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Soil Organic Carbon Storage (Sequestration) Principles and Management

Potential Role for Recycled Organic Materials in Agricultural Soils of Washington State

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Potential Role for Recycled Organic Materials in Agricultural Soils of Washington State

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Executive Summary

Climate change is a serious issue facing the world today. Rising atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHGs) are key contributing factors. Among GHGs, atmospheric CO_2 accounts for 60% of the global warming (Pearson and Palmer, 2000). The concentration of atmospheric CO_2 increased from about 280 parts per million (ppm) by volume prior to 1850, to 395.9 ppm in 2014 (http://www.esrl.noaa.gov/gmd/ccgg/trends/). While the increasing concentration of CO_2 is primarily associated with fossil fuel combustion, about 10% of the increase is estimated to be caused by changes in land use, including conversion of forest land for food production (IPCC, 2014).

Climate change could pose a significant threat to Washington State's environment and economy. It is estimated it could cost the state $10 billion per year by 2020, and $16 billion per year by 2040 from increased health care costs, storm damage, coastal destruction, rising energy costs, increased wildfires, drought, and other impacts (Washington State Department of Ecology [Ecology], 2012).

Soils, especially managed agricultural soils, have the potential to store (sequester) carbon (C) and contribute to mitigation of GHGs emissions. Increasing the amount of organic C in soils may not only mitigate GHG emissions, but also benefit agricultural productivity through improvements in soil health and environmental quality by reducing soil erosion (Lal, 2004a; Pacala and Socolow, 2004).

Soil C exists in two forms: inorganic and organic. Soil inorganic carbon (SIC) is the result of both weathering of the parent materials and carbonic acid (CO_2 dissolved in water) in the soil, precipitating as C minerals such as calcite, aragonite, and dolomite (Lal, 2007). Formation of secondary or pedogenic carbonates is an important mechanism of SIC sequestration in arid and semi-arid climates (Schlesinger, 1982). However, net C emissions from application of lime in agricultural soils can be significant, and dissolution and precipitation of carbonate minerals may actually emit as much or more C than is stored depending on the source of the C in the carbonic acid, the soil pH, and the amount of calcium in the soil (West and McBride, 2005; Schlesinger, 2000).

Soil organic carbon (SOC) is a complex of organic C compounds in the form of SOM. SOM includes everything in or on the soil that is of biological origin irrespective of origin or state of decomposition (Baldock and Skjemstad, 1999). It includes plants and animals in various states of decomposition, cells and tissues of soil organisms, and substances from plant roots and soil microbes. SOC originally comes from atmospheric CO_2 that is captured by plants through the process of photosynthesis. The amount of SOC is a balance of C inputs and C losses of organic material (Burke et al., 1989). The amount of SOC stored in a soil depends on factors such as climate, soil type, climate conditions, and land management practices that influence the addition and decay of organic matter.

SOC is commonly divided into three pools according to how fast it breaks down and is replaced: fast, slow, and passive pools. For C storage (sequestration) (long-term storage) purposes, it is desirable to increase the total amount of C in the slow and passive pools that break down slowly to release CO_2 back to the atmosphere.

The amount of SOC in the slow and passive pools can be increased by adding recycled organic materials (e.g. crop residues, animal manure, biosolids, and compost) into soil and by slowing down the rates at which this organic matter decomposes in the soil. Factors affecting the C sequestration include soil type, initial content of SOC, depth in the soil profile, and climate conditions.

Globally, soils contain about 3 times more C than the atmosphere and 4.5 times more C than all living things. A relatively small increase in C content in soils can make a significant contribution to reducing atmospheric CO_2 levels. It is estimated that increasing SOM content in soils up to a 2-meter depth by 5-15% could decrease atmospheric CO_2 concentrations by 16-30% (Baldock, 2007; Kell, 2011). These ideas have led to substantial attention to quantifying stocks of C in soils, mechanisms for stabilizing C in soils, and agricultural management practices, including application of recycled organic materials such as compost, biosolids, and biochar to increase soil organic matter (SOM) stocks (Lal, 2002; Smith, 2008).

In addition to helping mitigate climate change as resulted from increased soil C storage, use of recycled organic materials into soils results in a range of important environmental benefits (Lal, 2002; Smith, 2008). These benefits include:

- Improved soil health, water saving, and crop productivity.

- Reduced need for chemical fertilizers and pesticides.

- Reduced soil erosions by water and wind.

- Improved soil tilth.

According to the 2007 the United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS), there were about 7,600,000 acres of total cropland in Washington State, with a wide range of crops grown in both the east and western Washington of the state, where a majority of agricultural soils in the eastern Washington contained less than 3% of organic matter content. This offers a significant potential to store (sequester) C in soils through use of recycled organic materials such as compost, biosolids, and biochar.

If only 5% of the total cropland in the state received an estimated agronomic application rate at 5.0 dry tons of compost, or 2.0 dry tons of biosolids per acre per year, an estimated 1,900,000 dry tons of finished compost, or 760,000 dry tons of biosolids will be needed annually. This far exceeds the amount of compost (about 522,000 to 779,000 dry tons of compost) or biosolids (about 96,000 dry tons to 110,000 dry tons) produced statewide in 2010, 2011, and 2012.

Similarly, if biochar was applied to 5% of the total cropland at an agronomic application rate at 0.40 tons (800 1b) per acre per year, it would require about 150,000 dry tons (Sprinkle, 2014, personal email communication). While biochar production is new, the market is expanding rapidly. Producers to date in Washington State are nowhere near able to supply even a portion of the 150,000 tons.

Clear synergies exist between the availability of recycled organic materials such as compost, biosolids, and the low SOC content in agricultural soils in the state. Use of the recycled organic materials as a part of a system approach to improved soil management would provide an external source of stable organic C and has the potential to increase SOC sequestration in agricultural soils in the state.

However, recycled organic materials such as compost and biosolids generated in the state are not fully realized sources of organic C. For example, compost produced in the state has been primarily used in landscaping and similar purposes. Only relatively small quantities of compost are utilized by the agricultural and horticultural industries. Some compost facilities in the state have problems marketing their finished compost, leading to continued accumulation of finished compost at these facilities.

Even with an extensive body of research indicating that land application of biosolids contributes positively to recycling nutrients, soil properties, and fertility with low risks to the environment and human health (National Research Council, 1996; Pepper et al., 2008), perception and misconception still exist. Although biosolids have been promoted nationally and internationally for beneficial land application, about 17-20% of biosolids generated statewide were still disposed of in incinerators and/or landfills in 2010, 2011, and 2012. This may be due to higher costs associated with transporting biosolids to a beneficial use facility as compared to the disposal costs of biosolids in either incinerators or landfills. In many locations, community members are still speculative about the beneficial use of biosolids in general.

The high cost of compost purchasing, transportation, and application may be a major barrier to the widespread use of compost in agriculture. While about 94% (7,180,000 acres) of the total cropland in the state is located in the eastern Washington, a majority of compost (a range from 67-87% of the total) was produced at regulated compost facilities in the western Washington. The high cost of transporting compost from the western Washington to the eastern Washington may have partially contributed to the accumulation of compost at some facilities in the western Washington. There is a potential for compost to be used more in agriculture. This would help alleviate the continued accumulation of compost at these facilities. The issues of costs and proximity to markets need to be addressed if the markets for finished compost are to improve. Biochar supply in the future could lead the demand in the future, but that is expected to change as more users come to the market.

According to the latest Statewide Recycling Data from 2010-12, a total of 4,725,361, 4,477,441, and 4,460,649 dry tons of compostable organic waste stream were generated in 2010, 2011, and 2012, respectively, of which about 24.6% (about 1,167,000 dry tons), 24.7% (about 1,105,900 dry tons), and 27.1% (about 1,208,800 dry tons) were processed into compost. As disposal of organic waste stream in landfills or incinerators is becoming more environmentally costly, an increasing number of food scraps, yard debris, and other organic waste diversion programs and composting operations are expected to increase statewide over the next few years. This will result in more production and supply of finished compost in the market. Increased use of compost in agricultural and horticultural production systems will provide a useful means of recycling organic waste stream and reducing the need for synthetic fertilizer, while helping address finished compost marketing issues for some compost facilities.

Similarly, as the population of the state is projected to grow dramatically to 7.8 million by 2025 (Ecology Beyond Waste Plan, 2009), more biosolids are also expected to be generated. Likewise, biochar production is growing rapidly. These factors indicate there will be an even greater need to stimulate markets and provide beneficial end uses for the recycled organic materials in the future. Better education and marketing, and producing a quality product may help make this happen.

By increasing the demand for compost, biosolids, and biochar, it will help expand the process by “closing the loop,” while helping increase soil C storage (sequestration) to mitigate global climate change.” With the anticipated increase in diversion of organic waste materials from disposal, it is also important to explore other beneficial organic material management options such as anaerobic digestion.

Introduction

Climate change is a serious issue facing the world today. Rising atmospheric concentrations of CO_2 and other greenhouse gases are key contributing factors, with consequences of rising atmospheric and oceanic temperatures, increased acidification of ocean, global sea level rise, and increased frequency of extreme weather events (IPCC, 2014).

Atmospheric CO_2 has increased about 40%, from about 280 parts per million (ppm) by volume prior to 1850, to 395.9 ppm in 2014 (http://www.esrl.noaa.gov/gmd/ccgg/trends/). While the increasing concentrations of atmospheric CO_2 are primarily associated with fossil fuel combustion, about 10% increases in atmospheric CO_2 are estimated to be caused by changes in land use, including conversion of forest land for food production (IPCC, 2014). Increases in fossil fuel combustion and resulting atmospheric CO_2 emissions are projected to continue for the foreseeable future, with a doubling or even tripling of the pre-industrial atmospheric CO_2 concentration possible by the end of the 21st Century if mitigation steps are not taken (IPCC, 2014).

According to a report by Washington State's Integrated Climate Response Strategy (Ecology, State of Washington, 2012), climate change projections for Washington State indicate that temperatures will increase 3.2 °F degrees by 2040. This could pose a significant threat to Washington State's environment and economy. It is estimated it could cost the state $10 billion per year by 2020, and $16 billion per year by 2040 from increased health care costs, storm damage, coastal destruction, rising energy costs, increased wildfires, drought, and other impacts.

Key climate-related risks in Washington State include:

- Increased injuries and disease.
- Increased damage costs and disruptions to communities, transportation systems, and other infrastructure.
- Reduced water supply, loss of fish, wildlife, natural systems, and agriculture and forest industries.

Soils, especially managed agricultural soils, have the potential to store (sequester) and contribute to mitigating greenhouse gas emissions. By adopting recommended farming practices, agriculture contributes not only to soil conservation and water quality goals, but also to enhancing the amount of organic C stored in the soil and mitigating greenhouse gas emission effects on climate change (Lal, 2004a; Pacala and Socolow, 2004). Global efforts have been focused on both reducing emissions of greenhouse gases and increasing storage (sequestration) of C from the atmosphere through converting some plant photosynthesized C and storing it into soil pools (Lal et al., 2003).

Globally, soils contain about 3 times more C than the atmosphere and 4.5 times more C than all living things. Thus, a relatively small increase in agricultural soils can make a significant contribution to reducing atmospheric CO_2 concentrations. It is estimated that increasing SOM contents in soils up to a 2-meter depth by 5-15% could decrease atmospheric CO_2 concentrations by 16-30% (Baldock, 2007; Kell, 2011). These ideas have led to substantial attention to quantifying stocks of C in soils, mechanisms for stabilizing C in soils, and agricultural management practices including use of recycled organic materials such as compost, biosolids, and biochar to increase SOM stocks (Lal, 2002).

In addition to helping mitigate climate change as resulted from increased soil C storage, use of recycled organic materials into soils results in a range of important environmental benefits (Lal, 2002; Smith, 2008). These environmental benefits include:

- Improved soil health, water saving and crop productivity.
- Reduced need for chemical fertilizers and pesticides.
- Reduced soil erosions by water and wind.
- Improved soil tilth.

This report aims to address *Soil C Sequestration, Using Recycled Organic Materials Has Increased Based on Research Recommendations* identified in Milestone ORG H of the Washington State Department of Ecology's Beyond Waste Plan - Increasing Recycling for Organic Materials (http://www.ecy.wa.gov/beyondwaste/increaseOrganics.html). It summarizes an extensive literature review on:

- SOC's roles in soil health, mechanisms of soil C storage (sequestration), factors affecting SOC storage, and the mitigation of atmospheric CO_2 concentrations.
- Agricultural management practices, including use of recycled organic materials such as compost, biosolids, and biochar to store or sequester SOC in agricultural soils.
- Climate conditions and soil types in Washington State and selected soil properties affecting soil C storage.
- Estimated areas of cropland and compost production in Washington State.
- Potential for agricultural soils in Washington State to receive recycled organic materials such as compost, biosolids, and biochar to increase SOC.
- Existing major barriers to widespread use of biosolids and compost in agricultural soils.

Soil Organic Matter, and its Pools and Roles in Soil Health

Soil and soil carbon

Soil, the unconsolidated cover of the earth, consists of inorganic (mineral) and organic components, water, air, and living organisms. Soil is a biochemically weathered product of rocks and minerals through biological activity. Soils provide nutrients for plants and are capable of supporting plant growth. Soils are also home to a wide range of organisms and a repository for soil C (Buckman and Brady, 1970).

Soil C refers to the total C in soil, and it includes both inorganic and organic C forms. Soil inorganic C (SIC) is the result of both weathering of the parent materials and Cic acid (Carbon dioxide dissolved in water) in the soil, precipitating as C minerals such as calcite, aragonite, and dolomite (Lal, 2007). Formation of secondary or pedogenic carbonates is an important mechanism of SIC sequestration in arid and semi-arid climates (Schlesinger, 1982). However, net C emissions from application of lime in agricultural soils can be significant, and dissolution and precipitation of carbonate minerals may actually emit as much or more C than is stored (dependent on the source of the C in the carbonic acid, the soil pH, and the amount of calcium in the soil (Schlesinger, 2000). West and McBride (2005) estimated that net emissions from application of lime on agricultural acidic soils are 0.12 and 0.13 Mg C per Mg of limestone and dolomite, respectively.

SOC is a complex of organic C compounds in the form of SOM. SOM includes everything in or on the soil that is of biological origin, irrespective of origin or state of decomposition (Baldock and Skjemstad, 1999). It includes plant and animal remains in various states of decomposition, cells and tissues of soil organisms, and substances from plant roots and soil microbes. The ultimate product of the decomposition process is humus, an amorphous array of compounds highly resistant to further decomposition. Many organic compounds in the soil are intimately associated with inorganic soil particles. In agricultural soils, soil organic C content is usually less than 5% and decreases with soil depth (Baldock and Skjemstad, 1999).

SOC decomposes over the years and needs to be replaced by fresh organic matter to maintain soil C levels. As it decomposes, particle size decreases, residue becomes more nutrient rich, and turnover time increases from hours to days and hundreds of years.

SOC also constitutes a significant proportion of the terrestrial C storage and C fluxes in the global C balance. Therefore, it has the potential by the decomposition of its labile fractions to influence levels of atmospheric CO_2.

Soil carbon pools

Soils are the largest stock of C in the terrestrial environment (Jobbágy and Jackson, 2000), with about 60% in the form of SOM, and the remaining 40% in the form of inorganic C (e.g. carbonate, or $CaCO_3$).

The total amount of C stored in the top meter of soil is estimated to be 2,500 Pg C globally (1 Pg = petagram = 10^{15} g), including about 1,500 Pg of SOC, and 950 Pg C of inorganic soil C (SIC). This is about 3.3 times the amount of C in the atmospheric pool (760 Pg C) and about 4.5 times (560 Pg C) the amount of C stored in living vegetation (Lal, 2004b). The SOC pool plays an important role in the global C cycle and has a strong impact on agricultural sustainability, and environmental quality (Jenkinson et al., 1991; Stevenson, 1994).

The SIC pool is an important constituent in soils in arid and semiarid regions. It includes elemental C and carbonate and bicarbonate minerals (e.g. calcite and dolomite). There are two types of Cates: primary and secondary. The primary carbonates are derived from the weathering of the parent material, whereas the secondary Cates are formed through the conversion of CO_2 in soil air into carbonic acid and its reaction with Ca^{2+} and Mg^{2+} (Lal and Kimble, 2000).

Land use changes can cause the depletion of SOC pools stored in global soils. Globally, it is estimated conversion of native vegetation for agricultural production has resulted in losses of about 78 Pg C, with about 26 Pg C resulted from erosion and 25 Pg C from mineralization (Lal, 2004b). Guo and Gifford (2002) also estimated that about 42-59% SOC have been lost due to the conversion of native forest and grass for agricultural production in Australia. Most forest and grassland soils of the U.S. are estimated to have lost from 20-50% of their original SOC pool in the first 40-50 years of cultivation (Rasmussen and Collins, 1991; Camberdella and Elliott, 1992).

Reduction in SOC stocks associated with conversion of native vegetation for agricultural production is attributable to:

- Reduced inputs of organic materials due to harvest and stubble burning.
- Increased decomposition rates due to the cultivation.
- Loss of topsoil and organic matter due to soil erosion.

Cultivation may increase decomposition rates by exposing SOM occluded in soil aggregates to microbial degradation, because both disruption of soil structure leads to changes in porosity that create a more favorable decomposition environment. In addition, cultivation, especially when followed by fallow, creates favorable conditions for both wind and water erosion (Packer et al., 1992).

The depletion of SOC stored has created a great potential for agricultural soils to return soil C from the present to pre-conversion soil organic C level (IPCC, 2000), and could significantly change current atmospheric CO_2 concentrations (Wang et al., 1999).

Soil organic matter roles

SOM takes a central role in maintaining soil health because it affects soil physical, chemical, and biological functions, and is also critical to ensure secure food production. The process of decomposition is key to the cycling of macronutrients ((e.g. nitrogen (N), phosphorus (P), and sulfur (S)), and its effective management can reduce the need for fossil fuel consumption to supply nitrogen (N) fertilizer (Dungait et al., 2012). A wide range of roles SOM takes in soils have been cited by a number of researchers (Watts et al., 2006; Powlson et al., 2011). The benefits (Blair et al., 2006a, b; Lal, 2004c) of increased SOM include:

- Improved soil physical properties such as soil aggregation, water infiltration, hydraulic conductivity, and water holding capacity.

- Reduced risk of soil erosion.

- Increased soil biological heath.

- Increased agricultural productivity.

- Reduced needs for fertilizers, pesticides, and water.

A SOC concentration of less than 2% (or 3.4% SOM) is considered to be the threshold value below which soil function is impaired (Greenland et al., 1975; Lal, 2004c). Although there is little quantitative evidence for such a threshold (Loveland and Webb, 2003), Janzen (2006) proposed that the bioavailability of SOM is the major influence on soil properties. However, the general responses of soil organic C stocks in terrestrial ecosystems to changes in environmental conditions remains unclear, especially temperature and precipitation, and their combined effect (Wu et al., 2011).

In contrast, in addition to leading to increased atmospheric CO_2 concentrations, losses of SOM could have adverse impacts on soil quality, agricultural production, and the environment. The adverse impacts (Lal, 2004c, Whitbread et al., 1998) include:

- Depletion of plant nutrients (e.g. N, P, S).

- Increased soil bulk density.

- Loss of soil structure.

- Decreased water-holding capacity and hydraulic conductivity.

- Decreased cation-exchange capacity.

- Increased soil erosion and leaching of pesticides and heavy metals.

- Declined soil biological activity and diversity.

- Decreased crop yields.

Soil organic matter fractions

SOM is partitioned into different pools with varying decomposition rates or turnover times (Adair et al., 2008). The term “pool” is used to refer to theoretically separated, kinetically delineated components of SOM which share similar turnover times within the soil (Davidson and Janssens, 2006; Paustian et al., 1992).

The best known biogeochemical model of soil C dynamics – the CENTURY (Parton et al., 1987) model divides SOM into three pools in the mineral soils (from the most labile to the most recalcitrant to decomposition):

- Fast pool: This pool has a short turnover time, with fast decomposition (e.g. daily to annual), also referred to as the labile or active pool.

- Slow pool: This pool has a longer turnover time, with slower decomposition (e.g. annual to decadal), also referred to as the stable or humus pool.

