Chapter 7

Soil Amendments

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Abstract

Soil amendments can improve the sustainability of agricultural systems by building soil carbon and improving numerous other soil health indicators, including soil structure, water infiltration and retention, bulk density, nutrient availability, and microbial activity. This chapter covers some general considerations relevant to the use of soil amendments followed by a discussion of biosolids, animal manures, biochar, and black liquor. Topics covered include amendment composition, application rates, yield impacts, grain quality impacts, soil health benefits, nutrient loss concerns, and potential contaminants.

Key Points

- Although they are only rarely used in the dryland systems of the Inland Pacific Northwest, soil amendments can provide a range of soil health benefits by building soil carbon, reducing bulk density, and improving soil structure, water infiltration and retention, and nutrient availability.

Research results are coded by agroecological class, defined in the glossary, as follows:

● Annual Crop ▲ Annual Crop-Fallow Transition ■ Grain-Fallow

- Biosolids can be used by conventional producers, but not certified organic producers, and may be available at relatively low cost, though supply is limited. Biosolids applied to agricultural soils at agronomic rates and in accordance with current guidelines can result in equivalent or greater yields than equivalent use of chemical fertilizers.
- Manures can be an important resource for building or maintaining soil health for producers in proximity to concentrations of livestock. Manures with higher nutrient concentrations may provide some nutrients, particularly for certified organic dryland producers, though cost can be an issue.
- Biochar has the potential to positively impact pH and other soil health indicators, and can also improve productivity. However, economics currently limit its use in dryland agriculture. Likewise, black liquor has intriguing potential to improve soil health, and may become more feasible if paper production facilities are established in the inland Pacific Northwest.

Introduction

As discussed in Chapter 2: Soil Health, historical soil carbon (C) losses under agricultural cultivation in the **inland Pacific Northwest** (PNW) have been severe. At the Columbia Basin Agriculture Research Center (CBARC) near Pendleton, Oregon, conventional winter wheat-summer fallow depleted soil organic C by approximately 35% in the first 50 years after cultivation began, and up to 63% over 80 years of cultivation (Rasmussen et al. 1998; Ghimire et al. 2015). ■ Similar patterns of C loss contribute to reduced **soil health** across the dryland region (Brown and Huggins 2012).

Soil amendments, when economically and practically viable, could play a powerful role in slowing C losses and rebuilding soil C. In Douglas County, Washington, long-term **biosolids** applications every four years at any of three rates increased total soil C (Figure 7-1). These results are particularly striking in light of the fact that in the grain-fallow region, where a crop is only being grown every other year (and therefore residues are only being added to the soil every other year), soil C levels are unlikely to be maintained, even when tillage is reduced or eliminated (Machado 2011; Gollany et al. 2013). ■

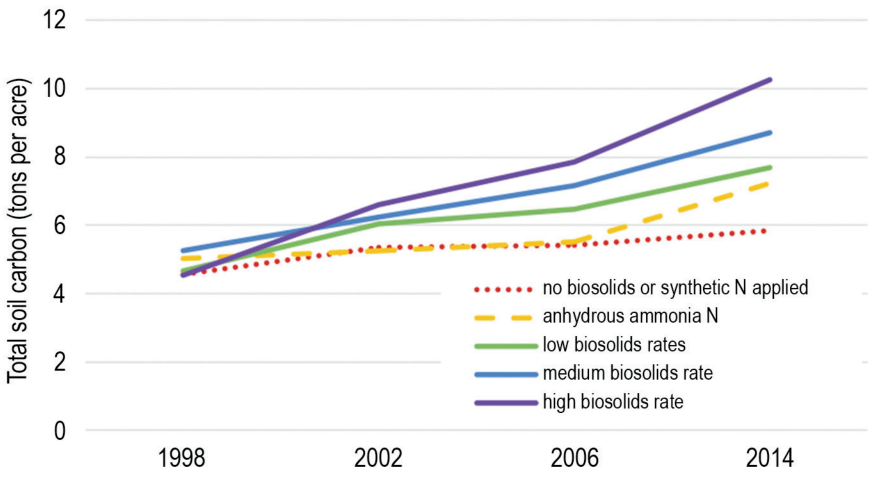

Figure 7-1. Total soil carbon measured in the top 3.9 inches of soil in a winter wheat-fallow system in Douglas County, Washington, after additions of biosolids every four years at a rate of 2.2, 3.1, or 4.0 dry tons per acre (green, blue, and purple solid lines). These rates were compared to no nutrient additions (red dotted) or addition of anhydrous ammonia at a rate of 50 lb per acre (yellow dashed); N = nitrogen. (Data from Pan et al. n.d.) ■

Beyond C, soil amendments can improve numerous physical, chemical, and biological properties of soil, and thus can be an important strategy for improving soil health and sustaining agricultural production over the long term (Figure 7-2). Amendments can improve **soil structure**, water **infiltration** and retention, nutrient availability, and microbial activity, while reducing **bulk density** (Brown et al. 2011; Cogger et al. 2013; Reeve et al. 2012; Wuest et al. 2005). Additional information on these factors can be found in Chapter 2: Soil Health.

Recycling organic C and plant nutrients contained in organic materials can also contribute to mitigating climate change (Brown et al. 2010). First, the buildup and storage of soil organic matter (SOM) draws carbon dioxide out of the atmosphere. Second, amendment-based plant nutrients can substitute for synthetic fertilizers, which generate greenhouse gases when they are produced. Although amendments often require transport, this has a relatively small effect on overall greenhouse gas balances (Brown et al. 2010). Meanwhile, impacts of soil amendments on emissions of nitrous oxide, a powerful greenhouse gas, from soils are likely to be complex when amendments substitute for conventional fertilizers. To date, these

