A PNW Extension Publication

Fertilizing with Biosolids

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Publication highlights

This publication will assist you in understanding what biosolids are, and how to use them to supply nutrients for crop production and improve soil health.

What are biosolids? Biosolids are a product of municipal wastewater treatment facilities. In order to become biosolids, raw solids must be treated to meet Environmental Protection Agency standards.

Fertilizer replacement value. Biosolids provide organic matter and nutrients (Table 3). A dry ton of anaerobically digested biosolids replaces approximately 35 lb N, 20 lb P (46 lb P2O5), 6 lb K (8 lb K2O), and 7 lb S from commercial fertilizers (Table 5).

Cropping systems and biosolids. Biosolids are commonly applied to cereal crops and to grasses grown for hay or pasture. Biosolids that meet the most stringent EPA standards are sold or distributed for use in landscaping and gardens.

Nitrogen. Biosolids application rates are based on crop nitrogen (N) requirement. Site-specific application rates are based on biosolids analyses, the crop to be grown, and on field history.

Phosphorus. Biosolids are an excellent source of phosphorus. Fields that are low in soil test phosphorus (P) are especially responsive to biosolids application, while fields with high soil test P are unlikely to benefit from biosolids application.

Potassium. Biosolids contain low concentrations of potassium (K). Monitor soil test K, and supply K from another source (such as fertilizer) to meet crop K requirement.

Sulfur. When biosolids are applied at agronomic N rates, they usually also supply sufficient S for crop production.

Soil pH. Long-term field studies demonstrate that most biosolids will slowly acidify soils (decrease soil pH). When biosolids are supplied at agronomic rates based on N, soil acidification occurs at a similar rate as soil acidification resulting from urea application. Lime-stabilized biosolids, available from a few small treatment facilities, act as a lime substitute and will increase soil pH.

Soluble salts. Repeated biosolids applications have not resulted in detrimental salt accumulations in soil, even at sites with low annual precipitation and no irrigation.

Soil health. Biosolids application affects soil chemical, physical and biological properties that contribute to overall soil health. Long-term monitoring of sites receiving biosolids applications indicates improved soil health, especially through increased soil organic matter.

Trace elements. Some trace elements are micronutrients for plants, while others are not (such as lead, mercury and cadmium). EPA rules specify allowable trace element concentrations in biosolids. Modern biosolids contain much lower concentrations of metals, such as lead (Pb) and cadmium (Cd), than were present historically (Tables 2 and 7). Biosolids are an excellent source of zinc (Zn) and other micronutrients that are sometimes deficient in alkaline soils (pH > 7).

Contaminants. EPA regulations are based on an extensive risk assessment of contaminants to human health and the environment. The effects of newer classes of contaminants present in biosolids is an ongoing area of research.

Appendices B, C, D and E summarize the research basis for our biosolids nutrient management recommendations for N, P and S.

Contents

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What are biosolids and how are they used?

Raw wastewater solids become biosolids via a multistep process at the treatment facility (Figure 1). Biosolids are produced from solids from primary and secondary wastewater treatment (top row in Figure 1). Raw solids are processed by digestion or other EPA-approved treatment processes (middle of Figure 1). The treated solids are separated into three categories based on EPA standards. Both biosolids and Exceptional Quality (EQ) biosolids meet EPA standards for land application, while the third category does not meet these standards, cannot be classified as biosolids and cannot be land-applied (bottom row of Figure 1).

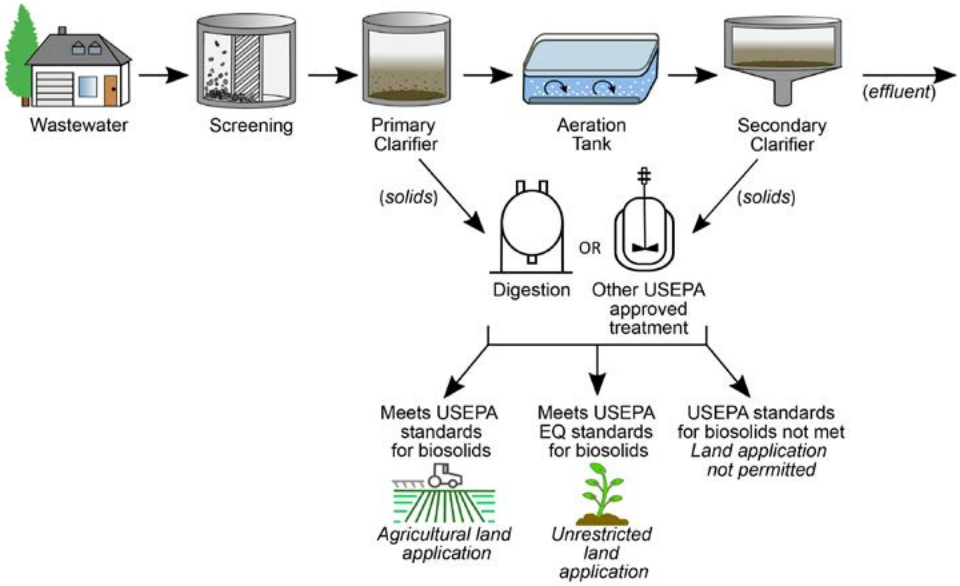

Illustration: A. Tomasek

Figure 1. How wastewater solids become biosolids.

Table 1 compares options for biosolids use based on quality characteristics.

When biosolids meet the EQ standard, the biosolids can be marketed as a product without the need for an application site permit. Appendix A provides additional details on EPA regulations for biosolids quality.

EPA standards do not address plant-available nutrient concentrations in biosolids, or the effect of the biosolids' treatment process on the nutrient content and availability. Some treatment processes that kill human pathogens in biosolids (composting or lime stabilization, for example) substantially reduce plant-available N and P in biosolids.

Meeting EPA Exceptional Quality standards is optional, increases processing costs and usually requires more infrastruture and energy use.

Table 1. Options for biosolids use based on biosolids quality characteristics [a]

Characteristic	Biosolids approved for land application	EPA Exceptional Quality (EQ) biosolids
Typical application site	Agricultural land	Landscaping and gardens
Field and crop management restrictions	Yes	None
Application rate limit	Based on crop N needs	None
Human pathogen reduction	Class B. Pathogens reduced by 95% to 99%	Class A. Pathogens eliminated
Trace element concentration limit	Meets standard for biosolids	Meets standard for EQ biosolids
Stabilization (meets vector attraction reduction std.)	Yes	Yes

[a] Biosolids quality, as defined by EPA, addresses human pathogen reduction (Class A or B), trace element concentrations and stabilization processes. Source: EPA CFR Part 503 (1993). See Appendix A for additional biosolids quality information.

Additional processing of biosolids is sometimes performed to reduce water content before transport to a land application site. Biosolids can be transported and applied as a slurry, which is 2% to 6% dry matter (DM), or as a semisolid material (>16% DM). Liquid biosolids are usually available only to farms close to a wastewater treatment plant because of transportation costs. Class B dewatered or “cake” biosolids (16–25% DM) are more suitable for transport to distant farms and grasslands.

Source control to reduce heavy metal concentrations in biosolids

Heavy metals were a concern when land application of biosolids began in the 1970s. However, the following source control activities have effectively decreased metal concentrations:

- Issuing permits for industrial wastewater sources that limit the allowable metals in wastewater treatment facilities' influent water. These permits require industries to adopt cleaner manufacturing processes or to pretreat wastewater to remove metals. Industrial sources are also required to routinely monitor for specific metals in their wastewater.
- Increasing the pH of city water supplies has reduced pipe corrosion and the concentrations of metals in wastewater.
- Using PVC pipe instead of metal pipe.

Metals in Portland, Oregon, biosolids have been reduced dramatically since 1981 (Table 2). Today, biosolids metal concentrations are similar for cities with industrial inputs (Portland, Table 2) and smaller cities with few industrial inputs (Oregon average, Table 7).

Table 2. Metal concentrations in City of Portland biosolids

Metal	**Metal concentration(mg/kg)**[a]				
	1981	1996	2005	2013	2020
Cadmium	40	5	3	3	2
Copper	1,000	481	384	374	281
Lead	900	181	108	85	54
Nickel	190	39	49	50	32
Zinc	2,200	834	921	1,165	1,083

[a] 1981 concentrations are approximate values. Data for 1996–2020 were derived from City of Portland biosolids management reports to Oregon Department of Environmental Quality.