- Passive pool: This pool has a much longer turnover time (e.g. decadal to centennial or millennial); also referred to as the refractory or recalcitrant pool.

The proportion of total soil C in each pool can vary widely, but is assumed to be in the range of 10% for the fast pool, 40-80% for the slow pool, and 10-50% to for the passive pool (Biala, 2011).

For C storage (sequestration), it is especially desirable to increase the total amount of C in the slow and passive pools that break down slowly. While building the content of the fast pool is important for C sequestration, it is also more vulnerable to loss if conditions change.

Fast (labile or biological active soil organic matter) pool

The fractions of fast (labile or biological active pool) include:

- Microbial biomass (e.g. chloroform-labile SOM, amino compounds, microwave irradiation labile SOM (B), and phospholipids).

- Labile substrates (e.g. mineralized C or N, estimated by incubation, substrate-induced activity, soluble, extractable by hot water or dilute salts, easily oxidized by permanganate or other oxidants).

- Residues (e.g. litter, vegetative fragments or residues, non-aggregated protected particulate matter).

The fractions of this pool also include simple sugars, amino acids, proteins, polysaccharides, and carbohydrate (Hopkins and Dungait, 2010), which may derive from microbes due to exudation and excretions, cell death, and decay (Hofman and Dusek, 2003). Some compounds (e.g. simple sugar) in the soil can decompose very quickly, with a less than one hour of half-life turnover time, because they are rich in energy, readily accessible to organisms, and rapidly assimilated (Boddy et al., 2007; Hill et al., 2008).

Cellulose and hemicelluloses polysaccharides are the most abundant substrates in plant litter (Dungait et al., 2005; Jia et al., 2008). It has been determined 60% of cellulose is mineralized in soil after one month, with an additional 7% decomposed within three months (Derrien et al., 2007), and the remainder persisting in soils long-term (Gleixner et al., 2002). It has been suggested soil polysaccharides play an important role in stabilization of soil microaggregates, (<250 µm) as their length and linear structure allow them to bridge the space between soil particles (Martens, 2000), and intact polysaccharides may become occluded within soil aggregates as components of intra-aggregate particulate SOM (Six et al., 2000a, b). Other compounds decompose relatively slowly, with a half-life (turnover) time from less than one hour to a few years.

Slow (stable soil organic matter) pool

The fractions of these SOM pools have a few years to decades of a half-life turnover time, and include:

- Partially decomposed residues and decay products (e.g. amino compounds, glycol proteins, aggregate protected particulate organic matter (POM).

- Some humic materials (e.g. acid/base hydrolysable humic substances, and mobile humic acids).

Passive (recalcitrant soil organic matter) pool

The fractions of passive (recalcitrant SOM) pool include:

- Refractory compounds of known origin (e.g. lipid, lignins, black C, and biochar).

- Some humic substances (e.g. high molecular weight, condensed SOM, humin, nonhydrolyzable SOM, fine-silt, coarse-clay associated SOM).

The recalcitrant SOM pool has decades to centuries of a half-life turnover time. The decomposition of lignin and its derivatives is often regarded as the rate limiting step in biological C cycling (Zhang et al., 2008; St. John et al., 2011). It is reported about 92% of total lignin extracted from soils decompose within one year (Rasse et al., 2006; Dungait et al., 2010), with the remainder decomposing within decades (Digac et al., 2005; Heim and Schmidt, 2007). A recent review concluded the literature is contradictory with regard to decomposition rates, but agreed most decompose within five years (Thevenot et al., 2010).

Actinobacteria are considered responsible for up to 15% lignin degradation in soils. Although they cannot completely mineralize lignin, they solubilize it to gain access to the associated polysaccharides (Dignac et al., 2005). Xylanases disrupt hemicellulose-lignin associations, without mineralization of the lignin per se, subsequently making the lignin more readily available to direct digestion (Dignac et al., 2005).

The perception of lignin as a recalcitrant compound is being questioned, as its selective preservation (if any) is only pertinent during initial decomposition with subsequent degradation being more rapid than bulk SOM (Marschner et al., 2008).

Humic substances, a series of relatively high molecular weight, brown to black substances, including humic acids, fulvic acids and humin, are formed by secondary synthesis reactions (Stevenson, 1982). They have been considered as the major pathway for SOM stabilization (Piccolo, 2001), due to its heterogeneity in size and resistance to enzyme attacks (Marschner et al., 2008), with 500-5000 years of a half-life turnover time. However, Stevenson (1982) recognized that humic substances are readily degradable when extracted from soils. This leads to the assumption that humic substances in soil are the mixtures of partially decomposed plant and microbial biomass that are inaccessible to soil microorganisms.

Black C is the charred remains of plant material which appears in soils as a result of human activity and natural fires (Dungait et al., 2012). Biochar is a similar material produced by thermally heating and pyrolysis of woody biomass, agricultural organics such as straw, or other feedstocks under a range of temperatures and process conditions without the presence of oxygen that result in black C cinder, organic waste, or other feedstocks under the absence of oxygen. Biochar is used as a soil amendment that can help C storage due to its recalcitrant nature of resistance to microbial degradation as well as potential benefits on soil quality (Krull et al., 2009).

Black C derived from biomass consists of a substantial component (5-50%) of organic C in some soils, with a much slower decomposition rate than SOM due to its highly condensed aromatic structure (Schmidt et al., 2001). Large charcoal particles originating from forest wildfires can remain in soils for thousands of years (Major et al., 2010). Lemann et al. (2006) suggested that conversion of biomass C to biochar sequesters about 50% of the initial C yielding more stable soil C than burning or direct land application of biomass. However, biochar is not completely inert since it can be used as a substrate by soil microorganisms (Wengel et al., 2006). Experimental results are contradictory, and both rapid (Bird et al., 1999) and slow (Shindo, 1991) decomposition of biochar were reported.

Black C has been C dated in soils in excess of 2500 years. "*Notwithstanding the remaining uncertainty about its precise turnover, black C has been found to be the oldest fraction of C in soil, older than the most protected C in soil aggregates and organo-mineral complexes (Pessenda et al., 2001), which is commonly the most stable C in soil. This indicates that in quantitative terms biochar is stable, with decomposition leading to subtle, and possibly important changes in the bio-chemical form of the material rather than to significant mass loss*."

Factors Affecting the Soil Organic Carbon Storage (Sequestration)

SOC originally comes from atmospheric CO_2 that is captured by plants through the process of photosynthesis. The amount of SOC is a balance of C inputs and C losses of organic material (Burke et al., 1989).

In natural ecosystems, rainfall and temperature are primary factors determining plant biomass input and subsequent decomposition of SOC for a given soil type. These factors determine the equilibrium SOC level. When additions of organic C equal the losses of organic C, equilibrium SOC levels are reached. In agricultural systems, SOC turnover rates and equilibrium levels are further impacted by management practices. For example, a substantial portion of fixed C from the process of photosynthesis is removed during the harvest, with 30-50% of fixed C as aboveground dry matter typically being removed for cereal crops (Hay, 1995; Johnson et al., 2006), with the remaining 50-70% of the annual fixed C as aboveground residues and belowground residues (e.g. root biomass).

Retaining crop residues generally greatly reduces soil erosion and minimizes water losses during fallow periods (Radford et al., 1992; Thomas et al., 2007b). However, crop residues retained on the surface of the field make only a small contribution to longer-term soil C stocks (Kirkby et al., 2006). In contrast, belowground residues (e.g. root biomasses) represent direct inputs into soil systems, being major contributors to SOC stocks (Jobbáby and Jackson, 2000). Roots generally decay slower than aboveground residues (Rasse et al., 2005).

Major C losses are from mineralization of organic materials and soil erosion (De Jong and Kachanoski, 1988; Paustian et al. 1997). Erosion has been a major loss mechanism for SOC from agro-ecosystems, which accounts for an estimated 20-50% of historic C losses (Lal, 2004b). Eroded SOC can be a net sink for or a net source of CO_2 depending both on the frame of reference and on the fate of this eroded material (Stallard, 1998; Yoo et al., 2005). Conventional cultivation practices promote the mineralization and losses as CO_2 of the more labile SOC fractions. Soil management practices such as conservation farming are designed to increase C inputs and minimize the C losses that are characteristics of traditional cultivation practices.

SOC, a major source of system stability in agroecosystems, is controlled by many factors that have complex interactions (Burke et al., 1989). These factors include soil properties, climate conditions (temperature and precipitation), and land use and management practices (Baldock and SKjemstad, 1999) as discussed below.

Soil properties

Soil depth and soil type

SOC level varies with soil depth and soil type. In general, SOC content decreases with increasing depth of soil profile. However, high content of SOC can be found at depths greater than 50 cm (e.g. some vertisols where shrink-swell nature of the soils encourages downward movement of organic matter) (Baldock and Skjemstad, 1999).

SOC level varies among soil types as shown by Eshwarn et al. (1993) in Table 1. On a world scale, Histosols contain the highest mean SOC levels, while Aridosols contain the lowest on a per unit area basis. The correlation between SOC and soil type is related to differences in climate, soil mineral composition, topography, and management practices (Baldock and Skjemstad, 1999).

Table 1

SOM Content in Washington State Soils

Soil Order (US Taxonomy)	Area (km^2 x 10^3)	SOC (Pg) (10^{15}g)	SOC (t/ha)
Alfisols	18,283	127	7.0
Andisols	2,552	78	31
Aridosols	31,743	110	4.0
Entisols	14,921	148	10
Histosols	1,745	357	205
Inceptsols	21,580	352	16
Mollisols	5,480	72	13
Oxisols	11,772	119	10
Spodosols	4,878	71	15
Ultisols	11,330	105	9.0
Vertisols	3,287	19	6.0

Soil texture

Soil texture influences the net mineralization of SOM and amount of SOC stored in the soil. The decomposition of organic matter is more rapid in sandy soils than in clay soils. Burke et al (1989) obtained pedon and climate data for 500 rangeland and 300 cultivated soils in the U.S. Central Plains grasslands, and statistically analyzed relationships between soil C and soil texture and climate. Their result indicated SOC increased with clay content, and SOC losses due to cultivation were lowest in clay soils.

Clay soils accumulate C relatively quickly, and sandy soils may accumulate practically no C, even after 100 years of high C inputs (Burke et al., 1989; Christensen, 1996). It was found that SOC losses in cultivation of virgin land were 20 times faster in sandy soil than in clay soils (Dalal and Mayer, 1986).

The higher the clay content (e.g. clay texture), the greater the ability of soils to retain C. Follett et al (2012) indicated that SOC stocks increased significantly with increasing percentage soil clay. Under native grassland, SOC increased at the rate of 1,203 kg ha^{-1} (1,073 1b ac^{-1}) per unit (%) increase in clay, and the respective rate of change in SOC under cropland was 105 kg ha^{-1} (94 1b ac^{-1}), and under a conservation reserve program was 498 kg ha^{-1} (444 1b ac^{-1}) (Follett et al., 2012). It is also observed that decomposition of humus, a recalcitrant component of SOC, is slower in clays and silts than in coarse soils (Dalal and Chan, 2001).

The presence of multivalent cations (e.g. calcium (Ca)-containing minerals or exchangeable cation), aluminum (Al) or iron (Fe) (as amorphous Al and Fe minerals), protects organic C from microbial degradation by adsorption and aggregation (Paul, 1984; Krull et al., 2001) through clay-SOM complexes and cation bonding (Oades, 1995). In addition, increasing silt content also increases water holding capacity, so that soil texture interacts with climate in controlling ecosystem process (Van Veen et al., 1985; Schimel and Parton, 1986).

Composition of soil minerals

Composition of soil minerals is important in determining the quantity of organic C stored in soil, its turnover time, and atmosphere-ecosystem C fluxes during long-term soil development (Torn et al., 1997). The presence of multivalent cations such as Ca^{2+}, Al^{3+} or Fe^{3+} leads to accumulations of organic C in comparison to other cation types (Krull et al., 2001).

Soil pH

Soil pH (hydrogen ion activity) controls soil microbial enzymatic efficiency (Olness, 1999). The mineralization of soil organic matter is most rapid at a pH optimum of about 6.7, suggesting that both hydroxyl and hydrogen ions are inhibitors of microbial respiration.

Liming acid soils or additions of ammonia fertilizers affect an acceleration of microbial decomposition of SOM due to change in hydroxyl or hydrogen ion concentrations, thus affecting the amount of SOC stored in the soil. Provided significant C inputs occur, decreasing soil pH in natural ecosystems result in increasing SOC, because soil surfaces are increasing occupied by organic C, and soil microbial activity decreases as pH decreases (Dalal and Chan, 2001).

Other soil properties

Other soil properties such as soil bulk density, pore space, and pore size affect the availability of soil water and oxygen, thus affecting the decomposition (mineralization) of SOC (Baldock and Skjemstad, 1999). Soil microbial respiration is maximized when water-filled pore space ranges from about 50-75%. Soil water-filled pore space is a function of soil water content and is largely controlled by soil clay content (texture) and soil organic matter content (Hudson, 1994).

Along with the combination of texture and clay content, total soil porosity or soil bulk density determines relative soil aeration, which controls soil microbial respiration. Native prairie soils have bulk densities of about 1.0, which tends to be too well aerated for optimal microbial respiration. This aids the accumulation of SOC. Soil bulk density of approximately 1.2 is ideal for microbial mineralization of soil organic matter, which results in decreases in soil C storage (Hudson, 1994).

Climate

Climate in the form of temperature and moisture affects both inputs and losses of organic matter in soils, thus impacting the amount of C stored in the soil, because both temperature and moisture serve as controls to SOC respiration rate (Jobbágy and Jackson, 2000; Conant et al., 2004). When sufficient water is provided, higher temperatures lead to faster decomposition of soil organic matter, less storage of C in the slow and passive pools, and greater loss of C through respiration (Canadell et al., 2007). In warm climates, soil generally contains less organic soil C than in cold climates (Lal, 2007).

Mean annual temperature (MAT)

Temperature has a direct effect on the rate of decomposition of SOC (Jenkinson, 1991). The decomposition of SOC is more rapid in tropical regions than in more temperature regions (Dalal and Chan, 2001). The recent finding of Follett et al. (2012) indicated that SOC decreased as MAT increased, and SOC decrease was 1,896 kg ha^{-1} per 1 °C (33.8 °F) (1,691 1b ac^{-1} per 1.8 °F) temperature increase in MAT. This finding was in agreement with the finding by Burke et al. (1989), who found SOC in both range and cultivated soils decreased with MAT to about 17 °C (62.6 °F).

Decrease of SOC with increasing MAT is supported by other studies, which show SOC decreased with increasing temperature as a result of increased microbial activity (McDaniel and Munn, 1985; LIoyd and Taylor, 1994) and decomposition rates (Kirshbaum, 1995). In general, microbial activity and decomposition rate double with each 10 °C increase in temperature. However, this temperature response will be moderated if moisture becomes limiting (Davidson et al., 1998).

Under other favorable conditions for plant growth, a higher favorable temperature results in high biomass of plant, thus leading to more inputs of organic C inputs. However, warm, moist environments can support high levels of microbial activity, thus leading to difficulty storing large amounts of SOC in areas with high temperatures due to a high decomposition rate. Soils in colder climates where decomposition rate is slower may accumulate C more rapidly than soils in warmer climates. Conversely, in warm climates, soil generally contains less SOC than in cold climates (Lal, 2007). This is contributable to higher decomposition rate of SOC through respiration under higher temperatures (Canadell et al., 2007).

Mean annual precipitation (MAP)

It is known that soil moisture affects microbial activity and several other physical processes such as water movement, and gas and solute diffusion. Precipitation effects on SOC stocks are also mediated through changes in vegetation via productivity (Homann et al., 2007). For example, Dalal and Mayer (1986) reported an increase in organic C in native soils of 48 kg C ha^{-1} for each mm of rainfall. In dry land systems, primary productivity is strongly limited by moisture (Epstein et al., 1996).

Burke et al. (1989) indicated a strong response of SOC in both cultivated and rangeland soils to annual precipitation in the U.S. Central Plains, with organic C increasing to about 80 cm (31.5 inches) annual precipitation, then leveling off. There is a decrease in C above 100 cm (39.4 inches) annual precipitation that may be an artifact of the quadratic model. The increase in organic C with precipitation reflects increases in plant productivity, hence C inputs. This agrees with research work by Sala et al. (1988), who showed nearly linear increases in productivity with increased precipitation (30-120 cm, 11.8-47.2 inches) across the Central Plains grasslands. The leveling off of SOC above 80 cm annual precipitation was interpreted as the net effect of decomposition rates increasing as rapidly as production above 80 cm (31.5 inches) precipitation.

However, research finding by Follett et al. (2012) show that MAP did not significantly affect SOC, but the ratio of mean annual precipitation (MAP) to potential evapotranspiration (PET), which is in essence an estimate of available water. Thus, an increase in SOC with an increase in this ratio agrees with studies that find an increase in SOC with increasing MAP.

Management practices

SOC levels in most uncultivated soils decline rapidly when cultivation starts, due to the reduced C inputs into soil systems, and the increased decomposition of plant residues and SOM under cropping systems. SOC levels in cropping system are significantly lower than the corresponding soils under natural vegetation. Globally, grassland and forest soils are estimated to lose 20-50% of the original SOC content after 40-50 years of land use change (Bruce et al., 1999; Swift, 2001).

Any management practices that impact the microbial activity and decomposition rate either directly or indirectly, and those that enhance productivity and return of plant residues to the soil affect the amounts of organic C stored in the soils. Management practices such as tillage accelerate the decomposition rate of SOC by making the organic matter more available to soil microorganisms to decompose. Minimum or no tillage with residue retention has shown higher potential to maintain and or reintroduce C into soils, compared to tillage (Allmaras et al., 2000; Baker et al., 2007). Management practices such as fertilization, irrigation, and use of recycled organic materials (e.g. compost, biosolids, biosolids, and animal manure) generally increase the amounts of organic C stored in the soils. More discussion is presented later in the report in the section entitled *Management Practices to Increase SOC Storage (Sequestration) in Cropland.*

Factors Limiting Soil Organic Carbon Storage (Sequestration)

Soil C levels reflect the balance of C inputs and C losses under native conditions (e.g. productivity, moisture, and temperature regimes), but do not necessarily represent an upper limit in C stocks (Six et al., 2002). SOC storage (sequestration) is usually measured in terms of total C stored, but how much C is stored and for how long this C can be stored depends on the pools (active/labile vs. recalcitrant/passive) and their cycling (Six et al., 2001; Gleixner et al., 2002), form of stabilization (chemical/physical), and physical location (inter/intra-aggregate vs. free) (Balesdent et al., 2000; Six et al., 2001) of the C in the soil.

Carbon saturation

Most current models of SOM dynamics assume first-order kinetics for decomposition of various conceptual pools of organic matter (McGill, 1996; Paustian, 1994), which means that equilibrium C stocks are linearly proportional to C inputs (Paustian et al., 1997). Blair et al. (2006a, b) found that the total C stocks increase linearly with input levels up to 200 Mg dry weight (dw) ha^{-1} for 15 years, without showing any signs of saturating behavior. These models predict that soil C storage 'efficiency' is constant, and the equilibrium soil C levels could increase continuously and without limit as steady-state C input levels increase.

While many long-term field experiments exhibit a proportional relationship between C inputs and soil C content across treatments (Larson et al., 1972; Paustian et al., 1997), some long-term experiments in high C soils show little or no increase in soil C content in response to two or three-fold increase in C inputs (Campbell et al., 1991; Paustian et al., 1997). The lack of response in SOC levels to varying levels of C input over many years suggests the possibility of an upper limit or 'saturation level' for soil C, which refers to the maximum level of C that a soil will be able to retain as stabilized SOM (Six et al., 2002a, Stewart et al., 2007), regardless of management options, production, or external inputs. As a result, additional organic material inputs to the soil remain as unprotected SOM that will rapidly degrade into CO_2 back to the atmosphere (Stewart et al., 2008).

The saturating level increases with clay content of soil because increased clay contents provide increased capacity to adsorb and protect organic C in soil from being degraded by soil microbes (West and Six, 2007). In a study of temperate and tropical mineral soils to quantify the relationship between soil texture and SOC, Hassink (1997) reported that as the upper limit for the adsorption of organic inputs to clay and silt was reached, adding more organic material to the soil did not lead to increased C sequestration.

