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CONSERVATION
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Biochar Field Trials in San Mateo County, CA
FINAL PROJECT REPORT

Agreement #68-9104-1-129
Between the United States Department of Agriculture-Natural Resources Conservation Service
And
San Mateo County Resource Conservation District

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Between the California Department of Conservation
And
San Mateo County Resource Conservation District

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Project Summary

The project, Biochar Field Trials in San Mateo County, CA, was conducted by the San Mateo County Resource Conservation District (RCD) to demonstrate biochar use in an agricultural operation within the local conditions of coastal San Mateo County and to provide a general overview of the effects and feasibility in the region. The project was funded through a Conservation Innovation Grant by the United States Department of Agriculture (USDA) –Natural Resources Conservation Service (NRCS) and by the California Department of Conservation (DOC). This final project report was prepared for the USDA-NRCS and the DOC and summarizes work completed to meet the goals of the RCD, USDA-NRCS and DOC. This project report also includes a technical report with detailed information about the field trials (Appendix A), in addition to the economic analysis deliverable (Appendix B) and the outreach material deliverable (Appendix C).

The RCD is a non-regulatory public benefit district to help people protect, conserve, and restore natural resources through information, education, and technical assistance programs. The RCD was responsible for project design, administration, project management, collecting field trial data, analyzing field trial and economic data, and generating final reports and outreach materials. The RCD partnered closely with the NRCS for technical expertise and formed a Technical Advisory Committee (TAC) comprised of NRCS scientists and the local NRCS District Conservationist. The TAC provided input and assistance throughout the project, particularly with regards to project design and data analysis. The TAC met a few times each year, with subgroups and individuals contributing to the project as needed and when opportunities arose. The RCD also partnered with UC Davis for initial work on the economic analysis portion of the project.

Program Goals and Objectives

The overall goal of this project was to demonstrate biochar use in a conventional agricultural operation in coastal San Mateo County, and provide an overview of the effects and feasibility of the practice in the region. Specific project objectives included:

- Monitoring the use of biochar on a local Brussels sprouts farm to gain an understanding of its impacts on crop production, soil health, nutrient retention (e.g. nitrate leaching) and carbon sequestration
- Assessing the cost benefit of biochar use to local farmers and identifying potential barriers and opportunities

Background

Biochar is a high-carbon charcoal created through the process of pyrolysis of organic materials. Pyrolysis involves partial combustion of organic material in a low oxygen environment at temperatures less than 700°C. This process preserves a large portion of the carbon in the material as it is being “charred,” and produces particles that are highly ionized, high in carbon, and highly stable in soil. Due to these properties the rate of oxidation and decay is very slow, estimated to take hundreds to thousands of years. The production of biochar from organic waste material, and its use as a soil amendment has received attention from a variety of disciplines for its social, environmental, and financial benefits, such as:

- Sequestration of atmospheric carbon and reduction of greenhouse gas emissions for climate change mitigation
- Management and use of plant and animal waste products from agricultural production (manure, crop by-products, etc.)
- Improvement to soil health and agricultural productivity when used as a soil amendment

The effects of biochar in agricultural applications are well-documented in research from several countries and organizations, most notably the International Biochar Initiative (IBI), Iowa State University in partnership with the USDA Agricultural Research Service, and Johannes Lehmann of Cornell University. A recent IBI review of field studies showed that biochar use as a soil amendment for multiple types of crops in different soil types and climate regimes have led to increased crop yields. Soil health benefits of biochar use have included increased soil nutrient content, retention and availability, as well as positive effects on mycorrhizal root colonization and beneficial microbial activity in the soil. Biochar soil amendments have also been reported to help address site-specific crop and soil health issues such as increasing pH in acidic soils, improving water-holding capacity of sandy soils, and increasing water infiltration rate in clay soils. Climate benefits have also been shown through carbon sequestration as well as reductions in nitrous oxide emissions to the atmosphere (Laufer and Tomlinson, 2013). In laboratory studies, certain types of biochar have also been shown to reduce leaching of nitrate from soils (Clough et al, 2013).

Biochar soil amendments were also economically viable under a variety of scenarios in published field studies. Various scales and types of biochar production technologies suggest good opportunities for expanding its use to new markets (Laufer and Tomlinson, 2013; Jirka and Tomlinson, 2014). With increases in food shortages, consolidation and loss of small family farms, costs of petroleum derived products and the looming threat of climate change, the use of biochar as a soil amendment may provide an inexpensive, ecologically sound and effective method of improving crop yields, soil health, water quality and mitigating greenhouse gas emissions.

Project Need

The capacity of biochar to amend soil, increase crop yield, and provide environmental benefits such as climate change mitigation, suggest that expanding its use could have both local and global significance. However, current research clearly indicates that social, environmental and economic benefits of biochar use in agricultural applications depend on numerous site-specific factors, and cannot be assumed. Availability and type of biochar (source material and production methods), soil and site conditions, crop type, farming practices, climate conditions, as well as the farmers' individual goals and objectives for biochar use, all affect its viability in different agricultural applications.

San Mateo County is located in Central California where agriculture is an important component of the local economy and represents a vital link to the region's cultural past. Local farmers and resource managers have shown interest in the potential benefits of biochar use in this area, including economic benefits from increased crop yields, reduced need for chemical fertilizers and carbon sequestration. Reduced nitrate leaching is another important potential benefit in this area where agricultural operations are often in close proximity to residential neighborhoods that rely on well-water.

The following key questions were identified to address these local needs as well as the goals of the USDA-NRCS and DOC:

- How does the use of biochar affect crop production, including crop yields and costs of application?
- What effects does biochar have on soil health for agriculture?
- Does biochar affect soil nutrient retention, and what are the implications for nitrate leaching?
- Does the use of biochar lead to additional soil carbon storage and have carbon sequestration benefits?
- What are the potential barriers and opportunities to local agricultural biochar use?

Methods Design

To demonstrate biochar use in an agricultural operation in San Mateo County and provide an overview of the effects and feasibility in the region, we developed a multi-faceted project that included the following:

- Field trial within a local conventional Brussels sprout operation to assess the effects of three different soil amendments (biochar, compost, and biochar-compost mix)
- An economic analysis of costs to a farmer for application of a biochar soil amendment
- Identification of barriers and opportunities for local biochar use

Field Trial

The field trial was conducted in two fields at a conventional farm growing Brussels sprouts near Half Moon Bay between the spring of 2012 and the fall of 2014. This location was chosen as it is representative of the local soil and climate conditions.

The field trial design was adapted from ‘A Guide to Conducting Biochar Trials’ by Julie Major of the IBI. This design consisted of two test plots in two different fields, both having a grid of 16 subplots (24 by 24 feet, each). In each test plot, this allowed for four replicates of the control plots with no treatment and four replicates of each of the treatments which were raw biochar, poultry manure compost, and a biochar-compost mix. The field trial was designed to capture three growing seasons based on recommendations for minimum study length from IBI. Treatments were randomized and applied once in the first year of the trial at a rate of 10 tons per acre for biochar-only; 10 tons per acre for compost; and 10 tons per acre for the biochar-compost mix. In the fall and spring of each year of the field trial, various parameters were monitored to assess impacts on crop yield, soil health, nitrate leaching, and soil carbon sequestration. Monitoring consisted of taking soil samples at various depths prior to application of treatments, and each subsequent spring. Each fall, soil sampling and quantification of crop and biomass yield were conducted. Spring soil samples were analyzed for soil health indicators and a composite suite of nutrients including soil organic carbon and nitrate. Fall soil samples were analyzed for the same parameters in addition to bulk density. See Appendix A for a detailed description of field trial methods.

Economic Analysis

Costs for application of biochar were estimated on a per-acre basis for the field trial site to represent these costs in a typical row crop system in coastal San Mateo County. Cost factors considered were based on studies for agricultural conservation practices done by the University of California Cooperative Extension faculty at UC Davis. These included labor and equipment costs for application of biochar, and material costs of biochar based on treatment application rates. Other variables considered in the analysis included a “convenience cost” to the producer (degree to which biochar application do or do not interfere with operations), and different application protocols. Potential increases to crop yields were considered to demonstrate possible cost benefit to farmers. See Appendix B for a detailed description of the economic analysis.

Identification of Barriers and Opportunities

Potential barriers, solutions and opportunities for biochar use in coastal San Mateo County were identified based on observations for the particular location, conditions and outcomes of the field trial and economic analysis, as well as factors reported in the literature on biochar. This information was used to discuss the potential translation of project findings into NRCS conservation practice standards.

Project Findings

Key project findings from the field trial, economic analysis and identification of barriers and opportunities are summarized in this section. The comprehensive results and discussion of all findings from the field trial and economic analysis are detailed in Appendices A and B.

