

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):

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

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 ($N_{\text{req}} - N_{\text{credits}}$) 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:

$$\text{PAN} = [\text{AN} \times (1-V/100) + \text{NN} + \text{ON}_0 \times K_0/100] \times (1-D/100) \times 20 \quad (4.1)$$

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:

$$\begin{aligned}
 N_{\text{prev}} = & [B_1 \times \text{ON}_1 \times (1-K_0/100) \times K_1 \\
 & + B_2 \times \text{ON}_2 \times (1-K_0/100) \times (1-K_1/100) \times K_2 \\
 & + B_3 \times \text{ON}_3 \times (1-K_0/100) \times (1-K_1/100) \times (1-K_2/100) \times K_3] \times 0.2 \quad (4.2)
 \end{aligned}$$

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.

$$\text{PAN} = [\text{AN} \times (1-V/100) + \text{NN} + \text{ON}_0 \times \text{K}_0/100] \times (1-D/100) \times 20 \quad (4.1)$$

where

$$\text{PAN} = \text{Net plant-available N, lb/t}$$

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.

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