The amount of C stored (sequestered) is finite: the increase in SOC content ceases as a new equilibrium value is approached (Powlson et al., 2011). This has been demonstrated by long-term studies, which show SOC does not accumulate indefinitely (Johnston et al., 2009). For example, results of a long-term experiment from the Broadbalk Experiment at Rothmsted, UK, shows that in the treatments with farmyard manure added each year, SOC increased considerably over the 160-year period. However, the annual rate of increase was greatest in the early years and very slow near the end as the soil approached a new equilibrium value for SOC (Johnston et al., 2009).

The time taken for soil to reach a new equilibrium is variable. Soil C levels may not reach a new equilibrium until 100 years after land-use or land management change in a temperate region such as Europe (Jenkinson, 1988; Smith et al., 1996). It takes a minimum of 20 years for soil C to approach a new equilibrium (Paustian et al., 1997). With improved management practices, this new equilibrium may occur in 50 years (Chan et al., 2008).

Soil C storage does not have unlimited potential to offset CO_2 emissions and the yearly benefits will continue for about 20-50 years. The final level of soil organic C depends on the ability of the soil to stabilize C, which is related to soil properties (e.g. soil cation exchange capacity, clay content and soil mineral composition), the prevailing soil moisture and temperature, the quality of the C added to soil, and the balance between the C input to the soil and C lost through respiration (Six et al., 2002a).

Soil C saturation suggests similar management practices may result in positive sequestration in one soil that is far from its maximum C stabilization level, while no change in another soil that is much closer to its saturation level (Six et al., 2002a). The further a soil is from saturation (e.g. the greater the saturation deficit), the greater its capacity and efficiency to sequester added C, whereas a soil approaching saturation will accumulate a smaller amount of SOC at a slower rate and efficiency (Hassink and Whitmore, 1997).

C saturation may be particularly important for understanding how much C the soil can sequester, how fast it can be sequestered, and for how long sequestration will occur through use of recycled organic materials (e.g. manure, compost, and biosolids).

Non-permanence

Soil C stored (sequestered) in soils is nonpermanent, as changes in agricultural management or land use can result in declining soil C levels. The change in land management leading to increased C in soil or vegetation must be continued indefinitely to maintain the increased stock of SOC (Freibauer et al., 2004). For example, if a grass or legume ley is included in an arable cropping system, at least part of the SOC accumulated during the ley period is lost after plowing for the next arable phase (Wu et al., 1998), although there will often be some overall increase in SOC in the long-term compared with continuous arable cropping if the ley-arable rotation is continued (Johnston et al., 2009).

By changing agricultural management or land use, soil C is lost more rapidly than it accumulates (Smith et al., 1996). Once equilibrium or a certain content of C is reached, it is still necessary to add significant amounts of C to maintain the attained soil C level. Agricultural soil with 50% clay content requires greater than 2.2 tons C ha^{-1} annually to maintain a given C level, while agricultural soils containing 30% clay content requires greater than 6.5 C tons ha^{-1} annually. In addition, the rate of C input has to be higher at higher existing soil C levels in order to maintain soil C stock at the level (Biala, 2011).

Even with these general limitations to the effectiveness of C sequestration in soil in mitigating climate change, storing (sequestering) additional C in soil could contribute to climate change mitigation in the medium-term in some regions of the world, depending on the options available for changes in management practices of land use. Practices to increase SOC in soil can start immediately without the need to develop new technologies (Powlson et al., 2011).
In situations where there is no net additional transfer of C from the atmosphere to soil, and thus no climate change mitigation, increasing or maintaining SOC content is always beneficial to soil quality and functions, especially for agricultural soils (Powlson et al., 2001) (*see Soil Organic Matter, and its Pools and Roles in Soil Health*).

Mechanisms of Soil Organic Matter Stabilization (Protection)

Stabilization (or protection) of SOM is a process which acts to slow the decomposition process. For example, some organic substances (e.g. lignin) are energetically costly for microorganisms to degrade, especially during the initial stages of decomposition (Kogel-Knabner et al., 2008) until more labile substrates are used up. Three main mechanisms have been proposed to be responsible for SOM stabilization (Christensen, 1996; Stevenson, 1994):

- Chemical stabilization.
- Physical stabilization.
- Biochemical stabilization.

Chemical stabilization

Chemical stabilization of SOM is the stabilization of SOM from microbial decomposition through chemical or physic-chemical binding between SOM and soil minerals (e.g. soil clay and silt particles). Research has reported a relationship between protection of organic C and N in soils and clay or silt plus clay contents (Feller and Beare, 1997; Hassink, 1997). Hassink (1997) observed a close relationship between the proportion of primary particles (<20 µm) in the soils and the SOM associated with this fraction in the top 10 cm of soil profile. The amount of SOM in the >20 µm fraction was not correlated with texture, and cultivation decreased the amount of SOM in the >20 µm fraction more than in the <20 µm fraction, indicating SOM associated with the <20 µm is better protected against decomposition.

Soil with a high clay and silt content may also enable the formation of micro- and macro-aggregates which can further protect SOM: Once the microaggregates are saturated with organic matter, additional organic matter would be found mainly in the sand-sized organic matter fraction (Jastrow, 1996; Tisdall and Oades, 1982), but cultivation would tend to break this down, as shown by Hassink (1997). The C fraction associated with fine silt sized particles (2-20 µm) was not significantly affected by tillage and natural abundance ^{13}C analyses showed it to be the oldest C fraction isolated from micro- and macro-aggregates (Six et al., 2000b).

In addition to the clay content, clay types (e.g. 2:1 versus 1:1 versus allophonic clay minerals) influence the stabilization of organic matter. Studies indicate there is a direct relationship between the silt plus clay content of soil and the amount of silt- and clay-protected soil C, indicating a saturation level of silt and clay associated with C (Hassink, 1997; Six et al., 2002b). However, this relationship was different between different types of land use, different clay types, and different silt plus clay size class. The silt- and clay-associated SOM was reduced by cultivation.

Physical stabilization

Physical stabilization of SOM is the stabilization of SOM from microbial decomposition through occlusion within macro- and/or micro-aggregates and adsorption onto minerals (Six et al., 2000a, b; Six et al., 2002b). The occlusion of SOM within aggregates contributes to:

- Inaccessibility of substrate to microbes and enzymes within soil aggregates (Killham et al., 1993; van Veen and Kuikman, 1990).

- Interactions of organic matter with minerals, metal ions and other organic substances (Dungait et al., 2012).

Physical inaccessibility of an organic substrate to microbes and extracellular enzymes is attributable to:

- Microorganisms and substrates are sparsely and heterogeneously distributed in the soil, and there are many physical and diffusional barriers to microbial movement in the soil due to the sparse and heterogeneous distribution of substrates in soil (Young et al., 2005).

- Pore sizes less than 0.2 µm in diameter are too small for most bacterial and fungal hyphae to enter, and enzymes can also be inhibited from entering as pore sizes decrease to less than 0.5 nm (Zimmerman et al., 2004).

- The hydrophobicity of numerous substrates, especially partially-oxidized materials, greatly reduces accessibility (Bachmann et al., 2008).

- Reduced diffusion of oxygen and enzyme into macro- and especially micro-aggregates (Sexstone et al., 1985), thus resulting in reduced microbial activity within the aggregates (Sollins et al., 1996).

Soil aggregation has a positive influence on the accumulation of SOM (Franzluebbers and Arshad, 1997; Paustian et al., 2000). Cultivation breaks up soil aggregates, thereby increasing the availability of organic C for soil microorganisms (Elliott, 1986; Six et al., 2000a, b). Studies indicate that the macro-aggregate (>250 µm) structure has a little physical protection for SOM (Beare et al., 1994; Elliott, 1986), whereas SOM is protected from decomposition in free (e.g.no within macro-aggregates) micro-aggregates (<250 µm) (Besnard et al., 1996; Skjemstad et al., 1996), and in micro-aggregates within macro-aggregates (Denef et al., 2001; Six et al., 2000c).

Interactions of organic matter with minerals, metal ions, and other organic substances involve various adsorption reactions with mineral surfaces, complexation, and precipitation reactions with polyvalent metals (Scheel et al., 2008). These complexes are contributable to SOM stabilization primarily by restricting enzyme and microbial access to the substrate (Vanloosdrecht et al., 1990).

The clay content and type of soil exert an indirect influence on the physical stabilization of particulate organic matter (POM). Franzluebbers and Arshad (1997) suggested that physical protection of POM within aggregates increases with clay content. Different clay types lead to different mechanisms involved in aggregation (Oades and Waters, 1991), thus influencing differently the protection of POM through micro-aggregation. Within the 2:1 clay minerals, clay minerals with a high cation exchange capacity (CEC) and larger specific surface, such as montmorillonite and vermiculite, have a higher binding potential than clay minerals with a lower CEC, such as illite (Greenland, 1965).

The physical protection of POM is seemingly mostly determined by micro-aggregation. It is hypothesized the maximum micro-aggregation determines the maximum physical protection capacity, which is in turn determined by soil clay content and type (Six et al., 2002a, b).

Biochemical stabilization

Biochemical stabilization of SOM is the protection of SOM from microbial decomposition due to the complex chemical composition of the organic matter (e.g. recalcitrant compounds such as lignin and polyphenols) and through chemical complexing processes (e.g. condensation reactions in soil) by the action of microbial populations (e.g. bacteria and fungi) and invertebrates, resulting in acquired stability (Christensen, 2001; Six et al., 2002a).

Biochemical protection of SOM occurs due to the complex chemical composition of the organic materials. This complex chemical composition can be an inherent property of plant residue, or be acquired during decomposition through the condensation and complexation of decomposition residues, rendering them more resistant to subsequent decomposition (Six et al., 2002b).

Management Practices to Increase Soil Organic Carbon Storage (Sequestration) in Cropland

SOC reflects the net balance of organic C inputs and losses. Therefore, agricultural management practices that increase C inputs through increasing crop productivity, or through the application of external sources of C (e.g. animal manure, compost, and biosolids), and/or reduce C losses can increase soil C storage (Lorenz et al., 2007). In general, the effective management practices which increase SOC storage include:

- Management to increase crop yields.
- Tillage and crop residue management.
- Crop rotation, pasture, and grazing management.
- Additions of organic matter.
- Alternative farming systems.

These management practices are summarized in Table 2.

Table 2

Agricultural Management Practices that Can Increase SOC Level

Management Practices	Mechanisms in C Sequestration	
	Increase Inputs	Decrease Losses
Cropping Land		
Adoption of conservation/no tillage	Yes	Yes
Use of winter cover crops	Yes	Yes
Improved crop nutrition	Yes	
Elimination of summer fallow	Yes	Yes
Use of forages in rotation	Yes	
Use of organic soil amendments	Yes	
Irrigation	Yes	
Pastureland		
Improved grazing regime	Yes	Yes
Fertilizer application	Yes	
Use of organic soil amendments	Yes	
Use of improved species	Yes	
Irrigation	Yes	
Rangeland		
Improved grazing regimes	Yes	Yes
Degraded Land		
Reversion to native vegetation	Yes	
Establishment of fast-growing crops	Yes	Yes
Application of fertilizers	Yes	
Application of organic soil amendments	Yes	
Drainage/leaching of saline soils	Yes	

Conservation tillage and crop residue retention

Conservation tillage was initially promoted as a way to save fuel in the 1970s (Pratley and Rowell, 1987). Its greater flexibility in seeding operations and reduced risk of soil erosion by wind and water are the primary two reasons for adoption of conservation tillage in the major grain production regions (Chan and Pratley, 1998). Conservation tillage includes minimum tillage, direct drill, and no-tillage systems. As a part of an overall conservation tillage plan, crop residue retention is considered critical in maintaining or improving crop yields with additional benefits of minimizing soil erosion, conserving soil moisture, and increasing SOC (Chan and Pratley, 1998).

In general, SOC levels are higher in no till systems than conventional till systems. When soil is tilled, soil aggregates are disturbed, which leads to increased decomposition rates of slow-turnover SOC pools (Balesdent et al., 2000). However, formation of the slow-turnover SOC pools may be much slower than losses, thus accumulation of SOC may not be as rapid as losses of SOC (Balesdent et al., 2000).

Adoption of no-tillage following conventional tillage generally results in SOC increases, but in some instances little or no increases are observed. In the Pacific Northwest, increases in soil profile SOC (20 cm) ranged from 0.03 to 1.95 Mg C ha^{-1} yr^{-1} and averages for different agroclimate zones ranged from 0.21 to 0.71 Mg C ha^{-1} yr^{-1} (Brown and Huggins, 2012). These values are within range of 0.3 to 0.8 Mg C ha^{-1} yr^{-1} reported by other studies (West and Post, 2002; Liebig et al., 2005) from comparison of no-tillage conventional till cropland.

Purakayastha et al. (2008) found SOC content in the depth of 0 to 20 cm from an unreplicated field survey was significantly higher under no-tillage compared to conventional tillage. There was no significant differences in SOC between 4 and 28 years of no-tillage practice, but particulate organic C (POC) in the surface 5 cm was significantly higher in the 28-year no-tillage site (8.1 Mg C ha^{-1}) compared to the 4-year no-tillage site (6.3 Mg C ha^{-1}). Gollany et al. (2006) found that increased SOC storage in the fine organic matter fraction with reduced tillage ranged from 0.16 to 0.18 Mg C ha^{-1} at N fertilizer rates of 15 and 180 kg N ha^{-1} under long-term (44 years) wheat-fallow system, compared to moldboard plowed soils.

However, a few studies reported that no-tillage and reduced tillage has more SOC compared to the conventional tillage counterpart (Rasmussen and Rhode, 1988). In a global analysis of long-term experiments, West and Post (2002) found the average relative increased SOC stock was 0.57 ± 0.14 Mg C ha^{-1} yr^{-1}, with 75% of the studies showing increased SOC stocks. Similarly, Baker et al. (2007) found that 37 of 51 studies reported positive results in no-tillage with sampling depth < 30 cm, while 35 studies with depths > 30 cm reported losses.

The majority of SOC increase under no-tillage was observed to be in the top of 10-15 cm, with insignificant changes or even decreases relative to conventional tillage at deeper depths (Angers and Eriksen-Hamel, 2008; Balesdent et al., 2000; Kern and Johnson, 1993; Thomas et al., 2007a, b). Angers and Eriksen-Hamel (2008) found there was a small, but significant increase in total SOC stocks under no-tillage, but all of this increase was observed in the upper 10 cm. This can be explained by residue burial to a greater depth due to tillage and shows that limited depth of soil sampling could result in over- or under-estimation of SOC stocks.

Recent research suggests reduced disturbance practices (e.g. no till cultivation or establishment of perennial vegetation) generally increase fungal-dominated pathways in organic matter cycling, which may increase the residence time of microbial residues and lead to their buildup in SOM (Stahl et al., 1999; Bailey et al., 2002).

Research reported no-tillage practices improve soil aggregation, C storage (sequestration), and aggregate stability (Mikah and Rice, 2004; Zhang et al., 2007). The increase in aggregate stability contributes to increased soil water infiltration and resistance to wind and water erosion (Zhang et al., 2007). Macroaggregate stability (> 250 µm diameter) is particularly sensitive to changes in management practices (Zibilske and Bradford, 2007). The loss of macroaggregate-occluded organic matter is a primary source of C lost due to changes in management practices (Six et al., 2002a, b; Mikha and Rice 2004; Jiao et al., 2006). Continuous cropping with reduced fallow frequency and no-tillage has a positive effect on macroaggregate formation and stabilization, as well as particular organic matter (POM) and SOC (Mikha et al., 2010).

Fallow and crop rotations

Fallowing has been primarily adopted to maintain soil moisture and nitrogen in semi-arid regions, and reduce weeds and disease (Sims, 1977). Fallows accelerate SOC losses by eliminating C source inputs during the fallow period, and by creating favorable moisture and temperature conditions for microbial decomposition and soil erosion. For example, fallow cropping every other year results in losses of SOC ranging from 0.09 to 0.65 Mg C ha^{-1} yr^{-1} within the surface of 30 cm (Horner et al., 1960), and ranging from 0.09 to 0.12 Mg C ha^{-1} yr^{-1}, recently reported by Rasmussen and Albrecht (1998).

Conversion of conventional tillage wheat-fallow to annual no-tillage continuous wheat system increased SOC to near native SOC level in the top 5 cm, but there was no difference in the surface 10 cm layer among no-tillage systems with various annual crop rotations in wheat-fallow regions in Washington State (Brown and Huggins, 2012). In another study conducted in Washington State, Gollany et al. (2012) reported that no significant changes in SOC in the top 30 cm of the sweep-tillage winter wheat (*Triticum aestivum* L.)-tillage fallow rotation and no till spring wheat-chemical fallow rotation, whereas SOC increased in the no-till spring barley (*Hordeum vulgare* L.)-spring wheat rotation. The apparent increase in measured SOC with continuous no-till spring cropping was the result of accumulated undecomposed crop residue that contributed to the labile C pool.

Reduced fallow frequency or eliminated fallow has the potential to reverse SOC losses and help restore degraded land (Lal et al., 1979). For example, Grace et al. (1995) found that SOC concentrations increased linearly with increasing frequency of pasture phase at the long-term permanent rotation experiments. Mikha et al. (2010) found that continuous cropping with reduced fallow significantly increased SOC, when compared with rotations that included fallow every second and third year. Dalal et al. (1995) found that SOC increase of 0.65 Mg C ha^{-1} yr^{-1} for four years under a grass-legume rotation system compared to continuous wheat cropping system.

Continuous cropping (wheat-corn-millet) significantly increased soil POM at the 0 to 5 cm depth by 29% compared to wheat-corn-fallow, and by 21% compared with wheat-corn-millet-fallow (Mikah et al., 2010). This result indicates that POM decreases with increased fallow frequency. This observation is in agreement with that reported by Mikha et al. (2006), who found an increase in soil POM level with the reduction in tillage intensity and fallow frequency. In higher precipitation of the dryland Pacific Northwest, including a perennial crop into an otherwise annual crop rotation (mixed perennial-annual rotation) was found to increase SOC stocks at the depth from 0-92 cm layer by 0.66 to 1.97 Mg C ha^{-1} yr^{-1} (Brown and Huggins, 2012).

Pasture management

In general, soils under pasture tend to have a higher SOC than cropped soils because they have a higher root to shoot ratio than many crops, are typically less disturbed, and have lower rates of SOC decomposition (Chan et al., 2010). Studies have demonstrated improving pasture management through seed sowing and fertilization application can increase SOC stocks (Chan, 1997; Chan et al., 2010).

Other pasture management practices (e.g. grazing management and use of other pasture species) are reported to increase SOC stocks. For example, among studies that examined different levels of grazing intensity, about 30% found lower SOC contents for moderately grazed compared to heavily grazed treatments (Conant et al., 2001). Nyborg et al. (1999) found that nitrogen and sulfur fertilization increased SOC stocks at a rate of 0.5-1.0 Mg C^{-1} ha^{-1} yr^{-1} over 5-13 years.

Generally, perennial grasses have a deeper, more extensive root system compared to annual ones. The use of perennial grasses in marginal pastures has the potential to increase SOC stocks. Young et al. (2009) found significant increases in SOC stocks (0.15 to 0.35 Mg C ha^{-1} yr^{-1}) at the depth from 0-20 cm over 6 years of repeated measurements when various perennial pastures were established.

Irrigated systems

Irrigation takes an important role in crop production in arid and semiarid regions. Compared to rain-fed crops, irrigated crops produce twice as much as plant biomass (Bucks et al., 1990). Irrigation increases C input to soils through increasing plant residues and root systems (Kong et al., 2005). Lal et al. (1998) estimated irrigation resulted in a SOC sequestration rate of between 50 and 150 kg C ha^{-1} yr^{-1}. Eve et al. (2002) estimated SOC sequestration due to irrigation in the western U.S. ranges from 0.25 to 0.52 Mg C ha^{-1} yr^{-1}. Entry et al. (2002) reported irrigation significantly increases SOC stocks under different pasture and conservation tillage compared to the native sagebrush ecosystem.

C storage (sequestration) is expected to increase if efficient water use allows the expansion of irrigated agriculture. Collins et al. (2012) estimated land-use shifts from arid native vegetation could sequester 8.0 Mg C ha^{-1}, and assuming 10% expansion of irrigated agriculture, 7.2×10^6 Mg C could potentially be sequestered in Pacific Northwest soils.