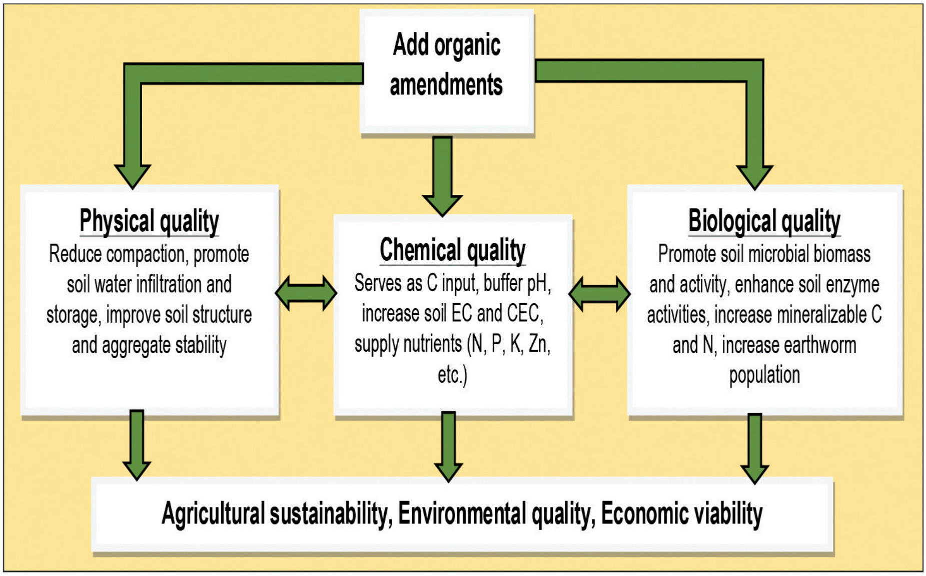

Figure 7-2. Improvement in soil health with organic amendments in dryland crop production. EC = electrical conductivity; CEC = cation exchange capacity; N = nitrogen; P = phosphorus; K = potassium; Zn = zinc; C = carbon. (Adapted from Cogger et al. 2013; Reeve et al. 2012; and Wuest et al. 2005.)

impacts are not well understood.

This chapter covers some general considerations relevant to use of soil amendments and discusses individual amendment products with a goal of providing an understanding of the situations in which they are most likely to be beneficial, along with some key factors related to their use. The chapter also points readers to Extension resources that provide more detailed information on biosolids and manures—the amendments growers are currently most likely to choose to apply. In addition to biosolids and manures, **biochar** and paper-manufacturing wastes ("black liquor") are briefly described, as these amendments may become relevant to some dryland growers in the future given technology advances and changing production economics.

Considerations in Using Amendments

Unlike traditional (synthetic) fertilizers, which have a consistent formulation and contain only the nutrients spelled out in the product description, amendments can be variable in nature and contain a suite of elements. A single amendment type, such as cattle manure, can vary substantially in composition, with differences resulting from different inputs (e.g., animal diet), differences in processing, and from seasonal or other types of variability. This makes testing of amendments using an appropriate lab prior to application critical.

In most cases, amendments provide C as well as a suite of plant macro and micronutrients. When amendments provide primarily C, with relatively low concentrations of nutrients, they should be used as soil conditioners to build SOM and improve soil health. In contrast, amendments that have adequate amounts of nutrients, in forms that are available to plants and with timing that matches crop needs, can also be used as the primary nutrient source for a crop.

The **carbon-to-nitrogen** (C:N) ratio is an important related factor that contributes to determining whether an amendment should be used primarily as a nutrient source or as a soil conditioner. Generally, amendments with a low C:N ratio (<15:1) decompose quickly and release nitrogen (N) rapidly in soil, while the decomposition of high C:N materials (>15:1) is slow, with the available N in the amendment and soil immobilized by microorganisms for their own needs as they carry out decomposition (Gale et al. 2006). Figure 7-3 illustrates that the addition of high C:N organic materials can temporarily diminish available N for crops due to higher microbial activity and greater assimilation of N by microbes for their growth. Later, ongoing scarcity of available N causes some soil microbes to die, releasing N. To address N **immobilization**, extra N fertilizer may need to be applied. A list of some common organic materials with their rough C:N composition is shown in Table 7-1.

When some amendments are applied to meet crop N needs, they provide other nutrients in excess. Therefore, growers applying amendments should evaluate the potential for nutrient losses, especially when applying amendments repeatedly over time. More information on the pathways of phosphorus (P) and N losses to the environment, and the factors contributing to risk of such losses, is provided in Chapter 6: Soil Fertility Management.

Amendment quality, including the amount of other nutrients, may also impact how much C from the amendment is stored in soils. In Pendleton,

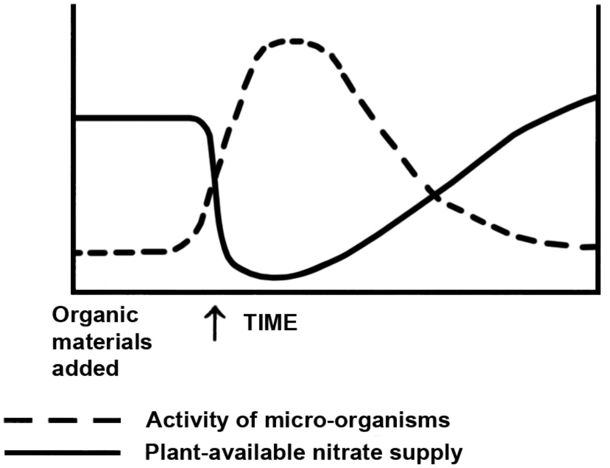

Figure 7-3: Generalized diagram showing temporary loss of plant-available soil nitrogen upon addition of organic materials with a high carbon-to-nitrogen (C:N) ratio. (Used with permission from Glewen 2016.)

Table 7-1. Selected common organic amendments and their approximate carbon-to-nitrogen (C:N) ratios.

Organic amendments	C:N[a]
High in C (relative to N)	
Sawdust	400
Wheat, oat, or rye straw	80
Green rye	36
Dairy separated solids	32
Alfalfa hay	20
Dairy solids compost	18
High in N (relative to C)	
Stockpiled dairy manure	15
Clover and alfalfa (early)	13
Beef manure compost	11
Poultry litter	10
Soil	10–12

[a]Nitrogen is always 1 in the C:N ratio.
Adapted from Bary et al. 2016; and Magdoff and van Es 2010.

Oregon, a field experiment comparing different amendments suggested that biosolids and un-aged cattle manure were substantially more efficient at sequestering C than other amendments, including alfalfa, wood sawdust, composted and uncomposted wheat residues, Brassica residues, sucrose, and cotton linters (Table 7-2). ■ Stable soil C gain appeared very closely related to the content of P as well as sulfur (S) in the amendments (Figure 7-4). Other important mechanisms that have been proposed for such differences in carbon storage efficiency include the amount of enhancement in primary productivity and the microbial processing that amendments have undergone (e.g., for biosolids or composted manures) (Brown et al. 2011; Cogger et al. 2013; Pan et al. n.d.).

A variety of other important factors also influence decisions about amendment use, including cost, availability, transportation, public acceptance, application methods, and the potential for contaminants. These vary from amendment to amendment, so are discussed in the subsequent sections.