Cropping systems and biosolids

Farmers who grow crops on nutrient-depleted soils will see the greatest benefit from biosolids. To maximize nutrient use, biosolids should be applied only occasionally to the same land. It typically takes only one or two biosolids applications to correct nutrient deficiencies and jump-start soil productivity. Additional applications will mainly serve as a source of nitrogen (N).

Most biosolids produced in Oregon and Washington by larger treatment facilities are transported east of the Cascades to farmers growing winter wheat or dryland pasture, where biosolids can be applied during most of the year. Biosolids are also applied to local pastures or hayfields west of the Cascades. West of the Cascades, winter precipitation often limits the land application of biosolids to summer and early fall. Biosolids are usually applied after crop harvest, while soil is dry enough to prevent compaction.

EPA considers Class B biosolids safe for application to all crops, provided that waiting periods between biosolids application and crop harvest are observed. For grasses and cereals, the predominant crops that receive biosolids, the EPA-prescribed waiting period is 30 days between biosolids application and harvest. Farmers should also consider crop marketing limitations for land receiving biosolids. Some food-processing companies will not accept crops grown on land that has received biosolids application. The US Department of Agriculture National Organic Program rules prohibit application of biosolids for certified organic crop production.

Grass fields managed for pasture or hay production are convenient for biosolids application scheduling because of the strength of sod to support application equipment and the short waiting period (30 days) required between application and crop harvest. Unlike commercial fertilizers (urea, for example), biosolids can be applied in the fall to stimulate pasture growth early the following spring.

High-quality grass pasture or grass hay can be produced with biosolids. With abundant N and S (key nutrients in protein), biosolids effectively increase forage protein. Biosolids also supply plant-essential micronutrients such as Cu, Zn and Mn. See EM 9224, *Nutrient Management for Pastures: Western Oregon and Western Washington* for additional information.

Grass fields with a history of frequent animal manure application are often unsuited to biosolids application. Permitted application rates for biosolids are based on crop nitrogen requirement (See PNW 511, *Worksheet for Calculating Biosolids Application Rates in Agriculture* for details). Fields with a history of manure applications may have a small need for additional N inputs.

Winter wheat is another crop commonly receiving biosolids application. Where sufficient precipitation allows annual cereal cropping, biosolids are applied between grain harvest (summer) and seeding (fall). Where summer fallow is practiced in Central Oregon and Washington, biosolids can be applied throughout the fallow year.

Biosolids are an effective replacement for commercial N inputs in cereal cropping systems, such as anhydrous ammonia or urea-ammonium nitrate (UAN). Plant-available N from biosolids can fully replace commercial N fertilizer for the first grain crop following application. The rate of N fertilizer required for grain production is also reduced for subsequent crops.

Increased soil organic matter, increased soil nutrients and improved soil physical properties following biosolids application can sometimes produce higher cereal grain yields than commercial (mineral) fertilizers. See “Biosolids and soil health,” page 15, and PNW 716, *Biosolids in dryland cropping systems*, for additional information.

Other Pacific Northwest crops to which biosolids have been applied include oats, barley, corn for grain, hops, grass for seed, hybrid poplars and Christmas trees.

Gardens and landscapes. Biosolids that meet EPA Exceptional Quality standards (Table 1: Appendix A) can be used in gardens and landscapes. Three types of EQ biosolids are produced and marketed for garden and landscape use: heat-dried products, biosolids composts and biosolids blends.

Heat-dried EQ biosolids have similar nutrient concentrations and availability as do anaerobically digested biosolids (Table 3), except some ammonium-N is lost during drying. Heat-dried biosolids are suitable as lawn and garden fertilizers. A major limitation to marketing heat-dried biosolids is nonuniform particle size. Some heat-dried biosolids contain fine particles that present a dust hazard and are a challenge to spread evenly.

Biosolids composts are made from biosolids composted with yard debris or wood waste. Biosolids composts have low N availability, similar to other composts, and are applied at high rates to quickly build soil organic matter.

EQ blends contain biosolids mixed with other organic and mineral materials such as sawdust, aged bark or screened sand. Blends are used variously as top-dressing for lawns, potting mixes, soil builders and raised bed amendments, or as manufactured topsoil.

Biosolids nutrients

Biosolids stabilization, processing and storage practices affect nutrient concentrations in the final product. Biosolids providers report total nutrient concentrations on a dry weight basis. Table 3 shows the range of nutrient concentrations typically reported for anaerobically digested biosolids in the Pacific Northwest. Nutrient concentrations listed in Table 3 were obtained from municipal reports and from university research studies.

The total nutrient concentration present in biosolids includes both rapidly and slowly available nutrient forms. Only a portion of total N, P, S, Ca and Mg concentrations shown in Table 3 are in plant-available forms at the time of application. In addition to the nutrients shown in Table 3, biosolids provide other plant-essential micronutrients, including copper (Cu), boron (B), molybdenum (Mo), zinc (Zn) and iron (Fe). Biosolids contain an insignificant quantity of sodium (Na). Sodium is not considered a nutrient and can be detrimental to crop production.

Biosolids from large wastewater treatment facilities have consistent nutrient concentrations over time. For example, City of Portland biosolids averaged 5.6% N in 2020, with monthly means ranging from 4.5 to 6.1% N.

For all nutrients except N, the long-term changes in soil nutrient status resulting from biosolids application can be monitored with soil testing. A long-term monitoring plan to track soil nutrient levels over time should use consistent sampling and analysis methods. Extension publications listed in the “For more information” section provide guidelines to design a soil sampling and testing program.

Table 3. Typical nutrient analysis values for anaerobically digested biosolids[a]

Nutrient analysis	Analysis	Analysis
	% dry wt.	lb/dry ton
Organic matter (LOI)	60–80	1,200–1,600
Organic Carbon (C)	35–40	700–800
Total Nitrogen (N)	4–7	80–140
C:N ratio	5–7	--
Ammonium-N	0.5–1.5	10–30
Nitrate-N	<0.01	<0.2
Phosphorus (P)[b]	1.5-3.5	30–70
Sulfur (S)	0.6–1.4	12–28
Calcium (Ca)	1–3	20–60
Magnesium (Mg)	0.4–0.8	8–16
Potassium (K)[b]	0.1–0.6	2–12
Sodium (Na)	<0.1	<2

[a] Nutrient analyses based on samples from 10–50+ biosolids production facilities per nutrient. Typical nutrient concentration range reflects professional judgment (D. Sullivan).

[b] Phosphorus and potassium are expressed on an elemental basis. To get P_2O_5 (phosphate), multiply P x 2.29. To get K_2O (potash), multiply K x 1.2.

Nitrogen (N)

Extensive research has been conducted to support our recommendations for N-based agronomic biosolids application rates. See Appendices B and C for a summary of these trials.

Forms of N in biosolids

Biosolids contain organic and ammonium-N; nitrate-N is absent in most biosolids. Ammonium-N is available to plants immediately after application. Organic N provides slow-release N since it must first be converted to ammonium-N by microbial activity. If biosolids are not immediately incorporated into the soil through tillage, some of the available ammonium-N is lost as ammonia to the atmosphere (Figure 2). Once in the soil, ammonium-N is rapidly converted to nitrate-N by soil microbial activity. Crops can use both these forms of nitrogen. Nitrate-N can be lost to the atmosphere through denitrification or to groundwater by leaching. Nitrogen loss is minimized by matching the biosolids application rate to crop N need and by following recommended biosolids application methods.

The proportions of ammonium-N and organic N in biosolids are related to the biosolids stabilization process (for example, digestion or composting) used at the wastewater treatment facility. Liquid, anaerobically digested biosolids often contain more ammonium-N than organic N. When these anaerobically digested biosolids are dewatered (the most common product offered to farmers), about 20% of total N is in the ammonium form, and 80% of total N is in organic form. Heat-dried biosolids contain trace concentrations of ammonium-N, with more than 90% of total N in the organic form.

