Land Application- a true path to zero waste?

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Executive summary

Each person in Washington State creates about 60 pounds of biosolids (solid residual from wastewater treatment), about the same amount of food waste, and about 150 pounds of yard waste each year. Manures generated from the animal products that we use total to another 10,000 pounds of waste per person per year. This study tested the benefits of recycling these organic residuals to soils. Soils sampled for the study included long-term replicated field trials and farmer's fields. The sites were distributed across Washington State and include a range of land uses including turf, ornamental crops, highways, agronomic crops and high value orchard crops such as pears, cherries and hops.

Biosolids and compost are generally applied to soils as a substitute for synthetic fertilizers. They are generally applied to soils to meet the nitrogen requirements of the crop. In addition to N, composts and biosolids will generally supply all necessary plant macro and micro- nutrients. Composts are also used as soil conditioners. As both biosolids and composts consist largely of organic matter, use of these amendments in lieu of synthetic fertilizers has the potential to alter soil properties. Increases in soil organic matter will result in increased soil carbon. Soils are the third largest carbon pool following oceanic and fossil carbon reserves. Soil carbon has been depleted as a result of conventional agricultural practices, changes in land use and deforestation. When soil carbon is increased other changes in soil properties associated with carbon content will occur. Previous studies have shown decreases in soil bulk density and increases in soil water holding capacity following increases in total soil carbon.

Results

For all studies in this sampling addition of organic amendments resulted in significant increases in soil carbon storage. Rates of carbon storage per dry Mg of amendment ranged from 0.012 in a long term study of turf grass to 0.54 in an organic pear orchard with a long history of compost use. In general, soils with the lowest carbon levels showed the highest levels of carbon storage. Carbon content in soils also increased with time, meaning that the organic matter added with the residuals application resulted in long term carbon increases in soils. Increases in soil carbon content were much greater when composts and biosolids were incorporated into the soils rather than surface applied.

For all sites included in this study, total nitrogen (%) in soils that received organic amendment addition was higher than conventionally fertilized or control soils for at least one of the rates of amendment tested. Soil physical properties generally improved as well. Bulk density decreased after amendment addition in a number of the sites tested. With the biggest decreases seen in the most compacted soils. In the site with the highest bulk density, incorporation of compost or biosolids reduced soil bulk density to half that of control soils. Finally soil water holding capacity was increased in 5 of the 9 sites sampled. Increases ranged from 10% to 50%. For both soil moisture tension levels tested, amendment or soil carbon were significantly positively correlated with water storage.

Prior studies conducted on the sites sampled for the current survey have shown a positive yield response associated with use of organic amendments. This has been statistically

significant in all of the studies where yield has been measured. This includes use of compost on ornamentals, compost and biosolids for highway plantings, biosolids for dryland wheat and biosolids for turf grass. For dryland wheat, biosolids amended plots had higher yields than control plots for 6 out of 7 growing seasons. The biosolids amended plots also outperformed the conventionally fertilized plots for 3 of the 7 harvests with results being similar to conventional fertilizers for the other harvests. For turf grass, the middle rate of biosolids application was similar to synthetic N and higher than control soils. The higher rate of biosolids application, outperformed the conventional fertilizer treatment. For ornamentals, positive response was observed for plant growth and appearance with red rosier dogwood for incorporated compost and bark (Cogger et al., 2008).

The results from this study indicate that adding organics to soils results in a wide range of benefits for plants as well as a cost effective way to sequester carbon.

Introduction

Use of compost is generally recognized as a beneficial practice. Compost is used widely in landscaping, home gardening and organic agriculture. Traditional feedstocks for compost include yard waste, animal manures, and municipal biosolids. However, many organic waste materials that are currently landfilled could effectively be diverted from landfills to compost facilities. An example of this is food scraps. Currently in the US, less than 2% of the food scraps generated are composted with the remainder being landfilled. According to US EPA estimates, food scraps constitute 11% by weight of municipal solid waste (US EPA, 2006). There are other components of MSW and agricultural residues that would also be suitable for compost feedstocks (Freer et al., 2005). In addition, although compost is generally recognized as beneficial and suitable for multiple end uses, the potential market for compost in the US is substantially larger than the quantity of material that is currently produced (Nora Goldstein, Biocycle Magazine).

The value of composting for generating carbon credits has been recognized. Landfill diversion of organics to compost facilities is a certified means to reduce greenhouse gas emissions on a number of carbon exchanges (Alberta Environment, 2008; Clean Development Mechanism, 2008;Chicago Climate Exchange, 2008). The protocol for each of these exchanges provides carbon credits for methane avoidance with no credits associated with compost use. Although use of compost is generally recognized as beneficial, these benefits have not been quantified across the range of potential end uses for this material. Potential benefits re use of compost from a greenhouse gas perspective include soil carbon storage and displacement of synthetic fertilizers.

Soils are the third largest carbon pool containing approximately 2500 Pg carbon ((Pg = petagram = 1 × 1015 g = 1 billion metric tons). The ocean contains 38,000 Pg C and the geological pool contains 5000 Pg C (Batjes and Sombroek, 1997; Lal, 2004). The surface soil organic carbon (SOC) pool is about three times larger than the atmospheric pool (830 PgC) and almost five times larger than the global biotic pool (560 PgC) (http://cdiac.ornl.gov/pns/convert.html#2). A range of factors including urbanization, deforestation, conventional tillage and use of synthetic fertilizers, have depleted the pool of carbon in soils. The Intergovernmental Panel on Climate Change (2000) estimates worldwide 136±55 PgC were released from soils from 1850-1998 due to land-use change, deforestation and soil cultivation (Batjes and Sombroek, 1997; Lal, 2004).

There is a general perception that carbon in soils is rapidly mineralized. However, soil organic carbon is a relatively stable long-lived pool. Some carbon in SOC exists as short-cycle "labile" compounds that turn over on the order of years to decades, but soil processes and microbial transformations upon soil organic carbon can produce more stabile C compounds with mean residence times measured in hundreds to thousands of years (Khanna et al. 2001; Campbell et al., 1967; Jenkinson and Rayner, 1977). Mean residence time (MRT) for carbon in soils is generally in the rage of 20-30 years (Lal et al. 1995; Post et al., 1992). In addition, the total organic carbon concentration of a soil is a function of the productivity of the site. More productive soils will promote more plant growth that will in turn lead to increased carbon deposition in soils.

Increasing SOC in agricultural, rangeland, and urban and degraded lands has been suggested as a viable means to sequester carbon in soils (Lal, 2004, 2007). Specifically, the use of carbon-rich organic soils amendments have been suggested as a means to increasing SOC concentrations. Organic amendments can increase SOC concentrations by increasing organic matter inputs by application and by associated increases in net primary productivity, increasing humification, and by increases in aggregation.

Use of organic soil amendments, such as compost, has been shown to increase the concentration of soil organic carbon (SOC). Data from short and long-term studies, across different soil types, climates, and under different land use practices, show greater soil carbon accumulation where organic amendments are used in comparison to sites that have been treated with synthetic fertilizer alone (Albiach et al., 2001; Albaladejo et al., 2008; Morlat and Chaussod, 2008; Mylavarapu & Zinato, 2009; Tian et al., 2009, Wallace et al. 2009). For example, Albaladejo et al. (2008) applied uncomposted organic residuals from municipal solid waste on a disturbed urban site in Spain. The site was sampled 16 years after amendment addition. The soil organic carbon (SOC) concentration in the treated plots was significantly higher than in the untreated plots at the 0-10cm depth, and increased with increasing application rate. SOC concentration was 0.79, 1.19, and 1.64% for the control, 130 and 260 Mg/ha plots respectively. In another long term study of residuals application to a vineyard, SOC in plots that received annual applications of cattle manure compost (20 Mg ha) or spent mushroom compost (16 Mg ha) were approximately double the control in the surface soil after 16 annual applications (Morlat and Chaussod, 2008). Subsoil (33 cm) carbon also increased in these treatments at the 16 year sampling. Sukkariyah et al (2005) looked at the long-term effects of a single biosolids application to a corn cropping system on a clay loam soil in Orange County, Virginia, USA. In 1984 biosolids were applied at of 0, 42, 84, 126, 168, and 210 Mg/ha. The initial carbon concentration in the control plot was 2.2% with carbon concentration in the soils receiving the highest biosolids loading rate of 6.5% immediately following amendment addition. In 2001, carbon in the control plots measured 2.1% with carbon content in the high biosolids treatment of 4.0%. These carbon values had remained consistent from 1992-2001 indicating that the biosolids application had resulted in new equilibrium carbon concentrations for the treated soil. In another long- term study, different crop rotations were tested along with different fertilizer inputs (Izaurralde et al. 2001). Net above ground productivity was approximately double in the farmyard manure amended soils in comparison to the control and synthetic fertilizer amended treatments. The authors attribute the increase in soil carbon concentrations in the manure amended soils to the increased above ground plant productivity.

Use of compost or organic amendments has also been associated with improvement in soil physical properties including bulk density (BD), aggregation, and increased water holding capacity and infiltration rates. Bulk density is an indirect measure of pore space, which is primarily determined by soil texture and structure. As pore space increases, bulk density decreases. High porosity increases water infiltration, aeration, and eases resistance to root penetration. Therefore, low bulk densities and high porosity are associated with good soil tilth, or the soils ability to support plant growth. Fine-textured surface soils such as silt loams, clays, and clay loams generally have a bulk density ranging from 1.00 to 1.60 g cm^3. Sandy soils, however, generally have bulk density values ranging from 1.20 to 1.80 g cm^3 (Brady and Weil, 2002). Khaleel et al. (1981) conducted a linear regression analysis using data from several different published studies. They found a significant linear relationship ($p<0.01$, $r^2=0.69$) between observed increases in soil organic carbon due to organic amendment application and the percent reduction in soil bulk density, despite differences in soil, crop, and amendment type. Among these studies there were 21 soil types ranging in texture from clay loam to coarse sand, 7 organic amendment types, and 8 crop types. More recent studies have confirmed this earlier finding. For example, Aggelides and Londra (2000) studied changes in bulk density after biosolids composts were applied to both a loam and a clay soil. Four different application rates(0, 39, 78, and 156 Mg ha^{-1}) were used in this study. In the loamy soil BD decreased from 1.37, 1.20, 1.13, to 1.10 g cm^3 with increased amendment application rate. Similar results were observed in the clay soil. Bulk density in the clay soils decreased from 1.12, to 1.05, 0.98, and 0.94 g cm^3 as the application rate increased.