Table 7-2. Effect of amendment type on soil organic carbon (C) accumulation in the surface (0–9.8 inches) of a silt loam soil near Pendleton, Oregon. Amendments were applied at similar C rates for five years and sampled 7 years after final amendment application. ■

Amendment (2230 lb C/ac)	Sequestration Efficiency[a]
	%
Municipal biosolids	49
Cattle manure (no bedding)	21
Alfalfa feed pellets	14
Wood sawdust	11
Composted wheat residue	11
Brassica residue	10
Wheat residue	9
Sucrose	5
Cotton linters	3

[a]Sequestration efficiency is calculated by increase in soil organic C compared with the treatment receiving no amendment, divided by the amount of C applied.
Adapted from Wuest and Reardon 2016; see also Wuest and Gollany 2012.

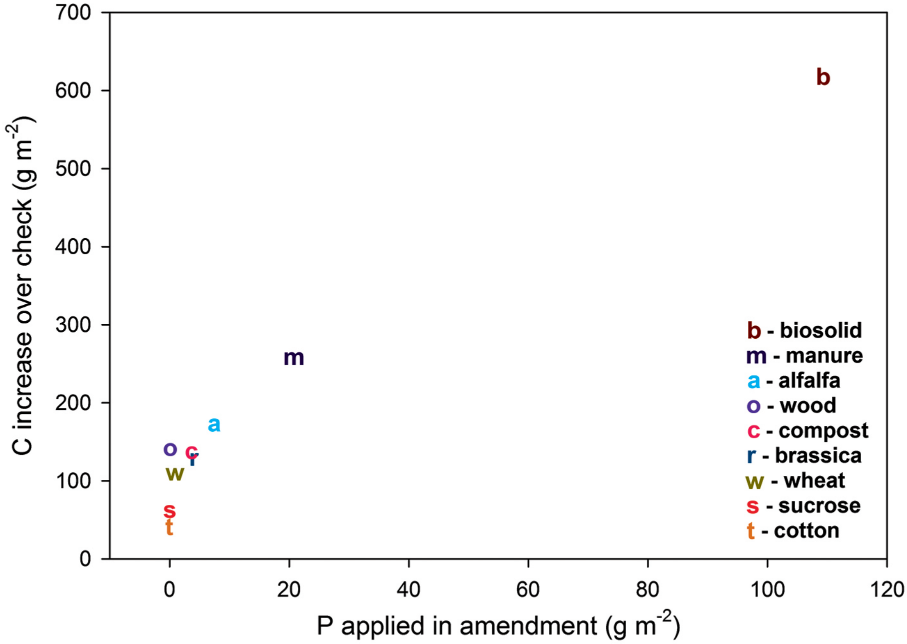

Figure 7-4. Phosphorus (P) applied in the amendment compared to amendment carbon (C) remaining in the soil seven years later. Soil C increase was calculated by subtracting soil organic C measured in the treatments receiving no amendments and is the average of the main plots treatments (n = 8). Amendments were applied at a rate of 250 g C per m^2 each year for five years (total 1250 g C per m^2; equivalent to 5.6 tons per acre). (Adapted from Wuest and Reardon 2016.)

Biosolids

Biosolids are materials produced by municipal wastewater treatment of organic solids, transformed through the treatment process into a product that is made up of living and dead wastewater treatment microorganisms, small inorganic particles, and insoluble compounds. Although there are other possible ways to manage biosolids, the majority are land-applied to recycle nutrients.

The biosolids most often used as soil amendments for dryland wheat are Class B biosolids (CFR Title 40). These biosolids have been treated to substantially reduce the level of biological pathogens and meet Environmental Protection Agency (EPA) standards for regulated contaminants including metals, some of which are required plant nutrients. Class B biosolids can be applied to crops whose edible parts do not make contact with the soil, as long as the applications are more than 30 days prior to harvest. In contrast, Class A biosolids meet more stringent requirements for pathogen reductions and can be used more widely, including in garden or landscaping applications in residential or commercial areas.

Grains are among the most common receiving crops for Class B biosolids in the inland PNW. Acreage in a grain-fallow rotation is particularly flexible for receiving biosolids because of the wide window for application during the **fallow** year (Sullivan et al. 2015). ■ In 2015, eastern Washington croplands received almost 44,000 dry tons of biosolids applied to roughly 15,500 acres (Peter Severtson, personal communication). Of this, 93% was applied to wheat, with the balance applied to grass hay, corn, hops, and other crops.

Because biosolids are a byproduct that must be managed by wastewater treatment facilities, they may be available at no cost or reduced cost to producers. In some cases, municipalities charge a transportation fee, application fee, or a fee equal to the N value of the biosolids (Sullivan et al. 2015). While permitting is required for all Class B biosolids, this is normally taken care of by the wastewater treatment plant or the private company that applies the biosolids (Weaver 2013).

The Extension publication Fertilizing with Biosolids (Sullivan et al. 2015) covers many practical aspects of biosolids applications, including additional information on nutrients, **pH**, and soil health considerations; how to use university fertilizer guides with biosolids application; and obtaining needed site approvals.

Composition, Nutrients, and Application Rates

Biosolids supply organic matter, plant macronutrients, and micronutrients, including those listed in Table 7-3 as well as copper (Cu), boron (B), molybdenum (Mo), zinc (Zn), and iron (Fe). Potassium (K) is notably absent. As indicated in Table 7-3, levels of organic matter and nutrients can vary considerably. When applied to meet crop N needs, biosolids generally provide P in excess of crop needs, though only about 20% to 60% of this P is plant-available (Ippolito et al. 2007; Cogger et al. 2013; Sullivan et al. 2015). Particularly for one-time applications, P may provide benefits to dryland cropping in the inland PNW if soils are deficient. Sulfur, Zn,

Table 7-3. Biosolids organic matter and macronutrients (dry weight basis, total elemental). Not all elemental content is plant-available.

	Usual Range (%)[a]	
Nutrient	Low	High
Organic Matter	45	70
Nitrogen (N)	3.0	8.0
Phosphorus (P)[b]	1.5	3.5
Sulfur (S)	0.6	1.3
Calcium (Ca)	1.0	4.0
Magnesium (Mg)	0.4	0.8
Potassium (K)[b]	0.1	0.6

[a]Usual range for freshly digested biosolids. Lagooned biosolids, composted biosolids, and alkaline-stabilized biosolids typically have lower nutrient concentrations.
[b]P and K are expressed on an elemental basis. Use the following conversion factors to convert to units used for fertilizer marketing: To get P_2O_5 (phosphate), multiply P by 2.29. To get K_2O (potash), multiply K by 1.2.
Reproduced with permission from Sullivan et al. 2015.

