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):

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

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:

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

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):

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

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.

Year	Plant N Requirements (lb/ac)						
	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.

References

Dyck, W.J., Gower, S.T., Chapman-King, R., and van der Wal, D. 1984. Accumulation in Above-Ground Biomass of Douglas-Fir Treated with Municipal Sewage Sludge. Seattle, WA: University of Washington. (Unpublished report).

Henry, C. 1991. Nitrogen dynamics of pulp and paper sludge to forest soils. Wat. Sci. Tech. 24(3/4): 417-425.