Organic amendments decrease soil bulk density in two ways. Organic matter is lighter than the mineral fraction of soils. By increasing the organic matter in soils, the weight of the soil is reduced. In addition, as the organic matter is decomposed by soil microorganisms, sticky exudates are formed as degradation byproducts. These exudates surround inorganic mineral particles and help to form stable aggregates. The aggregation of soil particles in turn increases pore space and reduces soil bulk density (Martens & Frankenberger 1992, Aggelides & Londra 2000, Lindsey and Logan, 1998,Tejada et al. 2009, Wallace et al., 2009). Many studies have found increased soil aggregates and aggregate stability following organic amendment addition. Lindsey and Logan (1998) measured size and stability of aggregates 4 years after biosolids were applied to a silt loam soil at rates ranging from 0 to 300 Mg ha^{-1}. They observed increases in both the size of aggregates as well as the fraction of water stable aggregates with increasing biosolids application rate. The highest biosolids loading rate (300 Mg ha^{-1}) had 3.5 times more stable aggregates than the control. Similar results were found for surface applied biosolids (60 Mg ha^{-1}) in comparison to control and fertilizer treatments in British Columbia and for compost and biosolids amended soils in Greece (Aggelides and Londra, 2000; Wallace et al., 2009). However, Cogger et al. (2009) observed a visible but not statistically significant increase in soil aggregation following compost incorporation. They noted that the high sand content of the soil may have been a factor in the lack of increase in water stable aggregates following compost addition.

The effect of organic amendments on soil water has been measured using a range of indexes. There are a number of factors that determine the plant available water in a specific soil. These include the rate at which water infiltrates into the soil, and total water content by weight and volume over a range of moisture tension. The rate at which water enters a soil either during a rainfall or irrigation event will determine the portion of the total rain that is absorbed by the soil and the portion that moves off the soil surface via overland flow. Once absorbed into the soil, a certain portion of the water will drain freely. Saturation is the term used to describe a soil when all pore space is filled with water. Field capacity is the term used to describe the soil moisture status after all free water has drained via gravity flow. The remaining water in the soil is held by soil matric potential onto soil particles. The level of tension holding the water at this stage is generally accepted to be between 0.1 and 0.33 bars. Permanent wilting point, the level of dryness at which plants can no longer recover if additional water is added to a soil, is generally considered to be 15 bar (Brady and Weil, 2002). Available moisture concentration in a soil has been defined as the total moisture between field capacity and permanent wilting point (Lindsey and Logan, 1998). However, moisture tensions between field capacity and 1 bar are pertinent for irrigated, high value agriculture. Soil texture is the primary factor affecting the quantity of water at each of these soil moisture tensions (Khaleel et al., 1981; Rawles et al., 2003). Clay soils, due to higher matric potential and smaller pore size will generally hold significantly more water by weight than sandy soils. Although organic matter has a high water holding capacity in comparison to the mineral fraction of soils, concentrations of organic matter in soils are generally low enough to make this effect negligible. Organic matter can alter a soil water holding potential by increasing soil pore space (a corollary to decreased bulk density) as well as through the water holding capacity of the organic matter itself. The effect of organic matter on improving soil water retention is more pronounced on sandy soils compared with clayey soils (Rawles et al., 2003).

Different studies have used different indexes to measure changes in soil water as a result of organic amendment addition with some showing increases in some or all measures tested. In a review of the literature on effects of compost addition on soil moisture, surface mulch applications of compost significantly increased soil moisture with increase proportional to application rate (Recycled Organics Unit, 2006). The affect of incorporated compost was less clear, with a much smaller increase in soil moisture observed. Cogger et al. (2009) saw increased infiltration for soils where compost had been used as a mulch or incorporated into the soil in comparison to control treatments. Moisture tension measures were also made in situ in this study using tensiometers. Soils with compost either surface applied or used as mulch stayed wetter longer than soils that didn't receive any amendments. When measures were taken in the root zone of plants, soils with surface applied compost stayed wetter than control or compost incorporated soils. Lindsey and Logan (1998) observed increased volumetric water content in biosolids amended soils at 3 different moisture tension levels. However, no difference in plant available water (defined as total water content from field capacity to permanent wilting point) was seen across the different treatments.

This study was conducted to characterize changes in soils following addition of a range of organic amendments. Soils from a range of experimental field plots located across Washington State as well as from working farms were included in the sampling. Soils were tested for total carbon and nitrogen, bulk density and water holding capacity at 0.1 and 1 bar of tension. By including a large number of sites with different soils, crops, and amendment histories, the goal of the study was to better characterize changes in soil following organic matter additions.

Materials and methods

Site Descriptions

Soil samples for this study were collected from both commercial farms and replicated field trials. Detailed descriptions as well as a summary table of all sites included in this study are presented below.

Commercial farms

Durfey- Duplicate sets of samples were collected from three types of crops from Natural Selection Farms, operated by Ted Durfey in Sunnyside Washington.

Cherry -Samples were collected from a commercial irrigated cherry (*Prunus bing, rainer*) orchard located in Sunnyside, WA. The site is on Warden silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids). Between the years of 2002 and 2008 (year of sampling), this site received annual compost applications of 15 Mg ha^{-1}. The cumulative loading rate was 105 Mg ha^{-1}. The compost used at this site was produced using orchard trimmings, fish waste, hops waste, and apple and grape pomace. The compost was incorporated into the top 5cm of the soil. Amendment was banded underneath the trees, and incorporated into the top 5cm of the soil. A conventionally managed cherry orchard with no history of compost application, located immediately adjacent to the compost amended orchard, on the same soil series, was used as the control field.

Grapes- This was a commercial grape vineyard (*Vitis labrusca*), under organic management, located in Sunnyside, WA. The site is on Warden silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids). Between the years of 2002 and 2008 (year of sampling), compost was applied annually to the working area in between the vines at a rate of 13 Mg ha^{-1}. The compost used at this site was produced using orchard trimmings, fish waste, hops waste, and apple and grape pomace. The compost was incorporated into the top 5cm of the soil. The cumulative loading rate of compost was 91 dry Mg ha^{-1}. Control samples were collected from a vineyard in an adjacent field with no history of organic amendment use. All samples were collected from the work row, where the amendment and fertilizer were applied.

Hops- Samples were collected from a commercial hops field (*Humulus lupulus*) located in Sunnyside, WA. The site is on Warden silt loam (Coarse-silty, mixed, superactive, mesic Xeric Haplocambids). In 2003 the site received a single large application of 140 Mg ha^{-1} of compost. The compost used at this site was produced using orchard trimmings, fish waste, hops waste, and apple and grape pomace. The compost was incorporated into the top 5cm of the soil. No additional compost applications have been made between that time and when samples for this study were collected. A neighboring hops field (about 1.5 km away), with no history of organic amendment application was used as the control field. The control field was also located on Warden silt loam.

Pear- This was a commercial pear orchard (*Pyrus communis*) located in Sunnyside, WA. The site is on Warden silt loam (Coarse-silty, mixed, superactive, mesic Xeric Haplocambids), and Esquatzel silt loam (Coarse-silty, mixed, superactive, mesic Torrifluventic Haploxerolls). Between the years of 2004 and 2008 (year of sampling), this site received annual compost applications of 16.7 Mg ha^{-1}. The compost used at this site was produced from orchard trimmings, fish waste, hops waste, and apple and grape pomace. The compost was incorporated into the top 5cm of the soil. The cumulative loading rate of compost was 84 dry Mg ha^{-1}. Amendment was banded underneath the trees, and incorporated into the top 5cm of the soil. Control samples were collected from the work row (area between the trees.

Dryden Samples were collected from a commercial certified organic pear (*Pyrus communis*) orchard, with a long history of compost use, located in Dryden, WA. At the time of sampling the site had received fifteen consecutive years of compost application (1993-2008), surface applied directly under the pear trees at a rate of approximately 9 Mg ha^{-1}. The cumulative loading rate of compost was 134 Mg ha^{-1}. A field on an adjacent farm, also a pear orchard, with no history of organic amendment use was used as the control. Both sites were located on Cashmont sandy loam (Coarse-loamy, mixed, superactive, mesic Aridic Haploxerolls) soils. Samples for both sites were collected from the area under the trees.

Replicated field trials

GP17: This was a long-term biosolids application study on a dryland wheat (*Triticum aestivum*)-summer fallow rotation in Douglas County, WA. The site is on a Touhey loam (coarse-loamy, mixed mesic Aridic Duric Haploxerolls), derived from a mixture of till and loess. The field plot design was a randomized complete block, with five treatments replicated three times. The treatments included three different rates of biosolids application (4.5, 6.7, and 10 Mg ha^{-1}), an unfertilized control and a fertilized control. The biosolids used at the site were Class B anaerobically digested biosolids cake (25% solids) from the King County municipal wastewater treatment plant. The experiment was established in 1994, and biosolids were applied to the soil every 4 years between 1994 and 2008. The fertilized control plot received agronomic rates of nitrogen and sulfur every 2 years (each crop year). Cumulative loading rates of biosolids were 18, 27, and 40 Mg ha^{-1} at the time of sampling.

CITL: This experiment was established at the Washington State University Puyallup Research Station (2606 W Pioneer Rd./Puyallup, WA 98371) in 2001. This study tested surface applied and incorporated compost in an urban ornamental landscape (Cogger et al. 2008). Compost made from urban yard waste and chipped Douglas-fir (Pseudotsuga menziesii) bark (used as a mulch) were used in this study. Samples from this study reflect the long-term impact of a single high rate application of compost. The experiment consisted of a factorial arrangement of three compost treatments (incorporated, surface-applied as mulch, and none) by two bark treatments (surface-applied as mulch and none). The field plot design was a randomized complete block with a total of six treatments replicated four times. Compost and bark were both applied to the plots at a level depth of 7.6cm. Bark was applied after compost. In this case, 7.6cm of compost was equivalent to an application rate of 224 Mg ha^{-1}. After compost and bark application the plots were planted to a mixture of Redosier Dogwood (*Cornus sericea L.*), Pacific Madrone (*Arbutus menzieseii*), Alaska Cedar (*Chamaecyparis nootkatensis*), Strawberry Tree

(*Arubutus unedo*), Fringe Tree (*Chionanthus virginicus*), Rhododendron 'Henry's Red', and Yellow Monkey Flower (*Mimulus luteus*). The site is on Puyallup find sandy loam (coarse-loamy over sandy or sandy-skeletal, isotic over mixed, mesic Vitrandic Haploxerolls). Only incorporated compost treatments were included in this sampling. Bark was cleared off of the soil surface prior to sampling.

FWC1: This site was a replicated field study at Washington State University Puyallup Research Station (2606 W Pioneer Rd./Puyallup, WA 98371) designed to test the effects of compost over time following a single application. The study was set up using a randomized complete block with 4 replicates in 1994. Treatments included food waste compost and 2 control treatments (Sullivan et al. 1998, 2003). In 1993, food waste composts were applied to the soil at 156 Mg ha^{-1}. Compost was incorporated into the surface 7.5-10cm of the soil by lightly disking the entire plot area. Tall fescue ('A.U. Triumph') (*Festuca*) was seeded the day after compost application and has been grown on the site since this historic application. The site has not been tilled since the beginning of the experiment. The site is on a Puyallup fine sandy loam (coarse-loamy over sandy or sandy-skeletal, isotic over mixed, mesic Vitrandic Haploxerolls), a deep, well-drained soil developed in recent alluvium.

