A PACIFIC NORTHWEST EXTENSION PUBLICATION

Biosolids in Dryland Cropping Systems

Photo: Brian Campbell, Natural Selection Farms

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Executive summary

Biosolids are a product of municipal wastewater treatment. Raw sewage solids must be processed to meet U.S. Environmental Protection Agency (USEPA) standards before they can be called biosolids. Biosolids contain organic matter and nutrients that are beneficial for soil, crop, and forage productivity.

This publication reviews the long-term effects of biosolids applications on soil health in dryland cropping systems east of the Cascades in Washington and Oregon. Findings reported here come from field trials that have continued for more than 10 years.

Major long-term findings are:

- Biosolids increase soil organic matter. In the three long-term trials summarized here, biosolids increased soil organic matter by more than 50 percent in the top 4 inches of soil as compared to a no-biosolids control. These field locations were in northcentral Washington near Waterville, and in northeast Oregon near Pendleton and Hermiston.
- Biosolids application enriches the supply of immobile nutrients—for example, phosphorus (P) and zinc (Zn)—in the topsoil. This increase in nutrients near the soil surface benefits crop growth, but it may also increase weed competition with dryland cereals. Soil testing can be used to monitor the accumulation of immobile nutrients following biosolids application.
- Soil salinity has remained low after repeated biosolids applications. Biosolids are low in soluble salts because soluble ions—for example, potassium (K) and chloride (Cl)—are discharged in the effluent from municipal wastewater treatment facilities.
- Biosolids are an effective replacement for commercial nitrogen (N) inputs such as anhydrous ammonia or urea-ammonium nitrate (UAN) in cereal cropping systems. 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. Organic N in biosolids typically releases 30-8-3-1 percent of its N in plant-available form in years 1, 2, 3, and 4 following a one-time biosolids application.
- The combination of increased soil organic matter, increased soil nutrients, and improved soil physical properties following biosolids application can sometimes produce higher cereal grain yields

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PNW 716 • February 2021

than fertilization with inorganic nitrogen and sulfur. Grain yield in a long-term Douglas County, Washington trial averaged 10 to 15 percent greater with biosolids compared to anhydrous ammonia.

Short- and long-term effects of biosolids application

Other Pacific Northwest Extension biosolids publications—*Fertilizing with Biosolids* (PNW 508) and *Worksheet for Calculating Biosolids Application Rates in Agriculture* (PNW 511)—emphasize short-term outcomes of biosolids applications, especially the amount of plant-available N provided for the first crop following a biosolids application. This publication addresses long-term outcomes (Figure 1).

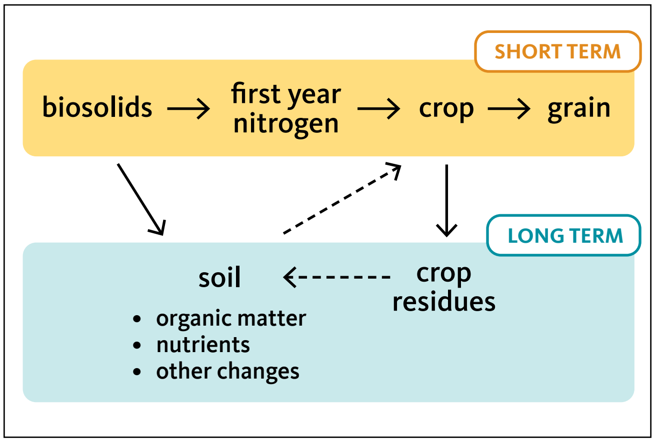

Figure 1. Short- and long-term effects of biosolids application on the soil-crop system. Agronomic rate (top) addresses the nitrogen need for a single year. Biosolids application provides multi-year benefits (bottom) by enhancing soil nutrient and organic matter content. Slow, long-term nutrient cycling processes are indicated by dotted arrows.

The challenge of soil organic matter maintenance in dryland cropping systems

Organic matter is important for the maintenance of microbial activity, and associated soil structure, nutrient cycling, and water infiltration benefits in soils. Routine maintenance of soil organic matter reduces soil susceptibility to loss by wind and water erosion.

Tillage-intensive agriculture has reduced soil organic matter by 20 to 60 percent in the course of a few decades through biological oxidation (Brown and Huggins, 2012; Ghimire et al., 2015, Ghimire et al., 2017). The traditional wheat-fallow rotation used in dryland production in the Pacific Northwest is a particularly difficult system in which to maintain organic matter because of the extended, tilled fallow periods that are part of each cropping cycle. During fallow, tillage and lack of biomass input contribute to the depletion of organic matter. Reducing tillage or initiating annual cropping can stop or reverse organic matter loss.

Biosolids can help rebuild organic matter in depleted soils

Biosolids application increases soil organic matter and soil carbon, a major constituent of organic matter. The increase in soil organic matter comes directly from biosolids themselves and from increased crop biomass production (Figure 1). In dryland cropping systems, biosolids typically increase grain yield with a corresponding increase in straw production by cereal crops. Not only does the extra straw provide a source of soil organic matter, it also protects the soil surface from erosion.