Organic farming systems

Many studies have demonstrated organic farming systems which rely on use of recycled organic materials (e.g. animal manures and compost) offer many benefits (Lotter et al., 2003; Marrior and Wander, 2006):

- Increased SOC storage (sequestration).
- Reduced greenhouse gas emissions.
- Lowered energy consumption.
- Maintained or increased farm profitability.

Sayre (2003) found SOC was increased by 15% and 28%, in two organic systems (one legume based and one manure based) respectively, compared to adjacent conventional farming systems. Wells et al. (2000) reported in vegetable farming, organic farming systems significantly increased SOC levels over conventional systems. Clark et al. (1998) also reported SOC stocks in the depth of top 15 cm increased by 0.3 and 0.5 Mg C ha^{-1} yr^{-1} for low-input crop rotation and organic systems respectively in California, while no change was observed in the conventional farming systems over the same period.

Azeez (2009) estimated an average of 20% higher SOC sequestration rates for organic farming, compared to conventional farming on the global scale. Pimentel et al. (2005) found in Pennsylvania, 22 years of manure based and legume-based organic farming systems increased SOC at a rate of 0.7 and 0.3 Mg ha^{-1} yr^{-1} respectively, compared to a conventional farming system. However, it was found that the new increased SOC was primarily in the biologically active fractions (Wander and Traina, 1996; Wander et al., 1994) that may have little permanence if there are no new inputs.

CO_2 emissions are about 40-60% lower in organic farming systems compared to conventional systems (Sayre, 2003), mainly because organic farming systems are not allowed to use chemical fertilizers which consume a large amount of energy for their production.

Use of recycled organic materials

Recycled organic materials include compost, biosolids, biochar, and other organic materials (e.g. animal manure and food waste). They are a valuable source of nutrients and organic matter.

Use of recycled organic materials represents direct inputs of organic C to the soil systems and an important source of plant nutrients. A large number of studies have shown increased SOC contents when compost, biosolids or manures are land applied (Kong et al., 2005; Schroder et al., 2008; Zinati et al., 2001). Increased SOC contents following land applications of recycled organic materials provide a range of benefits. These benefits (Cogger et al., 2008; Favoino and Hogg, 2008; Khaleel et al., 1981) include:

- Increased water holding capacity and water infiltration rates.
- Reduced bulk density.
- Improved soil tilth.
- Reduced erosion potential.
- Decreased need for herbicides, pesticides, and fertilizer uses.
- Improved yields and/or crop quality.

Recycled organic materials such as compost and biosolids are more effective than fresh plant residues in raising soil C, because compost and biosolids have already undergone a decomposition process, and the organic C contained is present as relatively more recalcitrant fractions (Inbar et al., 1990; Poulton, 1995; Zinati et al., 2001).

Applications of recycled organic materials offer a significant potential to store C in soils, but this potential depends on the factors controlling SOC dynamics (climate, soil type, and management practices), as well as the nature (e.g. chemical composition) of recycled organic materials applied. For example, clay soils have greater retention of added organic C than sandy soils (Coleman et al., 1996). Higher SOC levels were reported in compost-treated soil than those treated with animal manure treated soils, or fertilizer-treated soil, and control (Zinati et al., 2001). The higher levels of SOC are attributable to higher levels of more stable, less oxidizable C forms of humin, humic acid, and fulvic acid in compost-treated soil compared to the other amendments or control (Zinati et al., 2001).

This subsection discusses only compost, biosolids, biochar, and animal manure.

Compost

Composting is the controlled decomposition of organic materials such as animal manure, woody materials, lawn clipping, food scraps, and other organic matter. Composting involves a wide variety of physical, chemical, and biological transformations of the feedstocks. During the composting, most readily degradable compounds (e.g. sugar, starch, and protein) are broken down. After composting, a high fraction of the organic C (about 50%) contained in well-matured product is in the form of humic substances (e.g. humin, humic, and fulvic acids) (Inbar et al., 1990), and can be considered to be equivalent to the more stable SOC fractions (Baldrock and Skjemstad, 1999; Post and Kwon, 2000). It has been shown humic acids contained in compost consist of a stable fraction and a labile fraction, the relative contents of which depend on the duration of composting (Biala, 2011).

Although there is limited long-term research on the SOC storage (sequestration) rates by using compost, increased SOC storage (sequestration) has been reported in a number of short-term field experiments. For example, Reeve et al. (2012) observed significantly greater levels of SOC in the soil depth of 0- to 5-cm 16 years following the application of 50 Mg ha^{-1} dry weight of dairy manure compost to a wheat-fallow rotation compared with un-amended controls (143 g C kg^{-1} in amended soil vs. 89 g C kg^{-1} in unamended soil). Brown and Cotton (2011) also observed up to three times increases in SOC at the soil depth of 0- to 15-cm from farm sites with a history of compost use in California when cumulative loading application rates were from 101 to 448 dry Mg ha^{-1}. Significant changes were also observed in soil microbial activity (2.23 x control), gravimetric water (1.57 x control), and bulk density (0.87 x control). Increases in SOC indicate increases in C storage (sequestration) in soils following application of compost.

Lal et al. (1998) reported that the use of compost resulted in the SOC sequestration rate of 0.1 to 0.3 t C ha^{-1} yr^{-1}, and 0.2 to 0.5 t C ha^{-1} yr^{-1} in dryland and tropical areas, respectively. In studies in England, after 8 years of compost applications (1 site) and 5 years, a mean annual SOC increase of 60 kg C ha^{-1} yr^{-1} t^{-1} dry solids was observed (Wallace 2005; Wallace, 2007). This is similar to the annual rate of increase of 70 kg C ha^{-1} yr^{-1} t^{-1} dry solids reported in an experiment in Austria after 12 years of compost applications (Ros et al., 2006).

Biosolids

Biosolids, a byproduct of the wastewater treatment process, are classified as either Class A or Class B depending upon the pathogen reduction level. Pathogen reduction levels can be met through aerobic or anaerobic digestion, additions of lime or alkali, composting, or drying (USEPA, 1995). In order to be land applied, Class A or B biosolids must meet requirements by the United States Environmental Protection Agency's rule (USEPA 503), and Washington State's Biosolids Rule (WAC 173-308) which address concerns about possible pathogen transmittal, NO_3^--N pollution, and trace metal contamination. The requirements include:

- Pathogen and vector reduction.
- Monitoring of metal concentrations.
- Site-specific land use, including but not limited to:
  - Agronomic rate application calculations.
  - Buffers and site restrictions.

Biosolids contain nutrients and organic matter, and could be used as a valuable source of nutrients, especially nitrogen (N) and phosphorus (P), or as a soil amendment for agriculture, forestry, and remediation of degraded lands (Hettiarachchi et al., 2003; Ippolito et al., 2010). Land application of biosolids is the option favored internationally for sludge management compared to traditional landfilling and incineration options, as it contributes positively to recycling nutrients, soil fertility and crop production (National Research Council, 1996). Land application of biosolids is also likely to become an increasingly essential aspect of sustainable nutrient management as phosphorus becomes depleted (Steen, 1998).

Typically, biosolids are made of 40-70% organic matter, with organic C content ranging from 20-50%, total N ranging from 2-5%, and a C:N ratio of about 10-20 (Christensen, 2001). Land application of biosolids represents direct input of organic C to soils, and has shown to increase SOC content in short and long-term studies (Gibbs et al., 2006; Mantovi et al., 2005), which, in turn, leads to increased C storage (sequestration). For example, Brown et al. (2011) reported that biosolids applied either annually at agronomic nitrogen (N) rates or at a one-time high rate across resulted in C storage increases from 14 kg C ha^{-1} (not significant) in a study of turf grass to 540 kg C ha^{-1} t^{-1} in a commercial orchard in a range of sites in Washington State.

In another biosolids applications in dryland wheat study in Washington State, Cogger et al. (2013) observed SOC content was increased to 16.9 g kg^{-1} with modest rates of biosolids applied (28.1 Mg ha^{-1} cumulative from 1994-2012) compared to 12.9 g kg^{-1} with non-biosolids treated soil. Powlson et al. (2011) found that the application of digested biosolids resulted in 180 kg C ha^{-1} t^{-1}dry solids of the mean annual rate of SOC increase, while the application of raw biosolids resulted in 130 kg C ha^{-1} t^{-1} dry solids of the mean annual rate of SOC increase.

The mean values for C sequestration rates from the application of digested biosolids are greater than the corresponding value for raw biosolids. This supports the notion that similar to composting, much of the easily degradable C in biosolids is lost during the anaerobic or aerobic digestion process before it is land applied, thus when applied to soil, the organic C in digested biosolids is more resistant to decomposition than organic C in the raw biosolids.

However, beneficial land application of biosolids is generally based on crop N requirements. This will generally supply phosphorus in excess of crop needs (Cogger et al., 2001; Ippolito et al., 2007; Shober and Sims, 2003). This can result in accumulation of excess P in soils to values well above those needed for optimum crop yields. The excessive P accumulation is not harmful to crops (Peterson et al., 1994), but the accumulation of excess P in amended soils increase the potential for P losses from runoff and soil erosion to surface and ground waters, which can lead to surface water eutrophication, a water quality concern (Carpenter et al., 1998; Maguire et al., 2000).

The growing concern over excess P in soils has led to regulatory changes that could dramatically affect land-based recycling of biosolids. For example, 24 states (e.g. Maryland and Florida) in the U.S. now recommend or require P-based nutrient management plans for the land application of biosolids (Shober and Sims, 2003).

The risk of P loss is not simply related to the P supplied but depends also on soil site, and biosolids factors that can be assessed through a P site index (PSI) approach (Elliott and O’Connor, 2007). The use of PSI to identify P loss risks, adoption of conservation tillage to reduce erosion, rotation of biosolids application to sites with low soil test P levels, and development of wastewater treatment processes that reduce biosolids P will enhance the sustainability of biosolids beneficial land applications and allow continued C and N benefits associated with biosolids land application (Cogger et al., 2013).

Biochar

Biochar refers to a C-rich product through pyrolysis after biomass (e.g. wood chips, crop residues) has been heated at low temperatures (350-600 °C) in an environment with little or no oxygen (Amonette and Joseph, 2009). The use of biochar as a soil amendment has been investigated since the early 1800s, and has been proposed as a novel approach to establish a significant, long-term sink for atmospheric CO_2 in terrestrial ecosystems due to concern about global climate change and energy shortages (Lehmann et al., 2006; Lehmann and Joseph, 2009).

With the right feedstock and optimal pyrolysis, biochar retains 50% or more of the C contained in the original biomass (Lehmann et al., 2002; Laird, 2008). However, only about 3% of above ground biomass would be converted into forms similar to biochar (often called charcoal or biomass-derived black C in the respective literature) if the biomass is burned, and less than 10-20% C after 5-10 years of biomass decomposition (Glasier et al., 2002; Lehmann et al., 2006). Due to its relative recalcitrance against microbial attack, when biochar is applied to soil, it is remarkably stable and it takes thousands of years to degrade, thus slowing down terrestrial organic C released as CO_2 (Lehmann et al., 2006). Therefore, biochar represents high C sequestration value, compared to un-charred biomass materials.

Much of the recent interest in biochar as a soil amendment was prompted by studies of Amazonian soils (Terra Preta) in the Amazon Basin that have received large amounts of charred materials, the residues from biomass burning (Lehmann et al., 2006). These applications might be a result of both habitation activities and deliberate soil application by Amerindian population previously (Erickson et al., 2003). In these soils, the presence of charcoal was significant improvements in soil quality (e.g. SOM and nutrient concentrations) and increases in crop yields (Glaser et al., 2002; Lehmann, 2007; Novak et al., 2009). Large amounts of biochar derived C stocks remains in these soils today for thousands of years (Lehmann et al., 2006). The total C storage is estimated to be as high as 250 Mg C ha^{-1} compared to typical values of 100 Mg C ha^{-1} in Amazonian soils derived from similar parent material (Glaser et al., 2002).

In addition to increasing C sequestration and reducing greenhouse gas emissions, the production of biochar and its application to soil generally deliver immediate benefits:

- Increases soil pH and decreases the concentration of Al in acid soils (Hecht, 1982; Piccolo et al., 1997).
- Increases crop yields (Steiner et al., 2007).
- Increases cation exchange capacity, and improved nutrient retention and water holding capacity.
- Increases soil cation exchange capacity and soil microbial activity (Glaser et al., 2002, Lehmann et al., 2003; Lehmann and Rondon, 2005).
- Reduces emissions of other greenhouse gases such as methane and nitrous oxides (Rondon et al., 2005).

Application of biochar to sequester C in agricultural soils to mitigate climate change can only be accomplished economically if biochar has fertilizer or soil amendment value (Day et al., 2004). Currently, a limited amount of biochar material is used in agriculture in the world. Some research has demonstrated that some soils respond to biochar applications, with improved soil fertility and structure, while other soils do not show such benefits. Spokas et al. (2012) reviewed more than four dozen biochar and black C studies dating from 1950 to 2011 to assess agronomic impact beyond C sequestration, and they found that half of the studies reported positive effects on yield, 20% no effect, and 30% negative effect. The overall impact on yield ranged from +200% to -87%. Similarly, Glaser et al. (2002) observed a huge range of biochar application rates (0.5-135 tons ha^{-1}), as well as a huge range of plant responses (-29-324%). The positive effects on crop production are often associated with weathered or degraded and nutrient deficient soils, while application of biochar to fertile and healthy soils does not always show a positive result (Spokas et al., 2012).

However, there are some concerns about use of biochar (Bell and Lawrence, 2009). Due to recalcitrant nature of biochar to microbial degradation, the characteristics of a healthy soil could be compromised by converting organic materials, which are already scarce resources, into more expensive and relatively inert organic matter inputs. Due to these concerns, biochar should mainly be produced from waste streams of C such as forest residues (e.g. logging residues, dead wood), mill residues (lumber, pulp), urban wastes (yard trimmings, site clearing, pallets, wood packaging), or field crop residues that have already left the farm (Lehmann et al., 2006).

Animal manure

Addition of animal manure to croplands has been a common practice for maintaining agricultural productivity. There have several long-term agricultural experiments conducted to determine the impacts of different manure application rates (Blair et al., 2006a, b; Stewart et al., 2007).

A long-term field trial in England shows that applications of animal manure at a rate of 35 Mg ha^{-1} yr^{-1} since 1852 have increased SOC to 3% compared to 1% in non-manure treated soil (Poulton, 1995). In another long-term field experiment in Germany, the SOC levels in soils treated with manure at annual application rate of 200 Mg ha^{-1} yr^{-1} were found to be greater than those in adjacent non-cultivated grassland (Blair et al., 2006b). Increased SOC content indicates increased SOC storage (sequestration) in soils. Powlson et al. (2011) reported that the mean annual SOC sequestration rates of three long-term (>49 years) of manure applications ranged from 10 to 22 kg C ha^{-1} yr^{-1} t^{-1} dry solids, while SOC sequestration rates with shorter term experiments (8-25 years of farmyard manure, cattle slurry and boiler litter) were from 30 to 200 kg C ha^{-1} yr^{-1} t^{-1} dry solids. The mean value for the long-term manure application is higher than the value for shorter-term manure application, suggesting that rates of SOC storage decline in relation to inputs as total SOC content approaches an equilibrium.

The trend for a decreasing rate of annual SOC increase over time has been reported by Bhogal et al. (2006, 2007). The annual rate of SOC increase declines rapidly after about 20 years of manure application. At two sites where pig manures had been applied for only 8 years, the mean annual SOC increase rate was nearly 200 kg ha^{-1} yr^{-1} t^{-1} dry solids, while for the site where cattle manures had been applied for 144 years, the annual rate of increase (averaged over the entire period) had declined to 10 kg ha^{-1} yr^{-1} t^{-1} dry solids. This is consistent with the concept of soils moving toward a new equilibrium SOC content as discussed by Johnston et al. (2009).

While land application of animal manure provides many soil and crop production benefits, accumulation of excess P is also a water quality concern in soils receiving repeated application of animal manure (Sharpley et al., 1994). Consequently, a number of states in the U.S. have passed laws or established guidelines restricting the application of P in animal manures and/or fertilizers, such as those in Delaware, Maryland, and Virginia that restrict manure P applications and require some form of P-based nutrient management when soil test P exceeds a certain value (Coale et al., 2002; Sims et al., 2002). All lands receiving animal manure are required to implement a nutrient management plan in accordance with the USDA-NRCS Code 590 standard, which requires adoption of P-based manure management plans in field with high or very high soil test P levels, or when soil test P equals or exceeds threshold levels, or when a PSI assessment (Lemunyon and Gibert, 1993) indicates a high risk of P loss to water (USDA-NRCS, 2014).

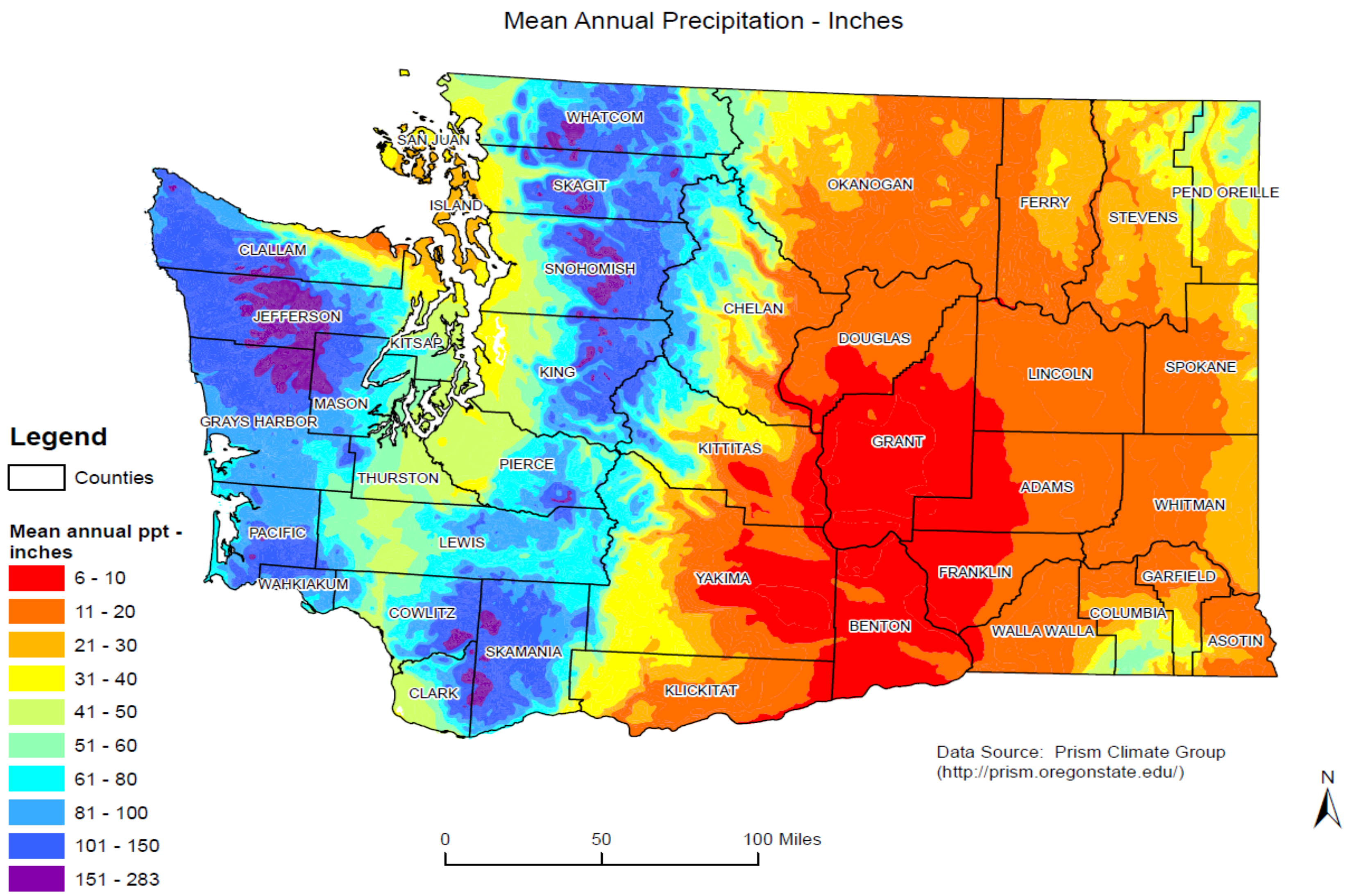
Climate and Types of Soil in Washington State

Climate of Washington State

As discussed previously (see *Climate*), climate in the form of temperature and moisture affects both inputs and losses of organic matter in soils, thus impacting the amount of C stored in the soil, because both temperature and moisture serve as controls to SOC and CO_2 respiration rate (Jobbágy and Jackson, 2000; Conant et al., 2004). When sufficient water is provided, higher temperatures lead to faster decomposition of soil organic matter, less storage of C in the slow and passive pools, and greater loss of C through respiration (Canadell et al., 2007). In warm climates, soil generally contains less organic soil C than in cold climates (Lal, 2007).