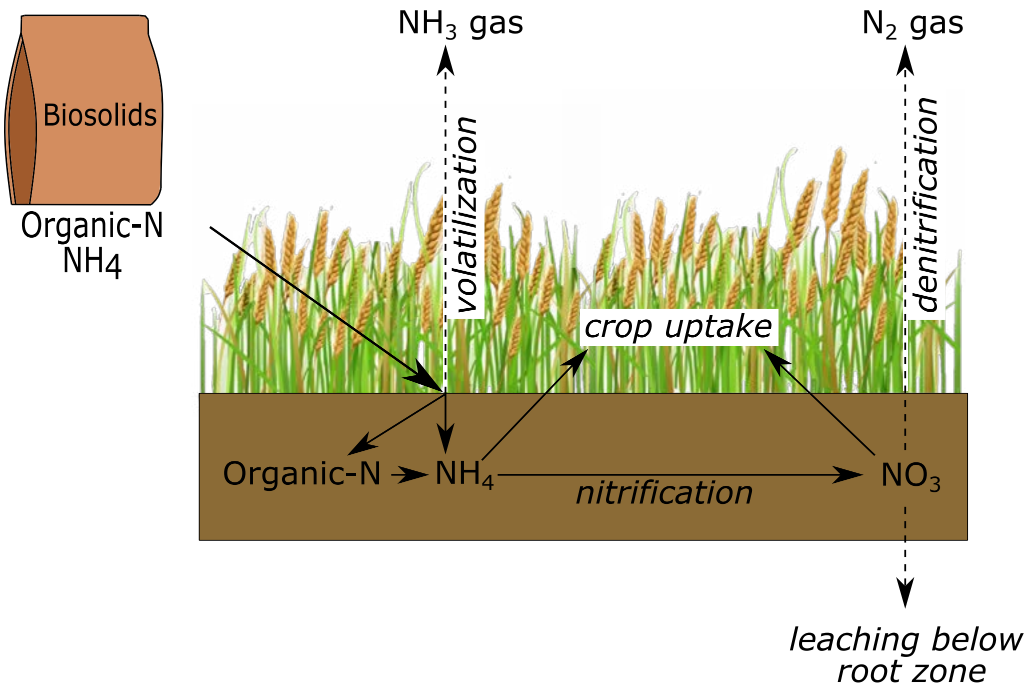

Illustration: Dari Biswanath and Abigail Tomasek

Figure 2. Biosolids N: forms, transformations and cycling. Biosolids contain organic and ammonium (NH_4) forms of N. The goal of agronomic management of biosolids N is to maximize crop N uptake and minimize leaching loss of nitrate (NO_3). Gaseous ammonia (NH_3) loss occurs rapidly after application (hours or days). Nitrogen loss via denitrification is small, and not considered in calculating agronomic rate.

Calculating biosolids application rates based on N. A companion publication, PNW 511, *Worksheet for Calculating Biosolids Application Rates in Agriculture*, provides a step-by-step process for calculating application rates that supply crops with adequate available N. The worksheet estimates ammonium retained and organic N mineralized from different types of biosolids. It uses the following general equation to forecast plant-available N (PAN) supplied by biosolids:

PAN = a (ammonium-N in biosolids) + b (organic N in biosolids)
+ c (organic N from previous biosolids applications)
where:
a = fraction of ammonium-N retained after application
b = fraction of organic N mineralized during the first growing season
c = fraction of organic N mineralized from previous biosolids applications on the same field

Ammonium-N retained after application. When biosolids are surface-applied (not tilled or injected into soil at application), a portion of the biosolids ammonium is lost as ammonia gas. Ammonia loss is rapid during the first hours after application.

Tillage or sprinkler irrigation immediately following biosolids application increases ammonium retention in soil. However, tillage or immediate irrigation is not feasible or desirable in many cropping situations.

When biosolids are not incorporated by tillage or overhead irrigation, ammonium retention is greater for liquid biosolids than for dewatered cake biosolids. With liquid biosolids, some of the ammonium immediately infiltrates below the soil surface, reducing ammonia loss.

Organic N mineralized during the first growing season after application. Following field application, organic biosolids N is converted to plant-available forms (ammonium and nitrate) by soil microorganisms through a process known as mineralization (Figure 2). The biosolids treatment process affects the rate of organic N mineralization after land application. Freshly digested biosolids usually contain more mineralizable N than do biosolids produced with more intensive stabilization processes (composting or long-term lagoon storage).

The organic N mineralization rate also is affected by soil temperature and moisture. Mineralization is most rapid when soil is moist and warm (above 60°F). When biosolids are applied to dry soil and not incorporated by tillage, N mineralization is delayed until soil moisture content increases.

Mineralization proceeds most rapidly immediately after biosolids application, provided soil temperature and moisture conditions are favorable. Usually, more than half of first-year N mineralizes within the first three to six weeks following biosolids application.

Repeated biosolids applications to the same field increase both plant-available N and residual soil N (Figure 3). Much of the residual N is stored in the soil in organic matter. Each year after application, a small fraction of the residual N is mineralized to plant-available forms (Figure 3).

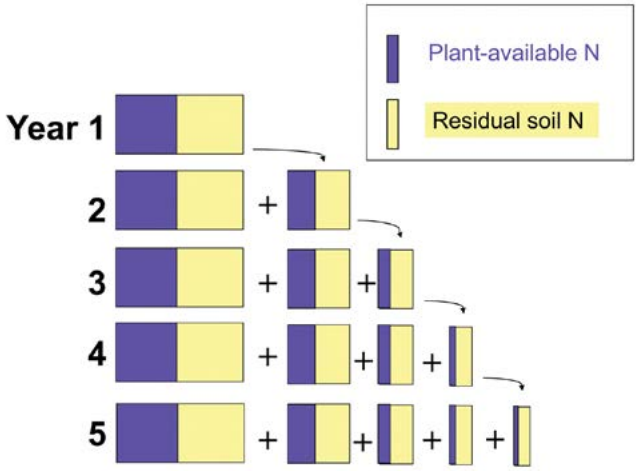

Figure 3. Conceptual illustration of long-term biosolids N cycling, when biosolids are applied annually at the same rate. Repeated biosolids applications to the same field increase both plant-available N (blue bars) and residual soil N (yellow bars). The residual N is stored in soil organic matter. Each year after application, a small fraction of the residual N is mineralized to plant-available forms. Adapted from D. Beegle (unpublished), Penn State University.

A small increase in soil organic matter reflects considerable storage of N in an organic form. An increase of 0.1% in soil organic matter (for example, from 3.0% to 3.1%) represents an increase in soil N of about 100 lb N per acre (0-to-6-inch depth).

Matching biosolids N to crop N requirement. The biosolids application rate calculations described here and explained further in PNW 511 are based on appropriate university nutrient management guides for the crop and region. Updated university nutrient management guides are not available for all crops. For crops without a recent nutrient management guide, the state regulatory agency typically consults with university faculty, private agronomists or both to determine a target N rate for the crop. Often, the regulatory agency requires soil testing, plant tissue testing or both to confirm that N supplied by biosolids is not excessive.

Phosphorus (P)

Biosolids are an excellent source of phosphorus (P). Fields that are low in soil test P are especially responsive to biosolids application, while fields with high soil test P are unlikely to benefit from application.

Table 4. Summary of P fertilizer recommendations from OSU fertilizer guide

Soil test category	West of the Cascades Bray P1 test (ppm)	East of the Cascades Olsen P test (ppm)	Is P fertilizer recommended?
Low	<20	<10	Yes, for most crops
Medium	20–40	10–25	Yes, for some crops
High	40–100	25–50	Only starter P fertilizer for a few crops
Excessive	100+	50+	No

Adapted from EC 1478, Soil Test Interpretation Guide (2011).

Two methods are routinely used in the Pacific Northwest — the Bray P1 test for acidic soils west of the Cascades, and the Olsen (bicarbonate) test for alkaline soils east of the Cascades. Agronomic interpretations of these soil tests are given in Table 4.

When soil test P values are low to medium (Bray P1 test below 40 ppm; Olsen P test below 25 ppm), a biosolids application is likely to correct soil P deficiency and increase crop yield. When soil test values are in the high or excessive range, biosolids P is unlikely to benefit crop production and may increase the risk of P loss to nearby water bodies (Figure 4).

When biosolids application rates are based on supplying plant-available N to meet crop requirements, resulting soil P is almost always greater than the crop can use. Most crops take up N and P in an approximately 10:1 ratio. A crop that takes up 100 lb N per acre takes up 5–20 lb P per acre.

Not all of the P in biosolids is plant-available. Research in the Pacific Northwest has demonstrated that plant-available P is typically 20% to 60% of total P present in biosolids. See Appendix D for details. Because the plant-available P content of biosolids is usually unknown, plant-available P accumulation in soil must be tracked with agronomic soil testing.

Controlling P loss to sensitive water bodies is an important environmental issue. High P inputs to surface waters can cause eutrophication and trigger algal blooms. Algal blooms can harm fish or other aquatic life, reduce water clarity, create unpleasant swimming conditions and odors, and interfere with boating and fishing. Some types of algae in these blooms can produce toxins that are dangerous to humans and can be lethal for pets and livestock.