In an 18-year study in Douglas County, Washington, biosolids applied at agronomic rates (2 or 3 dry ton/acre once every 4 years) increased soil organic matter by approximately 50 percent (0- to 4-inch depth) compared with a fertilized control treatment (Cogger et al., 2013; Appendix A). At Lind, Washington, biosolids increased wheat straw biomass by more than 20 percent in the first crop following biosolids application in a wheat-fallow rotation (Schillinger et al., 2018).

Managing nitrogen from biosolids

Soil organisms and crops cycle the N added from biosolids application (Figure 1). When soil organic matter increases, so does the quantity of N stored in the organic matter. The carbon-to-nitrogen ratio of soil organic matter is typically 10 to 14. At a field site in Douglas County, Washington, soil total N (0- to 4-inch depth) increased from about 0.09 to 0.13 percent after 4 biosolids applications over an 18-year period (Cogger et al., 2013; Figure A-1b, page 4). Soil organic matter increased following long-term application of biosolids to dryland pasture in northeast Oregon near Hermiston (Appendix C) and in a dryland wheat cropping system near Pendleton, Oregon (Appendix D).

The second crop that is produced after a biosolids application will usually require some inorganic N fertilizer to satisfy crop need. Research conducted in Douglas County, Washington, confirmed that the general estimate of additional plant-available N from previous biosolids applications found in the Extension publication *Worksheet for Calculating Biosolids Application Rates in Agriculture* (PNW 511) was sufficient for a wheat-fallow cropping system (Cogger et al., 2013). Estimates reported in PNW 511 indicate that 11 percent of the organic N contributed by biosolids becomes

Table 1. Guidance for biosolids management based on soil test P ranges.

Soil test P (Olsen method)	Plant need for additional phosphorus	Suggested biosolids management practice
0–20	Grain yield will likely increase from P application	Apply biosolids to increase soil test P to 20 ppm or more.
20–40	Grain yield will occasionally increase from P application	Monitor soil test P to determine trends over time. Limit commercial P fertilizer application to 5 to 10 lb P_2O_5, placed with the seed. Reduce biosolids application frequency.
40–60	No grain yield increase from P application	Reduce biosolids application frequency.
60+	No grain yield increase from P application	Rotate biosolids applications to fields with lower soil test P values.

available to the second crop after a biosolids application (8 percent in the fallow year, plus an additional 3 percent in the following crop year).

Some farmers adjust N fertilizer rates based on soil testing during the fallow year in a wheat-fallow cropping system. The nitrate-N measured in a fallow soil sample will reflect most of the residual plant-available nitrate-N mineralized from previous biosolids applications. In such circumstances, farmers may ignore the estimates of N mineralized from a previous biosolids application as instructed in PNW 511. Consult the appropriate land-grant university fertilizer guide for your region to determine how to estimate N fertilizer need based on soil nitrate testing.

Managing phosphorus from biosolids

Biosolids are a rich source of phosphorus (P), and soil test phosphorus increases following a biosolids application. See Table 1 for suggested biosolids management based on soil test P. Suggested practices are based on making best use of phosphorus, a scarce resource, rather than explicitly protecting surface water.

Keep in mind that soil test P values will likely vary by about 10 to 20 percent from the true soil value due to uncontrollable sampling and testing errors. A soil test P value of 60 ppm should be interpreted as falling somewhere between 50 to 70 ppm.

Conservation planning and the Phosphorus Index

Soil erosion is a major risk in dryland areas. Practices that reduce the risk of erosion are an essential component of conservation plans. Soil moves downhill with time, so hilltop soils are more shallow and less productive than the deeper soils present on toe slopes and bottomlands. Hilltops and upper slopes are typically the least productive management units in a field. These soils have lost much of their native organic matter due to erosion. Targeting these areas for biosolids application may be especially helpful in restoring their value to the overall cropping system. In addition, biosolids boost crop growth and straw production, thus increasing long-term soil organic matter content.

Conservation planning agencies such as the Natural Resources Conservation Service (NRCS) and local conservation districts are required to consider the risk of phosphorus (P) movement to water bodies as part of the conservation planning process. The “Phosphorus Index” is a risk assessment tool developed by USDA-NRCS and customized by state or regional NRCS conservation planners. Phosphorus Indexes take into account all cropping scenarios within a state or region (dryland, irrigated, high- and low-precipitation zones etc.). Agronomic soil test P results are only one component of a P Index.

Agronomic soil tests used in land-grant university fertilizer guides were developed starting in the 1950s to aid growers in assessing the potential economic benefit of fertilizer P applications. They were not intended to indicate environmental risk. When concern about excess P in surface waters arose in the 1990s, agronomic test results were shown to be correlated with the concentration of P present in soil eroded downslope and with the concentration of dissolved P present in runoff. However, in order to degrade water quality, P-enriched soil or runoff must be transported to a surface water body. The presence of high soil-test P does not constitute risk to water quality when a site does not include a transport path to a P-sensitive water body.