Crop Yield

Results from the three-year field trial suggest that the biochar-only and biochar-compost (mix) soil amendments had neutral or negative effects on crop yields for conventionally-grown Brussel sprouts in coastal San Mateo County. The compost-only treatment had a neutral or positive affect on crop yields. Another trend was lower crop yields across all the treatments and the control during the second harvest (fall 2013). A variety of factors that could have affected these results were considered, but no single cause or explanation for these outcomes was identified.

Table 1. Raw crop yield data.

NORTH	Total Fruit weight (lbs)				Percent change from control			
Treatment	**2012**	**2013**	**2014**	**All Years**	**2012**	**2013**	**2014**	**All years**
Biochar	315	208	215	738	-4	-3	-6	-5
Compost	315	217	226	758	-4	1	-2	-2
Mix	280	211	216	707	-15	-2	-6	-9
Control	329	214	230	773	NA	NA	NA	NA

SOUTH	Total Fruit weight (lbs)				Percent change from control			
Treatment	**2012**	**2013**	**2014**	**All years**	**2012**	**2013**	**2014**	**All years**
Biochar	263	184	271	718	-6	12	-5	-2
Compost	309	182	279	769	10	10	-2	5
Mix	268	191	257	715	-5	16	-10	-2
Control	281	165	286	732	NA	NA	NA	NA

Meta-analysis by Jeffrey et al (2011) of biochar effects on the yields of other row crops from both field and lab studies, suggests that the greatest positive effects on crop yield accrue from the liming effect of the biochar, and its improvements to water holding capacity and nutrient availability. Maintaining a soil pH greater than 6.5 is important to Brussels sprouts growth in this location, but in the field trial, the pre-planting lime application likely precluded this benefit of the biochar-only and mix soil amendments. Biochar particles are negatively charged and can improve nutrient retention and availability in soils with low cation exchange capacity (CEC), but the field trial soils had sufficient CEC levels, and this specific benefit of biochar was unlikely for this location. However, increased soil organic matter (SOM) may have been a mechanism for improved crop yield in some areas since this factor affects water-holding capacity and nutrient retention. Comparison of SOM and crop yields between the two test plots suggested that increased SOM levels due to the treatments in one test plot may have had a beneficial effect on crop yields, relative to the other test plot where SOM levels were not affected by treatments.

Studies have also shown that the application of a biochar-only treatment can initially have a negative effect on bioavailability of nutrients in the soil. Biochar binds well to positively charged nutrients [e.g., calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), and ammonium (NH_4)] that are essential for plant growth. Over time, this effect can enable biochar to act as a slow-release fertilizer in the soil, but initially it can limit nutrient availability. In one of the test plots, the first year crop yield results were relatively low in biochar-only treated soils, and much higher in compost-only treated soils. This suggested that these nutrient dynamics occurred and that nutrient availability played a role in plant growth for these soils. However, poor crop yields from mix treated soils in the first year relative to the other treatments and control conditions were contrary to these conclusions. Since the mix was pre-blended, the charged sites on the biochar particles should have adsorbed the nutrients in the compost, increasing nutrient availability. If nutrient availability was limiting growth, crop yields in the mix treated soils would have been expected to exceed those of the biochar-only treatment and control conditions.

Other key factors that may have influenced crop yield included weather and site specific conditions. Throughout the field trial weather conditions were fairly extreme with hot summers and small amounts of rain later in the season. This is likely the reason for lower overall crop yields in the fall of 2013. Site specific differences between the North and South plot (i.e., presence of shade, different Brussels sprout types, different soil conditions etc.) also likely accounted for variations in crop yield.

Soil Health

The following parameters were considered indicators for soil health and were monitored during the field trial (bulk density, soil organic matter, pH, CEC, electrical conductivity, nutrients-nitrate, ammonium, phosphorus, potassium, boron). Analysis of soil sampling results suggested that for certain soil conditions, the addition of the biochar-only, compost-only or biochar-compost mix soil amendments can improve the health of coastal San Mateo County soils for agricultural.

Bulk density is an indicator of root penetration capacity as well as soil porosity (water-holding capacity). The soil bulk density results suggested a potential soil health benefit resulting from the biochar-only and biochar-compost mix treatments. Over the course of the field trial, upper soil layer (0-6") bulk densities under control conditions increased significantly, approaching or exceeding the threshold that is ideal for plant growth (USDA, 1999b) in both test plots. However, upper layer bulk densities for soils treated with biochar-only and biochar-compost mix soil amendments did not similarly increase, and remained significantly below this threshold throughout the field trial. Within the upper soil layer where the amendments were initially mixed, biochar may have had a multi-year, stabilizing effect on bulk densities thereby helping maintain ideal soil conditions. For heavier soils such as those in coastal San Mateo County, this could help maintain ideal conditions for root penetration and soil porosity in the upper soil layer.

Soil organic matter (SOM) is a key indicator of soil health and can influence nutrient retention and availability, as well as water holding capacity, soil structure and stability. During the field trials, application of treatments to soils depleted in SOM, significantly increased SOM levels over multiple years, potentially providing these benefits. However, in soils with high initial levels of SOM, application of biochar-only and biochar-compost mix soil amendments did not increase SOM. Furthermore, the addition of the compost-only soil amendment under these conditions reduced SOM levels over time, potentially having negative effects on soil health factors associated with SOM. Overall, the field trial results suggested that the one-time application of a biochar or compost based amendment to SOM-depleted soils significantly increased SOM levels over multiple years and therefore likely had positive impacts on soil health.

Analysis of major macronutrient (nitrate-N, ammonium-N, phosphorus and potassium) and micronutrient (boron) levels in the soil did not indicate increased nutrient levels and impacts on soil health. However, the field trial may have been too short to see the long-term benefits associated with the treatments; particularly the biochar-only treatment as it acts as a slow-release fertilizer, and initially adsorbs nutrients as mentioned previously. Further, analysis of the particular biochar soil amendment used in the field trial indicated that it was largely composed of carbon and that levels of these other nutrients were insignificant compared to pre-treatment concentrations. So it is not surprising that increased nutrient concentrations were not seen within the short time frame of this study from the biochar-only treatment.

Conversely, the compost soil amendments contained higher levels of these nutrients so it is likely that nutrient concentrations in the soil would increase, at least initially. Over the course of the three-year field trial, significant differences between treatment and control concentrations of the various nutrients were reported for individual samplings. However, with the exception of the nitrate-N results, consistent positive or negative effects were not observed. Nitrate-N concentrations from the biochar-compost mix treatment in the fall samples in one of the plots were consistently greater than control conditions, suggesting that this treatment increased soil nitrate-N concentrations within this timeframe and in this location.

In general, results for potassium (K) were significantly less than recommended ranges for optimal growth, while phosphorus (P) concentrations were significantly higher than the recommended range; although, no consistent trends were observed between the two plots or the treatments and control. Throughout the field trial, the boron (B) concentrations were significantly below the recommended range. However, results suggested that the biochar treatment possibly had a marginal benefit for B concentrations in one of the plots where B concentrations were severely depleted.

Results for soil pH, electrical conductivity (EC) and CEC under control conditions and with the treatments were almost all within recommended ranges for soil health. Overall, these results indicated that for the location and specific design of the field trial, benefits of biochar related to these soil health factors were unlikely to apply here (Laufer and Tomlinson, 2013). A close look at soil pH results indicated that in one test plot, levels dropped significantly across all treatments and the control from fall of the first year to the fall of the last year. Meanwhile, in the other test plot, the compost treatment had a consistently significant acidifying effect in the surface soil layer relative to the control as well as the biochar-only and biochar-compost mix treatments. The causes of these pH results are unclear, but the implications are potentially important in San Mateo County as acidic soils can stimulate the growth of clubroot fungus (*Plasmodiaphora brassicae*) which has caused serious economic losses in this area in the past (University of California, 1992).

Nitrate Leaching

Results from the nitrate leaching analysis did not show consistent trends or substantial impacts from any of the treatments on nitrate leaching. Direct measurements of nitrate leaching were not performed as it was considered unrealistic within the study conditions and that results would be limited by a variety of confounding factors. Therefore, soil profile graphs and physical soil properties were used to visualize differences in nitrate movement through the profile between control and treatment subplots.

In general, nitrate is easily leached and moves quickly through the soil with water either laterally or vertically, which can contaminate surface and groundwater supplies (Kabir Zahangir, Pers. comm., January 15, 2016). The amount of nitrate available for the plant and to be leached is heavily influenced by soil conditions, on-farm practices and subsequent N dynamics.

Analysis of the nitrate profiles did not show substantial differences between the treatments and control. However, several patterns were identified such as lower nitrate concentrations in the first year and in the fall soil samples. There was also a general trend of higher nitrate concentrations in the shallow layers and lower concentrations in the deeper layers, particularly with the biochar and mix treatments.