FWC3: This is a replicated field study site on the Washington State University Puyallup Research Station (2606 W Pioneer Rd./Puyallup, WA 98371), in which 2 Class A biosolids products were surface applied over a course of 10 years (1993-2003). These two products were a dry pelletized material, and a traditional Class A cake. The materials were applied annually at 0, 6.72, 13.44 and 20 Mg ha^{-1} for total applications of 0, 67, 134 and 202 Mg ha^{-1}. The site was planted to tall fescue ('A.U. Triumph') in 1993, two months before treatment application, and has not been tilled since. The field plot design was a randomized complete block with eight treatments replicated four times (Cogger et al. 1999, 2001). In addition to the biosolids treatments, a control and an ammonium nitrate (applied at a single rate) treatment were included in the study design. The site is on a Puyallup fine sandy loam (coarse-loamy over sandy or sandy-skeletal, isotic over mixed, mesic Vitrandic Haploxerolls), a deep, well-drained soil developed in recent alluvium.

MGSS1: This is a replicated field study, located on the WSU Puyallup Research Station (2606 W Pioneer Rd./Puyallup, WA 98371), in which yard debris compost and a Class A biosolids-sand-sawdust blend (Tagro mix) were applied at different rates. Loading rates were based on depth of the material applied. Compost was applied at a rate of 0cm control, 2.5cm, 5cm, 7.5cm, and 10cm, biosolids was applied at 2.5cm only. All materials were applied as a single application 8 years prior to sampling. All amendments were incorporated after application and the site planted to turf-type perennial ryegrass. The site has been maintained as low-input turf. The field plot design was a randomized complete block with six treatments replicated four times. The site is on a Briscot loam (coarse-loamy, mixed, superactive, nonacid, mesic Fluvaquentic Endoaquepts).

Hwy16: This is a replicated field study established in 2007 along the side of Highway 16 in Tacoma, WA. The soils are compacted glacial outwash, highly disturbed due to cutting and compaction. Compost was applied to aid in the success of the Washington State Department of Transportation landscaping project. These disturbed soils received a single application of compost, one year prior to sampling. After compost application the site was planted to mixed shrubs. The field plot design was a randomized complete block with seven treatments replicated four times. Treatments were a bare soil control, yard debris compost applied at 224 Mg ha^{-1} (incorporated and surface applied), a biosolids-sawdust-sand product (Tagro mix) applied at 152 Mg ha^{-1} (incorporated and surface applied), and surface applied worm castings compost applied at 73.92 and 224 Mg ha^{-1}. Soil series is not provided as the soil in this study is compacted subsoil from construction of the roadway.

Systems: This is a replicated field study of organic management systems for intensive vegetable production located on the Washington State University Puyallup Research Station (2606 W Pioneer Rd./Puyallup, WA 98371). This study incorporates different organic amendment applications with different tillage treatments and different cover crop strategies. The tillage treatments include a standard tillage and a lower impact spading technique. The soil amendments for this experiment include a high carbon on farm compost product (feedstocks include yard debris, broiler litter, separated dairy manure solids, and animal bedding), and a low carbon composted broiler chicken manure product. Cover crop treatments include an annual fall-planted rye-vetch blend (*Secale cereale L.* and *Vicia villosa Roth*), an annual interseeded hairy vetch, and a rotational ryegrass-red clover (*Trifolium pratense*) pasture. The field plot design was a split-split plot with 12 treatments replicated 4 times. The site is on both Puyallup fine sandy loam (coarse-loamy over sandy or sandy-skeletal, isotic over mixed, mesic Vitrandic Haploxerolls)and Briscot loam (coarse-loamy, mixed, superactive, nonacid, mesic Fluvaquentic Endoaquepts).   Amendment rate was the only variable considered for this sampling. For this study, the low rate of chicken manure (11 Mg ha^{-1}) was used as the control treatment.

A list of all sites included in this study is also presented in Table 1.

Table 1. Site, location, type of site, crop, years of amendment application, annual and

e	Wa state County	Crop	Soil series	Treatments	First application	Application frequency	Cumulativ
							Mg
rfey	Yakima	Cherry	Warden silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids)	Fertilizer/Compost	2002	Annual	1(
	Yakima	Grape	Warden silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids)	Fertilizer/Compost	2002	Annual	9
	Yakima	Hop	Warden silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids)	Fertilizer/Compost	2003	Single	1
	Yakima	Pear	Warden silt loam (Coarse-silty, mixed, superactive, mesic Xeric Haplocambids), and Esquatzel silt loam (Coarse-silty, mixed, superactive, mesic Torrifluventic Haploxerolls).	Fertilizer/Compost	2004	Annual	8
rden	Chelan	Pear	Cashmont sandy loam (Coarse-loamy, mixed, superactive, mesic Aridic Haploxerolls)	Fertilizer/Compost	1993	Annual	1
-17	Douglas	Wheat	Touhey loam (coarse-loamy, mixed mesic Aridic Duric Haploxerolls	Control/Fertilizer/ Biosolids	1994	Biosolids- Every 4 years	18, 2
L	Pierce	mixed shrubs	Puyallup find sandy loam (coarse-loamy over sandy or sandy-skeletal, isotic over mixed, mesic Vitrandic Haploxerolls)	Control/Compost	2001	Single	2
y 16	Pierce	mixed shrubs	Disturbed site	Control/Compost/ Biosolids	2007	Single	74, 15
SS1	Pierce	turf	Briscot loam (coarse-loamy, mixed, superactive, nonacid, mesic Fluvaquentic Endoaquepts).	Control/Compost	2000	Single	92,186,
C1	Pierce	turf	Puyallup find sandy loam (coarse-loamy over sandy or sandy-skeletal, isotic over mixed, mesic Vitrandic Haploxerolls)	Fertilizer/Compost	1993	Single	1
C3	Pierce	turf	Puyallup find sandy loam (coarse-loamy over sandy or sandy-skeletal, isotic over mixed, mesic Vitrandic Haploxerolls)	Fertilizer/Biosolids	1993	nnual until 200	67,13
			Puyallup fine sandy loam (coarse-loamy over sandy or sandy-skeletal, isotic over mixed, mesic Vitrandic Haploxerolls)and Briscot loam (coarse-loamy, mixed, superactive, nonacid, mesic	Chicken			

composite samples were collected from three different locations per field for both compost amended and control soils. At the time of collection the soils were placed in brown paper bags. Within 5 hours of sample collection the paper bags were placed in a drying chamber set at 22-25° C to air dry. For more remote sites (all sites outside of Pierce county), the samples were placed and stored in plastic re-sealable bags, in a cool, dark place, until returning to the laboratory. The samples were never stored in the plastic bags for longer than 3 days. Once returning to the laboratory, the samples were placed in brown paper bags and placed in the drying chamber to air dry.

Samples for bulk density and water holding capacity were collected using a hammer-driven core sampler. Three samples were taken in each plot or commercial field site to a depth of 8 cm (Grossman and Reinsch, 2002). The core sampler contains an internal ring, which holds the intact soil core. This internal ring is able to slip out of the sampler, releasing it and the intact core for analysis. Immediately after removing the ring from the sampler, caps were placed on the open ends of the rings to hold the sample in place until analysis. All bulk density and water holding samples were stored in a 4° C cold room until we were able to begin analysis.

Laboratory Analysis

Total carbon and nitrogen analysis

Air-dry samples were ground and sieved to 2mm in size. A representative subsample was then ground to a fine powder, using a ceramic mortar and pestle, for total carbon and nitrogen analysis. Aliquots of the fine soil powder were weighed and analyzed for total carbon and total nitrogen using a dry combustion CHN analyzer (Perkin Elmer Inc, Waltham, MA). Each sample weighed between 25 and 35 mg. Two internal standards, of known carbon and nitrogen concentration, were used to check the accuracy of the instrument. Internal standards were run approximately every 10 samples, and were run in triplicate every twenty samples. Site samples were also run in duplicate every 10 samples.

Bulk density and Water-holding analysis

Soils collected for bulk density were also used for water-holding analysis. This enabled analysis of intact core samples and so avoided errors associated with loss of soil structure. The intact core was held in the ring for measurement of water-holding capacity at 0.1 and 1 Bar of tension. These two levels of tension were used to represent soil moisture conditions that cover the optimal range for plant growth.

Samples were tested for 0.1 bar water holding capacity using a sand tension table. The 0.1 bar soil moisture tension approximates the field capacity of a soil. Field capacity, or the state where all free water has drained out of a soil following a rain or irrigation event, is the ideal moisture status for plant productivity. The sand tension table is a specialized piece of equipment used to test soil samples for water holding capacity at very low tensions. Manufactured ceramic pressure plates that are commonly used for soil moisture measures are traditionally not reliable or accurate at this low pressure.

The sand tension table used for this study was constructed of a large plastic container (3 m x 1.1 m) fitted with a lid to minimize evaporative loss. Seven ceramic lysimeters, each connected to two plastic tubes (a water supply line and a vacuum line) are distributed inside the plastic container. Covering the lysimeters and filling the plastic container is a 200 mesh silica flour, an appropriate size of material to conduct tension at 0.1 Bar. The sand bed is flooded with water, which flows into the table from the water supply tank and out the ceramic lysimeters. Once the sand bed is flooded with water, fully saturated samples (still in their sampling rings) are placed on top of the silica flour surface. The vacuum valves are then opened, which drains water from the silica flour and samples simultaneously, at exactly 0.1 Bar of tension.

Soil cores were prepared for moisture measures removing the plastic caps and replacing them with nylon mesh. The mesh was fixed to one end (via rubber band), and the cores were saturated (Ψ=0) in their rings by slowly raising the water table during the course of a minimum of 24 hours. Subsequently, soils cores were equilibrated to -0.1 Bar by placing them on the sand tension table, controlled with vacuum pressure regulators (Topp et al., 1993, Moebius et al., 2007). Equilibrium was reached in 48 ±5 hours for all samples. Rather than automatically removing samples after 48 hours, equilibrium was confirmed by noting no change in sample weight over an 8 hour time period.

After soil samples reach equilibrium at 0.1 Bar on the sand tension table, they were weighed and moved to a ceramic high pressure plate apparatus (Topp et al., 1993) set at 1.0 Bar. One bar of pressure approximates the moisture status of soils at the low end of optimal moisture conditions. At higher moisture tensions, high value crops would require irrigation. For this measure, the intact cores were placed on soaked 1 bar ceramic pressure plates, within a pressurized chamber. The pressure within the chamber was maintained at 1.0 Bar until the samples came to equilibrium. Equilibrium was reached once water was no longer emitted from the chamber. After equilibrium was reached the samples were removed from the chamber and weighed.