Appendix A: Biosolids build soil health in a long-term dryland field trial

Douglas County, Washington

Situation

Decades of wheat production in a 2-year wheat-fallow rotation has reduced soil organic matter and degraded soil health in the inland Pacific Northwest. Fertilization with biosolids is an economical way to build organic matter in degraded soils while supplying nutrients for the crop.

A long-term on-farm trial was conducted in a dryland wheat-fallow rotation in Douglas County, Washington to evaluate the effects of biosolids on grain yield and soil health (Cogger et al., 2013).

Methods

A chisel plow was used for primary tillage in the summer fallow year, followed by shallow cultivation (twice during fallow). Winter wheat was harvested every other year. The experiment included these fertilizer treatments:

- Zero-N control
- Biosolids applied at three rates (2, 3, and 4.5 dry ton/acre), every fourth year (1994, 1998, 2002, 2006, and 2010). Total N applied by biosolids averaged 200, 320, and 460 lb N/acre per application. Plant-available N contributed (at about 40 percent of total N) by these biosolids application rates was estimated at 80, 130, and 180 lb N/acre per application (PNW 511). The low biosolids application rate supplied plant-available N at a rate close to the recommended N fertilizer rate.
- An inorganic N treatment (anhydrous ammonia at 50 lb N/acre plus sulfur at 10 lb/acre) applied every other year

Results

Grain yield averaged over all harvests beginning in 1996 was about 10 percent greater for the 2 dry ton/acre biosolids treatment compared to the anhydrous ammonia treatment.

Figure A-1 shows soil C, N, pH, and P when soils were amended with biosolids at 2 dry ton/acre or with anhydrous ammonia.

Soil organic carbon and nitrogen increased in the shallow tillage zone (0- to 4-inch depth). The amount of C stored in the soil was approximately 50 percent of the total biosolids C applied. Soil bulk density was lower

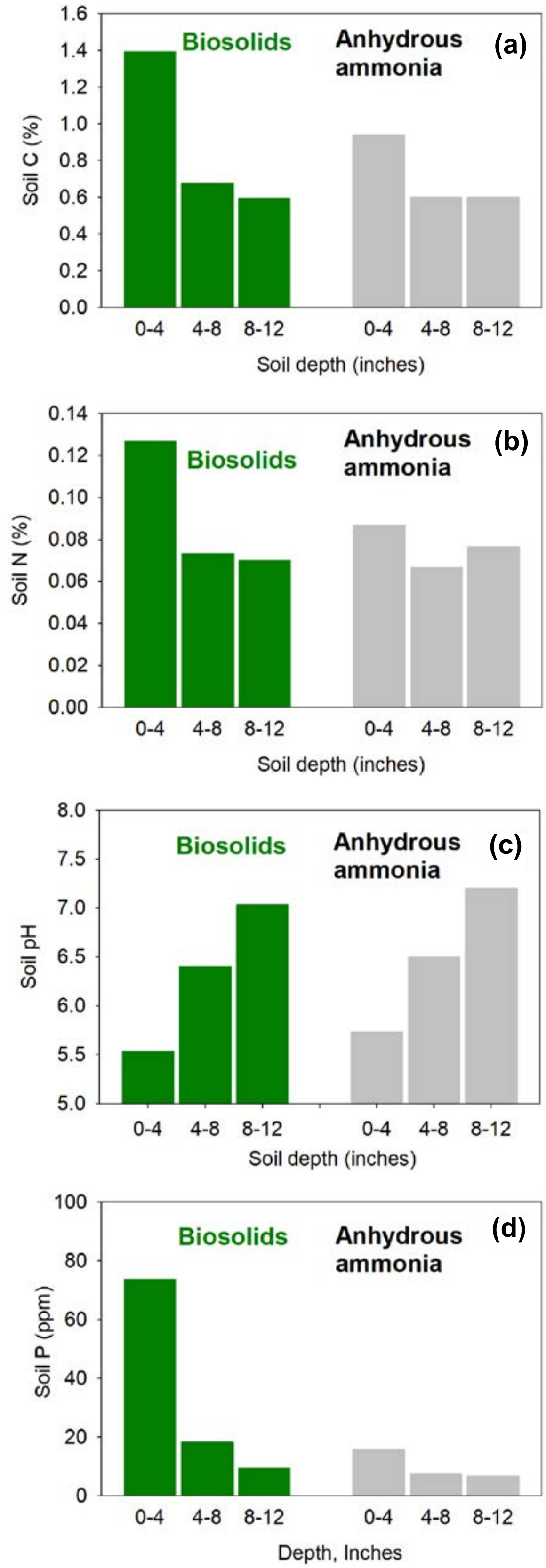

Figure A-1. (a) soil total C, (b) soil total N, (c) soil pH (1:1 soil:water method), and (d) soil test P (Olsen method) with depth at site GP-17 in Douglas County, Washington. Soil sampled in 2012, following five applications of biosolids (2 dry ton/acre per application) since 1994.

following biosolids applications, indicating improved soil aggregation and porosity (data not shown).