Lower nitrate concentrations were probably observed in the first year since soil samples were taken after plowing and disking but before addition of the treatments. Further, in subsequent years soil samples were taken not only after plowing and disking but also after the soil had received lime, fumigation, and fungicide which undoubtedly influenced soil conditions and nitrate dynamics. Higher nitrate concentrations were likely observed in the spring rather than the fall due to the fact that nitrate was utilized by the plant throughout the growing season and as crop residues and cover crops containing nitrogen were mixed into the soil in the spring. Mixing practices that took place in the spring, particularly tillage can also disturb the upper profile layers and compact deeper layers into a tillage pan, which was often detected during soil sampling events (Joe Issel, Pers. Comm., January 16, 2016). Tillage pans form a perched water table that can drain nitrate laterally into surface water rather than leaching into groundwater vertically (Plant and Soil, 2001).

Various studies have shown that soil amendments like biochar have potential to decrease nitrate leaching through a variety of mechanisms (Laufer and Tomlinson, 2013; Clough et al, 2013). Application of biochar can help maintain ideal bulk densities and soil porosity in upper soil layers which could support retention of nutrients and decrease nitrate leaching. The addition of SOM in biochar can also increase microbial assemblages and build soil health, which can increase water retention, and thereby decrease nitrate leaching (Clough, 2013). As mentioned previously, during the field trial, ideal bulk densities were maintained with biochar-based treatments while increases in SOM were seen with all treatments in SOM-depleted soils. These positive impacts on soil health could decrease the potential for nitrate leaching.

The composition of biochar also plays a large role in nitrate leaching as the type of feedstock used to make biochar as well as the pyrolysis temperature heavily influences the C:N ratio, CEC, and the types of ions that biochar adsorbs to; thereby affecting nutrient retention. For example, biochar with a high C:N ratio (> 30:1), like the one used in the study, can stimulate immobilization which renders nitrate unavailable to the plant and reduces potential for leaching.

These findings demonstrate that biochar-N dynamics are very complex especially in a study where many variables exist within an active farming operation. Identifying soil conditions, the composition of biochar and subsequent N interactions are especially important for understanding biochar- N dynamics and implications for nitrate leaching.

Carbon Sequestration

The pyrolysis of organic matter waste to produce biochar, results in the formation of recalcitrant organic carbon which is resistant to microbial decomposition and can persist for hundreds to thousands of years. When biochar is used as a soil amendment, this organic matter waste is effectively sequestered into the soil as carbon (Lehmann et al, 2006). Direct measurements of the recalcitrant portions of these organic carbon inputs were not possible in this field trial as the local soil control lab did not have these capabilities. But studies of biochar composition based on different types of feedstock and production methods suggest that the recalcitrant carbon content for the biochar used in the field trial was high since it was made from wood chips charred at a temperature 575-600°C (Singh et al, 2010; Novak et al, 2009). The amount of total organic carbon added to the soil through the treatments was estimated at 6.0, 2.3 and 8.3 tons/acre for biochar-only, compost-only and mix treatments (respectively).

To further assess the effects of biochar and the other soil amendments on carbon sequestration, the amount of total organic carbon in the soil (SOC) was calculated. The results did not show a consistent, significant increase in SOC over time from the treatments when compared with the control. However, the SOC levels suggested an effect in sub-surface soils (i.e. below the 6” depth) from the biochar treatment, and this trend would likely have continued with continued monitoring.

In addition to the carbon sequestered in biochar itself and increased levels in the soil, biochar has been shown to have other climate benefits. As discussed previously, biochar can act as a slow-release fertilizer, which can reduce the need for chemical fertilizers and reduce greenhouse gas emissions caused by manufacturing of fertilizers. The effects of biochar on beneficial microbial activity in the soil can also result in additional carbon storage in soils. Some studies have also reported reductions in emissions of certain greenhouse gases (N_2O and CO_2) from agricultural fields treated with biochar (Laufer and Tomlinson, 2013). In this field trial, the conversion of forestry waste into biochar likely avoided CO_2 and CH_4 emissions that would otherwise have been generated by the natural decomposition or burning of the waste. However, further discussion of climate benefits such as these was beyond the scope of this project, but should be considered for future studies focused specifically on local biochar use and carbon sequestration.

Economic Analysis

Cost estimations to apply a biochar soil amendment for a conventional farm in San Mateo County were made for two different application rates and equipment methods (1 ton/acre with a lime drop-spreader, and 10 tons/acre with a manure spreader) as well as two soil amendments (biochar-only, and a slightly more expensive biochar-compost mix). The estimated cost per acre to apply these treatments was relatively high: between $680 and $720 per acre to apply 1 ton/acre, and $6,150 and $6,575 per acre to apply 10 tons/acres.

Increased crop yields are one of the most commonly cited benefits of agricultural use of biochar in field studies. This economic benefit could not be estimated for the field trial because crop yield increases due to biochar soil amendments were not observed. However, to gain a better understanding of this potential benefit and inform the design of future studies of biochar, the economic analysis did consider the degree to which increases in crop yield could have affected cost benefit. Using the 2014 reported Brussels sprouts crop yields for San Mateo County (10.17 tons per acre) and the reported per ton price of $1,596, increases of 5%, 10% and 15% in crop yields would translate to increases in per acre crop values of $812, $1,623 and $2,424, respectively (Crowder, 2014). This suggests that in one growth season, crop yield increases of about 5% or more with the 1 ton per acre soil amendment application would provide an economic benefit to the farmer. Alternatively, if the yields were consistently 1-2% greater than the control yields over two or three seasons, this would also provide a benefit from a one-time biochar soil amendment application. However, at a higher application rate of 10 tons per acre, a 37-40% single-year crop yield increase (or about 13% greater for all three years) would need to occur for the farmer to begin to receive an economic benefit.

Overall, the economic analysis suggested that in a conventional farming system, cost and inconvenience to the farmer are the major drawbacks to using biochar as a soil amendment at the levels (i.e. 10 and 20 tons/acre) tested in the San Mateo County field trial. For example, application of biochar over a large field (e.g. the combined size of the fields where the test plots were located was approximately 150 acres) could be done with a lime drop spreader, but most likely no more than 2 tons/acre could be applied without causing significant disruptions to the pre-planting soil preparation steps. A manure spreader could be used to apply the soil amendment at a rate of 10 tons/acre. However, in a conventional farming system, compost and manure are not regularly applied, so the growers are unlikely to own this equipment.

Other benefits of biochar use that could be weighed against costs include improvements to soil health and reduced potential for nitrate leaching from the soil, as well as soil carbon sequestration. These potential benefits should be evaluated on a case by case basis because they depend heavily on the farming system and soil conditions, as well as the goals for biochar use.

Barriers and Opportunities

Significant barriers to biochar use as an agricultural soil amendment in coastal San Mateo County were identified based on the outcomes of the field trial and economic analysis, as well as factors reported in the literature on biochar.

Challenges associated with obtaining a sufficient supply of biochar create barriers to its use in a row crop operation similar in size to the one in the field trial. Only one commercial biochar producer (Energy Anew, Inc. in San Rafael, CA) was capable of supplying biochar in quantities that could be practical for a farm of this size and in this location. Even assuming that the producer can supply quantities sufficient to apply at a rate of 10 tons/acre, long-distance transport of this amount of biochar is impractical. One bulk semi-truck load can transport approximately 50 cubic yards of (dry) biochar, which is equivalent to about 17.5 tons. For a rate of 10 tons/acre, more than 80 semi-truck loads would have been needed to apply biochar over the 150 acres of Brussels sprouts fields at the field trial site. Cost is another big obstacle to biochar use. Costs identified in the economic analysis for biochar supplied in bulk were more than $200/cubic yard, or $600/ton.

Production of biochar onsite or more locally (i.e., within coastal San Mateo County) could help address transport challenges. However, the efficacy of this approach depends on having a reliable and sizable waste feedstock supply, as well as available space for biochar production and storage. Although agriculture is a significant part of the local economy, agricultural waste streams are unlikely to be both suitable and sufficient for larger-scale biochar production. The use of waste wood chips (e.g., from arborists) or wood from removal of invasive species, such as eucalyptus, could be explored as a local option for biochar feedstock.

Environmental concerns and potential economic losses during application of biochar are other potential barriers to use. Biochar is made up of small particles that are susceptible to wind and water erosion. Wind loss during transport, storage and application steps has been shown to reach as much as 30% of the original biochar quantity (Major, 2009). In addition to the potential economic losses that this would cause, the dust generated onsite could become a significant environmental and health hazard. Avoiding handling and application of biochar on windy days, and wetting the biochar helps minimize wind losses and environmental concerns. However, wetting the biochar can increase transport costs and limit options for application (e.g., a lime drop spreader would no longer be a suitable method).