Fe, and other micronutrients present in biosolids may also be beneficial when amounts in soils are below desired levels (Koenig et al. 2011).

Biosolids application rates in the inland PNW are generally based on crop N requirements, and typically range from 2.2–3.6 tons per acre of dry weight biosolids every 2 to 4 years in wheat-fallow rotations (Cogger et al. 2013). Biosolids contain ammonium-N, available to crops immediately after application. They also contain organic N, which must be converted (mineralized) over time before it is available to plants. Most biosolids do not contain nitrate-N (Sullivan et al. 2015). The Worksheet for Calculating Biosolids Application Rates in Agriculture (Cogger and Sullivan 2007) describes the calculation of agronomic application rates based on biosolids analysis, estimates of ammonium-N retained after application, organic N mineralized from the current and previous biosolids applications, crop N requirements, site information, and regulatory limits for trace element application. The values in this worksheet are based on short-term studies of biosolids additions in tilled grain-fallow rotations across a range of environmental conditions in the PNW (Sullivan et al. 2009; Cogger et al. 1998). For **no-till** systems, rates may need to be adjusted to account for higher rates of ammonia volatilization from unincorporated biosolids (Barbarick et al. 2012).

Yield Impacts

Biosolids applications can produce equivalent or better grain yields than typical applications of inorganic N in tilled and no-till wheat systems (Sullivan et al. 2009; Koenig et al. 2011; Barbarick et al. 2012). Preliminary results (4 years) suggest this is also true for biosolids that are applied to wheat grown with **conservation tillage** with an undercutter (Schillinger et al. 2015). ■

When yields are increased for dryland wheat compared to inorganic N, this is often attributed to the P or S provided by the biosolids (Koenig et al. 2011; Ippolito et al. 2007; Cogger et al. 2013). Other possible factors include improved soil physical properties, or the fact that N supplied by biosolids is made available gradually and thus may limit vegetative growth, reducing the potential for moisture stress and associated reductions in grain yield (Koenig et al. 2011).

Meanwhile, higher biosolids rates can lead to yield loss through lodging or excessively vigorous vegetative growth that leads to moisture stress (Cogger et al. 2013; Mantovi et al. 2005; Cogger et al. 1998). Application rates for biosolids take into account the amount of N available from all sources, minimizing this risk, though Sullivan et al. (2009) also recommend that growers who are applying biosolids choose varieties that are resistant to lodging.

Grain Quality Considerations

When making decisions about biosolids use, growers should be aware that biosolids applications generally raise grain protein, with a 0–13% increase in protein in the first and second crops following biosolids application (Cogger et al. 2013; low and medium rates). Practical experience across the region suggests that this increase is not generally so great that it leads to a negative impact on prices received (Andy Bary, personal communication).

It has also been suggested that biosolids applications might be more beneficial for hard red and hard white wheat since greater protein content is valued for these wheat types (Sullivan et al. 2009). While this may be true, biosolids should not be assumed to increase grain protein concentration for hard wheats when biosolids are applied immediately before planting (Koenig et al. 2011). From a grain protein perspective, application to hard wheats during the fallow year may be preferred if fallow is part of the rotation.

Soil Health Benefits

Biosolids applications can meaningfully increase soil C when used over time, and particularly when combined with other strategies such as reducing tillage and maximizing residue production and retention. Across regional dryland systems, the increase in total soil C after repeated biosolids applications has been up to 49–77% of the C added in biosolids, larger than most other types of amendments (Wuest and Gollany 2012; Wuest and Reardon 2016; Cogger et al. 2013, Pan et al. n.d.). ■ Factors that contribute to the impact of biosolids on long-term C levels likely include the balanced nutrients provided, increased primary productivity in comparison to conventionally fertilized soils, and the microbial processing that biosolids have undergone, as microbial C can be a major part of stabilized SOC. Generally speaking, the C benefit may be smaller if SOC levels are already high, as a steady state is approached or achieved (Lal 2001; Cogger et al. 2013; Brown et al. 2011).

Over the long term, biosolids may decrease bulk density, increase soil **water holding capacity**, and benefit other measures of soil health (Brown et al. 2011; Cogger et al. 2013) (Table 7-4). ■ Although Table 7-4 indicates a decrease in pH after biosolids application, soil pH can be increased or decreased depending on whether or not alkaline materials are used in the biosolids process (Sullivan et al. 2015).

Biosolids also generally increase soil **aggregation**, and it would generally be expected that this would reduce wind erosion (Neilsen et al. 2003; Wallace et al. 2009). This question is being explored in existing research on biosolids application in Lind, Washington, under both **conventional tillage** and conservation tillage with an undercutter (Sharratt et al. 2016). ■

Table 7-4. Improvement in soil physical and chemical properties at 0–3.9 inches after applying biosolids compared to chemical nitrogen (N) fertilizer or no N application in Douglas County, Washington. Little change occurred below the tillage zone (3.9 inches).

Treatment	Applied Rate[a]	Cumulative Rate	Total C	Total N	Bulk Density	pH	EC[b]	Olsen-P[c]
	lb/ac		%		$g\ cm^{-3}$		$dS\ m^{-1}$	ppm
Zero N			0.84a*	0.08a	1.26a	6.1a	0.08a	15a
Anhydrous Ammonia	50		0.94a	0.09a	1.22a	5.7b	0.08ab	16a
Biosolids	**ton/ac**							
Low	2.2	10.7	1.39b	0.13b	1.09b	5.5bc	0.13bc	74b
Medium	3.1	15.2	1.69c	0.15c	1.05bc	5.4c	0.18c	114c
High	4.0	20.1	1.64c	0.14c	1.02c	5.4c	0.16c	128c

[a]Anhydrous ammonia was applied every other year. Biosolids were applied every fourth year from 1994–2010.
[b]EC = electrical conductivity
[c]Olsen-P: soil test based on extraction with bicarbonate; extractable phosphorus (P) pool correlates to plant available P.
*Means within a column followed by different letters are significantly different ($P < 0.05$) by protected least significant difference.
Adapted from Cogger et al. 2013.

