APPENDIX A

Calculating Biosolids Application Rates for Agriculture

A.1 Overview

This Appendix is based on an extension bulletin developed by project team members Craig Cogger and Dan Sullivan for the Pacific Northwest (Cogger and Sullivan, 1999). The extension bulletin uses widely accepted procedures for nitrogen budgeting, which are applicable across the United States. This worksheet format was chosen because it is suitable for widespread use and is readily available to biosolids managers. An online version of the Pacific Northwest worksheet can be accessed in HTML and Excel formats (Sullivan and Cogger, 2000).

This appendix presents a modification of the Pacific Northwest worksheet. The modified worksheet presented here uses a new approach to estimate mineralization of plant-available nitrogen (PAN) from the organic fraction of biosolids. The modified approach is based on findings presented in the main body of this report. The worksheet presented in this chapter assumes that PAN is the critical element for determining agronomic loading rates for biosolids. Other factors may be more limiting than nitrogen at a given site or for a particular biosolids source such as the phosphorus contained in the biosolids.

The agronomic biosolids application rate calculated here is based on biosolids PAN, site characteristics, and crop nitrogen requirements. The calculations consist of six steps:

1. Collect information on the site and crop, including crop nitrogen requirement.
2. Estimate the PAN needed from the biosolids application.
3. Collect biosolids nutrient data.
4. Estimate PAN per dry ton of biosolids.
5. Calculate the agronomic biosolids application rate on a dry ton basis.
6. Convert the application rate to an "as is" basis.

Phosphorus can also be a nutrient limiting biosolids application rate. In the sections that follow, it is assumed that phosphorus is not the nutrient that limits land application rate.

This appendix consists of the following:

- ♦ A worksheet with instructions for completing the application rate calculations.
- ♦ The same calculations in equation form for those who prefer using equations.

A.2 How to Use the Worksheet

A.2.1 Collect Site Information

Note: The information in this section is not required by all state regulatory agencies.

Soil Series and Surface Soil Texture (Optional, Line 1.1)

Find the location on the county Natural Resource Conservation Service (NRCS) soil survey. Record the series name and surface texture of the predominant soil.

Previous Crop and Crop Rotation (Line 1.2)

The crop grown before biosolids application may affect nitrogen fertilizer recommendations in the university fertilizer guide. For example, nitrogen fertilizer recommendations are often lower following alfalfa than following wheat.

The length of the cropping cycle may also affect nitrogen fertilizer requirements. For example, nitrogen fertilizer recommendations are lower in a wheat-fallow cropping system (wheat crop every two years) than for wheat produced under an annual cropping system.

Crop Yield Goal (Line 1.3)

Field records for the last three to five years are the best source for crop yield estimates. Proven yields or county averages for most grain farms can be obtained from a local Farm Service Agency office or county extension office. It is important to note whether the yield records are on an "as is" or dry matter basis. Where field records are not available, first-year estimates can be made for a project using NRCS soil surveys, county production averages, or other local data sources.

A site that is used repeatedly for biosolids application should have yield data collected each year. This accumulated data should be used to determine crop nutrient requirements as recommended by a state land grant university. If crop yield data is not kept, additional monitoring may need to be conducted (for example, post-harvest soil nitrate testing) to ensure biosolids are applied at an agronomic rate.

Yield data is typically not available for grazed pastures because grazing animals consume the crop directly in the field. In these cases, the yield goal should be omitted (refer directly to Line 1.4). Plant nitrogen needs should be estimated from the appropriate pasture fertilizer guide recommendation based on the level of pasture management. (Refer to the U.S. Environmental Protection Agency's [U.S. EPA's] Part 503 grazing restrictions.)

Plant Available Nitrogen Needed to Produce Yield Goal (Line 1.4)

Plant available nitrogen needs can be estimated by referring to land grant university fertilizer recommendations or by consulting a qualified agronomist. These guides also provide information regarding phosphorus and potassium needs of the crop.