Agronomic soil test P methods (Bray P1 or Olsen) are also useful to evaluate the relative risk of P loss from a field to a water body (Figure 4, page 12). High or excessive soil test P does not impact crop yield, but it does increase the risk of P loss from a field. The Phosphorus Index is a risk assessment tool created by the USDA Natural Resources Conservation Service. Agronomic soil test P values have been integrated into it. The NRCS P Index assesses the relative risk of P movement from agricultural fields to nearby surface waters. In addition to soil test P, the NRCS P index also considers many site-specific factors. Field distance to a water body and soil erosion risk are often the most important factors to determine field susceptibility to P loss. Customized P Indexes for Washington and Oregon have been created by NRCS for west and east of the Cascades. These are available online.

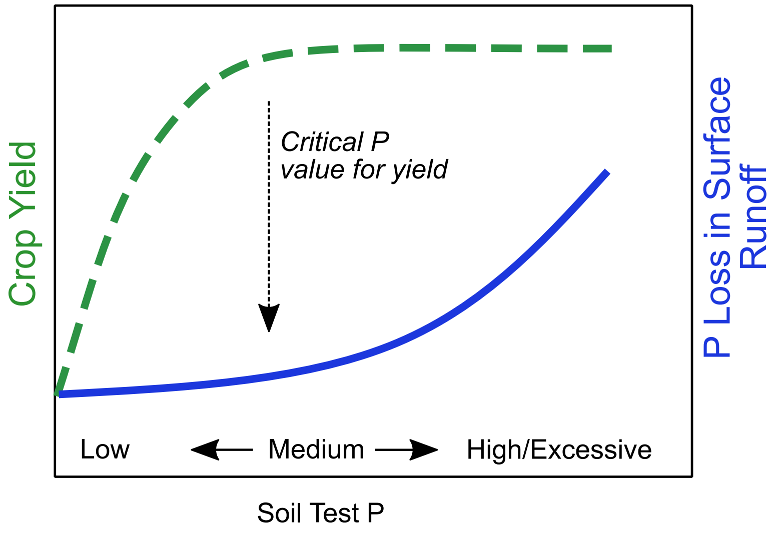

Figure 4. Agronomic and environmental interpretations of soil test P. Agronomic soil test P is used as an indicator of the likely benefit to crop production from P application. A soil P test is also a part of the NRCS P Index, a risk assessment tool. As soil test P rises above the level needed for crop production (dotted line), the risk of P loss in runoff increases (solid line). Adapted from *Agricultural Phosphorus and Eutrophication*, ARS-149 (2003).

Potassium (K)

Biosolids contain only a small amount of K relative to other macronutrients. In most situations, the contribution of biosolids to soil K fertility is insignificant. The lack of K in biosolids can have crop management implications in the following situations:

- When soil K is deficient, K must be supplied from fertilizer. Agronomic soil testing is used to forecast the need for K fertilizer application. Consult university fertilizer or nutrient management guides for crop-specific interpretation of soil test K values.
- Fertilizers, including biosolids, that are low in K can be beneficial for some ornamental crops that are sensitive to soluble salts or excess K, such as rhododendrons and azaleas.
- Potassium can accumulate in plant tissue when plants are grown on soils that are high in K. High concentrations of K in grass or legume forages can exacerbate animal nutritional disorders, such as grass tetany disorder in cattle. Biosolids are a low-K fertilizer alternative for forage production on soils that contain excessive K.

Sulfur (S)

Sulfate is the plant-available form of S. Sulfate is present in biosolids at the time of application, and additional sulfate is released as the biosolids decompose in soil. Recent research measured the amount of plant-available sulfate-S supplied by biosolids (Moore et al., 2022). During the first 12 weeks after biosolids incorporation into moist soil:

- Aerobic, anaerobic and lime-stabilized biosolids supplied 3–6 lb sulfate-S per dry ton
- Lagoon-stabilized biosolids supplied 11 lb sulfate-S per dry ton
- Sulfate-S supplied by biosolids compost was near zero

Additional detail on this study is provided in Appendix E.

Fertilizer replacement value of biosolids

Table 5 provides estimates for the fertilizer replacement values of N, P, K and S for the first year after application of anaerobically digested biosolids. This estimate is based on typical biosolids analyses and estimates of plant-available nutrients from university field trials. The fertilizer replacement values shown in Table 5 do not include the potential benefits to soil health from biosolids (see Soil Health section). Soil health benefits are difficult to express in simple economic terms and are unique to every location.

Table 5. Approximate first-year fertilizer replacement value of anaerobically digested biosolids

Nutrient[a]	Total nutrient	Available nutrient	Available nutrient	Nutrient value	Fertilizer replacement value
	% dry wt	% of total nutrient[b]	lb/dry ton[b]	$/lb[c]	$/dry ton
N	5	35	35	0.44	$15.40
P	2.5	40	20	0.93	$18.60
K	0.3	100	6	0.44	$2.64
S	1	35	7	0.31	$2.17
NPKS					$38.81

[a] Use the following conversion factors to convert to units used for fertilizer marketing To get P_2O_5 (phosphate), multiply P x 2.29. To get K_2O (potash), multiply K x 1.2.

[b] Estimated plant-available nutrient released in the first year after biosolids application, based on Pacific Northwest field research by Washington State University and Oregon State University.

[c] Nutrient value based on Willamette Valley (Oregon) fertilizer prices (April, 2021): urea ($402/ton), monoammonium phosphate ($520/ton), potassium chloride ($436/ton), and ammonium sulfate ($333/ton). The actual cost of a pound of nutrient from inorganic fertilizer varies, depending on nutrient form and analysis, transportation charges, market conditions and the quantity purchased. Cost of fertilizer application is not included.

Soluble salts

Biosolids contain lower concentrations of soluble salts than many organic fertilizers. For example, poultry manures typically contain 2% to 4% K (a soluble cation), as compared to 0.1% to 0.6% K in biosolids. Many soluble salts are separated from biosolids at the wastewater treatment facility and discharged in treated effluent water. As organic matter in biosolids decomposes after application to soil, some additional salts are released.

Repeated biosolids applications have not resulted in detrimental salt accumulations in soil, even at sites with low annual precipitation and no irrigation.

Case study: Dewatered cake biosolids (80% moisture) were applied annually for more than 10 years to dryland pastures near Hermiston, Oregon (6 inches of annual precipitation). However, electrical conductivity (a measure of soluble salts in soil) did not increase above 1 mmho/cm, a value considered low (EC 1478, *Soil Test Interpretation Guide*). Details on this trial are provided in PNW 716, *Biosolids in Dryland Cropping Systems*.

Soil pH

Biosolids application can increase or decrease soil pH, depending on the biosolids processing method (Table 6). Several factors determine how a biosolids application will affect soil pH. We recommend testing soil pH every three to five years at long-term biosolids application sites.

Table 6. Biosolids effects on soil pH

Type of biosolids	Biosolids input to soil	Effect on soil pH	Soil process description
All	Soluble salts	Temporary decrease	Cations displace acidity from soil clay and organic matter and move it into soil solution.
All	Organic N and S	Decrease	Oxidation of organic N and S to nitrate and sulfate produces acidity.
All	Exchangeable Ca and Mg	Increase	Supply non-acidifying cations.
Alkaline-stabilized	Ca oxides and hydroxides	Increase	Convert soil acidity to water and carbon dioxide.

Biosolids stabilized without alkaline materials

Following application of biosolids that do not contain added alkaline materials, the change in soil pH is the net result of the first three factors listed in Table 6. A drop in soil pH (acidification) of 0.2 to 0.5 pH units may often be observed shortly after application due to the addition of soluble salts and oxidation of organic N and S compounds in biosolids. This pH drop is typically short lived and balanced by the Ca and Mg contained in the biosolids.

Biosolids stabilized without alkaline materials will slowly acidify soil (reduce soil pH). Long-term field trials (over 10 years) in the Pacific Northwest have demonstrated that soil pH values were similar (within 0.2 to 0.4 pH unit) when crops were fertilized with anaerobically digested biosolids or with commercial N fertilizers.

A high rate application of biosolids compost can affect soil pH. For example, a 3-inch deep biosolids compost application for landscape establishment acidified soil by 0.5 pH units as compared to a no-compost control (Sullivan and Bell, 2015). By contrast, a high rate yard debris compost application increased soil pH by 0.3 units versus the no-compost control.