An important solution and opportunity to some of these barriers could be development of an NRCS Conservation Practice Standard to establish how to use biochar in an agricultural operation and to streamline implementation through a standard protocol. However, as our analysis indicates, additional studies (particularly field trials), are needed to further understand the benefits of biochar under certain conditions and relative to costs to see if development of a practice standard would be justified. For this reason, our findings were not translated further towards development of an NRCS conservation practice standard. If future studies find consistent benefits from biochar through multiple mechanisms and address some of the barriers identified here, then drafting a practice standard should be considered and would undoubtedly be a critical step to biochar adoption on a wide range of scales.

Conclusions and Next Steps

Biochar use in a conventional agricultural operation in coastal San Mateo County was successfully demonstrated through this field trial.

Biochar had a neutral or negative effect on crop yield, but field trial results pointed to potential soil health benefits. Consistent with other studies of agricultural biochar use, multi-year soil health benefits related to nutrient retention and availability, water holding capacity, root penetration and soil porosity were seen through SOM where soil conditions were poor or depleted. Although these soil health benefits did not translate into increased crop yields during the three growing seasons of the field trial, monitoring over a longer timeframe may have been needed to see these effects on plant growth. Furthermore, biochar-only or biochar-compost soil amendments may have had beneficial effects on soil through other mechanisms (e.g., increasing soil pH and/or fertility) that could have been masked or overwhelmed by existing farming practices such lime soil amendment application and multiple fertilizer applications.

Direct benefits to nitrate leaching and carbon sequestration could not be confirmed through the field trial, but the analysis highlighted complexities and challenges especially within a demonstration field trial where a variety of parameters were analyzed. To further understand the impacts of biochar on nitrate leaching and carbon sequestration, more focused and long-term studies are suggested using a specific type of biochar, while isolating key variables and using monitoring methods designed to measure effects directly.

Cost and inconvenience to the farmer, and insufficient access to biochar supply were considered the major barriers to using biochar as a soil amendment on a local conventional farm at the levels tested here. A scaled-back application of biochar at 1-2 tons/acre could potentially be feasible, particularly if this application could be seamlessly integrated into, or replace, an existing farming practice such as application of a lime soil amendment, or pre-planting fertilization. This approach could allow a conventional farm to apply biochar more frequently – possibly on an annual basis. Furthermore, if this biochar soil amendment was an effective substitute for an existing farming practice, costs to the farmer might be minimal even without an improvement to crop yields.

Overall, results highlight the value of field-testing biochar and biochar-compost soil amendments at lower application rates, and integrated into (or in lieu of) existing farming practices, to demonstrate a feasible practice for a conventional row crop farm of this scale in San Mateo County. Other parameters that could be considered for future studies include: multiple applications (e.g., annually); timing of soil amendment application(s); use a of other soil additives (e.g., zeolite); and length of the overall study.

Project Costs

Funding for this project was awarded to the RCD by the USDA-NRCS through a Conservation Innovation Grant on September 22nd, 2011 (Agreement #68-9104-1-129). Non-federal match was provided by the DOC as cash match, and as in-kind match from Dave Lea, Karen Klonsky, students and volunteers helping with soil and crop yield sampling.

The total project cost was: $112,820:

- The total amount awarded through the USDA-NRCS Conservation Innovation Grant was $75,000 and the amount spent was $75,000
- The total amount of non-federal match through this project was $37,820 and the total amount raised was $38,551 ($19,000 from DOC and $19, 551 from in-kind labor)

Therefore the total amount spent on the project was: $113,551

Project Tasks and Deliverables

The original contract term with the USDA-NRCS was from September 22nd, 2011-January 31st 2015 to complete project tasks and deliverables. Due to difficulties securing match funds and therefore performing project tasks, the RCD requested an extension to January 31st 2016 which was approved. Between November 2011 and May 2015, completed tasks included:

- Meeting with the TAC
- Assessing data needs
- Finalizing project design
- Timeline
- Conducting field trials (i.e. collecting soil samples and crop yield data)
- Discussing preliminary results

Between June 2015 and January 31st 2016 (after additional match funds secured), the RCD completed the remainder of the project tasks including data management and analysis, and completion of the following deliverables:

- A final project report which includes a detailed technical report (Appendix A)
- A cost-benefit analysis (Appendix B)
- Outreach products which include a project summary sheet and presentation (Appendix C)

Note that this project report and the technical report do not include water quality monitoring results as this was ultimately considered impractical and was approved through a second amendment to the USDA-NRCS contract on April 3rd 2015.

This project was also designed to consider how findings might translate into an NRCS draft interim conservation practice standard. However, this deliverable was not completed as the monitoring results were largely inconclusive and as the cost-benefit analysis failed to show a cost-benefit to the farmer. The RCD and the TAC agreed that it would be inappropriate to develop a conservation practice standard based on the findings from this study.

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Appendix A

Biochar Field Trials in San Mateo County, CA

Technical Report

SAN MATEO COUNTY
RESOURCE
CONSERVATION
DISTRICT

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Biochar Field Trials in San Mateo County, CA

TECHNICAL REPORT

Funding for this project was provided by:

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And

California Department of Conservation

February 1st, 2016

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Table of Contents

1. Background

Biochar is charred organic matter that can be used as a soil amendment in a variety of environments including agricultural operations. Studies have shown multiple benefits of biochar including improvements in soil health, crop yield, and reduction in nitrate leaching, in addition to climate change benefits (i.e. carbon sequestration and reduced nitrous oxide emissions) (Laufer and Tomlinson, 2013; Clough et al, 2013). Biochar is created through pyrolysis, a thermochemical decomposition process that involves partial combustion of organic material (feedstock) in a low oxygen environment at temperatures less than 700°C. This produces a light weight material with particles that are highly ionized, high in carbon, and highly stable in soil.

The pyrolysis of organic matter results in the formation of “recalcitrant” organic carbon which has a chemical structure (aromatic C rings) that is resistant to microbial decomposition. Due to this recalcitrant carbon content, the rate of oxidation and decay of biochar is very slow, estimated to take hundreds to tens of thousands of years (Lehmann et al, 2006; Lehmann and Joseph, 2009). Typically, biochar is high in carbon and low in nutrients (relative to compost soil amendments), but composition varies widely depending on the feedstock and pyrolysis methods (Downie et al, 2009; Chan and Xu, 2009). Biochar derived from wood feedstocks generally has higher carbon content and lower nutrient (ash) content relative to those derived from manure feedstock (Singh et al, 2010). Biochar made at higher pyrolysis temperatures can have a higher pH, porosity and surface area (which affect water holding capacity and nutrient retention), and a greater proportion of organic carbon content that is recalcitrant (Novak et al, 2009).

A recent International Biochar Initiative (IBI) review of field studies showed that biochar use as a soil amendment for multiple types of crops in different soil types and climate regimes led to increased crop yields and nutrient uptake by plants (Laufer and Tomlinson, 2013). Biochar can increase soil nutrient content, retention and availability, and have positive effects on mycorrhizal root colonization and microbial activity in the soil. Biochar soil amendments have also been reported to help address site-specific crop and soil health issues such as increasing pH in acidic soils, improving water-holding capacity of sandy soils, and increasing water infiltration rate in clayey soils. Benefits to soil health and crop yield were typically more evident in field trials in where soil conditions were poor (e.g., low cation exchange capacity, low organic matter, nutrient-depleted and acidic pH) (Laufer and Tomlinson, 2013).

Overall, field study results have shown that the effects of biochar use as a soil amendment vary significantly depending on type and amount of biochar applied, crop type and site conditions, as well as the design and duration of the field study (Laufer and Tomlinson, 2013; Verheijen et al, 2010).

2. Objectives

Along California’s central coast, agriculture is an important component of the local economy and represents a vital link to the region’s past. Local farmers and resource managers, particularly in coastal San Mateo County, have shown interest in the potential benefits of biochar as a soil amendment for improving crop yields, soil health, water quality, and mitigating climate change. However, the use of biochar in the region has not been demonstrated and the benefits have not been assessed, especially for the specific crop types (Brussels sprouts, mushrooms, leeks, peas, pumpkins, artichokes) and conditions relevant to this area.

The overall goal of this project was to demonstrate biochar use in a conventional agricultural operation in coastal San Mateo County, and provide an overview of the effects and feasibility of the practice in the region. The specific objectives of the field trial were to monitor biochar effects on: crop yield; soil health indicators; and factors that affect nutrient leaching and carbon sequestration. To ensure that this field trial supported the overall goal of understanding the feasibility of biochar use in conventional field production, farming practices were not altered with the exception of the one-time application of biochar and two other soil amendments.