Once water holding capacity measures were complete, the bulk density of the sample was calculated by drying the intact core soil sample. The samples were then placed in an oven at 105° C for 24 hours. The dried sample were then weighed. The dry weight was used to calculate % moisture at 0.1 Bar, 1 Bar, and bulk density. The internal ring used to collect soils and run moisture and bulk density analysis is of specific and known dimensions. The volume of each soil core sample is known. The bulk density was calculated as the weight of the soil per known volume of the ring.

Statistical analysis

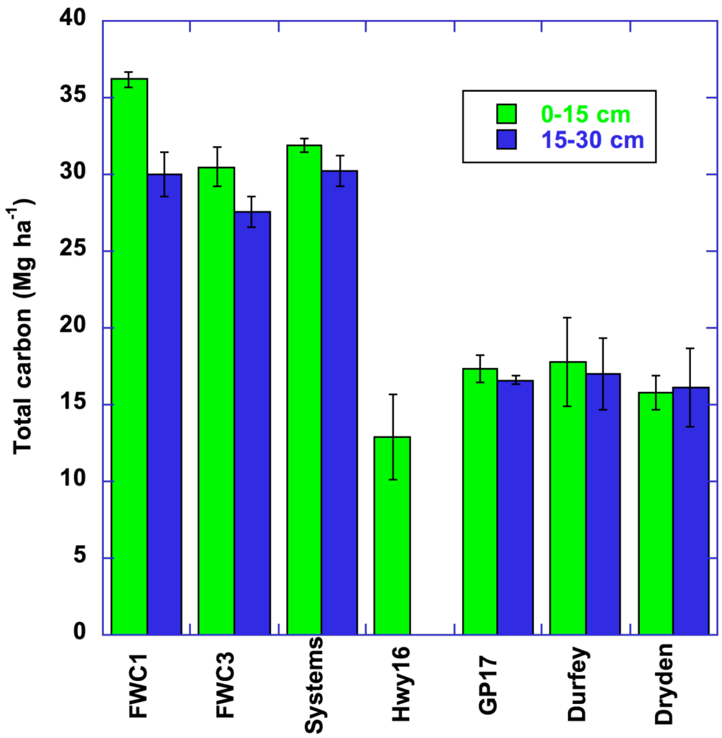
Statistical analysis was conducted using SPSS version 10.0.5 (SPSS, 1999). Treatment effects were testing using ANOVA. When the F value of treatment was significant ($p<0.05$), means were separated using the Waller-Duncan t-test with a significance level of $p<0.05$. Total carbon stored in the soil was calculated by multiplying the %C by the weight per volume of the soil (as given in the bulk density measure). As bulk density measures were not collected for the lower soil horizons, a single value for bulk density (1.44 g cm3) was used for all treatments across all sites. Total carbon stored for each treatment was calculated by summing the total carbon stored across all depths for each site. A linear regression model was used to determine what factors influenced gravimetric water content of the soils. A stepwise procedure with $p < 0.05$ was used with a range of quantitative factors included in the initial model. This procedure removes factors from the model unless they account for a significant fraction of the observed variation in the data.

Results

Soil carbon

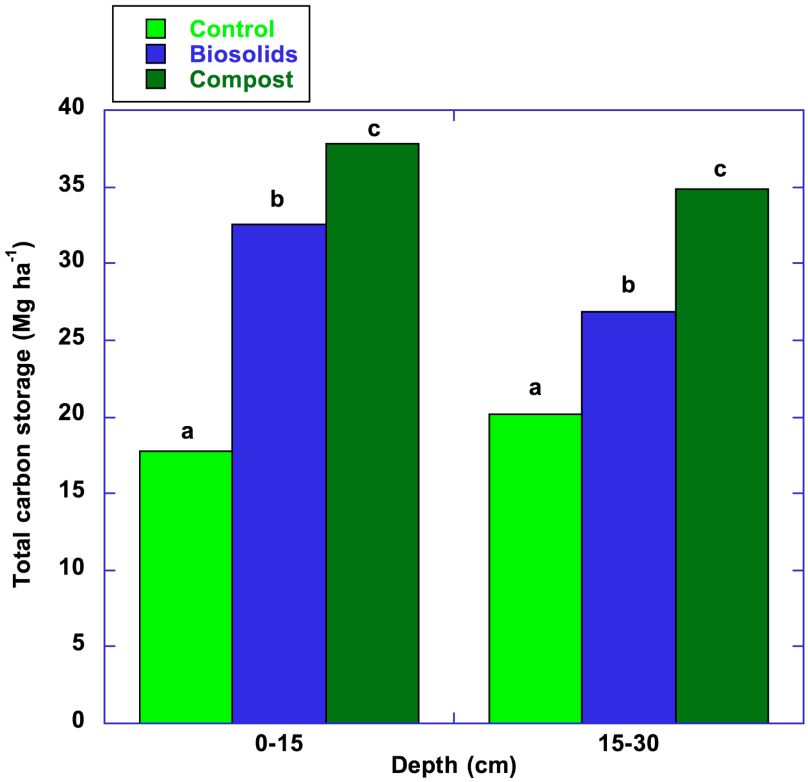
Site, depth and amendment were significant factors in total soil carbon storage. There were also significant interactions between these variables indicating that total carbon storage varied by site, depth and amendment. In general, there was more carbon stored at sites on the West side of the Cascades in comparison to disturbed sites (Hwy17) or sites located on the east side of the Cascades. Total carbon stored in the surface and subsurface depths of select control soils is shown in Figure 1.

Figure 1. Total carbon (% C x bulk density) for surface (0-15 cm) and subsurface (15-30 cm) horizons for select control soils sampled in this study. FWC1, FWC3 and Systems are located on the west side of the Cascades. Hwy17 is a disturbed site on the west side of the Cascades and the remaining sites are on the east side of the Cascades. Means and standard errors are shown.



Organic amendments significantly increased carbon storage over control soils at both the 0-15 and 15-30 cm depths (Figure 2). Averaging over all studies that included sampling at these depths, both treatments had higher soil carbon concentrations than control soils. While compost stored more carbon than biosolids, this result is not a direct comparison of biosolids and composts applied at the same cumulative loading rate at the same field site. It is not clear if direct, side by side comparisons would render similar outcomes. It does indicate that organic amendments, including composts and biosolids, increase soil carbon concentrations and total carbon storage in comparison to control soils.

Figure 2. Total carbon storage at the 0-15 cm and 15-30 cm depths for control (n=26), biosolids (n=33) and compost (n=63) amended soils sampled at these depths. Different letters indicate that means are significantly different ($p < 0.0000001$). As this data does not include side by side comparisons of biosolids and compost, results are not representative of carbon sequestration potential for similar sites and application rates for both materials.



Application rate was also a significant factor with generally higher carbon storage at higher cumulative loading rates of amendments. The effect of rate for two sites is shown in the graphs below (Figure 3a and 3b). At the GP17 (biosolids on dry land wheat) site, there was a clear effect of rate at the 0-15 cm depth with total carbon storage increasing with increasing biosolids application rate ($p<0.01$). All of the biosolids treatments had higher soil carbon than the control or fertilizer treatment with the higher soil carbon concentration in the soils that received the highest biosolids application rate. The same trend was seen in the 15-30 cm soil depth. However this was not statistically significant ($p>0.05$).

At the MGS1 site (turf in Puyallup) a similar although much less pronounced effect was observed. There was a trend to increasing soil carbon with increasing amendment application rate for both the 0-15 and the 15-30 cm depths. This increase was less pronounced than the increase observed at the GP17 site, however, total carbon stored in MGS1 soils was much greater than at the GP17 site. It is possible that the lower rate of increase at increasing application rate was related to the carbon status of the soil.

Figure 3a. Total carbon stored at the 0-15 and 15-30 cm depths for dryland wheat that has received synthetic fertilizer or municipal biosolids for cumulative biosolids loading rates of 18, 27 and 40 Mg ha-1. Means ± standard error are shown.

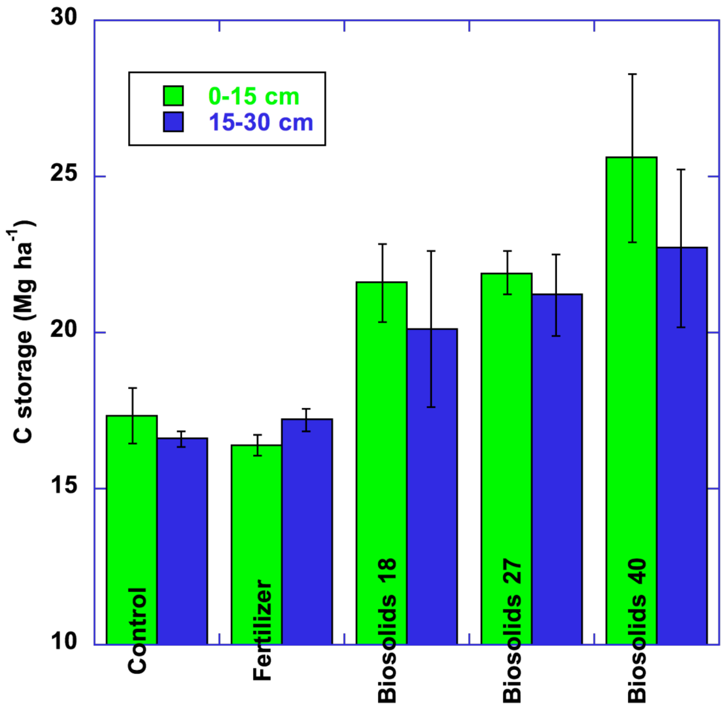
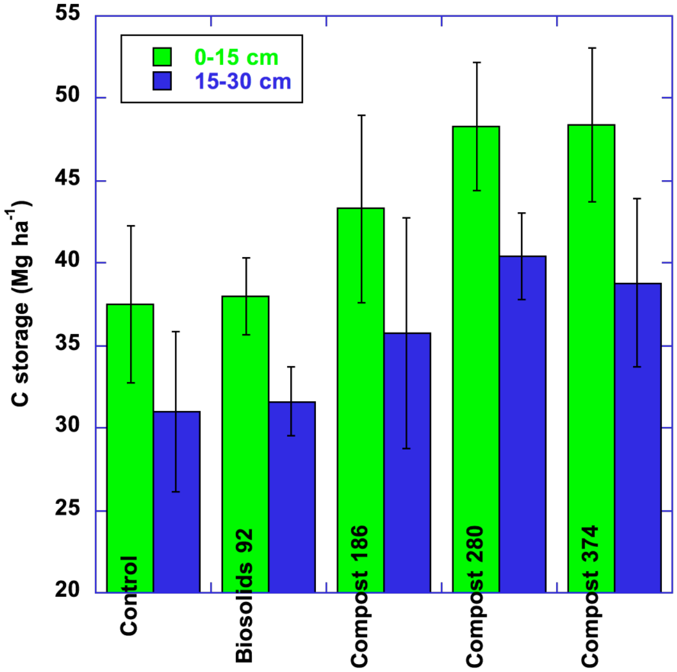


Figure 3b. Total carbon stored at the 0-15 and 15-30 cm depths for turf grass that had received a single application of compost or biosolids 8 years prior to sampling. Means ± standard error are shown.