Nutrient Loss Considerations

Though there are clear potential benefits from biosolids applications, one potential concern is whether biosolids applications can increase losses of N and P from agricultural systems. There has generally been only a small effect on soil nitrate-N after one-time biosolids applications to dryland wheat systems (Sullivan et al. 2009; Koenig et al. 2011). A recent analysis of N rates associated with repeated applications of biosolids to dryland wheat found that roughly 35% of the added N was stored in the top 3.9 inches of soil, while 24% to 37% was removed in grain (Pan et al. n.d.). ■ The remaining 28–41% was assumed to reside in the subsoil of the rooting zone as soil N, as root N in biomass, or lost to nitrate **leaching** or N volatilization. Increases in soil N may benefit crops by providing a pool of N that can be drawn on in addition to fertilizer N supplies, but can also indicate a higher risk of N loss.

Biosolids applications have also led to increases in bicarbonate-extractable P, with evidence of limited downward movement of P in both tilled and direct seed systems (Cogger et al. 2013; Ippolito et al. 2007; Barbarick et al. 2012). In areas where P is deficient, P loss is likely a relatively low concern for one-time applications at agronomic rates. Those carrying out repeated applications should test soil levels regularly and evaluate the potential for P loss under their local conditions (Sullivan et al. 2015). Phosphorus loss tends to be associated with soil erosion, and is most problematic when fields are in proximity to a water body.

Contaminants

Municipal wastewater facilities that produce biosolids treat wastewater from household and industrial facilities, which may contain various contaminants including metals, pathogens, antibiotics, some industrial and household chemicals, odorants, and aerosols. Contaminants that are not degraded during the biosolids treatment process are present in the resulting biosolids.

Historically, heavy metals were a concern in biosolids. However, concentrations of metals in biosolids have fallen sharply over the last 40 years since the passage of the Clean Water Act, and are no longer present in biosolids at concentrations that could cause human, animal, or environmental health issues (Mitchell et al. 2016; Sullivan et al. 2015). Concentrations of these metals in land-applied biosolids are regulated and monitored, and concentrations must be below federal limits that are set based on risk assessments.

Meanwhile, study of other known and emerging contaminants is ongoing, but the current available evidence suggests that biosolids applied to agricultural soils at agronomic rates and in accordance with current guidelines present low to minimal levels of risk from pathogens, antibiotics, industrial and household chemicals, and pharmaceuticals (Mitchell et al. 2016). The Extension publication Guide to Biosolids Quality (Mitchell et al. 2016) reviews the literature on potential contaminants in biosolids in more detail.

Manures

An increasing interest in improving soil health, the rise of fertilizer costs, and the unique nutrient needs of organic producers have all contributed to renewed interest in manure amendments in dryland systems. Meanwhile, applying manure to agricultural lands that are in need of nutrients or organic matter could help reduce nutrient overloading concerns for dairies, feedlots, and poultry operations. Across the main wheat-producing counties of the inland PNW, an estimated 1,377 tons of N, 2,013 tons of phosphate (P_2O_5), and 6,242 tons of potash (K_2O) is available in recovered manures (IPNI 2012).

However, economics currently prevents widespread use of manure in dryland agriculture. Manure is heavy relative to its nutrient content, and therefore relatively expensive to transport. Across the inland PNW, animal production is often practiced in concentrated areas, far from where the bulk of the dryland wheat is grown. South central Idaho is one exception. This region is dominated by dairy farms in combination with dryland fields on high plateaus. Production of organically certified wheat (with prices that are 2 to 3 times those of commodity wheat) and alfalfa hay in these areas allows for utilization of locally available manure. Further information about certified organic wheat practices in the inland PNW can be found in Organic Small Grain Production in the Inland Pacific Northwest: A Collection of Case Studies (Lorent et al. 2016).

Two other related practices are also receiving some interest, driven in part by these barriers to manure use. Particularly in wetter areas of the region, there is re-emerging interest in grazing **cover crops** or residues, a process that contributes to nutrient cycling through manure deposition by grazing animals. Meanwhile, some dryland organic producers use crop rotation with N-fixing crops such as alfalfa or pulses as the primary means to add N to their soils rather than manures (Lorent et al. 2016). For more information, see Chapter 5: Rotational Diversification and Intensification.

Manure can be applied in raw or aged form, or can be processed before land application. Potential treatments include primary and secondary solids separation, anaerobic digestion, composting, and nutrient recovery. Treatments result in products that may be quite different than raw manure. Sometimes more than one treatment process is used in sequence; for example, anaerobic digestion followed by separation of fiber and separation of fine solids. Some of these processes are active areas of research and commercial development.

Composting is the most common manure treatment. When manure is composted, it is managed in a way that allows microorganisms to decompose manure and bedding in the presence of air. Composts used in organic production need to be produced following the rules of the National Organic Program that specify, among other things, initial C:N ratios, time, and temperature requirements that must be achieved during composting. Composts can be applied to food crops without restriction.

Separated dairy solids (primary separation) are generated on many regional dairies by utilizing screens and rotary and screw presses to separate out easily settled fibrous solids (Ma et al. n.d.). Primary separated solids may be composted after separation. Meanwhile, secondary solids separation, in the early stages of commercialization in 2016, can be used following primary solids separation, with or without anaerobic digestion. This secondary process focuses on very fine, suspended solids that are clay-like in nature.

The Extension publication Fertilizing with Manure and Other Organic Amendments (Bary et al. 2016) covers a range of practical topics of interest to dryland producers considering manure use, including composition of different types of manures, manure testing, calculating application rates, applying manure, manure storage, and long-term effects of manure application. For those growing dryland forage crops, see also Manure Application Rates for Forage Production (Downing et al. 2007).

Composition, Nutrients, and Application Rates

Manures contain N, P, K, and other plant nutrients. Nutrient content of manures and manure-based products can vary widely, depending on the type of animal, diet, manure handling and storage, treatments applied, and other factors. Typical values for some of the more common uncomposted manure types are provided in Table 7-5, but these values should be used with caution. Testing following established methods is critical. While some manures have enough N (generally more than 2% N on a dry weight basis) to be used primarily as fertilizers to meet crop nutrient needs, others have less concentrated nutrients and should be primarily seen as soil builders (Bary et al. 2016). For example, separated dairy solids with total N of 1.4% and a C:N ratio of 32 are mainly soil builders.