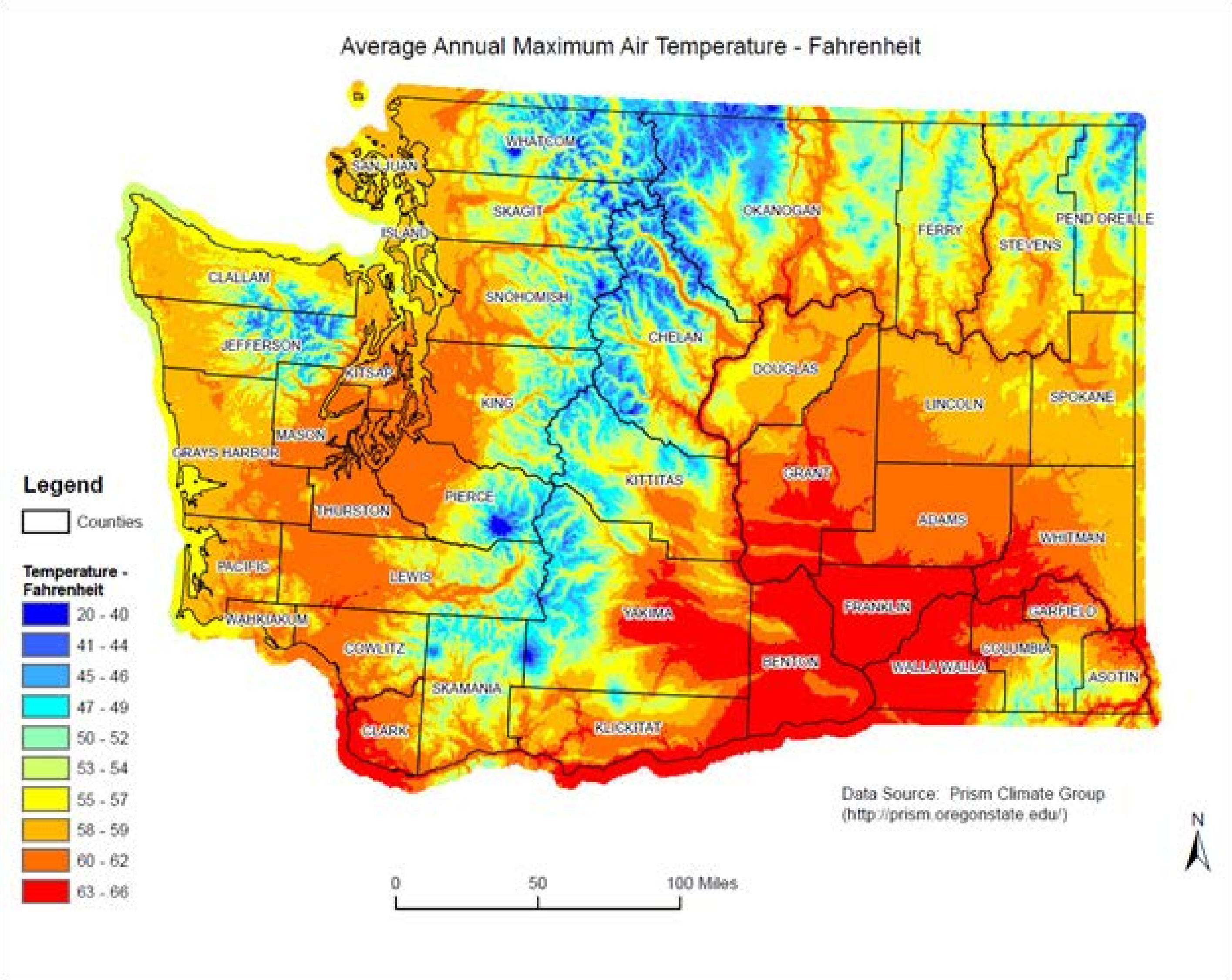
This section briefly presents climate conditions in the form of annual precipitations and air temperatures. The information was obtained from Western Climate Center (http://www.wrcc.dri.edu/narratives/washington/). In general, in the western Washington of the state a marine-type climate dominates, with comparatively cool summers and mild, wet, and cloudy winters, while in the eastern Washington of the state, the climate possesses both continental and marine characteristics, with warmer summers, colder winters, and less precipitation than western Washington State.

The annual mean precipitation in the state is shown in the GIS map in Figure 1, and the annual mean maximum and minimum temperatures are shown in the GIS map in Figures 2 and 3.



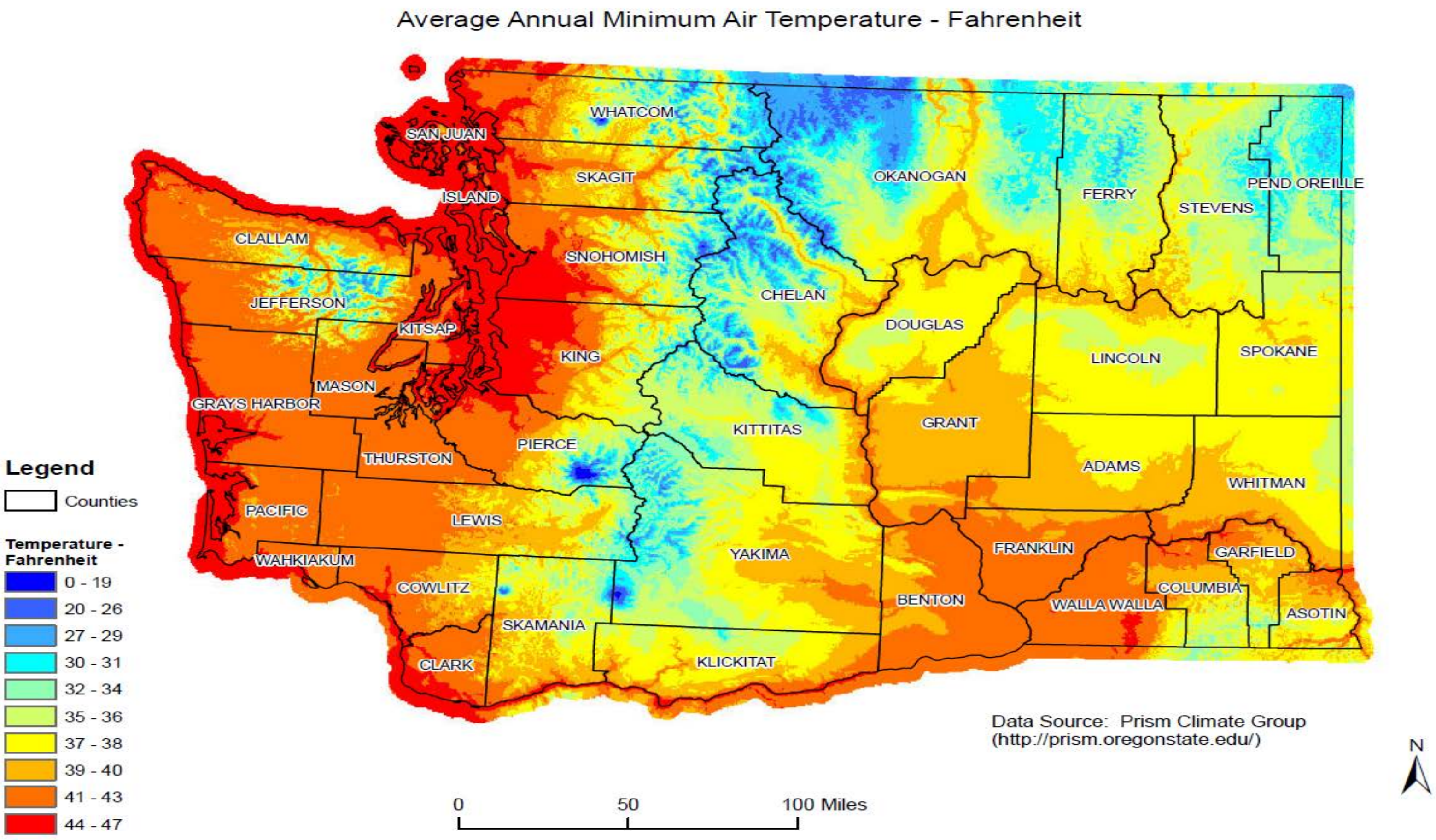
Data Source: Prism Climate Group
(http://prism.oregonstate.edu/)

Figure 1. Mean Annual Precipitation in Washington State



Data Source: Prism Climate Group (http://prism.oregonstate.edu/)

Figure 2. Mean Annual Maximum Air Temperatures in Washington State



Data Source: Prism Climate Group
(http://prism.oregonstate.edu/)

Figure 3. Mean Annual Minimum Air Temperatures in Washington State

In general, in the western Washington of the state, annual precipitation ranges from about 20 inches in an area northeast of the Olympic Mountains to 150 inches along the southwestern slopes. In July, the average maximum temperatures range from 65 °F in Northeast Olympic-San Juan area to 80 °F in East Olympic-Cascade Foothills area, with minimum temperatures of about 50 °F. In January, maximum temperatures range from lower than 32 °F to 45 °F, with minimum temperatures ranging from 25 °F to 38 °F.

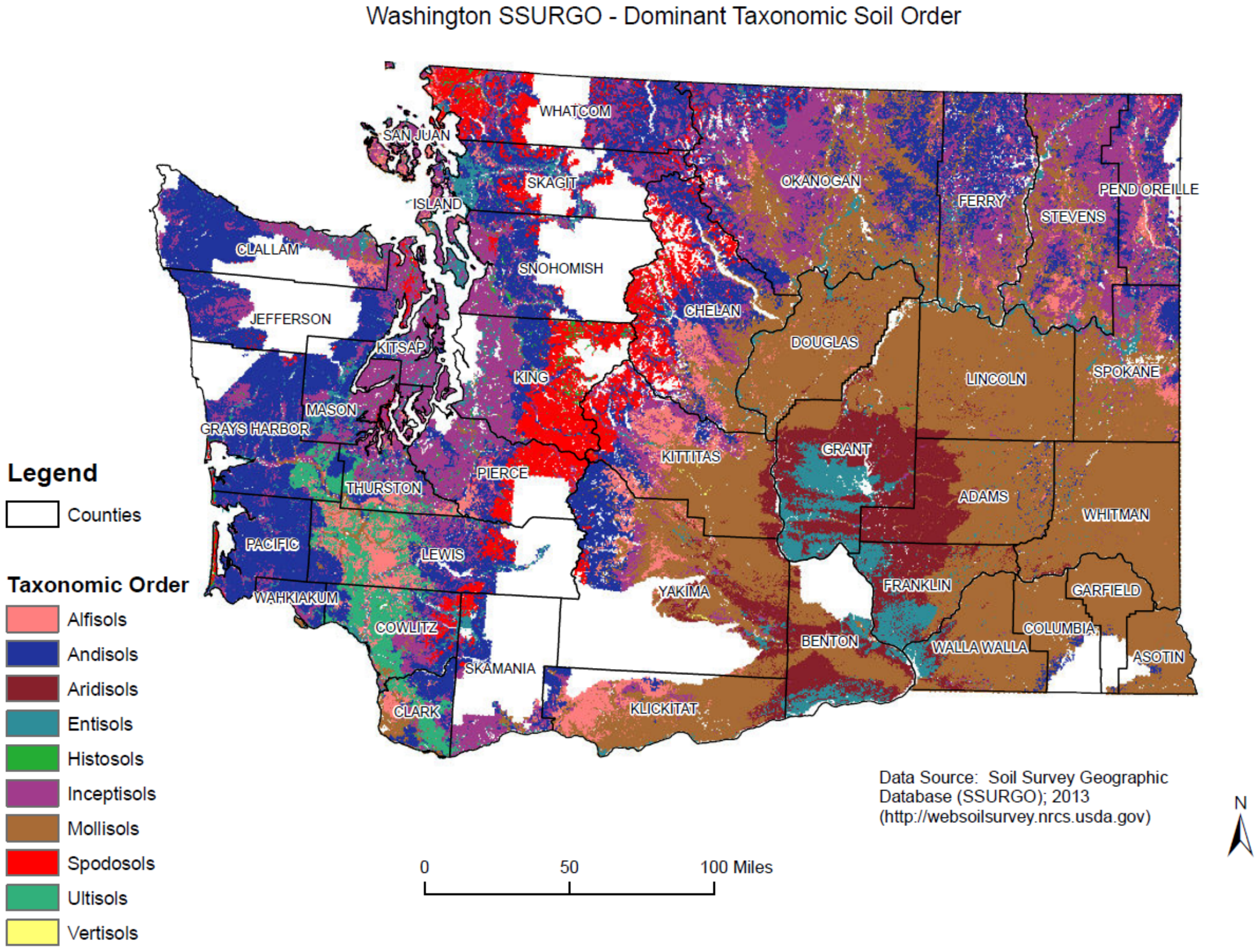
In the eastern Washington of the state, annual precipitation ranges from 7-9 inches near the confluence of the Snake and Columbia rivers, 15-30 inches along the eastern border, and 75-90 inches near the summit of the Cascade Mountains. In July, the average maximum temperature ranges from 70 °F in the area of east Slope-Cascades to 90 °F in Northeast area, with the minimum temperature from 45 °F to middle 50 °F; In January, the average maximum temperature varies from 25 °F to 40 °F, with minimum temperatures ranging from -15 °F to 25 °F.

Soil types in Washington State

Different soil types vary in their capacity to store (sequester) organic C. This capacity is dependent on the soils' inherent properties (e.g. soil texture, mineralogy) to retain organic C (SOC equilibrium levels). The mechanisms of SOC storage (sequestration) were discussed in earlier in this report (see *Factors Limiting Soil Organic C Storage*). While the area of agricultural soils within Washington State for increasing SOC storage (sequestration) by agricultural management practices is large, the characteristics of these soils must also be considered for the estimation of SOC storage (sequestration) potential.

Climate and parent material determine the dominant soil type and native vegetation that occur (Jenny, 1941, Franzluebbers and Follett, 2005). The U.S. soil taxonomy system categorizes soils into 12 soil orders in the United States (http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm). In Washington State, there are 10 soil orders (except Gelisols and Oxisols). A GIS map for soil orders in Washington State is shown in Figure 4.

The following information about the main formation process of 10 soil orders was obtained from the United States Department of Agriculture–Natural Resources Conservation Service (NRCS) http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/?cid=nrcs142p2_053588.


Washington SSURGO - Dominant Taxonomic Soil Order

Data Source: Soil Survey Geographic Database (SSURGO); 2013 (http://websoilsurvey.nrcs.usda.gov)

Figure 4. Soil Order Map in Washington State

Alfisols

Alfisols result from weathering processes that leach clay minerals and other constituents out of the surface layer and into subsoil, where they can hold and supply moisture and nutrients to plants. They formed primarily under forest or mixed vegetative cover and are productive for most crops.

Andisols

Andisols form from weathering processes that generate minerals with little orderly crystalline structure. These minerals can result in an unusually high water- and nutrient holding capacity as well as a high capacity to store organic C. Andisols tend to be highly productive soils.

Andisols include weakly weathered soils with much volcanic glass as well as more strongly weathered soils. They are common in cool areas with moderate to high precipitation, especially those areas associated with volcanic materials.

Aridisols

Aridisols soils are soils that are too dry for mesophytic plants to grow. The lack of moisture restricts the intensity of weathering processes and limits most soil development processes to the upper part of the soils. The redistribution and accumulation of soluble materials in some layers of the soils are common.

Entisols

Entisols are soils that show little or no evidence of pedogenic horizon development. They occur in areas of recently deposited parent materials or in areas where erosion of deposition rates are faster than the rate of soil development; such as dunes, steep slopes, and floodplains.

Histosols

Histosols are soils that are dominantly organic without perma-frost. Most are water-saturated year round, but a few are freely drained. Histosols are commonly called bogs, moors, or peats and mucks. Histosols form from decomposed plant remains that accumulate in water, forest litter, or moss faster than they decay.

Inceptisols

Inceptisols are soils of semiarid to humid environments that generally exhibit only moderate degrees of soil weathering and development. They have altered horizons that have lost bases or iron and aluminum, but retain some weatherable minerals. Inceptisols have a wide range in characteristics and occur in a wide variety of climates.

Mollisols

Mollisols are soils that have a dark-colored surface horizon, relatively high in content of organic matter. They are base rich throughout and therefore quite fertile. Mollisols characteristically form under grass in climates that have a moderate to pronounced seasonal moisture deficit.

Mollisols are used mainly as cropland. Generally, grains and sorghum are grown in the drier regions and maize (corn) and soybeans in the warmer, humid regions.

Spodosols

Spodosols are soils in which amorphous mixtures of organic matter and aluminum, with or without iron, have accumulated. In undisturbed soils, there is normally an overlying eluvial horizon, generally gray to light gray in color that has the hue of more or less uncoated quartz.

Most Spodosols commonly occur in areas of coarse-textured deposits under coniferous forests of humid regions. They have little silicate clay. The particle-size class is mostly sandy, sandy-skeletal, coarse-loamy, loamy, loamy- skeletal, or coarse-silty. They tend to be acid and infertile, but they can be highly responsive to good management

Ultisols

Ultisols are soils in humid areas. They form from fairly intense weathering and leaching processes that result in a clay-enriched subsoil dominated by minerals, such as quartz, kaolinite, and iron oxides. Ultisols contain an appreciable amount of translocated silicate clay (an argillic or kandic horizon) and few bases (base saturation less than 35%). Base saturation in most Ultisols decreases with depth.

Ultisols are typically acid soils in which most nutrients are concentrated in the upper few inches. Most of these soils supported mixed coniferous and hardwood forest vegetation at the time of settlement. Some are now used as cropland or pasture.

Vertisols

Vertisols are soils with a high content of expanding clay minerals. They have deep, wide cracks for some time during the year. They shrink as they dry and swell as they become moist. Because they swell when wet, Vertisols transmit water very slowly and have undergone little leaching.

Vertisols tend to be fairly high in natural fertility. The natural vegetation is predominantly grass, savanna, open forest, or desert shrub. Most Vertisols are well suited to mechanized farming if there is plenty of rainfall or irrigation water. Vertisols are well known among engineers because their unique properties limit engineering uses.

The distribution of soil orders in Washington State

Washington State is divided into two large geographic regions, eastern and western Washington (east and west of the Cascade Range), with a total of four agricultural statistics districts in the eastern Washington and one agricultural statistics district in the western Washington divided by USDA National Agricultural Statistics Services (NASS) (http://quickstats.nass.usda.gov/).

USDA Agricultural Statistics Districts are defined groupings of counties in each state, by geography, climate, and cropping practices. The geographic attributes include soil type, terrain, and elevation (mountains). The basic components of climate are mean temperature, annual precipitation and length of growing season. These factors influence the crops grown, the need to conserve soil moisture, and the use of irrigation (cropping practices).

Four agricultural districts in the eastern Washington include:

- Central District: 6 counties (Benton, Chelan, Kittitas, Klickitat, Okanogan, and Yakima).
- East Central District: 5 counties (Adams, Douglas, Franklin, Grant, and Lincoln).
- Northeast District: 4 counties (Ferry, Pend Oreille, Spokane, and Stevens).
- Southeast District: 5 counties (Asotin, Columbia, Garfield, Walla Walla, and Whitman).

The western Washington agricultural district covers a total of 19 counties (Clallam, Clark, Cowlitz, Grays Harbor, Island, Jefferson, King, Kitsap, Lewis, Mason, Pacific, Pierce, San Juan, Skagit, Skamania, Snohomish, Thurston, Wahkiakum, and Whatcom).