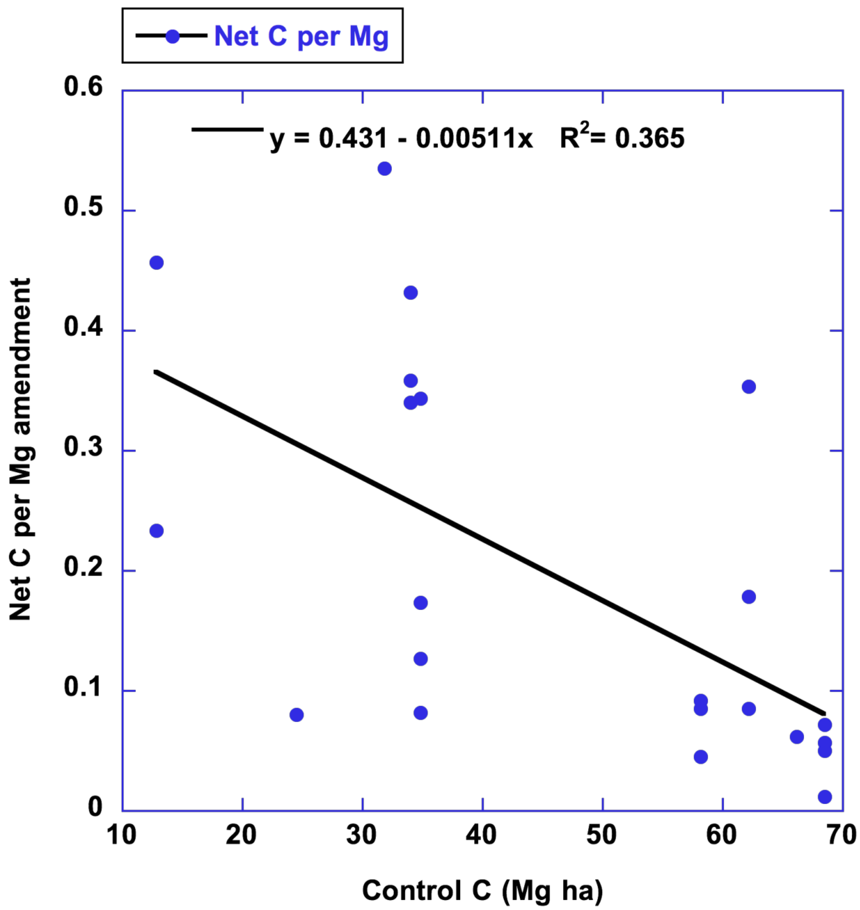


Net total carbon stored for each site (carbon in amended soils- carbon in control soils) as well as the Mg of carbon stored per Mg of amendment were calculated for all sites (Table 2). In general, sites that had higher total carbon before amendment addition stored less carbon as a result of the amendments than soils that had lower total carbon concentrations. Net carbon stored per Mg of amendment ranged from 0.012 for the low rate of biosolids addition to turf grass in Puyallup (MGSS1 site) to 0.53 Mg C per Mg compost at an organic pear orchard in Chelan County. In general, higher rates of carbon storage per Mg of amendment were observed on low carbon or disturbed sites. Lower net storage was found on carbon rich soils. This relationship was plotted and an adjusted R^2 of 0.365. Although this was statistically significant, the low value indicates other factors in addition to initial carbon in the control soil will likely influence the per Mg C storage for each Mg of residual applied to soils.

Table 2. Total carbon for amended and control soils, net carbon (amended –control) Mg per ha and net Mg C per Mg of amendment for all soils sampled in this study.

Site	**Rate**	**Depth**	**Total Carbon**		**Net Carbon**	**Net Mg C per Mg amendment**
			Amended	**Control**	**control)**	
	Mg per ha		Mg C per ha			
CITL	224	0-20cm	42.32	24.45	17.87	0.080
Dryden	134	0-30cm	103.5	31.85	71.65	0.535
Durfey	84	0-30cm	49.4	34.8	14.6	0.174
	91	0-30cm	42.2	34.8	7.4	0.081
	105	0-30cm	48	34.8	13.2	0.126
	140	0-30cm	82.9	34.8	48.1	0.344
FWC1	157	0-30cm	75.8	66.2	9.6	0.061
FWC3	67	0-30cm	63.8	58.1	5.7	0.085
	134	0-30cm	70.3	58.1	12.2	0.091
	202	0-30cm	67.1	58.1	9	0.045
GP17		0-30cm	33	33.93	-0.93	
	18	0-30cm	41.7	33.93	7.77	0.432
	27	0-30cm	43.1	33.93	9.17	0.340
	40	0-30cm	48.3	33.93	14.37	0.359
Hwy16	152	0-15cm	82.2	12.9	69.3	0.456
	224	0-15cm	65	12.9	52.1	0.233
MGSS1	92	0-20cm	69.6	68.5	1.1	0.012
	186	0-20cm	79.1	68.5	10.6	0.057
	280	0-20cm	88.7	68.5	20.2	0.072
	374	0-20cm	87.2	68.5	18.7	0.050
Systems	26	0-30cm	71.3	62.1	9.2	0.354
	68	0-30cm	67.9	62.1	5.8	0.085
	153	0-30cm	89.3	62.1	27.2	0.178

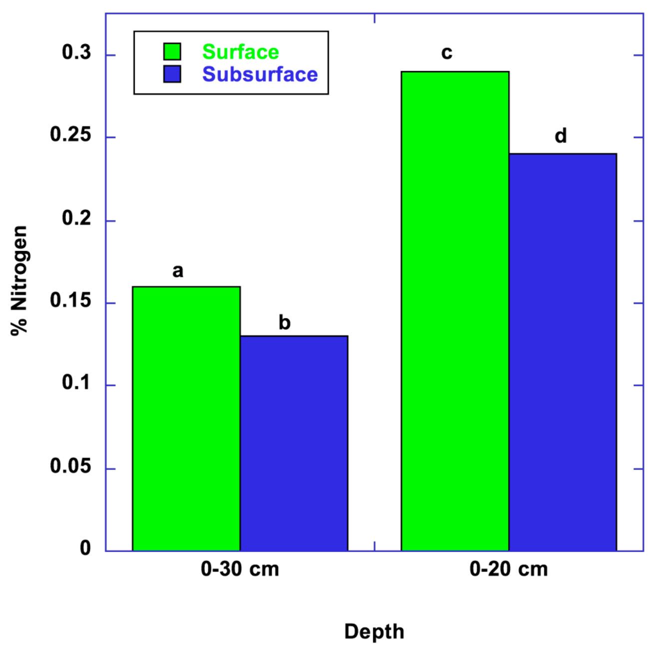
Figure 4. The relationship between total carbon in control soils and net carbon per Mg of amendment added for all soils sampled in this study. A linear regression was used to test the relationship between control carbon and net carbon per Mg of amendment. Although statistically significant, this regression does not explain the majority of the variation in the data.



Soil Nitrogen

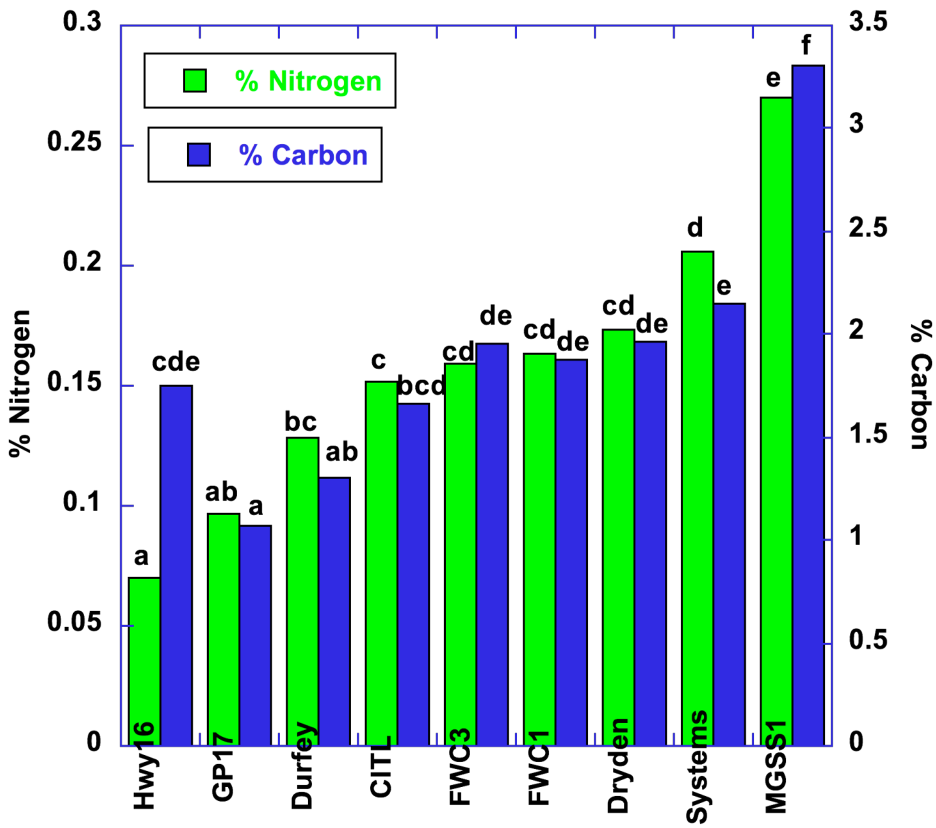
Site ($p<0.05$), cumulative amendment loading rate ($p<0.000001$), and depth ($p<0.000001$), were all significant factors in % soil nitrogen. The interactions between these variables were not significant indicating that that while changes in soil nitrogen varied by site and depth, there was a similar response to cumulative loading rage of amendments across all sites. As with carbon, the % nitrogen in soils was higher at the surface depths in comparison to the lower soil horizons. This would be expected as fertilizers and amendments that add N to the soils are applied to the surface soil. Even if incorporated, they are only incorporated into the surface. Organic matter deposition from plants will also provide N to the soils. The percent N by depth for soils sampled at 0-30 cm and 0-20 cm is shown in Figure 5.

Figure 5. Percent nitrogen concentrations across all soils sampled in this study where sampling included a surface and subsurface depth. Means include control, organic amended, and fertilized soils. Different letters over each value indicate that the reported values are significantly different ($p < 0.00005$).



Site was also a significant factor with some soils having higher total nitrogen concentrations than others. A stepwise regression analysis showed that % carbon was the primary factor in predicting % N with approximately 50% of the variability in N values accounted for by % C concentration in soils. As the % carbon in soils increased, there was a related increase in soil N for all except one of the sites sampled. Although form of nitrogen was not measured in this study, it is likely that a substantial portion of the N in the organics amended sites was in organic forms. This type of N is not immediately available for plant uptake. Organic N becomes plant available as the organic matter decomposes and a portion of the N in the organic fraction is released as mineral nitrogen into the soil. The other significant factors accounting for variability in % N included cumulative loading rate of amendment and bulk density. A graph of % N and % C for each site that presents the mean value across all treatments and depths for each site is shown below.