Soil pH values were similar with biosolids or anhydrous ammonia fertilization. Soil pH near the soil surface (0- to 4-inch depth) was more acidic (pH 5.5 to 5.7) than in soil below 4 inches (pH 6.4+). The effect of biosolids on soil pH observed here was similar to that observed in other field trials comparing biosolids to commercial N fertilizers. In general, soil acidification accompanying biosolids application is similar to that observed when plant-available N is supplied by anhydrous ammonia or urea.

Biosolids application increased soil test P (Olsen method) from less than 20 ppm (below agronomic need) to more than 70 ppm (above agronomic need). Excess soil test P from biosolids application is not a problem for crop production, but it is a potential environmental risk if soil erodes from the field and is deposited in a P-sensitive water body. Data collected from this site demonstrated that lateral transport (downhill movement) of biosolids P was not apparent (Appendix B).

Discussion

There are other benefits resulting from the increased organic matter following a biosolids application.

- Organic matter reduces cation leaching from the soil surface. Thus, soils become more resistant to the acidification caused by N fertilizers.
- Greater resistance to wind and water erosion is a result of the increased soil aggregation and porosity (reduced bulk density) accompanying biosolids application.
- Increased soil organic matter not only benefits soil health and crop production, but it also sequesters carbon, and thus is a tool for mitigating greenhouse gas emissions.

Biosolids increase soil organic matter in dryland wheat for two reasons: The biosolids themselves increase the resistant humic fractions in soil organic matter (Pan et al., 2017); and, even more importantly, they increase production of wheat straw, which adds organic matter to the soil after each harvest and protects soil from wind and water erosion.

Conclusion

This research clearly demonstrates that biosolids applications at agronomic rates for N build soil organic matter, sequester carbon, and improve the health of soils in a dryland wheat-fallow rotation. Agronomic biosolids applications should be considered a key conservation practice for dryland cereal cropping systems.

Appendix B: The potential for phosphorus movement away from biosolids application sites

Douglas County, Washington

Situation

When biosolids are applied to crops at agronomic rates for N, they supply more phosphorus than the crops need. Repeated biosolids applications will result in an accumulation of P in the soil. Excess P is not a problem for plants, but it could be a problem for water quality if the P reaches sensitive surface waters such as a lake or slow-moving stream. Phosphorus bonds to soil particles; most P movement occurs with the movement of eroded particles. The sloping lands often seen in dryland wheat-fallow systems, left bare for half of the rotation, increase the potential for erosion and P movement.

Methods

Phosphorus movement was measured at a WSU long-term dryland wheat experiment in Douglas County, Washington, where cumulative biosolids applications over 18 years ranged from 10 to 20 dry tons/acre, and total P applications ranged from 560 to 1120 lb/acre (Cogger et al., 2013; same field site discussed in Appendix A). A chisel plow was used for primary tillage in the summer fallow year, followed twice by shallow cultivation during fallow.

Lateral movement of P across the surface of the soil was assessed in 2014. Transects across three pairs of plots were sampled; each pair had a biosolids plot uphill from a plot that did not receive biosolids. Each transect began in the uphill biosolids plot (15 feet from the downhill edge of the biosolids plot) and continued in the downhill direction into the adjacent control (no-biosolids) plot. Soil samples were collected at 10-foot intervals across each transect.

Results

Following five biosolids applications over the 18-year period, soil test P had increased in the surface 4 inches of soil (left side of Figure B-1). Soil test P decreased outside the biosolids application area, with the lowest levels in the middle of the control plot (right side of Figure B-1). Thus, little or no transport of P from the uphill, biosolids plot to the adjacent, downhill control plot was observed.

Conclusion

This data shows increased soil-test P levels following repeated biosolids applications, but little transport of P from the biosolids plots to the adjacent, downhill, no-biosolids control plots at this central Washington site.

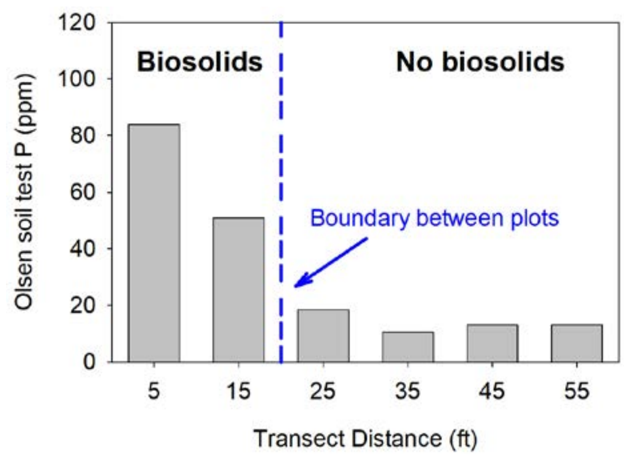

Figure B-1. Soil test phosphorus (Olsen method) at 0- to 4-inch depth across a transect with biosolids treated plots upslope (on left) and control plot downslope. Samples were collected at 10-foot intervals across the transect. Slope across transect was 5.7 percent.

Appendix C: Biosolids increase dryland pasture forage yield and quality

Madison Farms, Echo, Oregon

Situation

On dryland-pasture application sites east of the Cascades, soils are dry and firm enough to support biosolids application equipment during most of the year. Thus, these sites can be of interest to cities in western Oregon that lack winter biosolids storage. OSU Extension does not have a fertilizer or nutrient management guide that recommends fertilization practices for Eastern Oregon dryland pasture.