The percent area of each soil order varies in different agricultural districts (Table 3) due to differences in the dominant soil formation factors. In general, on the eastern Washington, Mollisols, Inceptisols, and or Aridsols dominate; while on the Western Washington, Andisols, Inceptisols, and or Spodisols dominate. More detailed discussions for distribution of soil orders in 10 geographic regions are described below.

Central Agricultural District

Mollisols, Inceptisols, Andisols, and/or Alfisols dominates in this district, with an average percent area of 48.5%, 15.0%, 14.1% and 10.2% distribution, respectively. There are small percent areas for Entisols, Histosols, Spodisols, Ultisols, and Vertisols for most counties in the district. The distribution of Aridisols in Benton County is the highest (45.1%), with lack of Alfisols, Andisols, Histosols, Spodosols, Utlisols and Vertisols distributed.

East Central Agricultural District

Mollisols and/or Aridosols dominate in this agricultural district, with a percent area of 62.4% and 21.9% on average, respectively. However, the distribution areas of Aridosols in Douglas and Lincoln Counties are small, which account for 1.8% and 2.3%, respectively.

Northeast Agricultural District

Inceptisols, Mollisols, and/or Alfisols dominate in this agricultural district, with an average percent area of 39.3%, 30.3%, and 19.8%, respectively. Other soil orders, Alfisols, Entisols, and Histosols, also can be found in these 4 counties, but with a low percent area of distribution ranging from 0.4% to 5.9%. Spodisols are the only soil orders distributed in the County Pend Oreille in this district, with a 0.7% area of distribution.

Southeast Agricultural District

Mollisols dominate in the 5 counties in this district, with a percent area of 92% distribution. Andisols, Aridsoils, Entisols, and Inceptisols can also be found in up to five counties, but with a low percent area ranging from 0.4% to 2.4% on average. The distributions of Aridisols and Entisols in Walla Walla County are relatively high, with a percent area of 8.5% and 7.7%, respectively.

Western Agricultural District

Andisols and/or Inceptisols dominate in this district, which account for an average of 45.1% and 30.3% of distribution in this agricultural district, with exceptions for King County, with the highest percent area of distribution (43.4%) for Spodosols. Note that Spodosols are in the mountains, where there is little agriculture. The remaining soil orders (Alfisols, Entisols, Histosols, Mollisols, and Utisols) have varying percent area of distribution, with an average ranging from 1.7% to 9.2%.

Table 3.

Total Acres and the Percent Area of Soil Orders in Washington State (Data Source: http://websoilsurvey.nrcs.usda.gov)

Agricultural Districts/Counties	**Total Acres**	**Soil Orders (%)**									
		Alfisols	**Andisols**	**Aridisols**	**Entisols**	**Histosols**	**Inceptisols**	**Mollisols**	**Spodosols**	**Ultisols**	**Vertisols**
Central											
Benton	798,569	0.0	0.0	45.1	18.5	0.0	0.1	36.4	0.0	0.0	0.0
Chelan	1,639,466	6.7	27.6	0.1	1.4	0.7	16.1	23.0	24.4	0.0	0.0
Kittitas	1,401,314	12.2	9.0	5.3	0.9	0.1	14.4	46.7	11.0	0.0	0.2
Klickitat	1,040,014	20.0	6.2	4.5	1.5	0.0	4.6	63.1	0.0	0.0	0.0
Okanogan	3,259,960	1.2	22.7	0.1	3.4	0.1	35.7	34.9	1.8	0.0	0.0
Yakima	1,671,832	7.5	18.6	16.3	1.5	0.0	5.4	49.2	1.4	0.0	0.1
Average	**1,843,280**	**10.2**	**14.1**	**6.6**	**1.8**	**0.1**	**15.0**	**48.5**	**3.6**	**0.0**	**0.1**
East Central											
Adams	1,229,230	0.4	1.7	37.9	1.3	0.0	0.3	58.5	0.0	0.0	0.0
Douglas	1,151,045	1.0	0.0	1.8	3.0	0.0	0.9	93.1	0.0	0.0	0.0
Franklin	790,036	0.0	0.0	39.3	28.9	0.0	0.1	31.5	0.0	0.0	0.0
Grant	1,698,394	0.0	0.0	44.3	24.8	0.1	0.5	30.4	0.0	0.0	0.0
Lincoln	1,475,016	0.0	0.5	2.3	1.7	0.0	0.8	94.5	0.0	0.0	0.0
Average	**1,278,623**	**0.3**	**0.1**	**21.9**	**14.6**	**0.03**	**0.58**	**62.4**	**0.0**	**0.0**	**0.0**
Northeast											
Ferry	1,360,133	2.8	36.0	0.0	4.2	0.1	32.8	24.3	0.0	0.0	0.0
Pend Oreille	780,010	7.5	24.0	0.0	3.3	0.4	57.2	6.5	0.7	0.0	0.0
Spokane	1,111,785	6.8	8.1	0.0	4.8	0.6	17.7	61.0	0.0	0.0	0.0
Stevens	1,571,993	6.4	10.9	0.0	3.6	0.5	49.3	29.4	0.0	0.0	0.0
Average	**1,205,980**	**5.88**	**19.8**	**0.0**	**4.0**	**0.4**	**39.3**	**30.3**	**0.18**	**0.0**	**0.0**
Southeast											
Asotin	363,643	0.0	1.8	0.0	0.6	0.0	0.0	97.6	0.0	0.0	0.0
Columbia	378,857	0.0	4.8	0.0	0.5	0.0	0.4	94.3	0.0	0.0	0.0
Garfield	360,735	0.0	0.9	0.0	0.1	0.0	0.0	99.0	0.0	0.0	0.0

Agricultural Districts/Counties	Total Acres	Soil Orders (%)									
		Alfisols	Andisols	Aridisols	Entisols	Histosols	Inceptisols	Mollisols	Spodosols	Ultisols	Vertisols
Walla Walla	803,845	0.0	1.3	8.5	7.7	0.0	0.7	81.8	0.0	0.0	0.0
Whitman	1,375,115	0.0	0.6	1.0	0.6	0.0	0.5	96.2	0.0	0.0	0.0
Average	**729,638**	**0.0**	**1.9**	**2.4**	**2.2**	**0.0**	**0.4**	**92.8**	**0.0**	**0.0**	**0.0**
Western											
Clallam	769,551	4.5	62.7	0.0	5.6	0.2	24.4	2.4	0.2	0.0	0.0
Clark	395,953	9.5	31.7	0.0	0.5	0.4	13.0	17.6	0.0	27.6	0.0
Cowlitz	716,582	6.7	21.8	0.0	7.7	0.3	18.9	3.3	7.6	34.0	0.0
Grays Harbor	1,007,094	0.8	69.0	0.0	3.4	0.4	13.9	1.8	0.8	10.2	0.0
Island	130,666	11.7	0.0	0.0	28.4	2.0	52.1	4.4	0.0	0.0	0.0
Jefferson	627,417	0.4	58.4	0.0	2.9	0.7	32.6	0.3	5.1	0.0	0.0
King	1,118,280	0.4	17.8	0.0	5.7	4.5	31.5	0.9	43.4	0.0	0.0
Kitsap	239,437	0.0	9.6	0.0	13.6	1.1	58.6	0.0	1.0	0.0	0.0
Lewis	1,141,730	21.0	33.1	0.0	2.5	0.2	13.2	5.3	5.4	19.5	0.0
Mason	570,018	0.0	43.2	0.0	14.9	1.6	39.9	0.6	1.3	0.0	0.0
Pacific	589,415	0.0	84.8	0.0	3.1	1.0	9.2	0.0	2.5	0.0	0.0
Pierce	814,208	5.7	17.9	0.0	5.1	1.5	45.3	1.7	23.9	0.0	0.0
San Juan	104,911	23.1	0.0	0.0	3.8	1.4	54.0	8.5	0.0	0.0	0.0
Skagit	771,291	2.8	42.0	0.0	16.5	0.6	18.6	0.1	19.8	0.0	0.0
Skamania	342,719	2.0	31.9	0.0	8.5	0.0	40.0	4.4	9.5	2.4	0.0
Snohomish	610,534	0.0	49.6	0.0	3.8	3.1	39.7	1.3	5.7	0.0	0.0
Thurston	460,210	12.9	21.0	0.0	7.0	2.4	40.6	3.9	0.0	12.8	0.0
Wahkiakum	164,906	0.0	68.3	0.0	2.9	0.0	17.9	2.4	0.0	2.2	0.0
Whatcom	1,052,098	2.0	41.6	0.0	1.8	1.4	22.8	0.8	30.9	0.0	0.0
Average	**571,937**	**3.7**	**45.1**	**0.0**	**3.9**	**1.7**	**30.3**	**2.1**	**9.2**	**3.8**	**0.0**

Selected characteristics of soils in Washington State

As discussed previously in this report (see *Factors Affecting the Soil Organic Storage*), many soil properties affect soil C storage (sequestration). In this section, only the following selected soil properties in Washington soils are discussed.

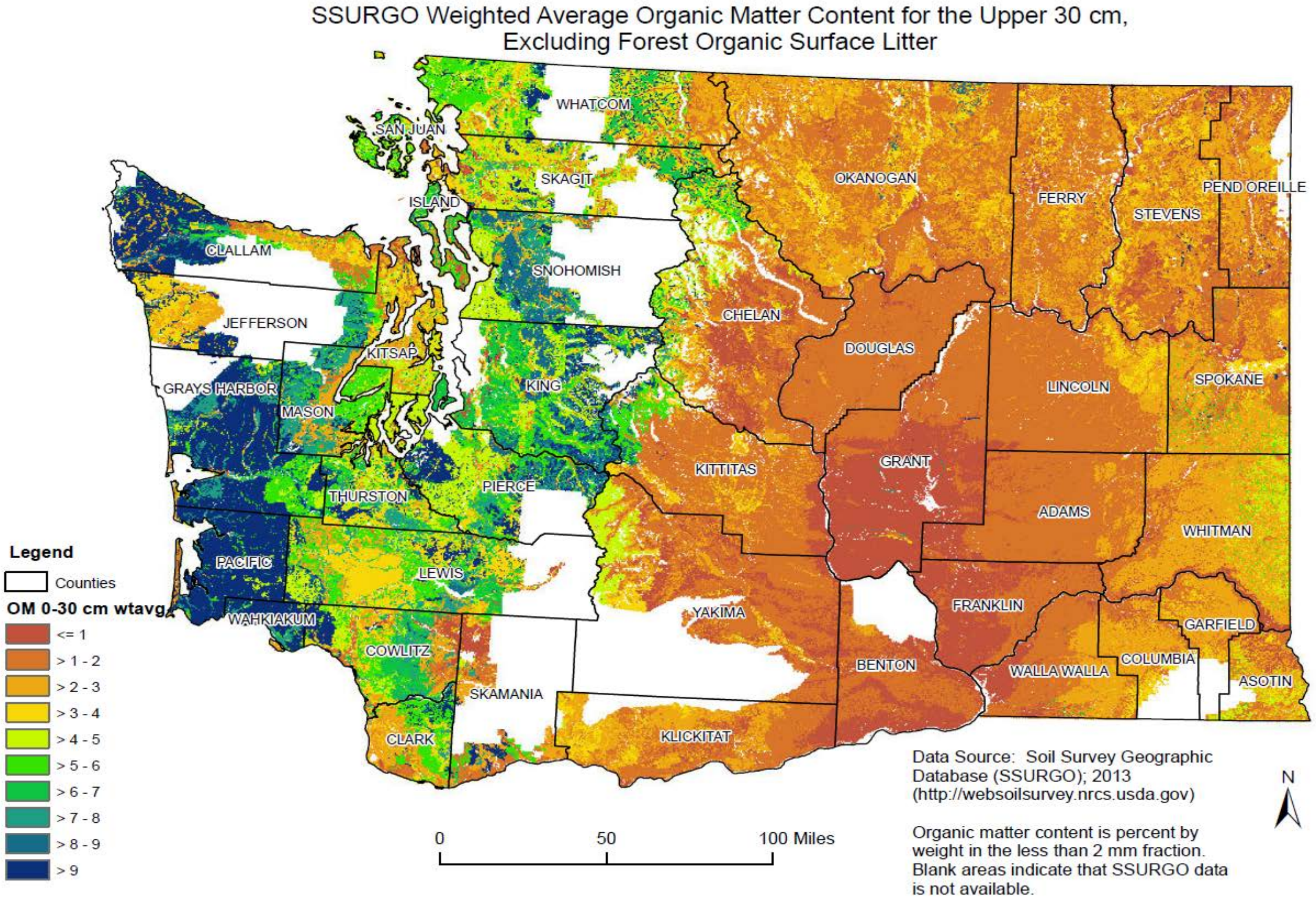
SOM content in Washington State soils

The amount of SOC in the form of SOM reflects a balance of C inputs and C losses of organic material (Burke et al., 1989), and factors affecting SOC include soil type, climate, and agricultural management practices. In general, SOC content in the top 30 cm (one foot) on the eastern Washington much less than that on the western Washington (Figure 5), thus SOC stored per square kilometer in the top 30 cm on the eastern Washington is much lower (Figure 6). The difference in SOM content between the eastern Washington and western Washington reflects differences in factors affecting SOC content that have been discussed (e.g. soil type, soil texture, and climate). As discussed previously, a SOC content of less than 2% (or 3.4% SOM) is considered to be the threshold value below which soil function is impaired (Greenland et al., 1975; Lal, 2004c).

On the eastern Washington, about 98.7% (three SOM classes: ≤1%, >1-2%, >2-3% combined) (Table 4) of soils contain less than 3% of SOM (or 1.74% SOC) in soils in the East Central Agricultural District, followed by the Northeast Agricultural District (about 89.2%), with the least (about 86%) in the Central Agricultural District.

On average, the area distribution for soils with SOM content >3-4% or higher in agricultural districts on the eastern Washington is only about 10%, while on the western Washington, the area distribution for soils with SOM content >3-4% or higher accounts for 86% . There are relatively high area distribution percentages of soils with a SOM class of greater than 2-3% in Northeast and Southeast Agricultural Districts on the eastern Washington(about 40% and 49%, respectively) (Table 4).

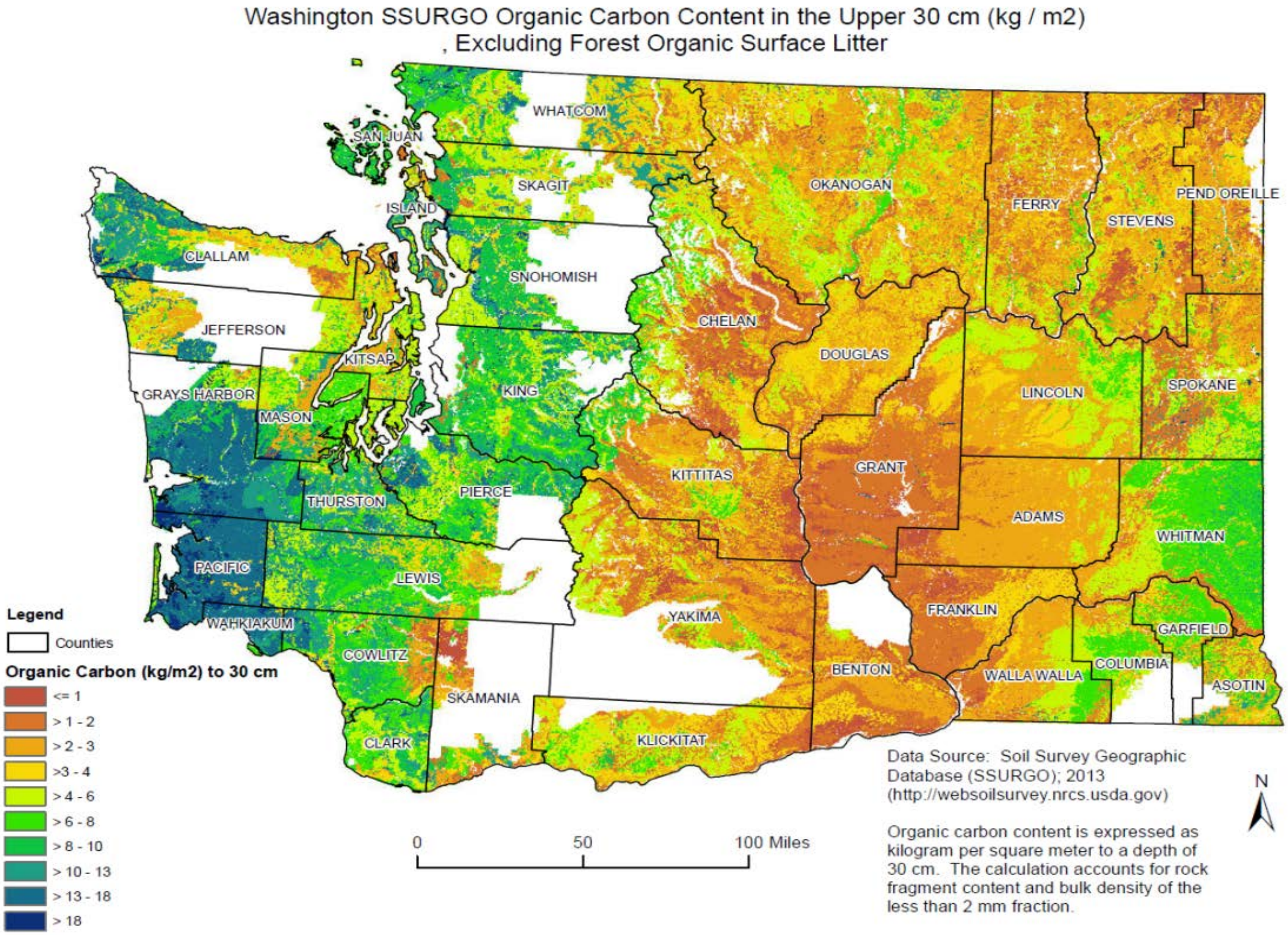
Overall, on the eastern Washington, about 90.3% of soils contain less than 3% of SOM, while only about 12% of soils in the western Agricultural District contain less than 3.0% of SOM (Table 4).



Data Source: Soil Survey Geographic Database (SSURGO); 2013 (http://websoilsurvey.nrcs.usda.gov)

Organic matter content is percent by weight in the less than 2 mm fraction. Blank areas indicate that SSURGO data is not available.

Figure 5. SOM Content in Washington State Soils



Washington SSURGO Organic Carbon Content in the Upper 30 cm (kg / m2)
, Excluding Forest Organic Surface Litter

Data Source: Soil Survey Geographic Database (SSURGO); 2013 (http://websoilsurvey.nrcs.usda.gov)

Organic carbon content is expressed as kilogram per square meter to a depth of 30 cm. The calculation accounts for rock fragment content and bulk density of the less than 2 mm fraction.

Figure 6. SOC Stored per Square Kilometer in the Top 30 cm in Washington State Soils

Table 4.