When nutrients are the main goal, understanding the forms of N in manure is important to choosing appropriate application rates and methods. When excreted, somewhere in the range of 50% of dairy or beef manure N may be in the form of ammonium (Ketterings et al. 2005). Ammonium can be lost through volatilization when manure is exposed to air, including during storage, and after land application, if not immediately incorporated into the soil. Ammonium can also be taken up by crops, either directly or after conversion to nitrate in the soil. Because of these dynamics, N contribution is generally greater for manures that are tilled-in compared to those left on the surface. Manure also contains organic N. Some forms of organic N break down quickly, while stable organic N compounds in manure can take as long as 5 years or longer to mineralize into the ammonium and nitrate forms that are available to plants (Russelle et al. 2016; Moore and Ippolito 2009).

The Manure Management Planner (***http://www.purdue.edu/agsoftware/mmp/***), developed by Purdue University, may be helpful for calculating uncomposted manure application rates to meet crop needs while protecting

Table 7-5. Typical nutrient content, dry matter, bulk density, and nitrogen (N) availability for uncomposted animal manures. Nutrients, dry matter, and density can all vary widely depending how manure is handled. Values for additional manure types can be found in Bary et al. 2016.

Type	N	P[a]	K[a]	Dry Matter	Density	Total N	C:N Ratio[b]	Available N[c]	
	lb/ton as-is[d]			%	lb/cu yd	% dry weight		% of total N	lb/ton as-is
Broiler with litter	56	27	39	68	850	4.1	11	40 to 60	22–34
Beef	14	4	12	28	1400[e]	2.4	15	15 to 30	2–4
Stockpiled dairy manure	18	6	35	50	1000	1.9	15	10 to 20	2–4
Dairy cow separated solids (primary separation)	6	1	3	21	1100	1.4	32	–5 to 10[f]	< 1

[a]Phosphorus (P) and potassium (K) are expressed on an elemental basis. Use the following conversion factors to convert to units used for fertilizer marketing: To get P_2O_5 (phosphate), multiply P by 2.29. To get K_2O (potash), multiply K by 1.2.
[b]Carbon-to-nitrogen ratio
[c]Available N is an estimate of the amount of N that becomes available to plants during the first growing season after application.
[d]"As-is" is typical dry mater content for solid manure stored under cover.
[e]Estimate based on value for manures and composts with high moisture (low dry matter).
[f]Negative value indicates N immobilization (conversion from available to unavailable form).
Used with permission from Bary et al. 2016. Data sources include Gale et al. 2006; Brown 2013; Moore et al. 2015; and unpublished PNW data from A. Bary, C. Cogger, D. Sullivan, and A. Moore.

surface and ground water quality. The tool uses existing state-specific fertilizer recommendations and information for estimating manure N availability from Extension and National Resources Conservation Service. While the tool can use standard manure production and nutrient values, supplying the tested nutrient content and volume will greatly improve accuracy. The tool provides suggested application rates, as well as a P index and N leaching index to give insight about the risk of nutrient losses to the environment.

In comparison to most raw manures, composted manures have less plant-available N (Table 7-6), as most of the easily mineralizable forms of N are converted to more stable organic forms or lost as ammonia gas during the composting process. Generally speaking, this means that composts are better used to build SOM and improve tilth, rather than as organic fertilizers (Gale et al. 2006; Bary et al. 2016). Composting also increases the amount of stabilized C, and makes the amendment more uniform and easier to apply.

In contrast to primary separated solids, secondary solids have a clay-like nature with smaller particle size and higher nutrient content, particularly P (Table 7-7). Research to date has focused on applications that provide P at agronomic rates to cropping systems such as potatoes that have high P requirements (e.g., Collins et al. 2016). Note that fine solids generated with systems utilizing polymers such as polyacrylamide may be incompatible with organic certification, though there is ongoing investigation regarding the use of natural polymers (Mehta et al. 2015).

Grain Quality Considerations

In irrigated systems in southern Idaho, excessive applications of manure elevated protein levels beyond desirable amounts for soft white wheat and barley, and also caused lodging (Moore 2016).

Soil Health Benefits

Manure applications are better able to maintain and increase SOM than crop residues, both regionally (Machado et al. 2011; Wuest and Gollany 2012; Wuest and Reardon 2016) and globally (Edmeades 2003). Elsewhere in the western US, one-time applications of composted manure have also

Table 7-6. Typical nutrient content, dry matter, bulk density, and nitrogen (N) availability for composted animal manures.

Type	N	P[a]	K[a]	Dry Matter	Density	Total N	C:N Ratio[b]	Available N[c]	
	lb/ton as-is[d]			%	lb/cu yd	% dry weight		% of total N	lb/ton as-is
Broiler litter "compost"[e]	44	26	33	57	900	3.8	10	30 to 40	12–18
Beef manure compost	18	7	22	64	900	1.4	11	0 to 10	2–4
Separated dairy solids compost (primary separation)	10	1	3	25	1400	2.1	18	0 to 10	0–1

[a]Phosphorus (P) and potassium (K) are expressed on an elemental basis. Use the following conversion factors to convert to units used for fertilizer marketing: To get P_2O_5 (phosphate), multiply P by 2.29. To get K_2O (potash), multiply K by 1.2. [b]Carbon-to-nitrogen ratio. [c]Available N is an estimate of the amount of N that becomes available to plants during the first growing season after application. [d]"As-is" is typical dry mater content for compost at the point of sale or use. [e]Broiler litter sold as "compost" is often not fully composted because no water was added to facilitate microbial decomposition during the process.

Used with permission from Bary et al. 2016. Values for additional composted manure types can be found in Bary et al. 2016. Data sources include Gale et al. 2006; Larney et al. 2006; and unpublished PNW data from A. Bary, C. Cogger, and D. Sullivan.

Table 7-7. Elemental composition of two anaerobic digestion (AD) recovered fine solids products and one commercial manure-based fertilizer.

	C	N	P	K	S	Ca	Mg	Fe	pH
Fertilizer Amendment	----------------	----------------	----------------	----------------	%	----------------	----------------	----------------	
AD Dairy fine solids 2-3-1	19.7	15	14	13	14	62	14	8	8.0
AD Poultry fine solids 4-6-2	20.7	39	26	18	13	82	25	2	7.7
Commercial poultry fertilizer (2-8-1, Perfect Blend)	25.6	18	34	10	30	70	7	1	6.3

C = carbon; N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Ca = calcium; Mg = magnesium; Fe = iron. Adapted from Collins et al. 2016.

raised SOC, with effects lasting at least 16 years after application (Reeve et al. 2012). Beyond improved SOM, manure applications have been shown to increase soil water infiltration and stability of soil compared to synthetic N fertilizer, with an associated increase in earthworm and mycorrhizal fungi activity (as measured by glomalin, a fungal glycoprotein) (Wuest et al. 2005) (Table 7-8). ■

Table 7-8. Effect of 70 years of organic amendments compared to synthetic nitrogen (N) fertilizers on soil properties of the surface soil (0–5.9 inches) in a winter wheat-summer fallow rotation near Pendleton, Oregon. ■ Differences between chemical fertilizer and manure and pea vine treatments were highly significant for all soil parameters shown here except earthworm counts.