The data presented here were collected at a field site managed by Madison Farms near Echo, Oregon. The objective of this long-term monitoring effort was to document changes in forage quantity and quality and in soil nutrient status in response to repeated biosolids applications to dryland pasture in an environment receiving 6 to 8 inches annual precipitation.

Biosolids application began at Madison Farms in 1990. At that time, it was unclear whether biosolids application would be of much benefit, given the scarcity of precipitation to support forage production. Most soils receiving biosolids at Madison Farms have a cemented caliche layer at 24 to 48 inches below the soil surface. Dryland pasture at the farm is dominated by annual grasses, primarily *Bromus tectorum* (cheatgrass). Pastures at the farm are grazed in early spring when cheatgrass is palatable.

Methods

Forage and soil data were collected annually in the spring (April or May) from paired sites: a control site receiving no biosolids application and a nearby site receiving biosolids application. Forage at the monitoring sites was not heavily grazed.

Dr. Don Horneck, an agronomist at OSU-Hermiston, collected the monitoring samples. Plant residue and residual biosolids were removed from the soil surface before collecting soil samples. Laboratory analysis was performed at AgriCheck Inc. (now AgSource), a commercial laboratory in Umatilla, Oregon, using standard methodology for soil testing in the western United States (Gavlak et al., 2005). A more complete monitoring report for this site for the period between 1999 and 2007 is available from OSU (Sullivan et al., 2008).

Table C-1 (page 8) shows soil test data (0- to 6-inch depth) from 1996 to 1999, following repeated annual applications of biosolids (cumulative application of 30 to 40 dry ton/acre). See Figure C-1 (page 8) for annual forage yield (1999–2014). See Table C-2 (page 9) for forage quality (2008–2014). Forage quality data for earlier years (1999–2007) is reported in Sullivan et al. (2008).

Results: Soil fertility

Soil organic matter at the 0- to 6-inch depth increased from 1.2 to 2.2 percent with biosolids application, even though soil was not tilled at any time following biosolids application.

Surface soil pH with biosolids was one pH unit lower (more acidic) than without biosolids. The soil pH measured with biosolids application (6.7) is not an immediate concern, although values less than 5.5 would be. When pH drops below 5.5, soil acidity can affect some crops.

Biosolids increased plant-available nutrients in soil. Soil test P, Cu, and Zn increased. Although soil pH declined, the quantity of exchangeable cations (K, Mg, and Ca) increased, an unusual result. Usually, exchangeable cations decline as soil pH declines. The maintenance of soil cations with biosolids application is likely due to 1) cations supplied by biosolids, 2) plant uptake of cations from deeper in the soil profile, followed by deposition of cations on the soil surface in crop residue, and 3) higher cation exchange capacity associated with increased soil organic matter.

Soil salinity, as indicated by electrical conductivity (EC) measurement, remained low at all sampling dates, indicating that biosolids application did not pose a long-term risk for salt accumulation, even in a non-irrigated semiarid pasture.

Soil profile nitrate-N was monitored on fields across the farm (Sullivan et al., 2008). For the period from 2001 to 2007, soil profile nitrate values remained relatively constant. Annual means for soil profile nitrate-N (0- to 36-inch depth) ranged from 70 to 150 lb/acre, with a 7-year mean of 111 lb/acre. This value was approximately equivalent to the average amount of N present in above-ground forage in the spring in those years (105 lb N/acre). This data indicates a long-term equilibrium between biosolids inputs and soil nitrate levels.

continued on page 9

Table C-1. Biosolids increase soil nutrient levels (0- to 6-inch depth) following repeated annual applications of biosolids to dryland pasture. Madison Farm, Echo, Oregon. Soil sampled after 7 to 9 annual applications of biosolids (cumulative biosolids application of 30 to 40 dry ton/acre).

Soil test	Soil test extract/ method	Unit	No biosolids[y]	Biosolids[y]
Calcium	exchangeable	meq/100g	8.7	9.5
Potassium	exchangeable	mg/kg	332	442
Magnesium	exchangeable	meq/100g	1.8	3.1
Boron	hot water extract	mg/kg	0.3	0.4
Organic matter	loss on ignition	%	1.2	2.2
Sulfate-S	calcium phosphate	mg/kg	3.7	8.2
Iron	DTPA	mg/kg	10.1	27.2
Manganese	DTPA	mg/kg	4.0	16.6
Phosphorus	Olsen	mg/kg	14	71
Copper	DTPA	mg/kg	0.8	7.4
Zinc	DTPA	mg/kg	0.5	9.6
Total bases	sum: Ca, Mg, K	meq/100g	11.4	13.8
pH	1:2 soil:water		7.5	6.7
Electrical conductivity (EC)	1:2 soil:water	mmhos/cm	0.2	0.3

[y]Average of annual soil samples collected from 1996 to 1999. Soil samples were collected approximately 6 to 12 months following a biosolids application (minimum of one growing season after application). Source: Table 2.1 (page 6) In: Sullivan, D.M. (2008) *Biosolids Increase Grass Yield, Grass Quality and Soil Fertility in Dryland Pasture*. Available online from OSU Scholar's Archive http://ir.library.oregonstate.edu/xmlui/handle/1957/43909.