Alkaline-stabilized biosolids

Some biosolids are stabilized with alkaline materials (calcium oxide or calcium hydroxide) to reduce odors and meet EPA pathogen reduction requirements. In a typical alkaline stabilization process, the biosolids/alkaline material mixture reaches a pH of 12 or greater for at least two hours. At this high pH, ammonia is quickly lost to the atmosphere, resulting in stabilized biosolids with a lower N content than those treated using other methods.

After land application, the residual alkaline material rapidly neutralizes soil acidity, and increases soil pH (the last process in Table 6). Thus, alkaline-stabilized biosolids act as a replacement for agricultural lime. Alkaline-stabilized biosolids sometimes contain 20% to 40% lime (0.2 to 0.4 ton of agricultural lime per dry ton of biosolids). The liming value of alkaline-stabilized biosolids can be roughly estimated by a calcium carbonate equivalency test at an agricultural testing laboratory.

Consider current soil pH and the crops that might be grown in rotation before applying alkaline-stabilized biosolids. Blueberries and some nursery crops that are adapted to acid soils (for example, rhododendrons and maples) can be harmed by increased soil pH.

In high pH soils (pH above 7), the nutrients provided by alkaline-stabilized biosolids are beneficial, but the resulting increase in soil pH is not. Lime application on high pH soils reduces plant availability of such nutrients as Zn, Fe or Mn, and may reduce crop productivity.

Biosolids and soil health

Biosolids application affects soil physical, chemical and biological properties that are critical to healthy soil functions (Figure 5).

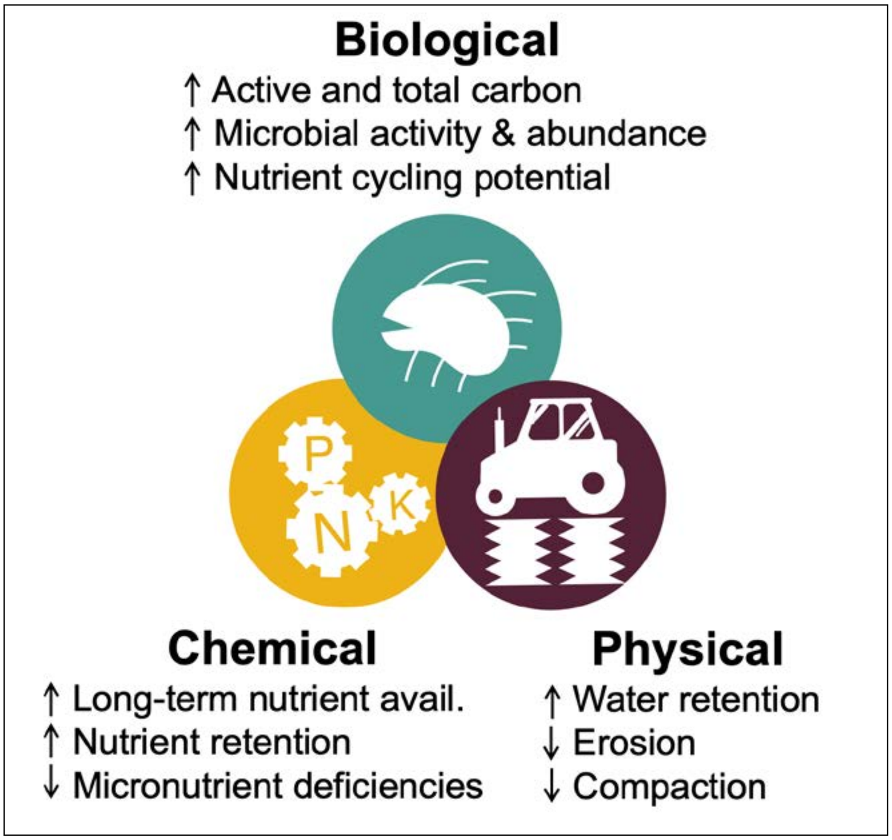

Image: D. Griffin-LaHue

Figure 5. Improvements in soil health with biosolids are often synergistic among chemical, physical and biological properties.

Soil organic carbon

Organic matter from biosolids is a food source for soil microorganisms. Microbial activity decomposes organic matter, cycles and releases nutrients, creates stable soil organic carbon (C), and builds soil structure. Soil organic C makes up about 50% of organic matter; it is a primary measurement of soil health. Changes in soil organic C are important criteria used to estimate the climate change mitigation potential of land management practices.

The organic C provided by a single biosolids application does not increase soil organic C content substantially. However, biosolids application can provide synergistic soil health benefits over the long-term when coupled with other soil management practices that favor accumulation of soil organic C, such as reduced tillage and cover cropping.

Across soils and cropping systems, biosolids applications produce long-term soil organic C increases:

- In a tilled, dryland wheat system in central Washington near Waterville, five biosolids applications of 3 dry tons per acre over 16 years doubled soil organic C content in topsoil (0 to 4 inches; Cogger et al., 2013a). PNW 716, *Biosolids in Dryland Cropping Systems*, summarizes increased soil organic matter following biosolids application at other Pacific Northwest sites.
- In an untilled perennial grass system at Puyallup, Washington, biosolids surface applications over 10 years increased C content in the topsoil (0 to 6 inches) by about

20%; 27% of biosolids C was retained as soil organic C. Soil organic C also increased in subsoil (6 to 12 inches), likely due to the action of earthworms and increased root growth (Cogger et al., 2013b).

Biological properties

Soil organic C can be slow to change, but "active" C pools are more dynamic in the short-term and represent the soil C food supply to microbes.

Recent Washington State University research in central Washington near Waterville demonstrated that biosolids effectively increase soil active C and microbial activity compared to unamended and conventionally fertilized soils. Active soil carbon was measured by the permanganate oxidizable C test (POXC) and microbial activity was assessed through mineralizable C measurements. Other studies confirm that microbial abundance, microbial activity and rates of biological nutrient cycling of N and S increase in soils treated with biosolids (Sullivan et al., 2006; Zerzghi et al, 2010).

The effect of a biosolids application on active C pools usually fades after 10 years (Avery et al., 2018). However, increased N mineralization activity was observed for 12 years after a one-time high rate application (approximately 13 ton per acre; Sullivan et al., 2006).

Physical properties

Biosolids application can reduce soil bulk density, leading to greater soil porosity that improves root growth, water and air flow, and water storage (Figure 6). In particular, plant-available water can increase. Plant-available water is the amount accessible to plant roots after drainage by gravity.

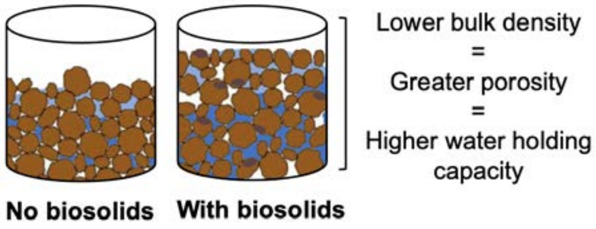

Image: D. Griffin-LaHue

Figure 6. Biosolids reduce soil bulk density and increase soil porosity and soil water holding capacity.

Brown et al. (2011) observed increased soil water holding capacity following biosolids application across different soils and production systems. Biosolids may reduce water demand in irrigated crops and increase drought resilience in dryland crops. Ongoing research in a dryland wheat system in central Washington shows that the application of biosolids every four years over 26 years increased plant-available water holding capacity equivalent to about 0.3 inches water in the top 6 inches of soil. This small increase can have a dramatic effect on productivity in arid, nonirrigated systems.

Soil aggregate stability is another measure of soil structure that improves after biosolids applications. Improved aggregate stability reduces the risk of wind and water erosion and improves water infiltration and drainage. Degraded soils with excess salt or sodium that limit plant growth may especially benefit from the soil aggregate, stability-building effect of biosolids.

Chemical properties

As discussed in other sections of this publication, biosolids increase soil organic matter, supply slow-release forms of many nutrients (for example, N and P), increase micronutrient availability (for example, Zn and Cu) and modify soil pH. Increased soil organic matter following biosolids application also increases the soil cation exchange capacity — the capacity of soil to store available nutrients.

Questions about biosolids

What limits the rate of biosolids application?

Agronomic application rates are based on matching plant-available N supplied by biosolids to the plant-available N needs of the crop.

How do biosolids compare to organic fertilizers in terms of plant-available N (PAN) supplied per ton?

Most biosolids supply 30–40 lb PAN per dry ton during the first year after application. This is approximately the same amount of PAN that is provided by a dry ton of poultry manure (EM 9235; *OSU Organic Fertilizer & Cover Crop Calculator: Predicting Plant-Available Nitrogen*).