3. Methods and Materials

In the spring of 2012, three soil amendment treatments (biochar, compost and a biochar-compost mix) were applied in test plots on a conventional farm growing Brussels sprouts in coastal San Mateo County. Over three growing seasons (2012, 2013 and 2014), the test plots were monitored for fruit yield and biomass, and physical and chemical soil properties to understand the effects of the treatments along with the control on crop yield, soil health, nitrate leaching and carbon sequestration.

a. Project Location

The field trial was conducted on two Brussels sprouts fields (North and South) on Cabrillo Farms; a 295-acre conventional farm located four miles north of Half Moon Bay, CA. See Section 3.b for detailed description of the location and layout of the field trial test plots.

i. Crop

Brussels sprouts (*Brassica oleracea var. Gemmifera*) belong to the Cole crop family which includes cabbage, broccoli, cauliflower, collards, kale, and kohlrabi. They are a slow-growing, long-bearing crop that requires cool weather conditions between 45F and 75F with optimal growth between 60F and 65F. The plants have a shallow root system with 70 to 80 percent of the root system found within the upper 8-20” of soil (Mills, 2001).

Brussels sprout seed is planted in greenhouses with seedlings ready for transplanting into fields 50 to 60 days later (USDA, 1999a). Two different varieties of Brussel sprouts were grown in the field trial. The Confidant variety mature in 140-160 days, whereas the Cobus is a late-season variety that takes longer to mature (180-195 days) and is more tolerant of winter weather (Pfyffer Associates, 2004).

Each plant is capable of producing 2.5-3 pounds of sprouts at harvest, but after post-harvest processing (i.e. cleaning, trimming, and removing damaged or large sprouts) commercial production per stalk is around two pounds (Mills 2001). In San Mateo County, commercial yields (in tons per acre) were reported as: 10.04 in 2012, 10.39 in 2013, and 10.17 in 2014 (Crowder, 2012, 2013, 2014).

Generally, Brussels sprouts crops require 15-20” of water during the growing season (Mills, 2001). When nitrogen (N) fertilizer is used in Brussels sprouts production along the central coast of California, it is typically applied in split applications: a pre-plant fertilizer in the beds followed by one or two side dressings of fertilizer in the beds, and finally application of fertilizer through the sprinkler water after growth is too dense for tractor traffic (Cahn, 2007).

Larvae of butterflies and moths (aphids and worms) are the most common insects that affect Brussels sprouts crops. Fungal and bacterial diseases that are common to the Cole crop family also affect Brussels sprouts crops. Ringspot is a foliar disease of particular concern in San Mateo County where fog is common (USDA, 1999a; UC IPM, 1997). Management of insects and disease is often done through chemical controls (spray application of pesticides, fungicides and bactericides) and cultural practices such as pre-planting lime application and crop rotation in fields (USDA, 1999a).

ii. Physical Soil Properties

On-site observations indicated that the soil type was Denison loam (DmA) and nearly level at both the North and South test plots. Field estimates of soil texture are summarized in Table. 1. The South plot had textures with more percent clay from 6-24" deep, and was sandier below 24" deep. However, both plots were in the same water-holding capacity class; and permeability of the slowest layer was the same for both. DmA has saturated hydrologic conductivity of 0.42-1.4 micrometers/second or 0.06-0.2"/hour which is in the slow permeability class. The surface soil layer has moderately slow permeability (1.4-4 micrometers/second or 0.2-0.6"/hour).

Table 1. Soil textures

	Texture	
Depth	North Plot	South Plot
Shallow (0-6")	Loam	Loam
Mid (6-12")	Loam	Loam or clay loam
Low (12-24")	Loam	Loam or clay loam
Deep (24-36")	Loam or clay loam	Sandy clay loam

iii. Climate and Weather Conditions

The field trial location in Half Moon Bay, California has a Mediterranean climate characterized by cool summers, mild winters, year-round coastal breezes, and overcast/foggy nights and mornings that usually clear by the afternoon (WRCC, 2006). The temperature range during the year is typically between 42F and 64F and rarely is below 37F or above 68F. From mid-September through early November average daily high temperatures are warmest, usually above 62F (CLVI, 2014).

Based on data collected from 1948 to 2006 in Half Moon Bay, average annual precipitation was 26.98" (WRCC, 2006). At the beginning of the growing season in May and June, the daily probability of precipitation drops from about 20% to 10%. From July through mid-September, daily probabilities of precipitation are lowest, typically below 10%.The probability of precipitation from mid-September through November increases from below 10% to greater than 30% (CLVI, 2014).

The weather conditions[1] for the years during the field trial are summarized below:

Year 1 (2012): Total precipitation, 25.63", was much greater than the subsequent years (2013 and 2014) of the field trial, though still less than the average annual amount (~27"). This year was also relatively cooler than 2013 and 2014 throughout the growing season from May through November (CLVI, 2014). Two days in October and two days at the start of November had daily high temperatures above 75F (US Climate Data, 2015).

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[1] Weather conditions are based on data from the Half Moon Bay Airport weather station which is directly across Highway 1 from Cabrillo Farms.

Year 2 (2013): Total precipitation for 2013 was very low: 6.38”. Precipitation in May, July, October and November were noticeably lower than expected for those months, but more than double the expected amounts in June and September (US Climate Data, 2015). For most days in August, daily high and low temperatures were above average, and the longest warm spell occurred from early to mid-September with greater than average high temperatures. October had five days with temperatures greater than 80F (US Climate Data, 2015). Overall, the latter part of the growing season had more extreme heat days, and was dryer than normal.

Year 3 (2014): Total precipitation increased in 2014 to 21.00”, but was still well below average annual precipitation (US Climate Data 2015). The longest dry spell occurred from August 7 to September 23 (48 days) with no precipitation (CLVI, 2014). The majority of days in July, August and September had daily high and low temperatures that were above the average, and the hottest month was October with an average daily high temperature of 68F and four days with high temperatures above 82F. Overall, the summer was hot and dry, whereas rain events in late October and November led to very wet conditions at harvest time (Dave Lea, Pers. comm., November 16, 2015).

b. Sampling Design

To begin monitoring effects of treatments, one 96 ft by 96 ft (0.212 acre) test plot within each field was selected. The two test plots, North and South, were each divided into sixteen, 24 ft by 24 ft (0.013 acre) subplots (see photo) to test four iterations of each of the treatments. In addition to the control, treatments for the North and South test plots were: biochar only, compost only, and a biochar and compost mix (mix).

Aerial image of Cabrillo Farms. The South and North plots are indicated as Plots 1 and 2 respectively. Each plot is 9,216 sq-ft, or 0.212 acre.

The recommended methods in “A Guide to Conducting Biochar Trials” by the International Biochar Initiative (pages 7-14) were used to design the layout of the subplots, and randomize the assignment of treatments to subplots (Major, 2009). Refer to Appendix 1 for the coordinates of the test plots, and the randomization values used to assign treatments to subplots. Table 2 indicates which treatments were assigned to the North and South subplots.

Table 2. Treatments applied to subplots

Treatment	North subplots	South subplots
biochar	1, 7, 14, 15	3, 14, 15, 16
compost	2, 3, 8, 9	6, 9, 10, 13
biochar/ compost (mix)	4, 6, 11, 13	1, 5, 7, 11
control	5, 10, 12, 16	2, 4, 8, 12

Aerial images showing the subplot layouts (numbered). Each subplot is 576 sq-ft, or 0.013 acres. The treatment replicates were assigned randomly to subplots.

c. Treatment Application

Biochar, compost and the mix treatments were sourced from Energy Anew, Inc. of San Rafael, CA. The biochar feedstock material was waste wood chips, and the pyrolysis process was done at a relatively high temperature range, 575-600°C. Compost consisted of a composted blend of poultry manure and plant material.

The Soil Control Lab in Watsonville, California provided information about the physical and chemical properties of the biochar and compost used in the treatment (Table 3).