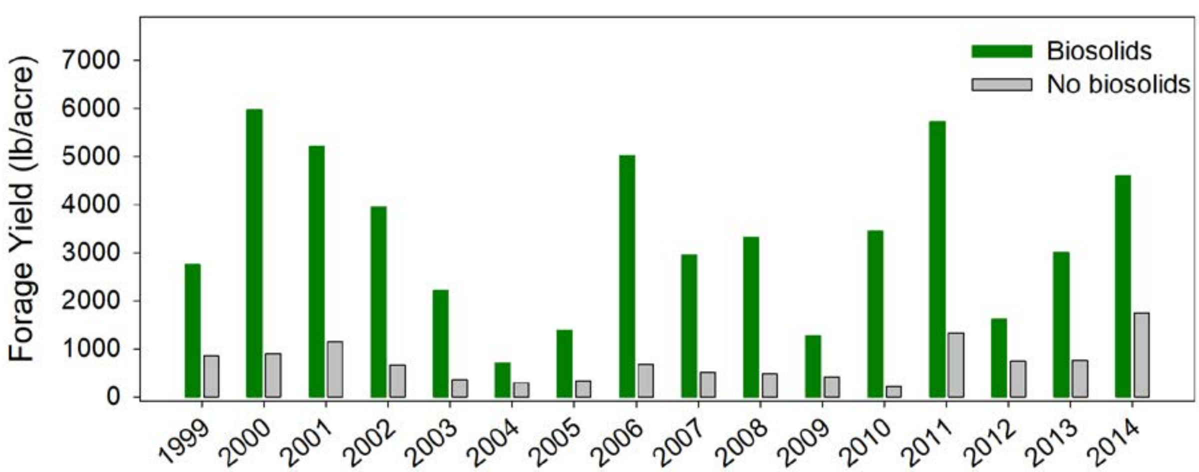

Figure C-1. Grass forage yield (dry matter basis) response to biosolids application. Echo, Oregon. Biosolids were applied every 12 to 24 months at a rate of 3 to 4 dry ton/acre.

Results: Forage yield and quality

Grass forage production varied from year to year at Madison Farms, likely related to variable timing and amounts of winter and early spring precipitation (Figure C-1, page 8). Forage yields increased with biosolids application, especially in wet years. Forage yields averaged 3,310 lb/acre with biosolids versus 740 lb/acre without biosolids.

Forage fertilized with biosolids produced more leaves and fewer stems, as reflected in higher plant N and crude protein, and lower fiber concentrations. Concentrations of other nutrients in forage increased after biosolids application (see Table C-2).

Conclusion

The monitoring data highlighted here show increased grass yield and improved grass quality from biosolids applications, even for dryland pasture with annual precipitation of 6 to 8 inches. Increased nitrogen availability is likely the major factor responsible.

Because biosolids applications promote annual grass growth, heavy grazing in early spring is necessary to make use of the increased forage production. Increased growth of some annual grasses (e.g. cheatgrass, *Bromus tectorum*) is undesirable on most "native" rangeland sites, so biosolids managers must choose dryland application sites thoughtfully.

Table C-2. Forage quality. Madison Farm, Echo, Oregon. 2008–2014.

Forage analysis[z]	No biosolids	Biosolids
	Forage yield (lb DM/acre)	
Biomass	740	3,310
	Feed quality (%)	
Crude Protein (%N × 6.25)	8	19
Neutral Detergent Fiber	56	50
Acid Detergent Fiber	34	27
	Macronutrients (%)	
Sulfur	0.11	0.29
Calcium	0.57	0.71
Phosphorus	0.19	0.37
Magnesium	0.18	0.26
Potassium	1.2	3.0
Sodium	0.02	0.03
	Micronutrients (ppm)	
Zinc	19	33
Copper	5	11
Molybdenum	0.5	1.1
Manganese	56	132

[z]Reported on a dry matter (DM) basis. Values are the mean of seven grass harvests, 2008–2014. Forage quality for 1999–2007 is reported in Sullivan et al. (2008).

Appendix D: Soil carbon sequestration in dryland agriculture by biosolids versus other organic amendments

Pendleton, Oregon

Situation

Degradation of soils and organic matter loss in dryland grain production has been well documented. Soil amendment with biosolids is one way of slowing or reversing organic matter loss. This 10-year experiment in Pendleton, Oregon (16.5 inches annual precipitation) compared the effects of biosolids and other organic amendments on soil organic carbon levels in a minimum-till, annual winter wheat system and in a continuous fallow.

Method

Amendments included municipal biosolids (anaerobically digested, dewatered, and air-dried), fresh cattle manure, softwood sawdust, wheat residue, brassica residue, and alfalfa foliage (feed pellets), each applied at a rate of 1.2 tons of organic carbon/acre/year for five years. The sawdust, wheat residue, and brassica residue treatments also received nitrogen fertilization, while the other treatments received no additional N.