Land grant universities publish fertilizer guides that estimate crop nitrogen requirements. The fertilizer guide most appropriate for the site and crop should be used. For major crops, guides may cover irrigated or non-irrigated (dry land) cropping and different geographic areas. Guides produced for irrigated sites should not be used when evaluating non-irrigated sites. When appropriate guides do not exist, a manager should consult the local Cooperative Extension Service, Natural Resources Conservation Service office, or a qualified agronomist for assistance.

Nitrogen fertilizer application rates listed in the fertilizer guides are based on cultural conditions and field growth trials under the specified climate, and are averaged over a variety of soil types and years. Fertilizer guide recommendations are not the same as crop uptake because they account for nitrogen available from mineralization of soil organic matter and the efficiency of nitrogen removal by the crop.

The nitrogen rate recommended in fertilizer guides typically assumes average yields, good management practices, and removal of nitrogen from the field through crop harvest or grazing. In terms of satisfying crop nitrogen needs, PAN from biosolids application is considered equal to fertilizer nitrogen.

Plant-Available Nitrogen Provided by Other Sources (Lines 1.5 to 1.11)

To ensure that there is not too much nitrogen applied to a crop, a manager must determine how much nitrogen comes from sources other than biosolids and soil organic matter. These sources of nitrogen are grouped into the three following categories in the worksheet:

1. Plant available nitrogen estimated by pre-application testing;
2. Adjustments to typical soil organic nitrogen mineralization (usually obtained from an agronomist); and
3. Information supplied by the grower.

Nitrogen Estimated by Pre-application Testing (Lines 1.5 to 1.6)

Irrigation Water: Because the amount of nitrate-nitrogen in irrigation water varies, it should be determined by water testing. Irrigation water containing 5 mg/L of nitrate-nitrogen will contribute 1.1 lb of nitrogen per acre-inch applied; irrigation water containing 10 mg/L of nitrate-nitrogen will contribute 2.3 lb of nitrogen per acre-inch.

Preplant Nitrate-Nitrogen in the Root Zone: Some fertilizer guides use preplant soil nitrate-nitrogen when calculating nitrogen fertilizer application rates. If these guides are used, soil test nitrate-nitrogen should not be counted in this worksheet because it has already been accounted for in the recommended fertilizer nitrotgen rate prescribed in the guide. Most often, soil test data are not needed for preplant nitrate-nitrogen when university fertilizer guides are used. Preplant nitrate-nitrogen data are most valuable in regions where winter leaching losses of nitrate are small.

Preplant nitrate-nitrogen can be estimated in the root zone by testing the soil in early spring. Samples should be taken in 1-ft increments to a depth of at least 2 ft. A local cooperative extension or NRCS office can provide guidance on appropriate soil sampling procedures.

Adjustments to Typical Soil Nitrogen Mineralization (Lines 1.7 to 1.9)

Nitrogen mineralization is the release of nitrogen from organic forms to plant-available inorganic forms (ammonium and nitrate). Soil organic matter supplies PAN through mineralization, but this is accounted for in the fertilizer guides. Sites with a history of cover crops, biosolids applications, or manure applications supply more PAN than sites without a history of these inputs, and biosolids recommendations must be adjusted based on this additional supply of nitrogen.

"Plow Down" of Cover or Green Manure Crops: Green manures and cover crops are not removed from the field, but are recycled back into the soil by tillage. An estimate of the nitrogen contributed from this plow down can be obtained by referring to the university fertilizer guides or by estimating the yield and nitrogen concentration of the cover crop. Recovery of green manure nitrogen by the next crop ranges from 10 to 50% of the total nitrogen added to the soil by the cover crop. Estimates of PAN contributed by green manure crops should be made by a qualified agronomist.

Previous Biosolids Applications: Previous biosolids applications contribute to PAN in the years following the initial application. In the worksheet, previous biosolids applications are considered "PAN from other sources." (Refer to Figure 4-5 and Figure 4-6 for residual effective nitrogen mineralization rates, E_{min}, from a specific area.)

For each previous biosolids addition (up to three years prior to this year), the pound of nitrogen per acre added is calculated using the following equation:

$$\text{(dry tons biosolids/acre)(biosolids organic N)(0.002)}(E_{min}) \qquad \text{(A.2.1-1)}$$

where:

biosolids organic nitrogen (N) is in units of mg/kg.