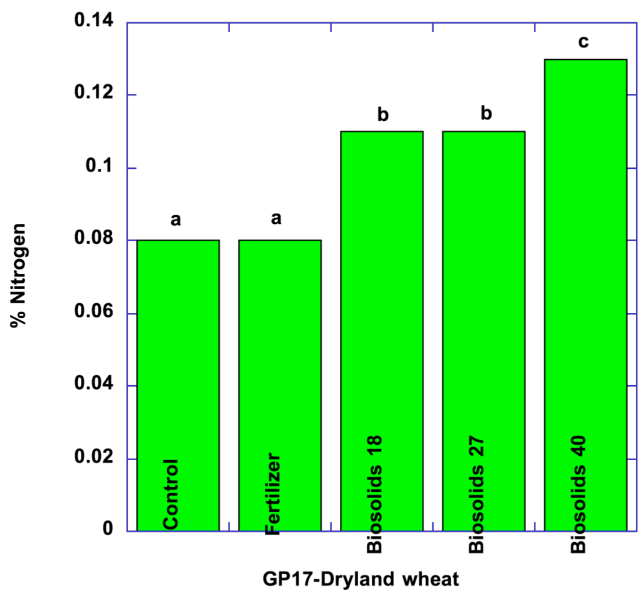
Figure 6. Percent carbon and nitrogen for all sites sampled in the study. The values shown are averaged across all sampled depths and treatments for each site. Columns for each variable with different letters are significantly different ($p<0.05$). This shows the variability of % C and %N for all sampled sites.

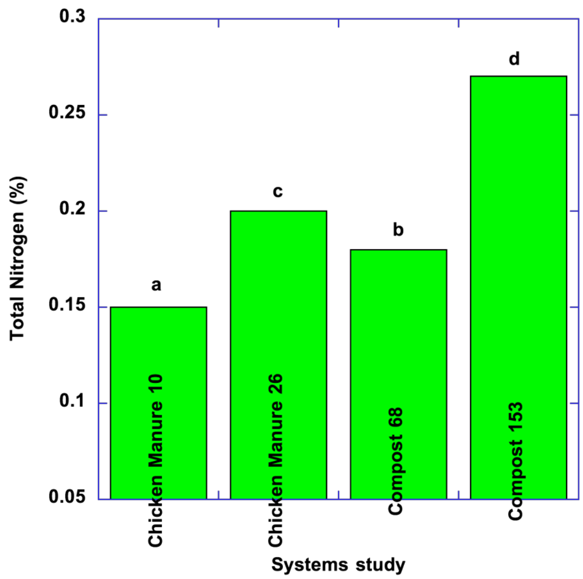


For every site sampled, soil % N concentrations in at least one of the amended treatments were significantly higher than %N in control or fertilized treatments. This increase was generally limited to the surface horizons, however, there were also instances in the lower sampled horizons where % N was higher in one of the amended treatments in comparison to control or fertilizer treatments. Across all sites, there were no instances where fertilizer or control (taken from farms where synthetic fertilizers were used in lieu of organic amendments) % nitrogen was higher than %N in the amended soils. It is important to note that % N is not a measure of plant available nitrogen. Percent N as a function of treatment and rate in the surface horizons are shown for two sites in Figure 7.

These results indicate that the range of organic amendments tested in this survey, including chicken manure, composts and municipal biosolids, all provide nitrogen to soils. The nitrogen provided by these amendments is sufficient to increase % soil nitrogen in comparison to control and conventionally fertilized soils.

Figure 7ab. Percent nitrogen concentrations in surface soils for biosolids amended soils in a replicated dryland wheat field trial in Chelan Douglas County and chicken manure and compost amended soils in an agriculture systems study in Pierce County. Means with the same letter are not significantly different ($p<0.05$)





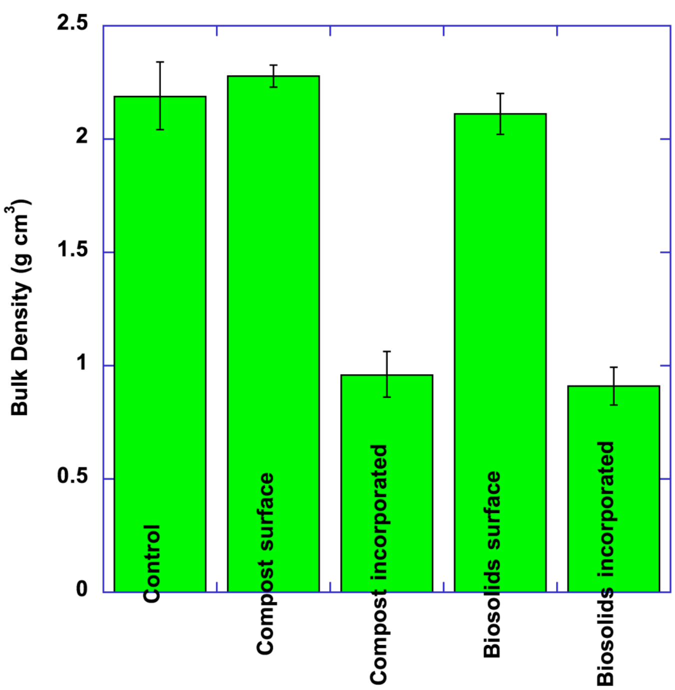
Bulk density

Bulk density is a measure of the weight of soil per unit volume. An approximate weight for the mineral fraction of soils is 2.65 g cm^3 with soil organic matter having a bulk density of 0.3-0.6 g cm^3. Bulk density measures for normal soils generally fall under a range of 1.0 to 1.6 g cm^3. Soil bulk density measures will reflect the tilth of the soil. Heavier soils or soils with higher bulk density are generally considered poorer soils. Higher bulk density will restrict root growth, reduce water infiltration rates and slow air diffusion in soils.

Bulk density samples were collected from the surface horizons for all of the sampled sites. Site and treatment, and the site x treatment interaction were significant factors for bulk density, indicating that bulk density varied by site and treatment. In addition, soil amendments did not have the same effect on bulk density across all sites. Most of the sites sampled had relatively low bulk density with the highest mean site value for cultivated sites of 1.23±0.01 g cm^3 at the dryland wheat site. This site is regularly cultivated and plowing is known to break up soil aggregates and increase bulk density. Average bulk density for the turf or landscape sites ranged from 1.01±0.01 g cm^3 for the FWC3 (biosolids in turf grass) site to 1.12±0.01 g cm^3 in the CITL (compost applied to landscape ornamentals). The exception was the HWY16 site where compost was added to highly compacted disturbed soils adjacent to a highway. Average bulk density at this site across all treatments was 1.86±0.12 g cm^3. This value is sufficiently high to negatively impact efforts to establish a plant cover on the site.

There was no significant effect of treatment on the two sampled sites maintained as no till turf grass, FWC1 and FWC3. There was a trend (not statistically significant) to decreased bulk density with increasing biosolids application at the GP17 dryland wheat site. At this site bulk density in the control and fertilizer amended treatments averaged 1.26 g cm^3 while bulk density in soils with the highest rate of biosolids averaged 1.19 g cm^3. Significant effects of treatment on bulk density were seen on select compost rates from Durfey (bulk density in the 91 Mg ha^{-1} at 0.83 g cm^3 and 105 Mg ha^{-1} at 0.89 g cm^3 versus control at 1.22 g cm^3), the Systems study and in the Compost in the Landscape study. A general pattern of decreasing bulk density with increasing application rates was observed. This effect was most clearly pronounced in the Hwy16 study. For this study, both surface applied and incorporated amendments were included in the experimental design. The study was sampled 1 year after treatments had been added to the soil. The control soil remained extremely compacted. Incorporated composts significantly reduced soil bulk density while surface applied amendments had no immediate effect (Figure 8).

Figure 8. Bulk density (g cm^3) for control, surface applied compost and biosolids and incorporated compost and biosolids at the Hwy 16 site. This site had highly compacted soils due to road construction. Means and standard errors are shown.



It is likely that over time, surface application of organic amendments will also reduce bulk density though surface application is not likely to have as pronounced an effect as incorporation of the amendments into the surface soil. In the Compost in the Landscape study, composts were also surface applied and incorporated. Six years after amendment application, surface applied compost significantly reduced the bulk density of the underlying soil from 1.23 to 1.18 g cm^3. The effect of incorporated compost was much greater with bulk density in that treatment of 1.04 g cm^3. Most of the soils sampled in the current study had low bulk density values. As a result, the response to compost amendments was not consistent across all sites. For sites with more compacted soils, incorporation of organic amendments provides a clear way to reduce bulk density and improve soil tilth.

Water holding capacity

For this study gravimetric and volumetric water holding capacity were measured on surface soils at 0.1 and 1 bar of tension. These tension levels were tested as they represent the water status of high value crops and turf grass, target end uses for different compost products. Improved water storage at these pressures is also likely indicative of improved water storage at higher moisture tension levels (Khaleel et al., 1981). Gravimetric water content represents the weight of water per associated weight of soil. The volumetric water content reflects the gravimetric content adjusted for bulk density. As organic amendments reduced the bulk density of soils at several of the sites sampled in this study, the gravimetric water content is potentially a more appropriate measure than the volumetric water content for measuring plant available water. Reduced bulk density will likely increase the depth of soil available for plant roots. This is not reflected in volumetric water holding capacity. Previous studies have shown that texture is the most significant factor affecting soil water holding capacity (Bauer and Black, 1992; Khaleel et al., 1981, Rawles, 2003). Texture in the sites sampled from this study had a relatively narrow range with the coarsest textured soils being sandy loam and the finest textured soils being silt loam. This likely downplayed the importance of texture in this analysis.

For the soils analyzed for water holding capacity in this study, organic amendments significantly increased total water at 0.1 or 1 bar of tension for 5 of the 9 sites sampled. Significant increases in water ranged from a 10% increase at 1 bar in the GP17 dryland wheat site for the highest rate of biosolids addition in comparison to the fertilizer and control treatments to a >50% increase in gravimetric water content for the 105 Mg ha compost application rate in a cherry orchard in Sunnyside, WA. Fraction water contents for all sites where amendment application had a significant effect on water content at 0.1 or 1 bar of tension are shown in Table 3. It is interesting to note that in one case, the control soil had a significantly higher water content than the compost amended soil. In this case (Durfey hops), although the soil series for both sampled sites was the same, the texture for the control and compost amended samples was different. The control samples were finer textured than the compost amended samples. As has been discussed previously, finer textured soils will contain higher total water concentrations than coarser textured soils.