Soil Parameters	Organic Amendments		Synthetic N Fertilizer	No Fertilizer
	Manure	Pea Vines		
	100 lb N/ac[a]	30 lb N/ac	80 lb N/ac	0 lb N/ac
Total carbon (C) (%)	1.590	1.260	1.170	1.090
Total N (%)	0.135	0.103	0.092	0.088
Wet Soil Stability				
Whole soil (proportion)	0.48	0.41	0.35	0.30
1–2 mm aggregates (proportion)	0.83	0.69	0.65	0.56
Water Infiltration				
Percolation (cubic inches per hour)	1.06	0.95	0.84	0.73
Ponded infiltration (inches per hour)	5.53	4.09	1.49	1.46
Total glomalin[b] (%)	0.259	0.235	0.214	0.213
Earthworm count (per square meter, sampled 9.8 inches deep)	107	120	60	67

[a]Pounds of N shown is on a per-crop cycle basis for all treatments.
[b]Glomalin is a glycoprotein produced by arbuscular mycorrhizal fungi. Its concentration has been associated with the abundance of water-stable aggregates, and it incorporates potentially large pools of soil C and N.
Adapted from Wuest et al. 2005; this table is also Table 2-3.

In the inland PNW, Cox et al. (2001) used compost (85% by volume animal manure and bedding, along with 10% coal ash and 5% food and landscaping waste) to restore eroded Palouse hilltops. Composts benefitted bulk density in some years, reduced soil impedance (low soil impedance is associated with improved root growth), increased water-stable aggregates, and increased total soil C. Compost also increased extractable P and available K, two nutrients that are usually less available on eroded hilltops (Pan and Hopkins 1991). After N immobilization was overcome, yields improved compared to untreated controls, likely through improvements in soil fertility, soil structure, and perhaps water infiltration. ●

Nutrient Loss Considerations

When manures are applied to crops to meet N needs, P is typically applied at rates 3 to 6 times greater than the crop can use (Moore and Ippolito 2009), while K is also usually in excess of plant needs. Loss of P and K will likely not be an issue if these nutrients are deficient in soils or for single applications, but soil levels should be monitored every three to five years, especially if applications are repeated over time (Bary et al. 2016).

Excess P and K can be managed in some cases through the inclusion of dryland forage crops, such as alfalfa, in the rotation. Forage plants can take up additional K as soil concentrations increase, benefitting soil nutrient balances—and alfalfa also has high P requirements. However, growers should note that excess K concentrations in forage can cause health problems for cattle, with suggested limits of 2% on a dry weight basis (Moore and Ippolito 2009).

Contaminants

Pathogens can be a concern with manures, though composting or anaerobic digestion can reduce (but do not eliminate) these concerns. As of late 2016, The Food and Drug Administration (FDA), as part of the Food Safety Modernization Act, which applies to produce normally eaten raw, was conducting a risk assessment and extensive research on the number of days needed between applications of raw manure as a soil amendment and harvesting to minimize the risk of contamination (FDA

2015). While the Food Safety Modernization Act specifically applies to fruits and vegetables normally eaten raw, it is possible that this guidance, when published, may also have spillover impacts on other crops. In the meantime, the FDA stated that it did not object to farmers complying with the USDA National Organic Program standards. Meanwhile, the National Organic Program standards, which would apply to organic dryland producers, requires a 90-day interval between the application of raw manure for crops that are produced for human consumption and whose edible parts do not come in contact with the soil (CFR Title 7). (A 120-day interval is required for crops whose edible parts come in contact with the soil.)

The Food Safety Modernization Act also addresses compost production, establishing limits on detectable amounts of bacteria (including *Listeria monocytogenes*, *Salmonella* spp., fecal coliforms, and *Escherichia coli* "E. coli" 0157:H7) for processes used to treat biological soil amendments, including manure (FDA 2015). Stabilized compost prepared using approved methods that conform to these standards can be applied without a specified waiting period before harvest, but must be applied in a manner that minimizes the potential for contact with produce during and after application.

Weed seed is another contaminant of concern, as weed seeds can remain viable after passing through an animal's digestive tract. Composting manure at sufficiently high temperatures will kill weed seeds, but quality control must be sufficient to ensure that all the manure is exposed to these conditions.

Manures can also contain antibiotics that may persist during manure storage and even after land application (Kuchta and Cessna 2009; Aga et al. 2005; Schlusener et al. 2003). However, concentrations are generally low, and the potential for environmental impacts is not well understood. Composting and anaerobic digestion effectively lower concentrations of some but not all antibiotics (Ramaswamy et al. 2010; Kim et al. 2012; Mitchell et al. 2013; Mohring et al. 2009).

Growers who are carrying out repeated applications of dairy manure over time should be aware of a low risk of copper toxicity. Copper sulfate ($CuSO_4$) from cattle foot baths is washed out of dairy barns along with manure and into wastewater lagoons. Moore and Ippolito (2009) suggest testing soils every 2 to 3 years if dairy manure applications are ongoing, and ceasing copper additions if soils tests indicate greater than 50 ppm DTPA-extractable copper.

Biochar

Biochar is charcoal-like material that is generated when organic materials are heated in oxygen-limited environments (Ronsse et al. 2013). Biochar has been receiving growing attention as a C-rich soil amendment that can improve measures of soil health. Recent meta-analyses of worldwide data from field experiments indicate that benefits exist under at least some agricultural conditions, with suggestions that important mechanisms that may include a liming effect, improved ability to retain nutrients, improved soil water holding capacity, and perhaps improved soil structure (Jeffery et al. 2011; Biederman and Harpole 2013; Liu et al. 2013). As of late 2016, biochar was available in limited commercial quantities from suppliers across the PNW (Tom Miles, personal communication).