Note: If biosolids have been in a lagoon or composted, the values of E_{min} in Figure 4-5 and Figure 4-6 are too large because the biosolids have been stabilized and will decompose more slowly than fresher materials. If biosolids have been composted but not aged, multiply E_{min} by 0.5. If biosolids have been in a lagoon for a few months, multiply E_{min} by 0.25. If the biosolids have been composted and aged or have been in a lagoon for years, multiply E_{min} by 0.1.

The estimates of nitrogen credits using Equation A2.1-1 are *in terms of the organic nitrogen originally applied*. This is intended to reflect the simplest method for projecting carry-over PAN at frequently used application sites. The method differs from more complex calculations involving a declining balance of biosolids organic nitrogen. After Year 4, biosolids nitrogen is considered part of stable soil organic matter and is not included in calculations.

Previous Manure Applications: Previous manure applications contribute to PAN in a similar manner to previous biosolids applications. An agronomist should be consulted to estimate this contribution.

Information Supplied by the Grower (Line 1.10)

Nitrogen Applied at Seeding: For best growth, some crops depend on starter fertilizers (nitrogen applied at seeding). These fertilizers usually supply nitrogen, phosphorus, and sulfur. Examples are 16-20-0 and 10-34-0. Starters are usually applied at rates that supply 10 to 30 lb nitrogen/ac. All the nitrogen supplied by starter fertilizer should be entered on line 1.10 in the worksheet.

A.2.2 Estimate PAN Needed from Biosolids

The next step is to estimate the amount of PAN the biosolids must provide, which represents the difference between the total PAN needed to produce the yield goal and PAN from other sources.

A.2.3 Collect Biosolids Data

To make the calculation, managers will need the following analyses:

- Total Kjeldahl nitrogen (TKN);
- Ammonium-nitrogen (NH_4-N);

- Nitrate-nitrogen (NO_3-N) (composted, air-dried, or aerobically digested biosolids only); and
- Percent total solids.

If laboratory results are on an "as is" or wet weight basis, they must be converted to a dry weight basis. To convert from an "as is" to a dry weight basis, the analysis should be divided by the percent solids in the biosolids and the result multiplied by 100. Total Kjeldahl nitrogen includes more than 95% of the total nitrogen in biosolids. In using the worksheet, it is assumed that TKN equals total nitrogen.

Ammonium-nitrogen usually comprises more than 95% of the total inorganic nitrogen in most biosolids. Ammonium-nitrogen includes both ammonia (NH_3) and ammonium (NH_4^+). Depending on the laboratory, results for ammonium-nitrogen may be expressed as ammonia or ammonium.

Nitrate-nitrogen analyses also include small amounts of nitrite. Nitrite concentrations are negligible in biosolids. There may be significant amounts of nitrate in aerobically digested biosolids, air-dried biosolids, or in composts. There is little nitrate in anaerobically digested biosolids; therefore, nitrate analysis is not needed.

Biosolids organic nitrogen can be determined by subtracting ammonium-nitrogen from TKN (line 3.6 to line 3.7). Percent total solids analyses are used to calculate application rates. Biosolids applications are calculated as the dry weight of solids applied per acre (for example, dry tons per acre).

A.2.4 Estimate PAN per Dry Ton of Biosolids

The estimate of PAN per dry ton of biosolids includes the following:

- Some of the ammonium-nitrogen,
- All of the nitrate-nitrogen, and
- Some of the organic nitrogen.

Inorganic Nitrogen Retained (Lines 4.5 to 4.7)

Ammonium-Nitrogen (Lines 4.5 to 4.6)

Under some conditions, ammonium is readily transformed to ammonia and lost as a gas. This gaseous ammonia loss reduces the amount of PAN supplied by biosolids. The following section explains the factors used to estimate ammonia-nitrogen retained in plant-available form after application.

Biosolids Processing. The following types of biosolids processing cause most of the ammonia-nitrogen to be lost as ammonia gas or converted to organic forms before application: drying beds, alkaline stabilization at pH 12, or composting.