The Area Distribution of Each SOM Content Class (0-30 cm, Weighted Average) in Washington State (%) (Data Source: http://websoilsurvey.nrcs.usda.gov)

Agricultural District	**SOM Content (%)**									
	≤1	**>1-2**	**>2-3**	**>3-4**	**>4-5**	**>5-6**	**>6-7**	**>7-8**	**8-9**	**>9**
Central										
Benton	50.1	48.1	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chelan	19.8	40.1	8.7	13.1	9.7	3.0	2.7	1.3	0.0	1.7
Kittitas	6.1	63.5	13.8	5.7	0.0	7.7	0.0	0.0	2.4	0.9
Klickitat	11.1	43.4	36.3	8.6	0.6	0.0	0.0	0.0	0.0	0.0
Okanogan	3.1	48.8	34.7	12.6	0.0	0.0	0.0	0.0	0.7	0.1
Yakima	21.3	53.5	11.5	5.0	8.7	0.0	0.0	0.0	0.0	0.1
Average	**18.6**	**49.6**	**17.8**	**7.5**	**3.2**	**1.8**	**0.5**	**0.2**	**0.5**	**0.5**
East Central										
Adams	11.7	80.9	7.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Douglas	5.4	93.3	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Franklin	59.5	40.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Grant	61.4	37.8	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.1
Lincoln	3.0	77.0	14.1	5.4	0.5	0.0	0.0	0.0	0.0	0.0
Average	**28.2**	**65.9**	**4.6**	**1.2**	**0.1**	0.0	**0.0**	**0.0**	**0.0**	**0.0**
Northeast										
Ferry	6.7	49.4	36.9	6.8	0.0	0.0	0.0	0.0	0.0	0.1
Pend Oreille	12.7	38.8	41.8	5.4	0.4	0.0	0.0	0.0	0.0	0.9
Spokane	4.4	34.2	47.2	8.8	1.0	3.7	0.0	0.0	0.0	0.6
Stevens	12.6	37.9	34.1	14.5	0.1	0.0	0.0	0.0	0.0	0.7
Average	**9.1**	**40.1**	**40.0**	**8.9**	**0.4**	**0.9**	**0.0**	**0.1**	**0.0**	**0.6**
Southeast										
Asotin	12.4	23.6	39.2	10.8	13.8	0.2	0.1	0.0	0.0	0.0

Agricultural District	**SOM Content (%)**									
	≤1	**>1-2**	**>2-3**	**>3-4**	**>4-5**	**>5-6**	**>6-7**	**>7-8**	**8-9**	**>9**
Columbia	5.6	24.8	57.2	12.3	0.2	0.0	0.0	0.0	0.0	0.0
Garfield	0.4	32.6	56.9	9.3	0.7	0.0	0.0	0.0	0.0	0.0
Walla Walla	17.4	52.1	28.1	2.0	0.0	0.0	0.4	0.0	0.0	0.0
Whitman	7.3	15.5	63.2	5.9	6.4	1.7	0.0	0.0	0.0	0.0
Average	**8.6**	**29.7**	**48.9**	**8.1**	**4.2**	**0.4**	**0.1**	**0.0**	**0.0**	**0.0**
Western										
Clallam	0.4	9.4	14.8	9.8	1.9	5.8	4.8	4.3	2.6	46.1
Clark	1.3	12.3	29.0	14.3	2.8	29.3	0.1	3.1	0.0	7.6
Cowlitz	5.9	9.9	12.6	13.0	8.1	16.7	14.8	11.2	0.8	8.0
Grays Harbor	0.1	0.6	1.7	0.4	5.1	11.4	2.5	15.2	0.1	62.9
Island	7.9	5.1	17.8	0.2	3.7	23.6	23.5	11.1	5.0	2.2
Jefferson	2.4	9.8	17.1	31.0	4.9	4.9	1.9	10.2	0.0	17.8
King	2.0	17.	2.0	7.4	12.6	17.9	20.3	5.0	16.0	15.1
Kitsap	0.0	5.1	41.4	17.4	27.7	3.2	3.7	0.0	0.0	1.5
Lewis	0.0	1.4	6.0	9.6	18.3	23.5	18.2	16.3	6.5	0.3
Mason	0.2	3.3	16.3	3.8	8.1	21.5	3.9	31.1	0.0	11.5
Pacific	0.0	1.4	2.3	0.0	2.3	2.5	0.0	5.2	0.0	86.3
Pierce	2.2	1.7	2.4	5.8	32.2	11.6	6.3	10.1	7.2	20.6
San Juan	1.2	0.0	2.6	4.1	37.0	41.2	5.4	1.7	2.0	4.7
Skagit	4.1	9.0	9.5	25.4	26.0	8.6	5.6	3.2	1.1	7.5
Skamania	17.3	26.8	32.0	1.5	1.4	8.7	1.8	2.2	0.0	8.4
Snohomish	0.6	1.4	7.3	7.7	19.9	6.9	3.9	16.3	30.4	5.6
Thurston	0.7	1.8	5.7	18.5	20.0	10.8	16.6	10.4	1.5	14.1
Wahkiakum	0.2	0.0	2.8	0.0	2.8	4.7	1.1	13.2	0.0	75.2
Whatcom	0.6	10.3	**12.2**	20.5	17.1	19.0	8.7	1.3	0.8	9.4
Average	**3.9**	**8.2**	**11.6**	**11.6**	**14.5**	**9.8**	**6.3**	**7.8**	**5.6**	**20.0**

Types of soil texture in Washington State soils

Soil texture is an important physical property of soils. As mentioned previously in this report, soil texture not only influences the nutrient, water, and air-supplying ability of soils, but also the net mineralization of SOM and amount of SOC stored in the soil. The decomposition of organic matter is more rapid in sandy soils than in clay soils. SOC increased with clay content, and SOC losses due to cultivation were lowest in clay soils (Burke et al., 1989). Clay soils accumulate C relatively quickly, and sandy soils may accumulate practically no C even after 100 years of high C inputs (Burke et al., 1989; Christensen, 1996). It was found that SOC losses in cultivation of virgin land were 20 times faster in sandy soil than in clay soils (Dalal and Mayer, 1986).

The 12 major soil texture classes are based on the relative percentage of sand, silt, and clay in the soils. However, in practice, three broad, yet fundamental groups of soil textures have been widely used: loam soils, sandy soils, and clayey soils.

The loam group contains many subdivisions such as sandy loams, silt loams, silty clay loams, and clay loams. However, for some soils, qualifying factors such as stone, gravel, various grades of sand, and others are taken into descriptively consideration for the three broad groups.

An ideal loam may be defined as a mixture of sand, silt, and clay particles which exhibits light and heavy properties in about equal proportions. It is roughly a half-and-half mixture on the basis of properties. The sandy group includes all soils of which sand makes up 70% or more of the material by weight, and contains many subdivisions such as gravelly sands, coarse sands, loamy sands, and fine sands. The clayey group includes all soils with > 35% clay and in most cases not less than 40%, and subdivisions of this group include sandy clays, silty clays, and clays.

This section discusses the area distribution percent of soils in the five agricultural statistics districts of Washington State based on only three broad groups, not subdivisions of each broad group. The area distribution percent for organic soils is also included (Table 5).

A majority of soils are loam soils in both the eastern and western Washington of the state, with small percent of soils being sandy soils and clayey soils (Table 5). Note these textural classes only apply to the surface horizon. For example, there are some soils that have a loamy surface horizon, but deeper horizons may be sandy or clayey. On average, the area distribution percent for loam soils ranges from approximately 92-98% of loam soils in four agricultural districts on the eastern Washington, while 88% of soils are loam soils in the western agricultural district. This indicates that most of soils in the state have a low content of clays, which limits soil C sequestration potential. An exception would be Andisols which have greater binding of organic matter, because of the type of minerals in soils. These minerals can result in an unusually high water- and nutrient holding capacity as well as a high capacity to store organic C in soil (see *Distribution of soil orders in Washington State*). Note the area distribution percent for clayey soils is relatively small, and there are some organic soils in the form of pet or much in a few counties in both the east and western Washington.

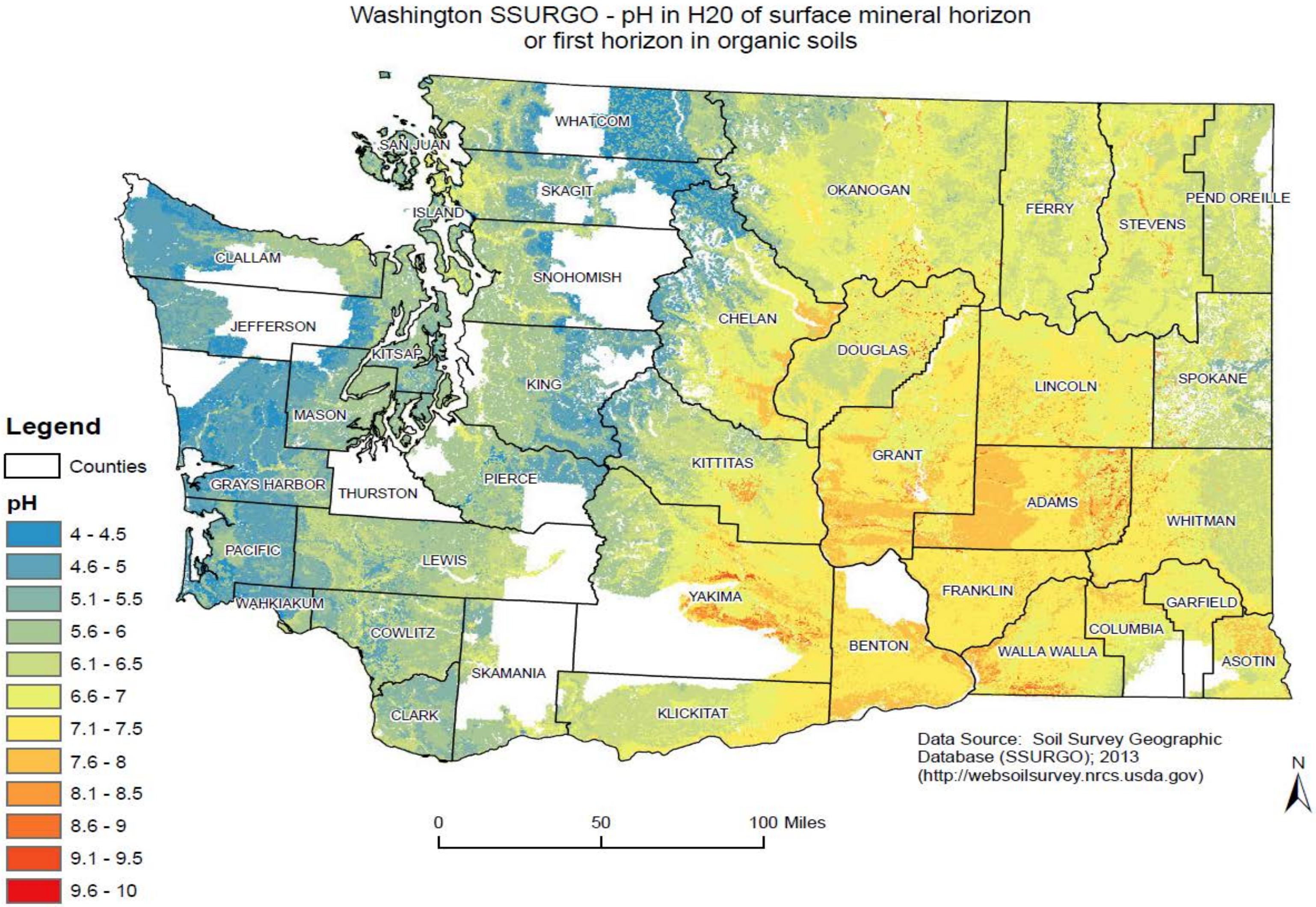
Table 5.
The Distribution of each Soil Type (Textural Class) in Washington State (%)
(Data Source: http://websoilsurvey.nrcs.usda.gov)

Agricultural Districts/Counties	Soil Texture			
	Loam Soils	**Sandy Soils**	**Clayey Soils**	**Organic Soils**
Central				
Benton	87.2	13.8	0.0	0.0
Chelan	97.0	3.0	0.0	0.0
Kittitas	98.7	0.8	0.3	0.2
Klickitat	97.0	2.8	0.2	0.0
Okanogan	95.6	2.8	0.0	1.6
Yakima	96.6	3.1	0.3	0.0
Average	**95.4**	**4.4**	**0.1**	**0.3**
East Central				
Adams	95.5	4.5	0.0	0.0
Douglas	97.0	3.0	0.0	0.0
Franklin	84.0	16.0	0.0	0.0
Grant	87.8	13.2	0.0	0.0
Lincoln	95.7	4.3	0.0	0.0
Average	**92.0**	**8.2**	**0.0**	**0.0**
Northeast				
Ferry	97.2	2.3	0.0	0.5
Pend Oreille	96.5	1.5	2.5	0.0
Spokane	94.1	5.0	0.0	0.9
Stevens	96.4	2.3	0.0	1.3
Average	**96.1**	**2.8**	**0.6**	**0.7**
Southeast				
Asotin	99.0	1.0	0.0	0.0
Columbia	99.1	0.9		
Garfield	99.3	0.7	0.0	0.0
Walla Walla	90.2	9.8	0.0	0.0
Whitman	100.0	0.0	0.0	0.0
Average	**97.5**	**2.5**	**0.0**	**0.0**
Western				
Clallam	96.0	2.5	0.0	1.5
Clark	97.7	0.8	1.5	
Cowlitz	77.4	21.0	0.4	1.1
Grays Harbor	95.5	3.0	1.0	2.5
Island	79.3	15.5	0.0	5.5
Jefferson	88.6	7.6	0.6	3.2

Agricultural Districts/Counties	**Soil Texture**			
	Loam Soils	**Sandy Soils**	**Clayey Soils**	**Organic Soils**
King	78.5	14.3	0.0	7.2
Kitsap	85.5	10.5	0.0	4.5
Lewis	86.3	12.2	0.4	1.1
Mason	86.7	6.0	0.0	7.3
Pacific	95.5	3.0	1.0	2.5
Pierce	82.6	9.8	1.1	6.5
San Juan	87.9	7.7	4.4	0.0
Skagit	85.8	10.7	0.0	3.5
Skamania	75.4	24.1	0.0	0.5
Snohomish	87.7	8.2	0.0	4.1
Thurston	89.1	6.8	0.0	4.1
Wahkiakum	**95.5**	**3.0**	**1.0**	**2.5**
Whatcom	93.6	1.5	1.0	3.9
Average	87.6	8.9	0.7	3.4

Soil pH ranges in Washington State soils

In general, soils in the eastern Washington of the state are alkaline with a pH >7.0, while soils are acidic in the western Washington of the state, with a pH< 7.0 and strong alkaline soils (pH>8.1) on the eastern Washington (Figure 7). There are some strong acid soils (pH < 4.0-4.5) on the western Washington, most likely in the forest mountains with high precipitations.



Washington SSURGO - pH in H20 of surface mineral horizon or first horizon in organic soils

Data Source: Soil Survey Geographic Database (SSURGO); 2013 (http://websoilsurvey.nrcs.usda.gov)

Figure 7. Soil pH Ranges in Washington State Soils

Land Uses, Compost Production from Regulated Solid Waste Facilities, and Biosolids Generation and Management Practices in Washington State

Land uses in Washington State

Land utilization is determined to a large extent by the terrain, soil, and climate. Table 5 summarizes agricultural land use areas in Washington State for 2007. The data was obtained from the United State Department of Agriculture (USDA) National Agricultural Statistics Services (NASS). A few counties in the both the west and eastern Washingtons chose not to publish data on pasture, grazing, animal treated, and organic production lands. Therefore, estimates of a total of land use areas in these counties excluded these data.

Out of 7,609,210 acres of total cropland in the state, there were about 7,182,150 acres of cropland 94.3%) on the eastern Washington, while only about 427,060 acres on the western Washington (5.7%) (Table 6).

- Out of the 7,182,150 acres of cropland on the eastern Washington:
    - 53.0% (3,808,453 acres) of cropland received fertilizer, lime and soil conditioners.
    - 22.3% (1,632,615 acres) was irrigated land.
    - 1.66% (119,359 acres) received manure.
    - 3.5% (252,339 acres) was pasture or grazing land.
    - 0.61% (43,648 acres) was used for organic production.
- Out of the 427,060 acres of cropland on the western Washington:
    - 41.3% (176,292 acres) of cropland received fertilizer, lime, and soil conditioners.
    - 24.2% (176,292 acres) was irrigated land.
    - 23.7% (101,247 acres) received manure.
    - 17.5% (74,625 acres) was pasture or grazing land.
    - 4.79% (20,407 acres) was used for organic production.

The data shows that the eastern Washington of the state is a major agricultural area. In addition, the eastern Washington grows a wider range of crops than the Western Washington (source: hhttp://www.wrcc.dri.edu/narratives/washington/). The eastern Washington is the major fruit production area, located in irrigated valleys along the Okanogan, Columbia, Wenatchee, and Yakima rivers. In the irrigated Central Basin, the more important crops include sugar beets, potatoes, alfalfa, corn, onions, beans, peppermint, spearmint, hops, and a variety of vegetable crops.

The major wheat producing areas include Big Bend, Waterville Plateau, Palouse Hills and Horse Heaven Hills. Dryland farming practices are generally followed in the small grain section, while on the western Washington, agriculture is confined to the river valleys and well-drained areas in the Puget Sound lowlands. The major crops grown include berry crops, cool season vegetable crops, flower bulbs, certified seed potatoes, and grass.

As previously discussed, compared to the western Washington, a majority of soils on the eastern Washington are lower in SOM content. Additionally, given that major cropland areas (94.7%) with wider range of cropping systems including fruit production and irrigated cropping systems are located in the eastern Washington, croplands there east provide much greater potential to store C through use of recycled organic soil amendments such as compost and biosolids.

Table 6.

Agricultural Land for Crop Production in Counties in Agricultural Districts in Washington State in 2007 (Acres)

(Data Source: http://quickstats.nass.usda.gov/)

Agricultural Districts/Counties	Areas of Cropland (Acres)					
	Total Cropland	**Fertilizers, Lime and Soil Conditioners Treated Land**	**Irrigated Land**	**Pasture or Grazing Land**	**Manure Treated Land**	**Organic Production Land**
Central						
Benton	476,548	222,107	181,585	12,043	5,531	10,702
Chelan	43,503	22,197	28,230	7,256	1,110	1,899
Kittitas	69,739	45,845	82,147	10,241	2,206	863
Klickitat	191,395	63,255	21,349	17,814	6,706	1,353
Okanogan	127,148	49,068	51,582	23,123	4,024	4,106
Yakima	344,505	198,222	267,566	24,349	27,742	4,813
Subtotal	**1,252,838**	**600,694**	**632,459**	**94,826**	**47,319**	**23,736**
East Central						
Adams	825,863	363,717	124,515	25,888	6,851	2,727
Douglas	539,531	214,512	19,409	17,192	889	2,902
Franklin	467,865	248,635	217,238	(D)*	8,096	1,744
Grant	771,805	521,165	469,790	(D)	33,217	6,051
Lincoln	743,236	410,193	32,071	16,801	2,827	1,807
Subtotal	**3,348,300**	**1,758,222**	**863,023**	**59,881****	**51,880**	**15,231****
Northeast						
Ferry	14,842	4,842	3,355	(D)	(D)	145
Pend Oreille	19,041	6,872	1,113	4,916	672	(D)
Spokane	394,876	246,119	13,458	21,717	9,451	389
Stevens	88,344	27,145	14,950	30,374	3,728	2,665

Agricultural Districts/Counties	**Areas of Cropland (Acres)**					
	Total Cropland	**Fertilizers, Lime and Soil Conditioners Treated Land**	**Irrigated Land**	**Pasture or Grazing Land**	**Manure Treated Land**	**Organic Production Land**
Subtotal	**517,103**	**284,978**	**32,876**	**57,007****	**13,851****	**3,199****
Southeast						
Asotin	80,438	37,354	307	(D)	132	(D)
Columbia	184,124	120,917	4,172	4,379	128	(D)
Garfield	174,571	97,705	474	3,465	246	
Walla Walla	567,192	261,940	92,438	12,691	4,558	1,426
Whitman	1,057,584	646,643	6,866	20,090	1,245	56
Subtotal	**2,063,909**	**1,164,559**	**104,257**	**40,625**	**6,309**	**1482****
Total on the eastern Washington	**7,182,150**	**3,808,453**	**1,632,615**	**252,339****	**119,359****	**43,648****
Percent of Treated Land of the Total land areas (%)	**-**	**53.0**	**22.7**	**3.51**	**1.67**	**0.61**
Western						
Clallam	8,750	3,336	4,500	1,205	1,757	680
Clark	34,296	10,184	4,413	5,314	3,256	459
Cowlitz	10,933	4,933	2,980	1,308	1,955	711
Grays Harbor	24,070	8,379	4,906	4,594	2,665	1,524
Island	8,557	3,441	1,839	741	1,522	83
Jefferson	3,833	937	628	1,259	575	843
King	17,963	5,152	3,339	5,699	6,745	1,426
Kitsap	3,674	997	926	913	(D)	340
Lewis	54,408	15,672	7,292	10,127	12,145	3,684
Mason	6,075	2,801	1,196	1,640	537	(D)
Pacific	15,042	2,746	2,299	4,867	2,200	(D)

Agricultural Districts/Counties	**Areas of Cropland (Acres)**					
	Total Cropland	**Fertilizers, Lime and Soil Conditioners Treated Land**	**Irrigated Land**	**Pasture or Grazing Land**	**Manure Treated Land**	**Organic Production Land**
Pierce	17,319	6,025	4,453	3,918	3,532	897
San Juan	9,033	1280	393	3,061	215	280
Skagit	69,810	45,922	16,286	8,246	11,762	3,320
Skamania	1,610	644	277	193	70	D
Snohomish	37,039	14,563	5,474	7,257	8,653	1,967
Thurston	26,283	9,121	6,907	6,081	8,054	924
Wahkiakum	4,660	378	207	2,237	964	670
Whatcom	73,705	39,781	34,987	5,965	34,640	2,659
Total on the Western Washington	**427,060**	**176,292**	**103,302**	**74,625**	**101,247**	**20,467**
Percent of Treat Land of Total land areas on the Western Washington	-	**41.2**	**24.2**	**17.5**	**23.7**	**4.79**
Total in the State	**7,609,210**	**3,984,745**	**1,735,917**	**326,964**	**220,606****	**64,115****

*Means the information is not for disclosure. **Estimate excluding data for counties with unpublished data.