Amendment applications ceased after five years. The entire experiment was placed in fallow for an additional three years, and then cropped to winter wheat for two years and fallowed again. Soil organic C was measured at the end of the three year fallow and again at the end of the experiment. During the entire experiment, soil disturbance was minimal. Tillage with a harrow mixed soil to a depth of 1 to 2 inches.

Results

Biosolids applications produced the greatest change in soil carbon at the end of the experiment (Figure D-1). The accumulation of soil C in the biosolids plots was equivalent to nearly half of the biosolids C applied (Figure D-1). This compares with 21 percent equivalent accumulation for manure C and an average of 11 percent for the other treatments. The biosolids treatment also had the greatest accumulation of soil N. The larger amounts of N and S supplied by the biosolids, along with its relatively high stability compared with the other amendments, could account in part for the greater accumulation of soil organic matter.

Conclusion

These results confirm the high rate of C sequestration seen in the Douglas County, Washington experiment (Appendix A), and indicate that biosolids are more effective than other amendments at retaining C in the soil. This is additional evidence of the positive role that biosolids can play in soil conservation in dryland agriculture.

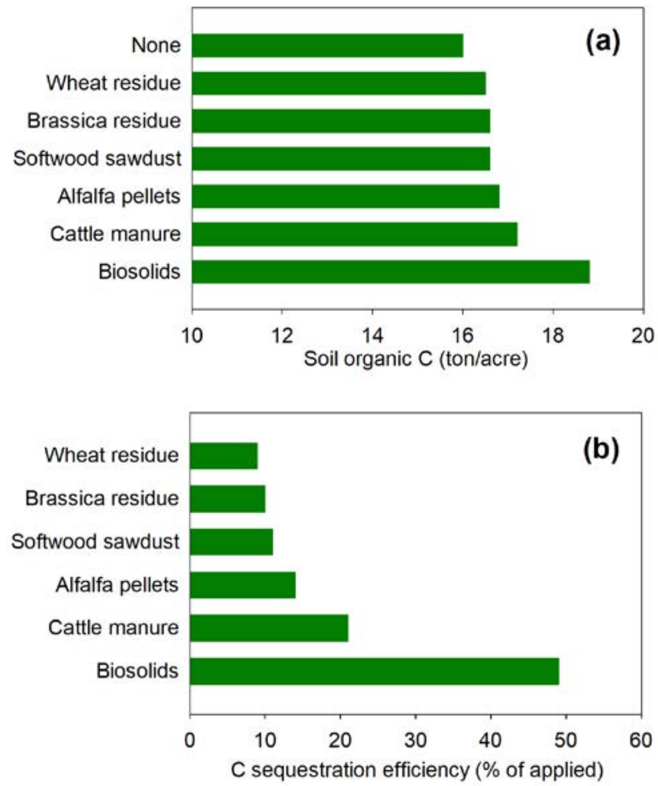

Figure D-1. Soil organic carbon (0- to 10-inch depth; Wuest and Reardon, 2016). Soil amendments applied Years 1–5. Soil sampled in Year 10. Soil organic C values shown in Figure D-1a were calculated as the means of in-crop and fallow treatments. Carbon sequestration efficiency was calculated as the increase in soil C for amendment treatments relative to the no amendment control (Figure D-1b).

Photo: Stewart Wuest, USDA Agricultural Research Service

Organic amendment application trial, Pendleton, Oregon.

For more information

Extension and Outreach Publications

Agricultural Phosphorus and Eutrophication (2nd edition). United States Department of Agriculture, Agricultural Research Service. https://sera17dotorg. files.wordpress. com/2015/02/ars-149-ag-p- eutrophication-2nd-ed-2003-1.pdf

Biosolids and conservation tillage: Long-term effects on grain, straw yield of dryland wheat. *Crops & Soils* https://doi.org/10.2134/cs2018.51.0408

Dryland Winter Wheat: Eastern Washington Nutrient Management Guide (EB 1987E) https://pubs. wsu. edu/ItemDetail.aspx?ProductID=13947

Fertilizing with Biosolids (PNW 508) https://catalog. extension.oregonstate.edu/pnw508

Monitoring Soil Nutrients Using a Management Unit Approach (PNW 570) https://catalog.extension. oregonstate.edu/pnw570

Phosphorus in Biosolids: How to Protect Water Quality While Advancing Biosolids Use. Water Environment Federation (WEF). http:// www.wrrfdata.org/ PhosphorusFS/WEF-PhosphorusFactSheet2014.html

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

Soil test interpretation guide (EC 1478) https://catalog. extension.oregonstate.edu/ec1478

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

Research publications, biosolids in dryland cropping systems in the Pacific Northwest

Brown, T.T. and D.R. Huggins. 2012. Soil carbon sequestration in the dryland cropping region of the Pacific Northwest. *Journal of Soil and Water Conservation* 67:406-415. https://doi. org/10.2489/jswc.67.5.406

Cogger, C.G., A.I. Bary, E.A. Myhre and A. Fortuna. 2013. Long-term crop and soil response to biosolids applications in dryland wheat. *Journal of Environmental Quality.* 42:1872-1880. https:// doi.org/10.2134/jeq2013.05.0109

Cogger, C.G., D.M. Sullivan, A.I. Bary and J.A. Kropf. 1998. Matching plant-available nitrogen from biosolids with dryland wheat needs. *J. Prod. Agric.* 11:41–47. https://doi.org/10.2134/ jpa1998.0041

Gavlak, R.G., D.A. Horneck and R.O. Miller. 2005. Soil, plant and water reference methods for the western region. (Third Edition). Western Region Extension Report (WREP-125). WERA-103 Technical Committee. http://www.naptprogram. org/files/napt/ western-states-method-manual-2005.pdf.