Biochar can be made from a wide range of biomass feedstocks, with lignocellulosic materials such as forestry or agricultural residues among the most common choices (Suliman 2015). The physical and chemical characteristics of biochar depend on the feedstocks used, the temperature and other conditions under which the biochar is produced, and the pre-treatments and post-treatments applied (Zhao et al. 2013; Ronsse et al. 2013; Suliman et al. 2017) (Table 7-9). Variations in performance depending on feedstock and soil type have been seen in greenhouse studies using biochar from the Palouse region of eastern Washington (Naff silt loam, Palouse silt loam, and Thatuna silt loam) (Streubel et al. 2011).

Application of biochar derived from forest wastes has benefitted pH and wheat yields under dryland wheat cropping in the inland PNW (Machado and Pritchett 2014) (Figure 7-5). At this site, applications of 10 tons per acre or more of biochar increased grain yield by 26% to 33%. Application above 10 tons per acre did not result in any additional significant yield increases, and biochar application did not influence test weight. Applying this alkaline biochar (pH 10.6) increased soil pH by a factor of 0.21 at the highest rate. ▲ While these results are encouraging, separate analysis

Table 7-9. Variation in elemental composition of four biochars made from different feedstocks, with pyrolysis at 500°C (932°F). In addition to the elements listed here, biochars also contained calcium, magnesium, iron, boron, copper, manganese, and zinc.

Biochar Source	Ash	C	N	P	K	S	pH
	------------ % by weight ------------						
Switchgrass	20.81 (0.8)[a]	59.2	1.99	0.47 (0.014)	3.28 (0.2)	0.11 (0.002)	9.4
Anaerobically digested fiber	15.44 (0.1)	65.8	2.23	0.76 (0.032)	1.17 (0.1)	0.30 (0.002)	9.3
Softwood bark	5.40 (0.2)	72.7	0.35	0.047 (0.003)	0.10 (0.01)	0.023 (0.001)	7.6
Wood pellets	1.16 (0.1)	78.2	0.13	0.022 (0.003)	0.10 (0.01)	0.017 (0.002)	7.2

C = carbon; N – nitrogen; P = phosphorus; K = potassium; S = sulfur.
[a]Values in parentheses are the standard deviations.
Adapted from Streubel et al. 2011.

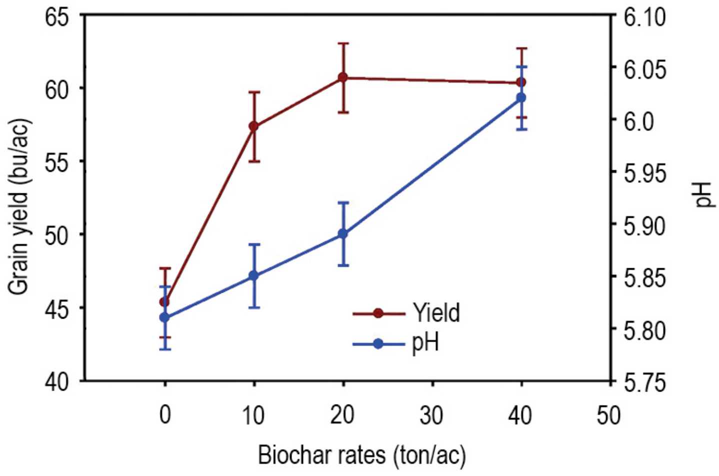

Figure 7-5. Biochar effects on soil pH and winter wheat yield in Athena, Oregon. (Adapted from Machado et al. unpublished; this figure is also Figure 2-10). ▲

suggests that biochar is not economical if only the liming impacts are considered (Granatstein et al. 2009; Galinato et al. 2011). ●

Ongoing research efforts are investigating whether biochars can be engineered to improve agronomic performance and economics. For example, biochar can be "charged" with nutrients (e.g., by absorbing manure effluent and associated nutrients) or oxidized (made to lose electrons). Recent laboratory studies have indicated that Quincy sandy soils from the irrigated region of Washington amended with biochar that had been oxidized by exposure to air held significantly more water than soils amended with non-oxidized biochar, with both out-performing non-amended soils (Suliman et al. 2017).

Paper Manufacturing Wastes

Among other uses, residues from cereal and grass seed systems can be used for papermaking. (See Chapter 4: Crop Residue Management.) Straw fibers are typically pulped with sodium hydroxide (NaOH) under pressure, a process that produces a large quantity of "black liquor," an organic byproduct that has traditionally been discharged into waterways where it can contribute to pollution. Possible alternative uses for the waste include as a soil amendment and K source. Greenhouse and field studies in irrigated corn in Washington state suggested that black liquor could be an effective fluid liming material and could increase soil biological activity as well as wet stable aggregates (Xiao et al. 2006; Xiao et al. 2007).

Conclusion

Soil amendments, when economically and practically viable, could play an important role in improving soil health in dryland systems by increasing soil C, reducing bulk density, and improving nutrient availability, soil structure, water infiltration and retention, and microbial activity.

Among amendments, biosolids applications can produce equivalent or better grain yields than typical applications of inorganic N in tilled and no-till wheat systems. When applied to meet the N needs of crops, biosolids also provide organic matter, P, S, Zn, Fe, and other micronutrients that may be beneficial to wheat when amounts in soils are below desired levels. Biosolids can be a relatively low-cost amendment because some costs are generally borne by the biosolids producers—though the supply of biosolids is limited because they are the byproduct of waste treatment. Those applying biosolids to wheat should be aware that application during the fallow year may increase protein levels compared to conventional fertilizers.

Manures are also effective soil amendments, though producers should carefully distinguish between manures with high enough N content to be used to provide nutrients to crops, and those that act mainly as a soil conditioner, building SOM. In comparison to most raw manures, composted manures have less plant-available N, and thus should be used as a soil conditioner. Nutrient content of uncomposted and composted manures can vary widely, depending on the type of animal, diet, manure handling and storage, treatments applied, and other factors.

When biosolids or manures are applied at agronomic rates for N, excess P is normally applied (for both biosolids and manures) and excess K is applied (for manures). This is usually a relatively low concern for one-time applications to dryland soils, but producers carrying out repeated applications should regularly test soil levels. Likewise, although concerns about contaminants such as pathogens and weed seeds exist, these can usually be managed.

Two other amendments, while not currently practical, may be of increasing interest in the future. Biochar, a charcoal-like material, has been receiving some attention as an amendment that could improve soil health through a liming effect, nutrient retention, water holding capacity, and enhanced soil structure. Application of biochar derived from forest wastes has benefitted pH and wheat yields under dryland wheat cropping in the PNW, though cost remains a barrier to use. Meanwhile, black liquor is another organic waste that may be used as a soil amendment to improve physical soil structure, raise pH, and provide K.

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