Should biosolids be applied to fields that have high or excess soil test P?

Biosolids application may be justified in fields with high or excess soil test P, situations for which university nutrient management guides would recommend no P application. This may be true where the application is expected to provide such benefits as nutrient supply and improved soil health, the field is not close to a water body, and the added P is unlikely to damage water quality. This scenario is common in dryland cropping systems east of the Cascades. See PNW 516, *Biosolids in Dryland Cropping Systems,* for additional information.

How does the time required for land application of biosolids compare to that of conventional synthetic fertilizer?

Biosolids application is much slower than conventional fertilizer application because of the large quantities of material involved. Several weeks may be required to complete biosolids application to large fields.

Can biosolids be used on farms that produce crops under organic certification?

Biosolids application is prohibited under USDA National Organic Program rules.

However, Class A biosolids are likely to have a lower risk for infection by human pathogens than manure processed under NOP rules. Treatment facilities producing Class A biosolids are required to demonstrate and document that their treatment process meets prescribed time and temperature standards. They are also required to monitor biosolids products for human pathogen indicator organisms, such as salmonella. These requirements under NOP rules are less stringent. For example, composted manure does not have to be tested for the presence of human pathogen indicator organisms before use on organically certified crops under NOP rules.

Should I be concerned about potential contaminants in biosolids that are not addressed under federal and state biosolids rules?

Wastewater may contain a variety of synthetic organic compounds. Current research indicates that these compounds do not pose a risk to human health when managed and applied according to state and federal rules. The presence of these chemicals in wastewater and the environment is an ongoing area of research. For more information regarding contaminants and biosolids, see FS192E: *Producer Guide to Biosolids Quality*.

How do biosolids use practices affect greenhouse gas emissions?

Analyses of the energy impacts of the production and use of biosolids are now a part of the engineering analyses performed when wastewater treatment facilities are upgraded. These analyses consider overall greenhouse gas emissions resulting from biosolids processing and use.

Land application of biosolids almost always results in lower greenhouse gas emissions than competing practices, such as burning or burying them in a landfill. The manufacture of 1 ton of commercial fertilizer N consumes the equivalent of about 3,000 cubic feet of natural gas. Biosolids are usually applied close to the site of their production, with reduced transport emissions compared to commercial fertilizers. Replacing commercial fertilizers with biosolids can reduce fertilizer production and transportation energy demands, recycle what otherwise would be waste products and store carbon in the soil for an extended period. Additional biosolids use close to urban centers and continued development of energy-efficient treatment processes will further increase emissions savings.

For more information

Agency contacts

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Oregon Department of Environmental Quality. https://www.oregon.gov/deq/wq/programs/Pages/Biosolids.aspx

Idaho Department of Environmental Quality. https://www.deq.idaho.gov/water-quality/wastewater/sludge-and-biosolids/

Extension and outreach publications

Biosolids in Dryland Cropping Systems (PNW 716) https://catalog.extension.oregonstate.edu/pnw716

Worksheet for Calculating Biosolids Application Rates in Agriculture (PNW 511) https://catalog.extension. oregonstate.edu/pnw511

Producer Guide to Biosolids Quality. (FS192E) https://pubs.extension.wsu.edu/producer-guide-to-biosolids-quality

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Appendices

Appendix A. EPA standards for biosolids quality

Biosolids quality, as defined by EPA, is based on:

- Human pathogen destruction.
- Trace element concentration limit.
- Organic matter stabilization.

This section gives an overview of these standards.

Human pathogen destruction

Pathogens are organisms, such as bacteria, that can cause disease. Before land application, biosolids must be processed to meet EPA Class A or Class B pathogen-reduction standards for pathogens that can cause disease in humans.

Class A biosolids are essentially pathogen-free. They are sold or distributed in urban areas for landscaping or turf fertilization, provided they also meet exceptional quality biosolids criteria for trace elements and vector attraction reduction.

Class B biosolids have been processed to significantly reduce, but not eliminate, pathogens. Biosolids of Class B quality usually are land-applied.

After land application, residual pathogens in Class B biosolids are killed by exposure to sunlight, drying conditions, unfavorable pH and other environmental factors. Management practices required at Class B biosolids application sites, including setbacks and access restrictions, protect public health. Class B biosolids pose no greater environmental or health risks than Class A provided the EPA guidelines for land application are followed.

Ceiling and exceptional quality trace element concentration limits

The federal rule administered by EPA sets thresholds for trace element concentration in biosolids. Some of the regulated elements are plant nutrients (Cu, Mo and Zn); at times, plants benefit from trace element application.

There are two sets of trace element concentration thresholds: ceiling concentration limits (the maximum allowed) and a more stringent set, exceptional quality (EQ) limits. Wastewater solids that exceed the ceiling concentration limits cannot be called biosolids and cannot be land-applied. Class A biosolids products meeting the EQ limits may be distributed directly to the public.

Table 7 shows the EPA ceiling concentration limit and EQ limit for various trace elements in biosolids, as well as Oregon and national averages for these elements.

Organic matter stabilization

Both Class A and Class B biosolids must meet stabilization standards to reduce odors and to reduce attractiveness to insects and rodents.

Table 7. Trace elements in biosolids: EPA concentration limits and average concentrations

Trace element	EPA ceiling concentration limit[a] (mg/kg)	EPA exceptional quality limit[a] (mg/kg)	EPA National Survey (2010)[b] (mg/kg)	Oregon biosolids average (2018)[c] (mg/kg)
Arsenic	75	41	7	5
Cadmium	85	39	3	2
Copper	4,300	1,500	558	285
Lead	840	300	77	20
Mercury	57	17	1.2	0.5
Molybdenum	75	75[d]	16	8
Nickel	420	420	49	20
Selenium	100	100	7	6
Zinc	7,500	2,800	994	635

[a] Source: EPA Guidelines for Pollutant Concentrations in Biosolids (40 CFR Part 503). The ceiling concentration limit is the maximum allowed for land application of biosolids. The exceptional quality limit applies to biosolids suitable for distribution without site approvals. To be called “exceptional quality biosolids” by EPA, biosolids must also be Class A for pathogen reduction.

[b] Source: Brobst, R.B. 2010. Targeted National Sewage Sludge Survey (TNSSS), summary of various trace elements. Presented at W2170 Multistate Workgroup Annual Meeting. Chicago, Illinois. June 6-7, 2010.

[c] Average across 66 Oregon municipal wastewater treatment facilities as reported to Oregon DEQ for 2018. Source: P. Heins, Oregon DEQ.

[d] The EPA exceptional quality limit for Mo is currently under review.

Appendix B. Biosolids supply plant-available N for wheat and grass crops

Agronomic rates for biosolids are based on supplying sufficient, but not excessive, plant-available N for crop production. Extensive research has determined the agronomic rate for forage grass (west of Cascades) and winter wheat (east of Cascades). Field research trials spanned multiple years and locations (Cogger et al., 2004; Sullivan et al., 2009; Cogger et al., 2013). Here we review key findings from those trials.

Winter wheat. Trials with soft white winter wheat were conducted primarily in wheat-fallow cropping systems in the 10- to 14-inch annual precipitation zone in central Washington (near Waterville) and northcentral Oregon (near Moro). At each field site, a range of biosolids application rates was applied and compared to the typical grower N application rate (approx. 50 lb N per acre). Most of the biosolids evaluated in the wheat trials were produced by anaerobic digestion and were applied during fallow as semisolid "cake" biosolids containing 20% to 25% dry matter (DM).

Overall, these wheat trials demonstrated that a biosolids application rate of 2–3 dry ton per acre provided sufficient N to achieve near-maximum crop yields (Sullivan et al., 2009; example in Figure 7). In these trials, biosolids were applied after wheat harvest (12 months prior to seeding the next crop) or in the spring of the fallow year (five months prior to seeding). Both application timings produced equivalent grain yields. When biosolids were applied at less than 3 dry ton per acre, soil profile nitrate accumulation was the same as for commercial N fertilizer. A 20-year study conducted near Waterville, Washington, demonstrated benefits of biosolids in supplying residual N across multiple cropping cycles (Cogger et al., 2013).