A stepwise regression analysis was also carried out for water content at 0.1 and 1 bar of tension. Variables included in this analysis were bulk density, cumulative application rate, total carbon stored, and texture. The stepwise procedure is an iterative process; variables are tested in the model to see if they account for a significant amount of variability in the data. If they do not, they are removed from the model. At 0.1 bar of tension, the analysis was able to account for over 50% of the variability in the data with a model R^2 value of 0.52. Variables included in the final model were bulk density and cumulative application rate. Bulk density was negatively correlated with water storage capacity and cumulative application rate was positively correlated with carbon storage. These results suggest that as bulk density increases, the ability of the soil to hold water decreases. In addition, increasing amendment application rate increases the ability of the soil to hold water. At the 1 bar of tension level, the model was only able to account for 40% of the variability in the data. As with the first model, bulk density was negatively correlated with the water content of the soil. In this model, texture was also negatively correlated with gravimetric water content. This may be an artifact of the range of textures in the soils that were sampled for this study. The textures in the soils sampled had a limited range, going from sandy loam to silty loam. The absence of a broader range of textures (soils with higher sand or clay contents) is likely a factor in this analysis. Previous research has clearly shown the importance of texture in water holding capacity of the soil with increasing fine fractions positively correlated with increased water content. Carbon storage was the third factor in the model with increased carbon positively correlated with increased water holding capacity.

Results from this study confirm earlier work that has demonstrated that organic amendments increase soil water holding capacity by reducing soil bulk density as well as by increasing soil carbon concentrations. As previous research has shown, soil texture is the most significant factor in determining soil water holding capacity. This suggests that increases in water holding capacity as a result of organic matter addition will be greatest in coarser textured soils or soils with high initial bulk density.

Table 3 Fraction water content (mean ± standard error) at 0.1 and 1 bar soil tension for sites sampled in this study where amendment had a statistically significant increase on total gravimetric water content of the soil.

Site		Water fraction			
Treatment	Texture	0.1 bar pressure		1bar pressure	
CITL	Sandy loam				
Control		0.38±	0.008	0.17±	0.024
Compost 224		0.48±	0.01	0.17±	0.01
Durfey					
Cherry	Silt loam	0.31±	0.012	0.13±	0.014
Cherry compost		0.48±	0.023	0.21±	0.012
Hops	Loam	0.41±	0.02	0.28±	0.033
Hops compost		0.4±	0.03	0.2±	0.014
	Sandy				

	loam				
FWC3	Sandy loam				
Fertilizer		0.47±	0.012	0.25±	0.01
Biosolids 67		0.5±	0.017	0.3±	0.016
Biosolids 134		0.48±	0.008	0.3±	0.01
Biosolids 202		0.49±	0.013	0.32±	0.012
GP17	Loam				
Control		0.36±	0.008	0.09±	0.002
Fertilizer		0.35±	0.008	0.09±	0.002
Biosolids 40		0.37±	0.009	0.1±	0.002
Systems	Sandy loam				
Chicken manure 11		0.34±	0.006	0.16±	0.013
Chicken manure 26		0.4±	0.03	0.22±	0.03
Compost 68		0.36±	0.004	0.16±	0.01
Compost 153		0.42±	0.007	0.23±	0.01

Life cycle analysis

Life cycle analysis is a tool used to evaluate the full range of costs and benefits of a particular product or practice. Life cycle analysis has been used to evaluate benefits and potential environmental costs associated with the use of composts. Different analysis have included different factors in their models. Two models will be reviewed and the results of this sampling will be compared to the results from these two models.

The US EPA Office of Solid Waste and Emergency Response, conducted a life cycle assessment of solid waste management that included a section on composting (EPA, 2006). The report noted potential benefits of compost use relating to increased soil carbon including increased soil productivity (multiplier effect), and fertilizer effect. These effects have the potential to increase soil carbon sequestration following compost amendment to soil. To determine potential increases in soil carbon following compost addition, EPA used the CENTURY computer model. This model does not allow for input of organic matter with high humus content or integrate this type of amendment addition with size and stability of the soil recalcitrant organic matter pool. For estimates of changes in soil carbon following compost use, EPA modified the model and ran simulations on use of compost for corn production at application rates ranging from 1.5 to 44 Mg ha with annual applications for 10 years. Different rates of fertilization were included in the model as well as different harvest practices. Their model concluded that carbon increases in soils would vary from 0.16 metric ton carbon equivalent (MTCE) per Mg compost immediately after application to 0.04 metric ton carbon equivalent (MTCE) per Mg compost 24 years after compost applications ceased. EPA also considered that a portion of the added compost would degrade very slowly and provided additional carbon storage based on this slowly degrading portion of compost. This fraction increased the soil carbon storage from compost use by slightly over 0.08 MTCE per Mg compost. The final model used by EPA uses a value of 0.05 metric ton carbon equivalent per wet Mg of feedstocks composted. If a moisture content of 50% feedstocks and a 50% volume reduction during composting is assumed, this results in a carbon credit or carbon storage of approximately 0.2 MTCE per dry Mg compost. No other benefits are attributed to compost use in this report.

In another life cycle analysis of composting, the Recycled Organics Unit of the University of New South Wales derived potential benefits from compost use through a review of literature related to compost use (Recycled Organics Unit, 2006). This report modeled two types of use for compost: surface application to vineyards and incorporated into soil for cotton production. They also considered two types of compost in their analysis: a high nutrient value compost and a high carbon compost for use as a mulch. The potential for benefits associated with compost use were considered for soil carbon sequestration, fertilizer replacement, erosion control, increased water holding capacity and infiltration rates increased yield, improved tilth, and improved soil structure

Table 4. Summary of results from the ROU LCA for compost. Two different types of compost for two different end uses were modeled in this exercise. A high nutrient compost applied to irrigated cotton fields at 25-50 Mg ha-1 and a low nutrient compost applied as a surface mulch to vineyards at a depth of 10 cm per ha. (Recycled Organics Unit, 2006).

Impact	**Tangible (potential) benefits**	
	Incorporated	Surface mulch
Water use	Increase water holding capacity of top 0-15 cm soil layer by 2.4-3%	Increase moisture retention of top 0-1[illegible] cm soil layer by 9.8%
	Savings of 0.13-0.16 ML of water per ha per season in irrigated agriculture	Savings of 0.95 ML of water per ha pe[illegible] season in irrigated agriculture

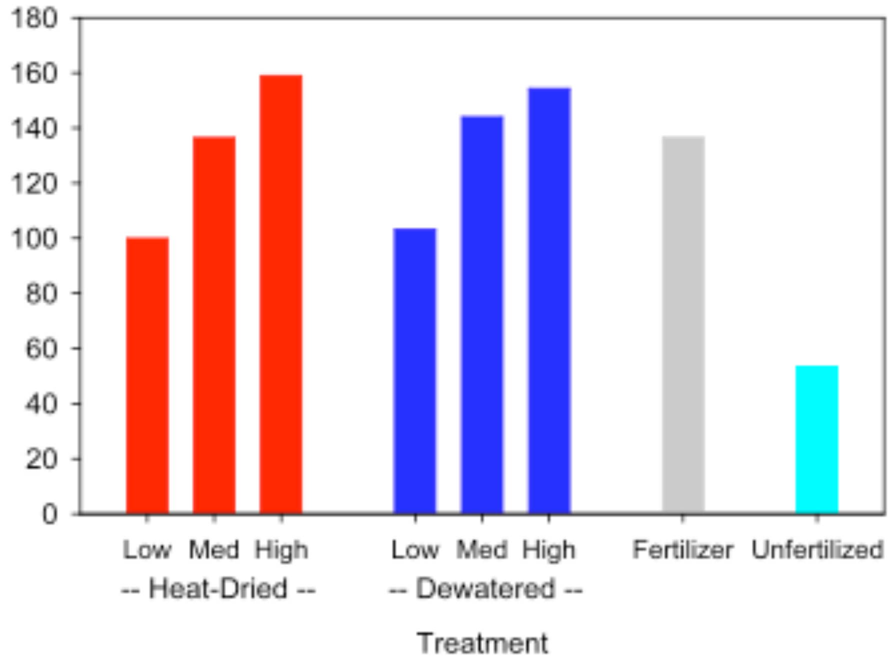
Fertilizer use	Savings of 34-68 kg of N, 29-57 kg of P and 24-48 of K per ha per year of application	Savings of 34-68 kg of N, 29-57 kg of and 24-48 of K per ha per year of application
Herbicide/pesticide use	Potential suppresion of soil born pathogens	Surface application will suppress weed
Carbon sequestration	Sequestering about 2.9-5.9 tons of carbon per ha after 10 years	Sequestering about 11.5 tons of carbon per ha after 10 years
Sodicity	Potential savings of 2-5 tons of gypsum per ha in affected lands. No quantitative data yet available	No data
Erosion	Preventing a soil loss of 2.3 to 4.2 tons per ha annually	Preventing a soil loss of 17.5 tons per annually
Soil structure	Bulk density decreased by 4.1 to 7.6%	No data
Yield response	Increase yield by 19.5 to 21.5%	Increase yield by 19.5 to 21.5%

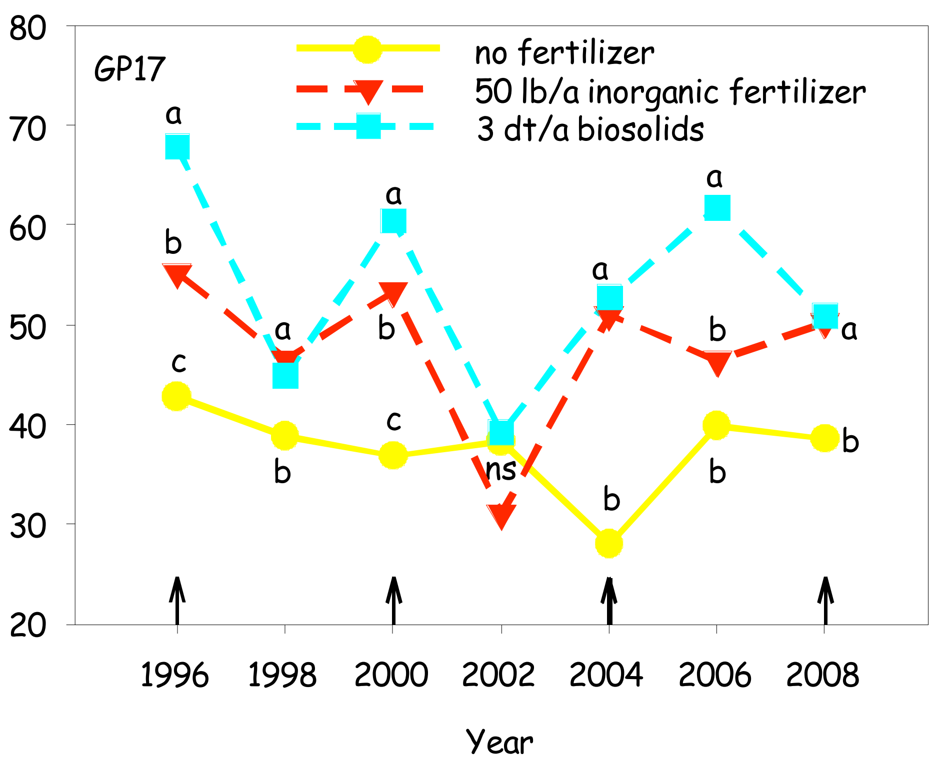
Total carbon sequestration per dry Mg of compost in this analysis is 0.058 Mg C per dry Mg compost for cotton production (using the high rate of application and low estimate for total carbon sequestered) and 0.038 Mg C per dry Mg compost for use as a mulch. Both of these estimates are significantly lower than the single EPA value. However, the ROU study considers a much broader range of potential benefits associated with compost use in their evaluation, leading to a significant value associated with use of organic soil amendments.

