N uptake data with the following equations:

Apparent N recovery for biosolids, $ANR_{biosolids}$ (% of N applied) =

$$[(NUP_{biosolids} - NUP_{nofert})/NAPP_{biosolids}] * 100$$

where:

$NUP_{biosolids}$ = grass N uptake with biosolids, lb/acre

NUP_{nofert} = grass N uptake without N fertilizer, lb/acre

$NAPP_{biosolids}$ = total N applied as biosolids, lb/acre

A similar equation was used for calculating apparent N recovery for fertilizer N:

Apparent N recovery for fertilizer N, $ANR_{fertilizer}$ (% of N applied) =

$$[(NUP_{fertilizer} - NUP_{nofert})/NAPP_{fertilizer}] * 100$$

where:

$NUP_{fertilizer}$ = grass N uptake with N fertilizer, lb/acre

NUP_{nofert} = grass N uptake without N fertilizer, lb/acre

$NAPP_{fertilizer}$ = total N applied as fertilizer, lb/acre

A "fertilizer N equivalent" for biosolids was then calculated, by assuming that the grass was equally efficient in utilizing plant-available N from biosolids or a fertilizer N source:

Fertilizer N equivalent, FNE (% of biosolids total N applied) = $(ANR_{biosolids}/ANR_{fertilizer}) * 100$

where:
$ANR_{biosolids}$ = Apparent N recovery for biosolids, % of N applied
$ANR_{fertilizer}$ = Apparent N recovery for fertilizer N, % of N applied

Alternately, the relationship between biosolids N availability and fertilizer N availability can be expressed as a ratio:

Fertilizer N Equivalent Ratio, FNER = $ANR_{fertilizer}/ANR_{biosolids}$

where:
$ANR_{fertilizer}$ = Apparent N recovery for fertilizer N, % of N applied
$ANR_{biosolids}$ = Apparent N recovery for biosolids, % of N applied

Example Calculation:

Fertilizer N was applied at a rate of 200 lb N/acre/yr. Biosolids applied at a rate of 400 lb total N/acre/yr. Measured grass N uptake was 200 lb/acre with biosolids, 220 lb/acre with fertilizer N, and 100 lb N/acre with no N fertilizer applied.

So, variables are:

$NAPP_{biosolids}$ = 400
$NAPP_{fertilizer}$ = 200
$NUP_{biosolids}$ = 200
$NUP_{fertilizer}$ = 220
NUP_{nofert} = 100

$ANR_{biosolids}$ = [(200 - 100)/400] * 100 = 25% of total N applied

$ANR_{fertilizer}$ = [(220-100)/200] * 100 = 60% of total N applied

Fertilizer N equivalent (FNE) = (24/60) * 100 = 41.6%

Fertilizer N equivalent ratio (FNER) = 60/25 = 2.4 lb biosolids N per lb of fertilizer N

Results and Discussion. Fertilizer N equivalent values from our research with dewatered and heat-dried biosolids are presented in Table A-1 (two locations in western Washington). Also listed is the N fertilizer equivalent for liquid biosolids at a location in Oregon's Willamette Valley (Kiemnec et al., 1987).

Our research results (Table A-1) show that biosolids were a consistent source of plant-available N on different soils, for different biosolids processing methods (heat-dried, dewatered, and liquid) and for different grass species (tall fescue, perennial ryegrass, and prairiegrass). In the first year of application, biosolids total N was 29 % as effective as fertilizer N (3.7 lb biosolids total N was equivalent to 1 lb fertilizer N). In the second consecutive year of biosolids application, biosolids total N was 53 % as effective as fertilizer N (1.9 lb biosolids N was equivalent to 1 lb fertilizer N).

The difference between FNE for year 1 and year 2 of consecutive application (53-29 = 24 % of biosolids total N) demonstrates the residual N availability from the first year application. This residual N is derived from:

- additional mineralization of biosolids applied during the first year
- recycling of first-year N stored in the unharvested stubble, roots, and crowns of a perennial grass crop

Conclusion. Biosolids provide slow-release N for perennial grass cropping systems. Biosolids application rates should be reduced substantially for the second consecutive year of application to perennial grasses. In the first year of application, biosolids total N was 29 % as effective as fertilizer N. In the second consecutive year of biosolids application, biosolids total N was 53 % as effective as fertilizer N.

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Table A-1. Fertilizer N equivalent (FNE) and fertilizer N equivalent ratio (FNER) for anaerobically-digested biosolids applied to irrigated perennial grasses in western Washington and western Oregon.[a]

Years Consecutive Biosolids Application	Biosolids Processing	Grass	FNE[b]	FNER[c]
			% of N applied	
1	Dewatered	Per. ryegrass	17	5.9
		Prairiegrass	35	2.9
		Tall fescue	37	2.7
	Heat-dried	Per. ryegrass	23	4.3
		Per. ryegrass	27	3.7
		Tall fescue	40	2.5
	Liquid	Tall fescue	27	3.7
1, Avg.	all		29	3.7
1, Std dev.	all		8	1.1
2	Dewatered	Per. ryegrass	60	1.7
		Prairiegrass	43	2.3
		Tall fescue	59	1.7
	Heat-dried	Per. ryegrass	57	1.7
		Per. ryegrass	61	1.7
		Tall fescue	49	2.0
	Liquid	Tall fescue	42	2.4
2, Avg.	all		53	1.9
2, Std. dev.	all		8	0.3

[a] Data sources for dewatered and heat-dried biosolids: Sullivan et al. (1997), Cogger et al. (1998), Cogger et al. (1999). Data source for liquid biosolids: Kiemnec et al. (1987).

[b] FNE = Fertilizer N Equivalency for biosolids determined by grass N uptake:
$FNE = ANR_{biosolids}/ANR_{fertilizer} * 100$
A FNE of 50 means that 50% of biosolids total N was plant available.

[c] FNER = Fertilizer N Equivalency Ratio for biosolids determined by grass N uptake;
$FNER = ANR_{fertilizer}/ANR_{biosolids}$
A FNER of 2 means that 2 lb biosolids total N has the same available N as 1 lb of fertilizer N.

Appendix G

Pacific Northwest Agricultural Biosolids Management References

Appendix G

Pacific Northwest Agricultural Biosolids Management References
(Updated Jan. 1999)

Perennial grass production (west of Cascades):

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