Table 3. Properties of biochar and compost used in the treatments

Indicator	Biochar	Compost	Units	Calculated increases to nutrient concentrations (ppm) in 0-6" soil layer due to application of treatments [2]		
Ash	23.4	51.6	%			
SOM	76.6	48.4	%			
Organic C	59.5	23	%			
Inorganic C	.21	*	%			
pH	8.02	7.91	unit			
Bulk density	0.39	0.21	g/cm3			
EC	0.58	5.2	mmhos/cm	Biochar	Compost	Mix
NO_3^--N	18	1.1	ppm	.018	.0011	.0191
NH_4^+-N	77	950	ppm	.077	.950	1.027
P	1100	9000	ppm	1.1	9.0	10.1
K	2300	8600	ppm	2.3	8.6	10.9
Boron	29	12	ppm	.029	.012	.041

* Not reported

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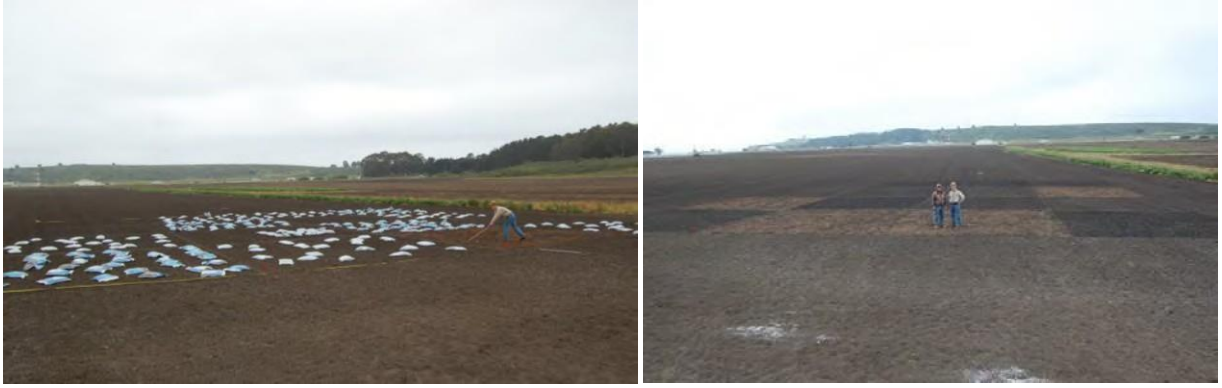
[2] Only the shallow depth soil sample results are referenced for these concentration increases because following the application of treatments in spring 2012, farming practices (e.g., disking and rototilling) mixed the treatments primarily into the shallow soil sampling depth. For an application rate of 10 tons/acre to the surface soil layer (i.e., 0-6"), nutrient concentrations were calculated to have increased by a factor of 0.001, assuming an acre of soil 6" deep weighs 2 million pounds.

The biochar only and compost only treatments were each applied at a rate of 10 tons/acre.[3] The mix consisted of 10 tons/acre biochar and 10 tons/acre compost. For the field trial, application of the treatments (biochar, compost and mix) was done once, in spring 2012. The treatments were applied by hand with a rake to achieve even application across each subplot. As shown in Table 4, in the North plot, this hand application was following by rototilling to achieve a shallow mixing of the soil 6-8" deep. However, rototilling was not done in the South plot. Instead an additional disking with a 15" blade mixed the treatments into the soil 6-8".



Treatments being applied (left) in the North field on 5/15/12. Right: North field immediately after treatments applied on 5/5/2012.

d. Farming Practices

The farming practices during the field trial are detailed in Table 4. During the 2012, 2013 and 2014 growing seasons, Cabrillo Farms grew Brussels sprouts on approximately 150 acres. One hundred acres of the Confidant variety were grown in the North field, while 50 acres of the Cobus variety were grown in the South field. The Confidant variety matures in 140-160 days from transplanting and the Cobus variety in 180-195 days from transplanting (Pfyffer Associates 2004). The 2012 season was the first time that Cabrillo Farms had grown the Cobus variety.

Immediately following harvest in November 2011 for Confidant in the North field, and in December for Cobus in the South field, the fields were disked three times. Approximately 50-60 days before planting, in late February or early March, the Brussels sprouts seeds were started in the greenhouse. Preparation of the fields for planting in early May began with disking the soil three times to turn in the cover crop, followed by plowing 12-14" deep to break up compacted soils and bring soil to the surface where it was further broken up by disking three more times (6-8" deep). In 2012, the treatments were applied at this point. In all three years of the trial, the field was rototilled at this point, with the exception of 2012 in the South field where one disking was done instead. (Note that in subsequent years, the treatments were not reapplied before rototilling).

Lime was then applied at 1 ton per acre and mixed to a depth of 6-8" with one disking pass. Fumigant (Vapan) and fungicide (Tetraclore) were applied next, followed by a pre-planting fertilizer (15-15-15) at 350 lbs/acre. Starters grown in a greenhouse were planted in rows (separated at 3 feet) with 1.5 feet between plants. Approximately 11,500 Cobus variety starters per acre were planted in the Southfield, and 14,500 Confidant variety starters per acre in the North field.

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[3] For reference, dry biochar bulk density is about 700lbs/cubic yard, meaning that each ton applied was approximately 2.86 cubic yards (Personal communication, Trip Allen, Energy Anew Inc, January 16, 2016.)

After planting, farming practices followed a rotating cycle of irrigation, cultivating and pesticide and fertilizer application. Irrigation occurred approximately every 20 days (for a total of seven times and 18" of water applied over the growing season); cultivation was done three times; and pesticide spraying was done six times over the course of the growing season. Two post-planting fertilizer applications were done: a side-dressing application (15-15-15 at 400 lbs/acre) 30 days after planting and an in-irrigation application (soluble 26-0-18 at 100 lbs/acre) 60 days after planting.

Between 90 and 100 days after planting, the plants were topped (i.e., the tops of the plants were broken off) to promote uniform sprout growth along the stems. Sprouts were harvested 150-160 days (for the Confidant variety) or 180-195 days (for the Cobus variety) after planting.

Table 4. Farming practices during the field trial

Step	Time frame	Notes from farmer
Disking (3x)	Nov/ Dec (2011)	Mixes crop residue into soil. 15" disk mixes to approximately 6-8" depth.
Seeding	Feb	Seeding of Brussels sprouts was done in greenhouse
Disking (3x)	May	Turns cover crop in -15" disk mixes to approximately 6-8" depth.
Plow	May	Plow breaks up compact layers and digs up chunks of clay. Plow depth was 12-14".
Disking (3x)	May	Breaks up clay chunks. 15" disk mixes to 6-8" depth.
Treatments applied in 2012 only	*5/15/2012*	*Treatments (biochar, compost and mix) were applied once during the field trial in 2012.*
Rototill	May	Shallow mixing to 6-8" depth 2012: In the South plot, instead of this rototill step, an additional disking (15" blade) was done, mixing to 6-8" depth.
Lime	May	Lime, 1 ton/acre.
Disking (1x)	May	Mixes lime into soil. 15" disk mixes to 6-8" depth.
Fumigate	May	Vapan
Fungicide	May	Tetraclore
Fertilizer	May/June	15-15-15, 350lb/acre. Pre-planting fertilizer is incorporated into beds.
Planting	May/June	Planted 100 acres Confidant (14,500 starters/acre), 50 acres Cobus variety (11,500 starters/acre)
Irrigation	May/June - Nov/ Dec	Approximately every 20 days, or 7x during growing season. Applied via sprinklers with 18" of water over the growing season.
Cultivation	May/June - Nov/ Dec	3x during the growing season. Shallow mixing less than 6" deep.
Pesticide Spray	May/June - Nov/ Dec	6x during growing season. Pests: cabbage aphid, diamond back worm, ring spot, root maggot.
Fertilizer	June	15-15-15, 400lb/acre. One-time side-dressing fertilizer applied 30 days after planting.
Fertigation	July	Soluble 26-0-18 fertilizer, 100lbs/acre. One-time in-irrigation fertilization done about 60 days after planting.
Break tops	Oct/ Nov	Done about 90-100 days after planting to promote uniform sprout

		growth along stems.
Harvest, sorting and cleaning	Nov/ Dec	Confidant variety harvested in early-mid November. Cobus variety harvested in mid-November in 2013 and early December in 2012 and 2014.

e. Sampling Methods

i. Crop Yield

Crop yield sampling in North plot (11/7/12). Top: View of the North plot just prior to sampling. Bottom: Harvesting the fruit from the sampled stalks into the buckets

Brussels sprouts yields for the North and South plots were sampled at the time of harvest in each year of the field trial (See Table 5 for the sampling dates.) At each sampling, two types of yield data were recorded for each subplot within the North and South plots to inform biomass and crop yield. To measure biomass the stalk with fruit attached was cut at the base and then weighed using a hanging scale. Twenty one stalks were harvested randomly from each subplot and weighed. To measure crop yield, all fruit from the 21 sampled stalks were then harvested and placed in 5-gallon buckets and weighed. Within the test plots, harvesting of plants was done by hand, while a mechanical harvester was used for the rest of the North and South fields.

Table 5. Crop yield and soil sample collection dates

Year	Plot	Spring	Fall
2012	North	*Sampling date: 5/3* Only one soil sample at each depth (0-6”, 6-12”, 12-24” and 24-36”) was taken at the center of the North plot. Sampling was done after deep plowing, but prior to disking.	*Sampling date: 11/7* Crop yields were sampled approximately 1 week after farmer's workers had harvested the rest of the North field, and total weight in buckets included some rotten fruit.
	South	*Sampling date: 5/3* Only one soil sample at each depth (0-6”, 6-12”, 12-24” and 24-36”) was taken at the center of the South plot. Sampling was done after deep plowing and disking.	*Sampling date: 12/7*
2013	North	*Sampling date: 5/6*	*Sampling date: 11/7*
	South	*Sampling date: 5/9*	*Sampling date: 11/12*
2014	North	*Sampling date: 5/23*	*Sampling date: 11/19*

	South	*Sampling date: 5/26*	*Sampling dates: 12/1 and 12/4*

**Note that the Cobus variety of Brussels sprouts grown in the South plot mature later than the Confidant variety grown in the North plot which is the reason for the later sampling dates.*

ii. Soil

Soil samples were taken at planting time (spring) and harvest (fall) at the following depths and volumes: 0-6" (gallon), 6-12" (gallon), 12-24" (quart) and 24-36" (quart). In spring 2012, only one soil sample at each depth was taken from the center of the North and South plots. All subsequent, spring and fall soil samplings were taken from the centers of each of the 16 subplots in the North and South plots. In the fall, a core soil sample was also taken at each depth in each subplot using a 3" diameter core sampling cylinder. Dates that soil samples were collected are shown in Table 5.