For this study, a subset of the variable evaluated in the ROU study were tested in our sampling. These included carbon sequestration per Mg amendment, changes in soil bulk density, total soil nitrogen, and changes in soil water holding capacity. Previous research on a portion of the replicated field sites included in our study has included measures of yield response. As discussed earlier, for all studies in this sampling, excluding the MGSS1 turf study, addition of organic amendments resulted in significant increases in soil carbon storage. Rates of increase per dry Mg of amendment ranged from 0.012 (not significant) in a long term study of turf grass to 0.54 in an organic pear orchard with a long history of compost use. There was a negative relationship between total carbon stored in the soil with carbon storage per Mg of amendment, indicating that maximum storage per Mg was associated with lower carbon status soils. For all sites included in this study, total nitrogen (%) in soils that received organic amendment addition was higher than conventionally fertilized or control soils for at least one of the rates of amendment tested. Bulk density was significantly decreased in a number of the sites tested. These decreases were generally observed in sites with higher bulk density. In the site with the highest bulk density, incorporation of compost or biosolids reduced soil bulk density to half that of control soils. Finally soil water holding capacity was increased in 5 of the 9 sites sampled. Increases ranged from 10% to 50%. For both soil moisture tension levels tested, amendment or soil carbon were significantly positively correlated with water storage.

Prior studies have shown a positive yield response associated with use of organic amendments. This has been statistically significant in all of the studies where yield has been measured. This includes use of compost on ornamentals, compost and biosolids for highway plantings, biosolids for dryland wheat and biosolids for turf grass (Cogger et al 1999,2001,2008). Yield response of dryland wheat and turf grass is shown in Figure 9. For dryland wheat, biosolids amended plots had higher yields than control plots for 6 out of 7 growing seasons. The biosolids amended plots also outperformed the conventionally fertilized plots for 3 of the 7 harvests with results being similar to conventional fertilizers for the other harvests. For turf grass, the middle rate of biosolids application was similar to synthetic N and higher than control soils. The higher rate of biosolids application, outperformed the conventional fertilizer treatment. For ornamentals, positive response was observed for plant growth and appearance with dogwood for incorporated compost and bark (Cogger et al., 2009). The results from this study indicate that it is appropriate to attribute a wide range of benefits to use of organic amendments across a wide range of end uses.

Figure 9. Yield response to organic amendment addition for biosolids applied to turf grass (a) and biosolids applied to dryland wheat (b)





Conclusions

Results from this sampling clearly illustrate the benefits associated with land application of composts and biosolids. Benefits were observed for soil carbon storage and total soil nitrogen for all of the sites sampled. Benefits were also observed for reduced bulk density and improved soil water holding capacity at a number of the sites that were sampled. Previous research on a portion of the experimental plots that were included in the current study also indicate a positive yield response, either equivalent or superior to conventional fertilizer associated with the use of composts and benefits.

The magnitude of the benefits varied based on initial site conditions and site management. The greatest benefits for all measured variables were seen on sites where initial carbon was lowest and bulk density highest. For example, total Mg carbon stored per Mg of amendment applied ranged from a low of 0.01 to 0.54. The low value was from a long term turf study with control carbon storage of 68.5 Mg C per ha. The high storage value was from an irrigated pear orchard where carbon storage in a neighboring orchard that had not received compost application was 32 Mg C per ha. Similarly, the largest decrease in bulk density was seen at the HWY 16 site, where compost and biosolids were incorporated into highly compacted disturbed soils. Incorporation of organic amendments reduced bulk density at this site from > 2 g cm^3 to <1 g cm^3. This indicates that it would be possible to maximize benefits associated with the use of organic amendments by targeting applications to low productivity or disturbed sites.

Benefits were also observed for soil nitrogen concentrations and, in certain cases for soil water holding capacity. Previous research has shown that organic amendments increase plant yield in comparison to control plots and conventional fertilizers. In a dryland wheat trial sampled for this study, total nitrogen was significantly higher in all rates of the biosolids amended soils in comparison to both the control and synthetic fertilizer. At the highest rate of biosolids application (cumulative loading of 40 Mg ha^{-1}), the soil had 10% more water than any other treatment at 1 bar of tension. Previous research on this site has shown that for 7 harvests, biosolids treated plots outyielded synthetic fertilizer for 3 and provided comparable yield for the remaining 4 harvest years.

These results suggest that composting and land application of the organic residuals identified in the State biomass inventory would provide a wide range of benefits for soils in Washington State.

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Appendix

Net carbon storage (Mg ha^{-1}), total nitrogen (%) and bulk density (g cm^3) for all sites sampled on the east side of the Cascades. Means ± standard error are shown. Numbers followed by an * are statistically different from control soils.

	Rate	C Storage		Total N		Bulk Density	
	Mg ha^{-1}			%		g cm^3	
Dryden							
0-15 cm							
Control		15.75	1.1	0.076	0.011	1.2	0.11
Compost	134	80.2*	18	0.46*	0.04	1.02	0.15
15-30 cm							
Control		16.1	2.56	0.062	0.009		
Compost	134	23.3*	0.9	0.09*	0.001		
Durfey							
0-15 cm							
Control		17.8	2.9	0.13	0.01	1.19	0.06
Compost	84	36.5*	2	0.2	0.01	1.22	0.06
Compost	91	23.1*	1.2	0.19*	0.02	0.83	0.0001
Compost	105	25.6*	2.43	0.18*	0.004	0.89*	0.07
Compost	140	43.6*	3.6	0.24	0.06	1.06	0.05
15-30 cm							
Control		17	2.32	0.09	0.006		
Compost	84	12.9	2.33	0.07	0.01		
Compost	91	19.1	4.4	0.09	0.007		
Compost	105	22.4*	2.7	0.09	0.02		
Compost	140	39.3	11.6	0.14	0.007		
GP17							
0-15 cm							
Control		17.33	0.9	0.08	0.004	1.26	0.02
Fertilizer		16.4	0.35	0.08	0.001	1.26	0.02
Biosolids	18	21.6*	1.24	0.12*	0.007	1.21	0.02
Biosolids	27	21.9*	0.7	0.11*	0.002	1.25	0.03
Biosolids	40	25.6*	2.7	0.13*	0.01	1.19	0.02
15-30 cm							
Control		16.6	0.25	0.08	0.002		
Fertilizer		17.2	0.37	0.08	0.002		
Biosolids	18	20.1	2.5	0.09	0.006		
Biosolids	27	21.2	1.3	0.1	0.006		
Biosolids	40	22.7	2.55	0.1*	0.01		

Net carbon storage (Mg ha^{-1}), total nitrogen (%) and bulk density (g cm^3) for all sites sampled collected from the west side of the Cascades maintained as no till turf grass. Means ± standard error are shown. Numbers followed by an * are statistically different from control soils.

	Rate	C Storage		Total N		Bulk Density	
	Mg ha^{-1}			%		g cm^3	
FWC1							
0-15 cm							
Fertilizer		36.2	0.5	0.18	0.002	1.11	0.01
Compost	157	43.6*	0.9	0.23*	0.006	1.1	0.03
15-30 cm							
Fertilizer		30	1.4	0.13	0.005		
Compost	157	32.2	0.057	0.13	0.002		
FWC3							
0-15 cm							
Fertilizer		30.5	0.9	0.15	0.003	1.03	0.02
Biosolids	67	35.5*	1.24	0.19*	0.003	1	0.03
Biosolids	134	40.9*	0.9	0.22*	0.003	1.02	0.02
Biosolids	202	37.8*	2	0.2*	0.01	1.01	0.02
15-30 cm							
Fertilizer		27.6	1	0.1	0.005		
Biosolids	67	28.3	0.9	0.11	0.004		
Biosolids	134	29.4	1	0.11	0.003		
Biosolids	202	29.3	1.2	0.11	0.005		
MGSS1							
0-10 cm							
Control		37.5	4.8	0.24	0.03		
Biosolids	92	38	2.3	0.25	0.01		
Compost	186	43.3	5.7	0.3	0.04		
Compost	280	48.3	3.9	0.34*	0.03		
Compost	374	48.4	4.7	0.34*	0.03		
10-20 cm							
Control		31	4.9	0.21	0.3		
Biosolids	92	31.6	2.1	0.21	0.1		
Compost	186	35.8	7	0.25	0.05		
Compost	280	40.4	2.6	0.3	0.02		
Compost	374	38.8	5.1	0.27	0.03		

Net carbon storage (Mg ha^{-1}), total nitrogen (%) and bulk density (g cm^{3}) for all remaining sites sampled collected from the west side of the Cascades. Sites include an agronomic site (Systems), an ornamental landscape site (CITL) and a disturbed site (Hwy17). Means ± standard error are shown. Numbers followed by an * are statistically different from control soils.

	Rate	**C Storage**		**Total N**		**Bulk Density**	
	Mg ha^{-1}			%		g cm^{3}	
CITL							
0-20 cm							
Control		24.45	0.7	0.08	0.002	1.23	0.01
Compost	224	42.32*	13.8	0.19*	0.006	1.07*	0.02
Systems							
0-15 cm							
Chicken manure	11	31.9	0.4	0.15	0.002	1.27	0.01
Chicken manure	26	34.1*	0.6	0.2*	0.003	1.04*	0.01
Compost	68	35.9*	0.6	0.18*	0.007	1.22*	0.01
Compost	153	42.2*	0.7	0.27*	0.005	0.9*	0.01
15-30 cm							
Chicken manure	11	30.2	1	0.12	0.005		
Chicken manure	26	37.2	1.11	0.15	0.005		
Compost	68	32	0.8	0.13	0.005		
Compost	153	47.1*	2.1	0.27	0.07		
Hwy16							
0-15 cm							
Control		12.9	2.8	0.02	0.006	2.19	0.15
Compost surface	74	12.9	3.8	0.014	0.005	2.23	0.09
Compost inc	152	82.2*	3.1	0.2*	0.06	0.9*	0.15
Compost surface	152	12.4	2.21	0.02	0.003	2.1	0.09
Compost inc	224	65*	1.5	0.2*	0.03	1*	0.1
Compost surface	224	14.8	1.5	0.02	0.003	2.3	0.06