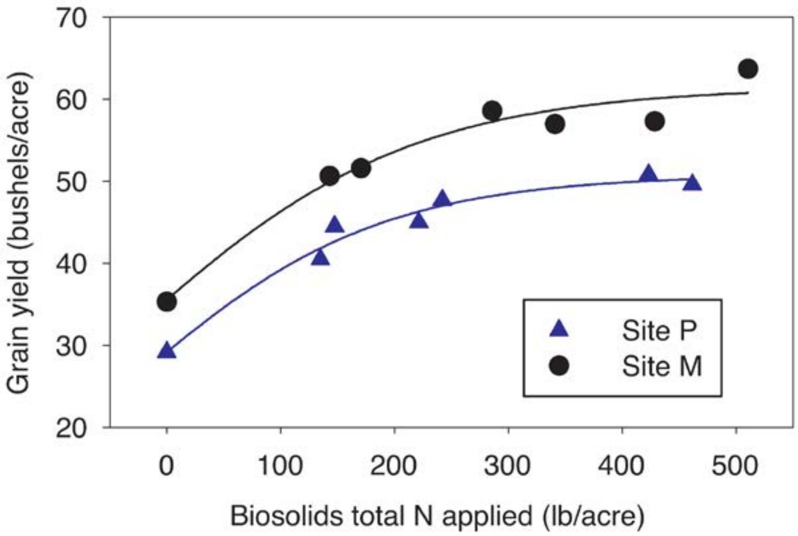

Figure 7. Effect of biosolids application rate on grain yield at two field sites (wheat-fallow cropping system near Moro, OR). A dry ton of biosolids contained approximately 100 lb. total N, so biosolids application rates shown here are roughly 1.5 to 4.5 dry ton per acre. Grain yield was the same for biosolids applied 12 months prior or five months prior to wheat seeding. Source: Shearin (2000).

Grass for forage. The authors determined the response of an irrigated cool-season grass (tall fescue for forage) to biosolids N in two-year trials (1998-99 and 1999-2000) in western Washington (Puyallup, Washington; Cogger et al., 2004). In the first year of each trial, biosolids were applied in spring and summer (April–June). No additional biosolids were applied in the second year of either trial, allowing for the measurement of the residual effects of biosolids applied the previous year. Grass N uptake was determined by harvesting five to six times per year at the early boot growth stage and compared to the N uptake of grass fertilized with inorganic N fertilizer. First year PAN recovered by forage was similar for biosolids produced via aerobic or anaerobic digestion, or lime stabilization (33–40 lb PAN per dry ton of biosolids; Table 8). PAN was lower for biosolids held in a lagoon for years prior to dredging. Plant-available N produced the second year after biosolids application was 5–7 lb per dry ton, except for lagoon biosolids (zero PAN).

Table 8. Plant-available N from biosolids determined in a field trial with irrigated tall fescue forage[a]

		Biosolids analysis			Plant-available N			
Biosolids stablization	No. of facilities	Total N	Ammonium-N	C:N ratio	First year	Second year	First year	Second year
		% dry wt	% dry wt.		% of total N	% of total N	lb/dry ton	lb/dry ton
Aerobic	3	5.1	0.4	6.7	32	6	33	7
Anaerobic	8	5.4	0.7	6.6	37	4	40	5
Lagoon	4	2.2	0.3	11.0	15	-1	6	0
Lime	2	4.7	0.1	6.5	43	6	40	5

[a] Source: Cogger et al. (2004).

Appendix C. Plant-available N from heat-dried biosolids

Class A heat-dried biosolids are in wider use as drying technologies improve and as biosolids treatment facilities are upgraded to produce them. Heat-dried biosolids are produced at large and small treatment plants in the Pacific Northwest, including Pierce County, LaCenter and Sumner in Washington, and Stayton and Myrtle Creek in Oregon. Heat-dried biosolids products (90% to 95% DM) are more economical to transport than biosolids cake (16% to 25% DM), and they can be bagged for retail marketing. Energy cost and availability limits heat-drying as a technology for biosolids processing. Energy produced from methane or from solar is expected to reduce cost and net greenhouse gas emissions in the future. A few fertilizer manufacturers for the turf and landscape market include heat-dried biosolids as a component in their specialty fertilizer products.

Objective

Determine plant-available N (PAN) release from heat-dried biosolids vs. a common organic fertilizer (feather meal).

Methods

Heat-dried biosolids were obtained from large and small facilities. Millorganite® and Soundgro®, marketed as bagged commercial products, were produced in large-scale high temperature drying facilities and were pelleted to uniform size. Small-scale facilities produced biosolids from LaCenter and Sumner, which were nonuniform in particle size.

Field trials. Researchers determined plant-available N from biosolids and feather meal fertilizers in field trials with winter wheat at the Oregon State University Hyslop Agronomy Farm near Corvallis, Oregon. Separate fields were used for the 2012 and 2013 trials, so there was no carryover of biosolids N from year to year. Fertilizers were broadcast-applied in March when the wheat was at the late tillering stage. Plant-available N was estimated using a N fertilizer equivalency method with urea as the standard (urea-N = 100% plant-available). We determined grain N uptake (grain yield x N concentration), at harvest to estimate PAN.

Laboratory trial. Fertilizers were incorporated into a moist silt loam soil collected from the field trial site and held at 72° F during the incubation period. We determined soil nitrate after two weeks and estimated net PAN from fertilizer compared to a no-fertilizer control soil.

Photo: Dan Sullivan

Results

Laboratory incubation. Plant-available N from heat-dried biosolids mineralized rapidly in the moist, warm soil samples. After two weeks of incubation, PAN% was 30% to 38% for biosolids vs. 57% for feather meal.

Field trials. PAN measured in our field experiments was released in less than eight weeks following application. Wheat takes up most of its N during stem elongation, or late March to mid-May at our field location. Plant-available N averaged 42% of total N for heat-dried biosolids vs. 66% for feather meal in the first year of the trial. PAN in the second year averaged 32% for biosolids vs. 50% for feather meal.

Conclusion

Heat-dried biosolids supplied rapidly available N under cool spring temperatures and rainfed field conditions. About 3 dry tons of heat-dried biosolids were required to provide the same amount of PAN as 1 ton of feather meal. PAN for heat-dried biosolids was similar to PAN reported for anaerobically digested, dewatered "cake" biosolids in other OSU and WSU research.

Table 9. Plant-available N from Class A heat-dried biosolids compared to feather meal, a common organic fertilizer

Organic fertilizer		Plant-available N (PAN)			
		Field trials[a]			Incubation[b]
Source[c]	Total N	2012	2013	2012–13	
	%	% of total N	% of total N	lb/ton	% of total N
Feather meal	11.1	66	50	111–147	57
LaCenter (WA)	7.2	36	29	42–52	33
Millorganite® (WI)	5.5	47	39	43–52	38
SoundGro® (WA)	6.2	42	33	41–52	33
Sumner (WA)	5.8	42	27	31–49	30

[a] Field trials. PAN estimated using a N fertilizer equivalency method with urea as the standard fertilizer (urea-N is 100% plant-available). Grain N uptake was determined at harvest and was the N response variable used to estimate plant-available N. Source: D.M. Sullivan, unpublished.

[b] Incubation of fertilizers in moist silt loam soil at 72 °F in the laboratory. PAN was determined at two weeks after fertilizer addition. Source: D.M. Sullivan and A. Heinrich, unpublished.

[c] Source = WA (Washington State), WI (Milwaukee, Wisconsin). Millorganite® and Soundgro® are registered trademarks.

Appendix D. Plant-available P from biosolids

Biosolids processing methods affect the value of biosolids as a P fertilizer, and the risk of P loss in runoff from fields after application. Soluble P carried by runoff to water bodies can reduce water quality.

This appendix discusses two laboratory analyses used to characterize the fertilizer value of biosolids and their risk to water quality:

1. Water-extractable phosphorus (WEP)
2. Phosphorus Sorption Index (PSI)

Both tests have been validated by research in Oregon and across the United States.

Water-extractable phosphorus

Rationale. The greatest hazard to water quality occurs when a highly soluble P source is surface applied to soil and heavy precipitation follows the application. The water-extractable P test was created to rank organic fertilizers for water quality risk.

Method overview. Biosolids P is extracted by shaking with water and measuring P concentration in the water. The protocol developed for national use for organic fertilizers uses a 1:100 dry biosolids:water ratio (Kleinman et al., 2007). Water-extractable P (WEP) is often expressed as a ratio (WEP:total P).

Interpretation. In field trials, higher WEP values indicates higher risk of P loss in runoff. For example, in a rainfall simulator study, the concentration of P in runoff was five to 10 times greater for animal manures (beef, dairy, poultry; n=7) than for dewatered biosolids (n=5; Kleinman et al., 2007). Both biosolids and manures were applied at equivalent total P application rates, but manures had higher WEP than biosolids (Kleinman et al., 2007). The ratio of WEP:total P reported in most research studies is less than 0.2 for most biosolids, 0.3 to 0.5 for manures, and 0.8 to 1.0 for ammonium phosphate or calcium phosphate fertilizers.