Application Method. Ammonia loss occurs only with surface application. Injecting liquid biosolids eliminates ammonia loss because the injected liquid is not exposed to the air. Surface applications of liquid biosolids lose less ammonia than do dewatered biosolids. For liquid biosolids, the ammonia is less concentrated and is held as ammonium on negatively charged soil surfaces after the liquid contacts the soil. Ammonia loss is fastest just after application to the field. As ammonia is lost, the remaining biosolids are acidified (that is, each molecule of ammonia loss generates one molecule of H^+ [acidity]). Acidification gradually slows ammonia loss. Biosolids that remain on the soil surface will eventually reach a pH near 7, and further ammonia losses will be small. Losses of ammonia after six days on the soil surface are close to zero.

Days to Soil Incorporation. Tillage to cover biosolids can reduce ammonia loss by adsorption of ammonium-nitrogen onto soil particles.

Table A-1 estimates the amount of ammonium-nitrogen retained after field application. In order to use this table, information is needed on biosolids stabilization processes, method of application (surface or injected), and the number of days to soil incorporation.

Table A-1. Estimates of Ammonium-Nitrogen Retained After Biosolids Addition.

	Surface Applied			Injected
Days to incorporation	Liquid	Dewatered	Composted or Drying Bed	
	NH_4-N retained, % of NH_4-N applied			
0 to 2	80	60	100	100
3 to 6	70	50	100	100
over 6[†]	60	40	100	100

[†] use these values if biosolids will not be incorporated with tillage.

Nitrate-Nitrogen (Line 4.3)

One hundred percent availability of biosolids nitrate-nitrogen is assumed.

Organic Nitrogen Mineralized (Lines 4.8 to 4.9)

Biosolids organic nitrogen is not available to plants at the time of application. Plant available nitrogen is released from organic nitrogen through microbial activity in soil carbon — a process called *mineralization*. Mineralization is more rapid in soils that are warm and moist, and is slower in soils that are cold or dry.

Different biosolids decomposability and nitrogen mineralization rates have been observed in various field trials and laboratory studies including the current study. It is important to recognize that biosolids decomposability falls into the three following groups.

- Fresh biosolids produced by a number of treatment processes including aerobic and anaerobic digestion, air drying, heat drying, and lime stabilization;
- Biosolids stored in lagoons for more than six months; and
- Composted biosolids.

For the first growing season after biosolids addition, the pound of nitrogen per acre added is calculated using the following equation:

$$(\text{biosolids organic N})(0.002)(E_{min}) \qquad \text{(A.2.4-1)}$$

A manager should refer to Figure 4-5 and Figure 4-6 for effective nitrogen mineralization rates, E_{min}, from a particular area. Biosolids organic nitrogen is in units of milligrams per kilogram.

It is important to remember that biosolids nitrogen mineralization occurs in two steps: rapid and slow. The initial rapid nitrogen mineralization can be a large part of the total nitrogen mineralization in Equation A.2.4-1. To estimate this initial rapid mineralization, 0.23 should be divided by E_{min} and the result multiplied by 100. This is the percentage of first-year mineralization that will occur within a few days after land application. It is important to remember that this mineralization nitrogen may be lost if a crop is not growing at the time of land application.

Note: If biosolids have been in a lagoon or composted, the values of E_{min} in Figure 4-5 and Figure 4-6 are too large because the biosolids have been stabilized and will decompose more slowly than fresher materials. If biosolids have been composted but not aged, E_{min} should be multiplied by 0.5. If biosolids have been in a lagoon for a few months, E_{min} should be multiplied by 0.25. If the biosolids have been composted and aged or in a lagoon for years, E_{min} should be multiplied by 0.1.

A.2.5 Calculate the Agronomic Biosolids Application Rate

This calculation can be performed using the results of the previous sections, as shown in lines 5.1 through 5.3.

A.2.6 Convert Agronomic Biosolids Application Rate to "As Is" Basis

The appropriate conversion factors (given in Step 6) can be used to convert to gallons, acre-inches, or wet tons per acre.