It is important to note that in spring 2012 only one soil sampling each was taken in the North and South plots at each depth. As such, for the soil parameters analyses described in Section 3.f.ii, results were uniform with no standard error for this sampling point. (This did not affect bulk density results which were only analyzed in fall of each year.) Also, the spring 2012 soil parameters data did not reflect the effects of biochar, compost or mix treatments because this sampling in spring 2012 was taken prior to the application of treatments. In spring 2012, the North soil sampling was done after plowing the soil (12-14"deep), but prior to the three disking (6-8" deep) steps that followed, whereas the South sampling was done after plowing and disking three times (Figure 1). Physical differences of the field surfaces can be seen in photos of the North and South plots (see photos) taken at the time of these initial soil samplings.

Views of the North (top) and South (bottom) plots at the time of initial soil samplings on 5/3/12.

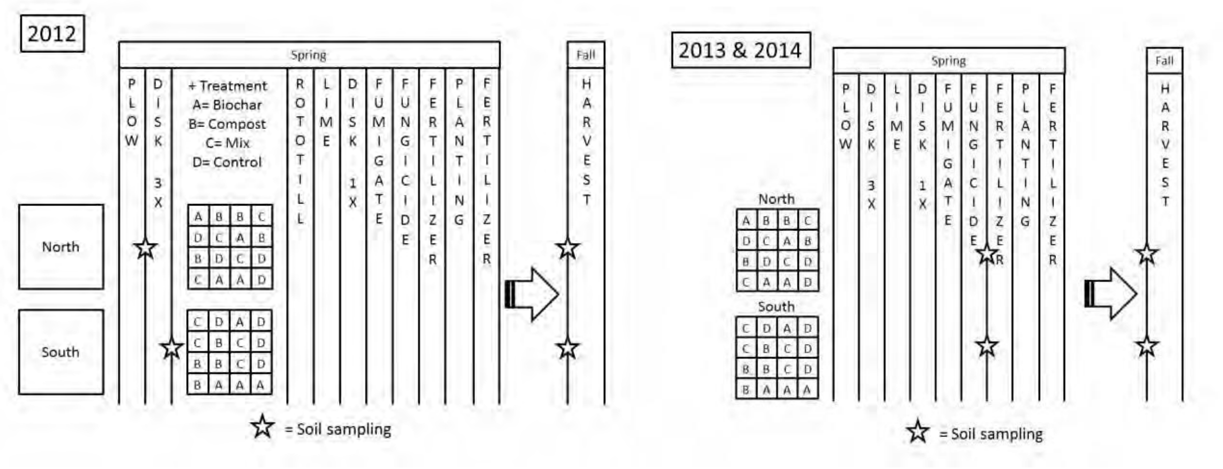

Figure 1. Timing of soil sampling during each growing season.

f. Analysis Methods

i. Crop Yield

The Brussels sprout fruit yield and biomass sampling data were analyzed to determine if significant gains or losses resulted from the treatments over time and when compared with the control.

Fruit weights were summed for each subplot within the North and South plots. For each treatment within the North and South plots, the total fruit weight by treatment (i.e. the sum of the four replicate subplot yields) was calculated. For each treatment within a plot (North or South) average fruit weight per subplot and average stalk with fruit weight in each subplot were also calculated. Standard errors for these averages were calculated for each treatment following the recommend method in “A Guide to Conducting Biochar Trials” by the International Biochar Initiative (Major 2009), and then the data was analyzed with respect to differences between treatments and the control, between North and South plots, and over time. Due to the different varieties of Brussels sprouts grown in the North and South plots, yield data from the plots were not combined in the analysis results and discussion. Crop yield results from the subplot samplings were also scaled to per-acre yields based on an assumption of 14,500 plants per acre for Confidant (North plot), and 11,500 plants per acre for Cobus (South plot).

ii. Soil

Soil samples were tested for various physical and chemical parameters to assess impacts on soil health, nitrate leaching and carbon sequestration. Analysis of the shallow (0-6”) and mid (6-12”) depth samples for a composite suite of soil parameters (see Table 6) was conducted by the Soil Control Lab in Watsonville, CA. The low and deep (12-24” and 24-36”) samples were solely analyzed for nitrate as nitrogen (nitrate-N) at Canada College in Redwood City, CA (Robert Tricca- Chemistry laboratory), to generate nitrate-N profiles. Note that in fall 2013 these low and deep samples were analyzed for nitrate-N by the Soil Control Lab instead of Canada College. The 3”soil cores taken each fall were used to determine bulk density. This analysis was performed by Ken Oster (Area Resource Soil Scientist, Templeton, CA, NRCS) following the methods in the Soil Quality Test Kit, Chapter 4, pp 9-10 and 13 (USDA, 1999b).

Soil data from each subplot, at each sampling depth, were averaged across treatment replicates (subplots) within the North and the South plots for each year. Standard errors for these averages were calculated for each treatment following the recommend method in “A Guide to Conducting Biochar Trials” by the International Biochar Initiative (Major, 2009). Then the data was analyzed with respect to differences between treatments and the control, between North and South plots, and over time. The following sections describe the methods for assessing soil health based on bulk density, soil organic matter, nutrients, electrical conductivity, pH and cation exchange capacity. Additionally, nitrate-N soil profiles and soil organic carbon data were used to assess potential changes to nitrate leaching and carbon sequestration, respectively.

Table 6. Analysis methods for soil parameters

Indicator	Unit	Method
Nitrate-N	mg/Kg	Potassium chloride extraction
Ammonium-N	mg/Kg	
P	mg/Kg	Olsen method (extraction with sodium bicarbonate)

Electrical conductivity (EC)	dS/m	Saturation paste: saturated extraction and analyses
pH	Unit	
Cation exchange capacity (CEC)	meq/100g	
K	mg/kg	Neutral ammonium acetate extraction
B	mg/Kg	$CaCl_2$ (calcium chloride dehydrate) extraction
Soil Organic Matter (SOM)	%	Walkley and Black methodology
Soil Organic Carbon (SOC)	%	

**Note that for low (12-24”) and deep (24-36”) samples, only nitrate-N was analyzed.*

Bulk Density

Bulk density is an indicator of root penetration capacity as well as soil porosity (water-holding capacity). For the loam and clay loam soil textures present in the North and South fields (see Table 1), ideal bulk density for root penetration is <1.40 g/cm^3. At 1.6 g/cm^3, bulk density in these soil types can affect root growth, and bulk densities >1.75 g/cm^3 restrict root growth (USDA, 1999b, Section II, Page 57). In the field trials, bulk density testing was done in the fall, after the soil had reconsolidated through crop growth and irrigation. Spring samples were not taken to avoid measuring the effect of tillage. Using bulk density data, percent soil porosity was also calculated for each of the fall samples.

To understand the effects of the treatments, the shallow (0-6”) and mid (6-12”) depths results are most relevant because of how the biochar was initially mixed into soil with a rototiller (North plot) or by disking (South plot). In the second and third years (2013 and 2014), a plowing 12-14” deep was done at the beginning of the planting cycle, potentially mixing residual material from the original treatments below the initial mixing depth of 6-8”. Treatment effects on bulk densities in the low (12-24”) and deep (24-36”) samples were not discussed because none of the farm practices would have physically mixed the soils below 14” during the field trial. Instead, bulk densities in these low and deep soil layers were compare to ideal bulk density range(s) based on soil texture(s) (Section 3.a.ii) to see if there is a physical barrier to leaching of nitrates. Note that the ideal bulk density range is for root penetration, not percolation, but it is likely that the range would be similar for the latter. (Ken Oster, Pers. comm., September 14, 2015)

Soil Organic Matter (SOM)

Soil organic matter (SOM) is an important indicator of nutrient availability, water holding capacity and moisture retention of the soil, as well as other beneficial soil health properties (NRCS, 2014c). SOM levels were analyzed to identify potential effects of the treatments compared with the control on soil health during the three-year field trial.