Recent versions of nutrient management planning software developed by the Natural Resources Conservation Service (NRCS) employ WEP:total P values to predict short-term risk of P loss in runoff. These computer simulation models predict P loss in runoff for many field management scenarios.

Phosphorus Sorption Index

Rationale. Iron (Fe) and Aluminum (Al) bind to P in insoluble forms. Biosolids from different sources contain different amounts of P, Al and Fe. The Phosphorus Sorption Index (PSI) is the molar ratio of P to Al plus Fe: [P/(Al + Fe)] in biosolids. As PSI increases, the solubility of P in biosolids increases, because there is not sufficient Al and Fe to bind to the P. When P is bound to these metals, it is not soluble, and therefore not plant-available.

Method overview. Biosolids samples are digested to determine total P, Al and Fe concentrations. Biosolids PSI is calculated as the molar ratio of P to Al plus Fe: [P/(Al + Fe)]. OSU research (Choate, 2003) showed that determination of PSI by strong acid digestion (nitric acid plus hydrogen peroxide; similar to EPA 3051 digestion method) yielded similar PSI values to those obtained by the most common research method (acid-ammonium oxalate extraction). For that reason, we recommend total metals analysis (EPA 3051 digestion) to determine PSI on a routine (non research) basis. The expense of adding Al and Fe determination to a biosolids elemental analysis is minimal.

Interpretation. The P Sorption Index indicates the P solubility and P fertilizer value of biosolids. Water soluble P in biosolids increased as PSI increased (Figure 8). The relative P fertilizer value of biosolids increased as PSI increased (Figure 9). Biosolids WEP and biosolids P fertilizer value increase when biosolids PSI exceeds 0.6 (Figures 8 and 9).

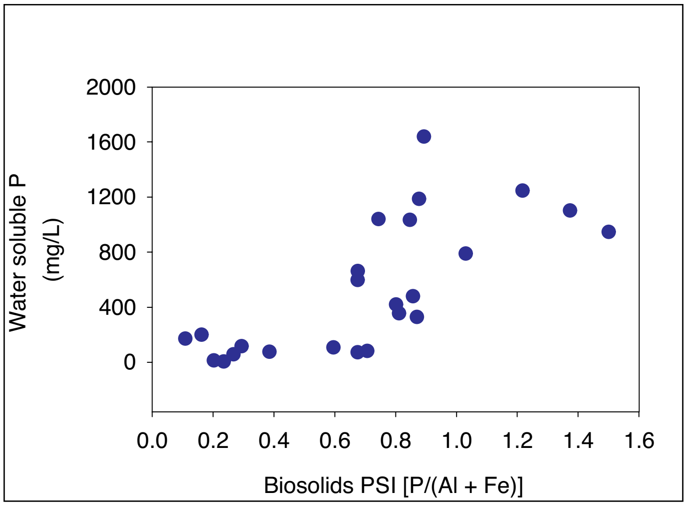

Figure 8. Figure 8. Water-extractable P (WEP) in biosolids increases with the Phosphorus Sorption Index (PSI) — the molar ratio of P to Al + Fe in biosolids. Each data point represents a city biosolids source. Water-soluble P was extracted from biosolids using a 1:10 dry biosolids:water ratio. Data from Choate (2003).

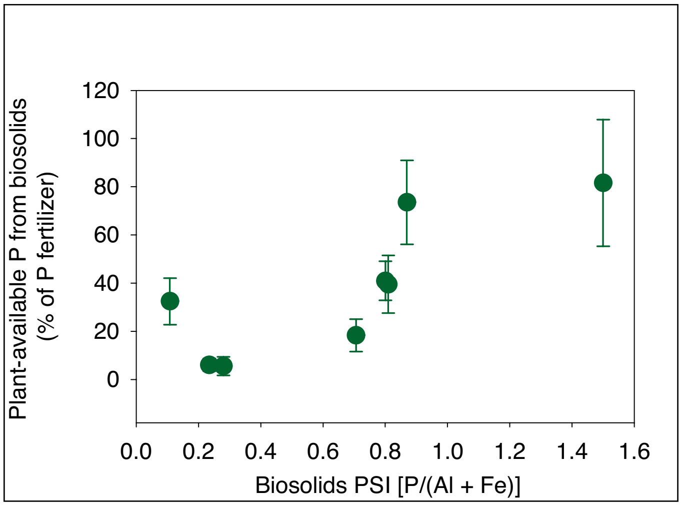

Figure 9. Plant-available P from biosolids increases with the Phosphorus Sorption Index (PSI) — the molar ratio of P to Al + Fe in biosolids. Each data point represents a city biosolids source. Error bars represent the range in measured plant-available P across five different Oregon soils. Plant-available P from biosolids was measured using anion exchange resin strips incubated in biosolids-amended soil. Plant-available P from biosolids is expressed relative to available P from triple super phosphate fertilizer. Data from Sullivan and Choate (2019).

Appendix E. Plant-available S from biosolids

Plant-available sulfate-S release following biosolids incorporated into moist soil was determined in a 12-week laboratory incubation at 77° F (Table 10; Moore et al., 2022). Net sulfate-S accumulation in biosolids-treated soil was determined with reference to sulfate-S concentration in the untreated control soil receiving no sulfur application. The soil used in the incubation was a Walla Walla silt loam, a common soil series present in eastern Oregon and Washington dryland cereal production fields.

Key findings:

- Biosolids produced by different treatment technologies varied in total S concentration from 0.5 to 1.6% total S.
- Sulfate-S release averaged 3 to 6 lb per dry ton for biosolids produced by aerobic or anaerobic digestion, or by lime stabilization.
- Sulfate-S release from compost was near zero (0.3 lb per dry ton).
- Lagoon-stabilized biosolids provided the most sulfate-S release (11 lb per dry ton).
- The ratio of organic C to total S in biosolids (C:S ratio in Table 10) was correlated with sulfate-S accumulation in soil. As C:S ratio increased, sulfate-S decreased.

This research confirms that most biosolids provide sufficient S for crops when applied at agronomic rates based on N. For example, after 12 weeks incubation, PAN for biosolids produced by anaerobic digestion ranged from 30 to 40 lb per dry ton (data not shown), accompanied by release of 6 lb sulfate-S per dry ton (Table 10). The ratio of PAN to sulfate-S provided by these biosolids was 5:1 to 8:1. Normal plant development typically requires a N:S ratio of 8:1 to 12:1 in plant tissue.

Table 10. Plant-available sulfate-S release from biosolids at 12 weeks following incorporation into a Walla Walla silt loam soil.

		Biosolids analysis			**Plant-available S[b]**	
Biosolids stabilization	No. of facilities	Organic C[a]	Total S	C:S ratio	Range	Avg
		%	%		% of total S	lb/dry ton
Aerobic	2	39	1.0	44	11–19	3
Anaerobic	5	37	1.1	35	27–37	6
Compost	2	32	0.4	89	3–6	0.3
Lagoon	2	22	1.6	14	26–46	11
Lime	1	25	0.5	48	52	5

[a] Biosolids organic C (%) is approximately equal to biosolids organic matter as determined by Loss-On-Ignition (LOI) x 0.58

[b] Plant-available S present after 12 weeks incubation in moist soil at 77 o F.

Source: Source: Moore et al (2022)

Appendix F. History of this publication

1998-present. PNW 508, *Fertilizing with Biosolids*, was first published in 1998 and was updated in 2007, 2015 and 2021 (this version) by authors from OSU Extension and WSU Cooperative Extension.

1993. EPA rules for sewage sludge (biosolids) were updated and published in 40 CFR EPA Part 503: https://www.epa.gov/biosolids/biosolids-laws-and-regulations.

1990s. The term *biosolids* replaced *sewage sludge*. The name change occurred about the same time (1993) as the adoption of the new EPA rule for biosolids.

1981. Agronomic recommendations, based on field trials conducted by Oregon State and other land-grant universities and federal rules were published as FG 64, *Fertilizing with Sewage Sludge*.

1970s-1980s. Field trials to evaluate N and trace element uptake by sweet corn and tall fescue were conducted by OSU faculty and graduate students. Principal investigators included T.L. Jackson, D.D. Hemphill Jr., V.V. Volk and G. Kiemnec.

1972. USA Clean Water Act amendments empowered EPA to develop standards for land application of sewage sludge.

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