A.3 Other Considerations for Calculations

Small acreage sites without a reliable yield history: Some communities apply biosolids to small acreages managed by "hobby farmers." In many of these cases, there is no reliable yield history for the site, and the goal of management is not to make the highest economic returns. In order to maintain agronomic use of biosolids nitrogen on these sites, biosolids can be applied at a rate substantially below that estimated for maximum yield.

Equipment limitations at low application rates: At some low-rainfall dry land cropping locations in the arid West, the agronomic rate calculated with the worksheet may be lower than can be spread with manure spreaders (usually about 2 dry tons/ac). Similarly, application of low solids content slurry may be limited by the volume of water applied rather than nitrogen.

Denitrification and immobilization: Denitrification (the loss of nitrate-nitrogen as gaseous N_2 or N_2O) and immobilization (the loss of nitrate-nitrogen or ammonium-nitrogen by incorporation into organic compounds) can occur following biosolids application. At agricultural sites, these losses are usually not included in biosolids loading rate calculations because university fertilizer guides account for average losses because of these processes. A local permitting agency should be consulted before including denitrification or immobilization losses in the loading rate calculations.

Nutrient monitoring via soil testing: The agronomic rate calculation presented here is not a substitute for nutrient monitoring via soil testing. Soil nitrate and phosphorus tests are used to monitor the balance between biosolids application rates and crop removal of nutrients. Other tests, such as available potassium, calcium, magnesium, sulfur, micronutrients, pH, and conductivity may provide important agronomic information to optimize crop growth.

Soil nitrate tests are a "picture in time" that reflect the recent balance between

- Crop uptake of nitrate;
- Nitrate released from mineralization of soil organic matter, biosolids, and crop residues; and
- Nitrate losses via denitrification and leaching.

Soil profile nitrate-nitrogen testing at the beginning and end of the growing season may be useful for confirming calculations at intensively used (that is, repeat-application) sites. The objective for considering carryover nitrate-nitrogen is to avoid a significant surplus that might leach below the root zone. Many climate and soil variables must be considered in interpreting results.

Repeated application of biosolids at a site may also increase soil phosphorus concentrations. Runoff and eroded sediment from application sites can move phosphorus to surface water, where it can reduce water quality. Therefore, a manager may need to evaluate the risk of offsite phosphorus movement in phosphorus-sensitive watersheds. The Phosphorus Index, available from a local land grant university or state NRCS office, is one tool that incorporates soil test data with site characteristics to predict the relative risk of offsite phosphorus movement.

Monitoring nitrogen losses: In order to assure that land application is not adding excess nitrogen to surface waters, stormwater runoff and irrigation return flows can be monitored. Both volume and concentrations of organic and inorganic nitrogen forms are recommended so that the mass of nitrogen loss can be estimated. In order to assure that land application is not adding excess nitrogen to groundwaters, monitoring the root zone and water tables is recommended. These monitoring efforts can be used to establish whether or not a land application program is an environmental concern.

Fine-tuning estimates of short-term available nitrogen for site-specific conditions: Soil sampling a few weeks after biosolids incorporation can be used to check the estimates given here for short-term nitrogen availability following a biosolids application. Soil should be sampled to incorporation depth (0 to 6 in. or 0 to 12 in.) and analyzed for ammonium plus nitrate-nitrogen. At least three separate composite soil samples consisting of 20-plus soil cores are needed for this estimate to get an average with a standard deviation. A control (no-application) area in the same field also must be sampled to correct for background ammonium plus nitrate-nitrogen. A professional soil scientist should be contacted for assistance.

Other limitations on application rates: A variety of other factors may limit application rates in some situations, including the following:

- ***Soil infiltration rate and runoff potential.*** The amount of water applied with low-solids slurries can limit application rates. Biosolids must be applied at rates that do not result in offsite runoff during land application.
- ***Pasture management.*** Surface applications of biosolids to pastures should also be limited to rates that do not smother the grass.

- *Trace elements.* Trace element application rates may limit biosolids application rates if the biosolids do not meet the pollutant concentration limits in Table 3 of U.S. EPA Part 503.
- *Special projects* such as mine reclamation may have the objective of soil improvement and increasing soil organic matter levels rather than meeting crop nutrient needs in the year of application. For these projects, biosolids application generally occurs as a single event at relatively high rates.