Ghimire, R., S. Machado and K. Rhinhart. 2015. Long-term crop residue and nitrogen management effects on soil profile carbon and nitrogen in wheat–fallow systems. *Agronomy Journal* 107: 2230-2240. https://doi.org/10.2134/ agronj14.0601

Ghimire, R., S. Machado and P. Bista, 2017. Soil pH, Soil Organic Matter, and Crop Yields in Winter Wheat–Summer Fallow Systems. *Agronomy Journal*, 109:706-717. https://doi.org/10.2134/ agronj2016.08.0462

Koenig, R.T., C.G. Cogger and A.I. Bary. 2011. Dryland winter wheat yield, grain protein and soil nitrogen responses to fertilizer and biosolids applications. Applied Environ. Soil Sci. https://www.hindawi.com/journals/ aess/2011/925462/

Pan W.L., L.E. Port, Y. Xiao, A.I. Bary and C.G. Cogger. 2017. Soil carbon and nitrogen fractionation balances during long-term biosolids applications. *Soil Science Society of America Journal* 81:1381-1388. https://acsess. onlinelibrary.wiley.com/doi/full/10.2136/ sssaj2017.03.0075

Pi H., Sharratt, B., Schillinger, W. F., Bary, A. I. and Cogger, C. G. 2018. Wind erosion potential of a winter wheat–summer fallow rotation after land application of biosolids. *Aeolian Research*, *32*, 53–59. https://doi.org/10.1016/j. aeolia.2018.01.009

Pi H., Sharratt, B., Schillinger, W. F., Bary, A. and Cogger, C. 2018. Chemical composition of windblown dust emitted from agricultural soils amended with biosolids. *Aeolian Research*, *32*, 102–115. https://doi.org/10.1016/j.aeolia.2018.02.001

Schlatter, D. C., Paul, N. C., Shah, D. H., Schillinger, W. F., Bary, A. I., Sharratt, B. and Paulitz, T. C. 2019. Biosolids and Tillage Practices Influence Soil Bacterial Communities in Dryland Wheat. *Microbial Ecology*, *78*(3), 737–752. https://doi. org/10.1007/s00248-019-01339-1

Schlatter, D. C., Schillinger, W. F., Bary, A. I., Sharratt, B. and Paulitz, T. C. 2018. Dust-associated microbiomes from dryland wheat fields differ with tillage practice and biosolids application. *Atmospheric Environment*, *185*, 29–40. https://doi.org/10.1016/j.atmosenv.2018.04.030

Shearin, T.E. 2000. Winter wheat response to nitrogen, phosphorus, sulfur, and zinc supplied by municipal biosolids. M.S. Thesis. Oregon State University. https://ir.library.oregonstate.edu/xmlui/handle/1957/28397

Sullivan, D.M., C.G. Cogger, A.I. Bary and T.E. Shearin. 2009. Predicting biosolids application rates for dryland wheat across a range of Northwest climate zones. *Comm. in Soil Sci. and Plant Analysis* 40:1770–1789.

Sullivan, D.M., D.A. Horneck, and M. Ronayne. 2008. Biosolids increase grass yield, grass quality, and soil fertility in dryland pasture. City of Portland, Bureau of Environmental Services. http://ir.library. oregonstate.edu/xmlui/handle/1957/43909

Taylor, S.E., Pearce, C. I., Chowdhury, I., Kovarik, L., Leavy, I., Baum, S., Bary, A. I. and Flury, M. 2020. Long-term accumulation, depth distribution, and speciation of silver nanoparticles in biosolids-amended soils. *Journal of Environmental Quality*, *49*(6), 1679–1689. https://doi.org/10.1002/jeq2.20156

Wang, Z. and Flury, M. 2019. Effects of freezing-thawing and wetting-drying on heavy metal leaching from biosolids. *Water Environment Research*, *91*(6), 465–474. https://doi.org/10.1002/wer.1011

Wuest, S.B. and C.L. Reardon. 2016. Surface and root inputs produce different carbon/nitrogen ratios in soil. *Soil Science Society of America Journal*. 80:463-471. https://doi.org/10.2136/sssaj2015.09.0334

Wuest, S.B. and H.T. Gollany. 2012. Soil organic carbon and nitrogen after application of nine organic amendments. *Soil Science Society of America Journal*. 77:237-245. https://doi.org/10.2136/sssaj2012.0184

Published September 2018, revised February 2021