Compost production from regulated solid waste facilities in Washington State

According to the latest statewide recycling data for 2010-12, a total of 4,725,361 tons, 4,477,441 tons, and 4,460,649 tons of compostable organic materials (on a dry weight basis) were generated statewide. Of those materials, about 24.6%, 24.7%, and 27.1% were processed into compost, respectively.

Table 7 summarizes the amount of finished compost produced from the state's regulated solid waste facilities for 2010-12. The data shows that:

- There were a total of 21, 23, and 21 counties with regulated compost facilities in the state in 2010, 2011, and 2012 respectively, with a little less than a half facilities (8-11) located on the eastern Washington.

- A total of 779,506 tons, 712,852 tons, and 522,279 tons (on a wet weight basis) of finished compost were produced statewide for 2010, 2011, and 2012, respectively, with 82.8% (679,966 tons), 66.3% (472,532 tons), and 88.9% (110,081 tons) produced from the facilities on the western Washington, and 18.2% (99,540 wet tons) in respective years.

- The annual amount of compost generated in each county with regulated compost facilities varied greatly, from less than 20 tons in Klickitat County to about 91,000 tons in Grant County on the eastern Washington, and from approximately 60 tons in Grays Harbor County to about 305,000 tons in Snohomish County on the western Washington.

The Northeast Agricultural District was the only agricultural district with no regulated compost facilities in its four counties (Ferry, Pend Oreille, Spokane, and Stevens) in 2010, 2011, and 2012. A reduced amount of finished compost produced statewide was seen from 2010-12.

Table 7.
Total Compost Produced from Regulated Solid Waste Facilities in Washington State from 2010-12 (Data Source: Ecology's Solid Waste Facilities Database)

Agricultural Districts/Counties	Total Finished Compost Produced[*] (Tons, on a Wet Weight Basis)		
	2010	**2011**	**2012**
Central			
Benton	-**	1,128	2,398
Chelan	6,045	9,128	13,582
Kittitas	-	1,982	1,870
Klickitat	17	22	16
Okanogan	-	-	-
Yakima	7,829	10,845	7,634
Subtotal	**14,848**	**23,104**	**25,500**
East Central			
Adams	-	-	-
Douglas	-	-	-
Franklin	17	22	17
Grant	63,339	90,897	38,007
Lincoln	440	40,173	32,059
Subtotal	**63,796**	**194,888**	**70,083**
	-	-	-
Northeast			
Ferry	-	-	-
Pend Oreille	-	-	-
Spokane	-	-	-
Stevens	-	-	-
Subtotal	**-**	**-**	**-**
Southeast			
Asotin	-	-	-
Columbia	-	-	-
Garfield	-	-	-
Walla Walla	14,985	17,835	9,599
Whitman	5,912	4,495	4,900
Subtotal	**20,897**	**22,329**	**14,499**
Total on the Eastern Washington	**99,540**	**240,321**	**110,081**
Percent of total compost produced Statewide on the Eastern Washington (%)	12.8	33.7	21.1
The Number of Counties with Regulated Compost Facilities	8	10	10

Western			
Clallam	1,983	1,834	2,808
Clark	2,473	963	263
Cowlitz	605	-	1,023
Grays Harbor	-	57	-
Island	4,150	3,410	4,048
Jefferson	2,967	2,919	2,750
King	250,931	133,016	83,335
Kitsap	4,840	5,844	-
Lewis	-	-	-
Mason	10,560	11,065	7,062
Pacific	-	-	-
Pierce	51,246	58,977	54,833
San Juan	-	-	-
Skagit	8,838	13,636	9,197
Skamania	-	-	-
Snohomish	305,007	198,140	239,098
Thurston	29,463	35,806	-
Wahkiakum	-	-	-
Whatcom	6,903	6,864	7,799
Total on the Western Washington	**679,966**	**472,531**	**412,215**
The number of counties with Regulated Compost Facilities	**13**	**13**	**11**
Total in the State	**779,506**	**712,852**	**522,297**

*The unit “tons” was calculated from original data (cubic yards) by using a coefficient (1 cubic yard = 1,100 1b). **No compost facilities in counties or no finished compost produced in a specific year.

Biosolids generation and its management practices in Washington State

According to Ecology's Solid Waste Facilities Database, it is estimated 95,516 dry tons, 102,950 dry tons, and 110,970 dry tons of biosolids were generated statewide in 2010, 2011, and 2012, respectively.

Tables 8-10 summarize management practices of biosolids generated in the state in five agricultural statistics districts for 2010-12. The data shows that:

- Management practices through beneficial use accounted for the most proportion of the total biosolids generated in state, with a range from 79.8% to 83.4% of the total generated being land applied in agricultural fields, forest sites, reclamation sites, home gardening, and/or as a composting feedstock, followed by the disposal through incinerators, with a range from 15.6% to 19.9% of the total biosolids generated, disposal by landfills was the least, with a range from 0.11% to 0.49%.

- Among the total amount of biosolids beneficially used, agricultural fields received the largest proportion of biosolids, with a range from 58.6% to 62.9% of the total biosolids generated, which was greater than the other beneficial uses combined.

- Out of a total of 39 counties in the state, about 32 counties land applied biosolids beneficially, with about 21 counties land applying biosolids ranging from a few tons to less than 1000 dry tons in either 2010, 2011, or 2012, with about 13 counties (Douglas, Yakima, Spokane, Benton, Lincoln, Cowlitz, King, Kitsap, Lewis, Mason, Pierce, Snohomish, and Whatcom) land applying greater than 1000 tons of biosolids in either 2010, 2011, or 2012.

Note there were only four counties statewide that disposed of biosolids statewide in incinerators for 2010-12. All four counties (Clark, Skagit, Snohomish and Whatcom) are on the western Washington, while no counties are located in eastern Washington**.**

Table 8

Estimated Amount of Biosolids Landfilled, Incinerated, and Land Applied in Washington State in 2010

(Data Source: Ecology's Solid Waste Facilities Database)

Agricultural Districts/Counties	Landfilled	Incinerated	Agricultural land applied	Total land applied
	Dry Tons			
Central				
Benton	0	0	363	1,139
Chelan	0	0	10	11
Kittitas	0	0	44	44
Klickitat	0	0	137	137
Okanogan	0	0	272	342
Yakima	67	0	11,189	10,917
Subtotal	**67**	**0**	**12,015**	**12,590**
East Central				
Adams	0	0	30	30
Douglas	0	0	20,787	20,787
Franklin	0	0	0	0
Grant	0	0	110	110
Lincoln	0	0	277	277
Subtotal	**0**	**0**	**21,104**	**21,174**
Northeast				
Ferry	0	0	0	0
Pend Oreille	0.5	0	48	48
Spokane	0	0	5,710	5,893
Stevens	0	0	152	152
Subtotal	**1**	**0**	**5,910**	**6,092**
Southeast				
Asotin	0	0	0	0
Columbia	0	0	0	60
Garfield	0	0	0	0
Walla Walla	0	0	438	551
Whitman	0	0	557	557
Subtotal	**0**	**0**	**995**	1,168

Agricultural Districts/Counties	Landfilled	Incinerated	Agricultural land applied	Total land applied
Total on the Eastern Washington	**69**	**0**	**40,124**	**41,054**
Western				
Clallam	68	0	0	275
Clark	55	10,250	412	477
Cowlitz	13	0	5,494	5,494
Grays Harbor	0	0	0	67
Island	0	0	117	230
Jefferson	0	0	0	288
King	0	0	0	6,771
Kitsap	84	0	0	992
Lewis	0	0	5,956	8,116
Mason	0	0	1,770	1,925
Pacific	0	0	44	99
Pierce	0	0	537	5,912
San Juan	4	0	0	0
Skagit	0	613	87	253
Skamania	0	0	0	0
Snohomish	0	3,901	2,914	3,230
Thurston	0	0	0	0
Wahkiakum	0	0	0	0
Whatcom	0	4,258	907	1,018
Total on the Western Washington	**225**	**19,022**	**0**	**35,146**
Total in the State	**293**	**19,022**	**58,332**	**76,201**
Percent of the Total Generated (%)*	**0.30**	**19.8**	**60.8**	**79.4**

*Percent of the total generated (%) = the amount of biosolids managed (tons)/total biosolids generated (tons). The total biosolids generated was 95,156 tons in 2010.

Table 9

Estimated Amount of Biosolids Landfilled, Incinerated, and Land applied in Washington State in 2011

(Data Source: Ecology's Solid Waste Facilities Database)

Agricultural Districts/Counties	Landfilled	Incinerated	Agricultural land applied	Total land applied
	Dry Tons			
Central				
Benton	0	0	435	1,086
Chelan	0	0	865	864
Kittitas	16	0	2	2
Klickitat	0	0	99	99
Okanogan	94	0	242	256
Yakima	71	0	5,903	5,903
Subtotal	**181**	**0**	**7,545**	**82,11**
East Central				
Adams	0	0	25	25
Douglas	0	0	24,343	24,359
Franklin	0	0	673	673
Grant	0	0	168	168
Lincoln	300	0	2,510	2,510
Subtotal	**300**	**0**	**27,718**	**27,735**
Northeast				
Ferry	0	0	0	0
Pend Oreille	0	0	48	48
Spokane	0	0	6,827	11,314
Stevens	0	0	189	189
Subtotal	**0**	**0**	**7,064**	**11,551**
Southeast				
Asotin	0	0	0	0
Columbia	0	0	0	71
Garfield	0	0	0	0
Walla Walla	0	0	529	522
Whitman	0	0	548	548
Subtotal	**0**	**0**	**1,070**	**1,141**

Agricultural Districts/Counties	**Landfilled**	**Incinerated**	**Agricultural land applied**	**Total land applied**
	Dry Tons			
Total on the Eastern Washington	**481**	**0**	**43,397**	**48,638**
Western				
Clallam	0	0	0	283
Clark	0	6740	239	307
Cowlitz	16	0	6139	6,150
Grays Harbor	0	0	0	69
Island	0	0	97	113
Jefferson	0	0	0	295
King	0	0	0	5,270
Kitsap	0	0	0	2,065
Lewis	0	0	8967	11,286
Mason	0	0	1967	2,182
Pacific	0	0	57	114
Pierce	0	0	527	5,758
San Juan	6	0	0	0
Skagit	0	675	219	245
Skamania	0	0	0	0
Snohomish	0	4313	2398	2,776
Thurston	0	0	0	0
Wahkiakum	0	0	0	0
Whatcom	0	4327	723	845
Total on the Western Washington	**22**	**16,055**	**21,333**	**37,755**
Total in the State	**503**	**16,055**	**64,730**	**86,392**
Percent of the Total Generated (%)*	**0.49**	**15.6**	**62.9**	**83.9**

*Percent of the total generated (%) = the amount of biosolids managed (tons)/total biosolids generated (tons). The total biosolids generated was 95,156 tons in 2010

Table 10

Estimated Amount of Biosolids Landfilled, Incinerated, and Land Applied in Washington State in 2012

(Data Source: Ecology's Solid Waste Facilities Database)

Agricultural Districts/Counties	Landfilled	Incinerated	Agricultural Land Applied	Total Land Applied
	Dry Tons			
Central				
Benton	0	0	410	773
Chelan	0	0	0	0
Kittitas	0	0	2	2
Klickitat	0	0	71	71
Okanogan	23	0	173	220
Yakima	0	0	17,204	17,400
Subtotal	**23**	**0**	**17,861**	**18,466**
East Central				
Adams	0	0	10	10
Douglas	0	0	30,174	30,187
Franklin	0	0	545	545
Grant	0	0	183	432
Lincoln	0	0	21	2,441
Subtotal	**0**	**0**	**30,933**	**33,615**
Northeast				
Ferry	0	0	0	0
Pend Oreille	0	0	48	48
Spokane	0	0	5,429	5,630
Stevens	0	0	131	131
Subtotal	**0**	**0**	**5,607**	**5,808**
Southeast				
Asotin	0	0	0	0
Columbia	0	0	0	0
Garfield	0	0	0	0
Walla Walla	0	0	546	546
Whitman	0	0	800	800
Subtotal	**0**	**0**	**1,346**	**1,346**

Agricultural Districts/Counties	Landfilled	Incinerated	Agricultural Land Applied	Total Land Applied
	Dry Tons			
Total on the Eastern Washington	**23**	**0**	**55,747**	**59,235**
Western				
Clallam	0	0	0	778
Clark	0	10,540	478	546
Cowlitz	10	0	156	7,857
Grays Harbor	0	0	0	48
Island	0	0	124	248
Jefferson	0	0	0	277
King	4	0	4	3,072
Kitsap	76	0	0	2,150
Lewis	0	0	4,573	6,113
Mason	0	0	2,060	2,303
Pacific	0	0	51	107
Pierce	0	0	807	5,821
San Juan	8	0	0	0
Skagit	0	672	159	866
Skamania	0	0	0	0
Snohomish	0	4,566	211	644
Thurston	0	0	0	0
Wahkiakum	0	0	0	0
Whatcom	0	4,178	694	829
Total on the Western Washington	**97**	**19,957**	**9,317**	**31,658**
Total in the State	**120**	**19,957**	**65,063**	**90,894**
Percent of the Total Generated (%)*	**0.11**	**18.0**	**58.6**	**82.0**

*Percent of the total generated (%) = the amount of biosolids managed (tons)/total biosolids generated (tons). The total biosolids generated was 95,156 tons in 2010

As discussed in the previous section, management practices such as minimum tillage and reduced summer fallow present opportunities to accumulate SOC through the processes of C storage (sequestration). Use of recycled organic materials such as compost, biosolids, and biochar presents additional opportunities to increase soil C storage in agricultural soils of Washington State.

However, biosolids and compost generated in the state are not a fully realized source of organic C for agricultural soils. Some compost facilities statewide have problems marketing their finished compost. A major barrier to the widespread use of compost in agriculture may be the cost associated with purchasing compost, transportation, and application to agricultural fields.

Even with an extensive body of research indicating that land application of biosolids contributes positively to recycling nutrients, soil properties and fertility with low risks to environment and human health (National Research Council, 1996; Pepper et al., 2008), public perception and misconception still exist. Although biosolids have been promoted for beneficial land applications, about 17-20% of biosolids generated statewide were still disposed of in incinerators and landfills in 2010, 2011, and 2012 (Tables 8-10). This may be due to higher costs associated with transporting biosolids to beneficial use sites as compared to disposing of them in either incinerators or landfills. In many locations, community members are still speculative about the beneficial use of biosolids in general.

Clear synergies exist between the available source of organic C in recycled organic materials such as compost and biosolids, and the need to increase organic C content in agricultural soils in the state. As the number of food scraps, yard debris, and other organic waste diversion programs is expected to increase statewide over the next few years, an increasing amount of organic materials diverted from landfills and processed into compost will be expected to increase. As the production and supply of finished compost increase, there will be an even greater need to stimulate markets and provide end uses for the material. Similarly, as the population of the state is projected to dramatically grow to 7.8 million by 2025 (Ecology Beyond Waste Plan, 2009), more biosolids will also be generated. Better marketing and producing a quality product may help make increase its use and public awareness. By increasing the demand for compost, it will help keep the process moving by “closing the loop.” With the anticipated increase in materials, it is also important to explore other beneficial organic material management options.

As discussed, while approximately 94.3% of cropland is located on the eastern Washington, about 67-87% of the total amount of compost was produced on the Western Washington. The transportation factor might have partially contributed to the accumulation of compost at some facilities on the western Washington. These issues of costs and proximity to markets need to be addressed if the markets for finished compost are to improve.

Research in Australia suggests that a radius of 200-250 km (124-155 miles) be the limit to transport and apply recycled organic products such as compost to agricultural land. A major barrier to the widespread use of compost in agriculture may be the cost of compost purchasing, its transportation, and application. To promote the increasing use of compost in agriculture, the compost industry may need to adjust its marketing strategies to promote how compost improves soil health and crop productivity.

Conclusion

Agricultural soils in Washington State have high potential to store (sequester) organic C through the use of recycled organic materials such as compost, biosolids and biochar, especially on the eastern Washington, where a majority of soils (90.3%) are low in organic matter content.
If only 5% of the total cropland received an estimated agronomic application rate at 5.0 dry tons of compost, or 2.0 dry tons of biosolids per acre per year, about 1,900,000 dry tons of finished compost, or 760,000 dry tons of biosolids will be needed annually. This far exceeds the amount of compost (about 310,000 to 470,000 dry tons of compost) or biosolids (about 96,000 tons to 110,000 million dry tons) in 2010, 2011, and 2012.

However, biosolids and compost are not fully realized sources of organic C for agricultural soils. Although biosolids has been promoted for beneficial land applications, about 17-20% of biosolids generated were disposed of in incinerators and landfills. This may be due to higher costs associated with transporting biosolids to a beneficial use facility as compared to the costs of disposal of them in either incinerators or landfills, although an extensive body of research indicates that land application of biosolids contributes positively to recycling nutrients, soil properties and fertility with low risks to environment and human health (National Research Council, 1996; Pepper et al., 2008).

In addition, some compost facilities statewide have problems marketing their finished compost, leading to continued accumulation of finished compost at these facilities. There is a potential for facilities to increase their use of compost in agriculture, which would help alleviate the issue of marketing.

An existing major barrier to the widespread use of compost in agriculture may be the cost associated with purchasing finished compost, its transportation, and application to agricultural fields. In addition, while approximately 94.3% of cropland of the state is on the eastern Washington, about 67-87% of the total compost was produced on the western Washington. This transportation factor might have partially contributed to the continued accumulation of compost at these facilities. The issues of costs and proximity to markets need to be addressed if the markets for finished compost are to improve.

Similarly, if biochar was applied to 5% of the total crop land at an agronomic application rate 0.40 tons (800 1b) per acre per year, it would require about 150,000 dry tons (Sprinkle, 2014, personal email communication). While biochar production is new, the market is expanding rapidly. Producers to date in Washington State are nowhere near able to supply even a portion of the 125,000 tons.

Clear synergies exist between the availability of recycled organic materials and the low SOC content in agricultural soils in Washington State. The use of the recycled organic materials such as compost, biosolids, and biochar as a part of a system approach to improved soil management would provide an external source of stable organic C and has the potential to increase the SOC sequestration in agricultural soils.

As the number of food scraps, yard debris, and other organic waste diversion programs is expected to increase statewide over the next few years, more compostable organic materials may be diverted to compost facilities, leading to more production and supply of finished compost in the market. As the production and supply of finished compost increase, there will be an even greater need to stimulate markets and provide end uses for the material. To promote increasing use of compost in agricultural soils, the compost industry may need to adjust its marketing strategies to promote how compost improves soil health and crop productivity.

As the population of the state is expected to increase, more biosolids will also be generated. Likewise, biochar production is growing rapidly. There will be an even greater need to stimulate markets and provide beneficial end uses for the recycled organic materials. Better education, marketing and producing a quality product may help make this happen. By increasing the demand for organic materials such as compost, biosolids and biochar, it will help expand the process by “closing the loop, while helping reducing atmospheric CO_2 levels as resulted from increased soil C storage (sequestration).”

With the anticipated increase in organic waste streams to be generated in the state, it is also important to explore other beneficial organic material management options such as anaerobic digestion.

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