A.4 Worksheet

Collect Site Information

Line No.	Category	Units	Your Information	Example
1.1	Soil series and texture (NRCS soil survey)			Puyallup sl
1.2	Crop rotation			perennial grass hay
1.3	Yield goal			5 tons/acre/year
1.4	Plant available N (PAN) needed to reach yield goal	lb N/acre		200
1.5	NO_3-N applied in irrigation water	lb N/acre		10
1.6	Preplant NO_3-N in root zone†	lb N/acre		0
1.7	Cover or green manure crop†	lb N/acre		0
1.8	Previous biosolids applications (Eq. 2.1)	lb N/acre		30
1.9	Previous manure applications	lb N/acre		0
1.10	Starter fertilizer	lb N/acre		0
1.11	Total PAN from other sources (sum of lines 1.5 to 1.10)	lb N/acre		40

† Do not list here if these N sources were accounted for in the N fertilizer recommendations from a university fertilizer guide.

Estimate the Amount of PAN Needed From Biosolids

Line No.	Category	Units	Your Information	Example
2.1	PAN needed to produce yield goal (line 1.4)	lb N/acre		200
2.2	PAN from other sources (line 1.11)	lb N/acre		40
2.3	PAN needed from biosolids (line 2.1 - line 2.2)	lb N/acre		160

Collect Biosolids Data

Line No.	Category	Your Information	Example
3.1	Moisture content of biosolids		liquid
3.2	Biosolids processing method		anaerobic
3.3	Surface-applied or injected		surface-applied
3.4	Days to incorporation		more than 6
3.5	Expected application season		March to September

Line No.	Category	Units[†]	Your Information	Example
3.6	Total Kjeldahl N, TKN	Mg/kg		50,000
3.7	NH_4-N	Mg/kg		10,000
3.8	NO_3-N (composted or aerobically digested biosolids only)	Mg/kg		not analyzed
3.9	Organic N (line 3.6 - lines 3.7 and 3.8)	Mg/kg		40,000
3.10	Total solids	%		2.5

[†] If units are % for TKN, NH_4-N or NO_3-N, then multiply by 10,000 to convert to mg/kg

Estimate PAN per Dry Ton of Biosolids

Line No.	Category	Units	Your Information	Example
4.1	TKN (line 3.6 × 0.002)	lb N/dry ton		100
4.2	NH_4-N (line 3.7 × 0.002)	lb N/dry ton		20
4.3	NO_3-N (line 3.8 × 0.002)	lb N/dry ton		0
4.4	Organic N (line 3.9 × 0.002)	lb N/dry ton		80
4.5	NH_4-N retained (Table 2.1)	%		60
4.6	NH_4-N retained (line 4.2 × line 4.5 ÷ 100)	lb N/dry ton		12
4.7	Inorganic N retained (line 4.3 plus line 4.6)	lb N/dry ton		12
4.8	First year E_{min} (Figs. 4-5 and 4-6)			0.30
4.9	PAN from organic N (line 4.4 × line 4.8)	lb N/dry ton		24
4.10	First year PAN (line 4.7 + line 4.9)	lb N/dry ton		36

Calculate the Agronomic Biosolids Application Rate

Line No.	Category	Units	Your Information	Example
5.1	First year PAN needed (line 2.1)	lb N/dry ton		160
5.2	First year PAN in biosolids	lb N/dry ton		36
5.3	Agronomic biosolids application rate (line 5.1 ÷ line 5.2)	lb N/dry ton		4.4

Convert to "As Is" Basis

Desired Units	Equation	Your Calculation	Example
gallons per acre =	line 5.3 ÷ line 3.10 × 24,000		42,000
acre-in per acre =	line 5.3 ÷ line 3.10 × 0.88		1.55
wet tons per acre =	line 5.3 ÷ line 3.10 × 100		176

Conversion Factors

1% = 10,000 mg/kg = 10,000 ppm

1 mg/kg = 1 ppm = 0.0001%

1 wet ton = 1 dry ton ÷ (% solids × 0.01)

1 dry ton = 1 wet ton × (% solids × 0.01)

1 acre-in. = 27,000 gal

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