For this analysis, spring 2012 results could not be compared directly with results from other spring samplings in 2013 and 2014 because these were taken at a later step in the field preparation compared with 2012 (Figure 1). Furthermore, the spring 2012 samples were taken prior to the treatment application. To approximate the additional amounts of SOM in spring 2012 due to the treatments, estimates of these were made based on each treatment application amount and composition, and then added to the biochar, compost and mix spring 2012, shallow (0-6”) depth results (see Section 3.a.ii). Only the shallow depth soil sample results were adjusted because following the application of treatments in spring 2012, farming practices (e.g., disking and rototilling) occurred primarily in the shallow soil sampling depth.

The adjusted SOM values for the spring 2012 shallow depth reflect only the unaccounted-for additions due to the biochar, compost and mix treatments. The adjusted values do not approximate the effects on SOM that could have occurred from the other additional steps in 2013 and 2014 (i.e., disking rototilling, lime addition, fumigation, fungicide and fertilizer applications).

Nutrients

Levels of nitrogen (N), phosphorus (P), potassium (K), and Boron (B) were analyzed to assess soil health and nutrient availability to the plant, as these are essential nutrients for maintaining plant growth and physiological function, Table 7 shows recommended concentration ranges for nitrate as nitrogen (nitrate-N), ammonium as nitrogen (ammonium-N), P, K and B for Brussels sprouts grown in the location of the field trial.

Table 7. Recommended ranges for nutrients

Nutrient	Recommended range
Nitrogen as nitrate (nitrate-N)	10-50 ppm
Nitrogen as ammonium (ammonium-N)	5-25 ppm
Phosphorus (P)	22-65 ppm
Potassium (K)	246-409 ppm
Boron (B)	1-4 ppm

** Ranges are specifically for Brussels sprouts growth at the field trial location (Soil Control Lab, 2014).*[4]

Electrical Conductivity (EC)

Electrical conductivity (EC) is a measure of the concentration of water-soluble salts in soils. Specific recommended EC range(s) for Brussels sprouts are not reported, but they fall within a "moderately sensitive" classification which corresponds to an average threshold of 1.4 dS/m (USDA, 1999b, p. 60). However, the upper EC threshold for reduced Brussels sprouts yields in this location is likely higher than this. The Soil Control Lab provided a broad EC range (0.2 – 4.0 dS/m) for growth of Brussels sprouts based on knowledge of local conditions and crop yields in coastal San Mateo County. Furthermore, cabbage and broccoli crops, both of which are in the same family as Brussels sprouts, *Brassica oleracea*, have measured EC thresholds of 1.8 and 2.8 dS/m, respectively (Hanson, 2006, p. 20, Table 4).

pH

Soil pH is a measure of the acidity or alkalinity of a soil, which affect processes such as the availability of plant nutrients, activity of microorganisms, and the solubility of soil minerals. The Soil Control Lab recommends a pH range (for growth of Brussels sprouts at the field trial location) of 6.5 to 7.5, which is comparable with USDA Soil Quality Test Guide ranges (USDA, 1999b).

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[4] The following conversions were used for ppm in a 6" layer of soil:
P: Soil Control Lab recommended range for P2O5 in a 6" soil layer was 100-300 lbs/acre: Pounds P2O5 * 0.5 * 0.4364 = P ppm
K: The Soil Control Lab recommended range for K2O in a 6" soil layer was 592-986 lbs/acre: Pounds K2O * 0.5 * 0.8302 = K ppm.

Cation Exchange Capacity (CEC)

CEC is a measure of the ability of soils to retain cations such as calcium, magnesium, potassium and other positively charged nutrients, as well as some chemical pesticides. The recommended CEC range from the Soil Control Lab for Brussels sprouts grown at this location is 10-20 meq/100g, which is comparable with the 15-25 meq/100g range expected for the dark loam soil types found at the field trial location (Mengel, 1993). Therefore an overall CEC range of 10-25meq/100g was used in the analysis.

iii. Nitrate Leaching

Nitrate leaching occurs when water enters the root zone and carries nitrate that is not utilized by the plant through the soil into ground water where it can cause contamination (USDA 1999b). Direct measurements of nitrate leaching were not performed as it was considered unrealistic within the conditions of the field trial and that results would be limited by a variety of variables within the existing farming operation. Therefore, the overall potential for nitrate leaching and changes due to the treatments were inferred from analysis of chemical and physical soil sampling data. This included transforming nitrate-N data into soil profile graphs to visualize differences in nitrate movement through the profile between control and treatment subplots.

iv. Carbon Sequestration

Recalcitrant organic carbon that forms during the production of biochar by pyrolysis is resistant to decomposition by soil microorganisms, allowing the carbon to remain sequestered from the atmosphere for hundreds to thousands of years. Thus the effects of a biochar soil amendment on carbon sequestration can be determined through measurements of recalcitrant organic carbon in the soils. For this field trial, total organic carbon in the treatments and soil samples was analyzed (Tables 3.3a and 3.6.2a). The local soil testing lab did not have the abilities to quantify various fractions of total organic carbon (including recalcitrant). As such, the analysis and discussion of carbon sequestration for the field trial considers the total organic carbon added to the soil in the treatments and the amount of total organic carbon [i.e. the soil organic carbon (SOC)]. Comparisons of SOC among treatments and the control over time were used to identify potential changes to carbon sequestration due to biochar.

The total organic carbon (in tons/acre) applied to the soil in the field trial (i.e., in the biochar, compost and mix treatments) was calculated by multiplying the measured percent organic carbon content (reported in Table 3) of the biochar (59.5%) and compost (23%) by the application rate 10 tons/acre. These amounts were combined to estimate the mix treatment which was 10 tons/acre each of biochar and compost.

SOC was measured by the Soil Control Lab from the collected soil samples. Percent SOC is calculated by weight, meaning that small changes in bulk density (e.g., 1-2%) can affect the SOC percentages. The analysis of SOC took into account this effect of bulk density by converting the SOC percentages reported by the lab to tons/acre-6" using the measured bulk densities (g/cm3) for the same samples. Bulk density measurements were only taken in the fall of each year. As such, SOC in tons/acre-6" was calculated for fall 2012, 2013 and 2014. SOC was calculated for 6" soil depths (i.e., in units of tons/acre-6") because this corresponded to the depth-interval of soil sampling. The following equation was used:

$$\text{SOC (tons/acre-6”)} = (\%\ \text{SOC}/100) * \text{Bulk Density (g/cm}^3\text{)} * 758$$

The conversion factor of 758 for a 6” soil layer depth was derived as follows (Donovan 2011, p. 32):

tons/acre-6” = g/cm^3 * 1 kg/1000 g * 2.204622622 lbs/kg * tons/2000 lbs * 16.38706 cm^3/in^3 * 144 in^2/ft^2 * 48560 ft^2/acre * 6” = g/cm^3 * 758

4. RESULTS

a. Crop Yield

Overall, the compost treatment and control resulted in the highest fruit yields. With the few exceptions noted here, no significant differences were observed between treatments and control (see Figure 2). In the North plot, the average fruit weight in the mix treatment subplots was significantly less than the control by 15% in 2012 and 6% in 2014. The biochar treatment also resulted in a significant decrease of 6% compared with the control in 2014 in the North plot. In 2013 in the South plot, the mix treatment resulted in a significant increase (16%) over the control.

In both the North and South plots, significant decreases in yields across all treatments occurred in 2013 relative to 2012 levels. In 2014, North plot yields remained low, but South plot yields returned to 2012 levels.

Table 8. Crop yields[5]

NORTH	Total Fruit weight (lbs)				Percent change from control			
Treatment	**2012**	**2013**	**2014**	**All Years**	**2012**	**2013**	**2014**	**All years**
Biochar	315	208	215	738	-4	-3	-6	-5
Compost	315	217	226	758	-4	1	-2	-2
Mix	280	211	216	707	-15	-2	-6	-9
Control	329	214	230	773	NA	NA	NA	NA

SOUTH	Total Fruit weight (lbs)				Percent change from control			
Treatment	**2012**	**2013**	**2014**	**All years**	**2012**	**2013**	**2014**	**All years**
Biochar	263	184	271	718	-6	12	-5	-2
Compost	309	182	279	769	10	10	-2	5
Mix	268	191	257	715	-5	16	-10	-2
Control	281	165	286	732	NA	NA	NA	NA

Table 9. Equivalent fruit yields in tons per acre for each treatment. [6]

	NORTH			**SOUTH**		
Treatment	**2012**	**2013**	**2014**	**2012**	**2013**	**2014**
Biochar	27	18	19	18	13	19
Compost	27	19	20	21	12	19
Mix	24	18	19	18	13	18
Control	28	18	20	19	11	20

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[5] Twenty-one plants were randomly sampled per replicate (four replicates per plot).

[6] The averaged pounds of fruit per stalk for each treatment were determined by dividing the treatment fruit weight sums (above) by 84. This average fruit weight per stalk was multiplied by 14,500 Confidant plants/acre in North plot, and 11,500 Cobus plants/acre in South plot to calculate the per-acre yields.

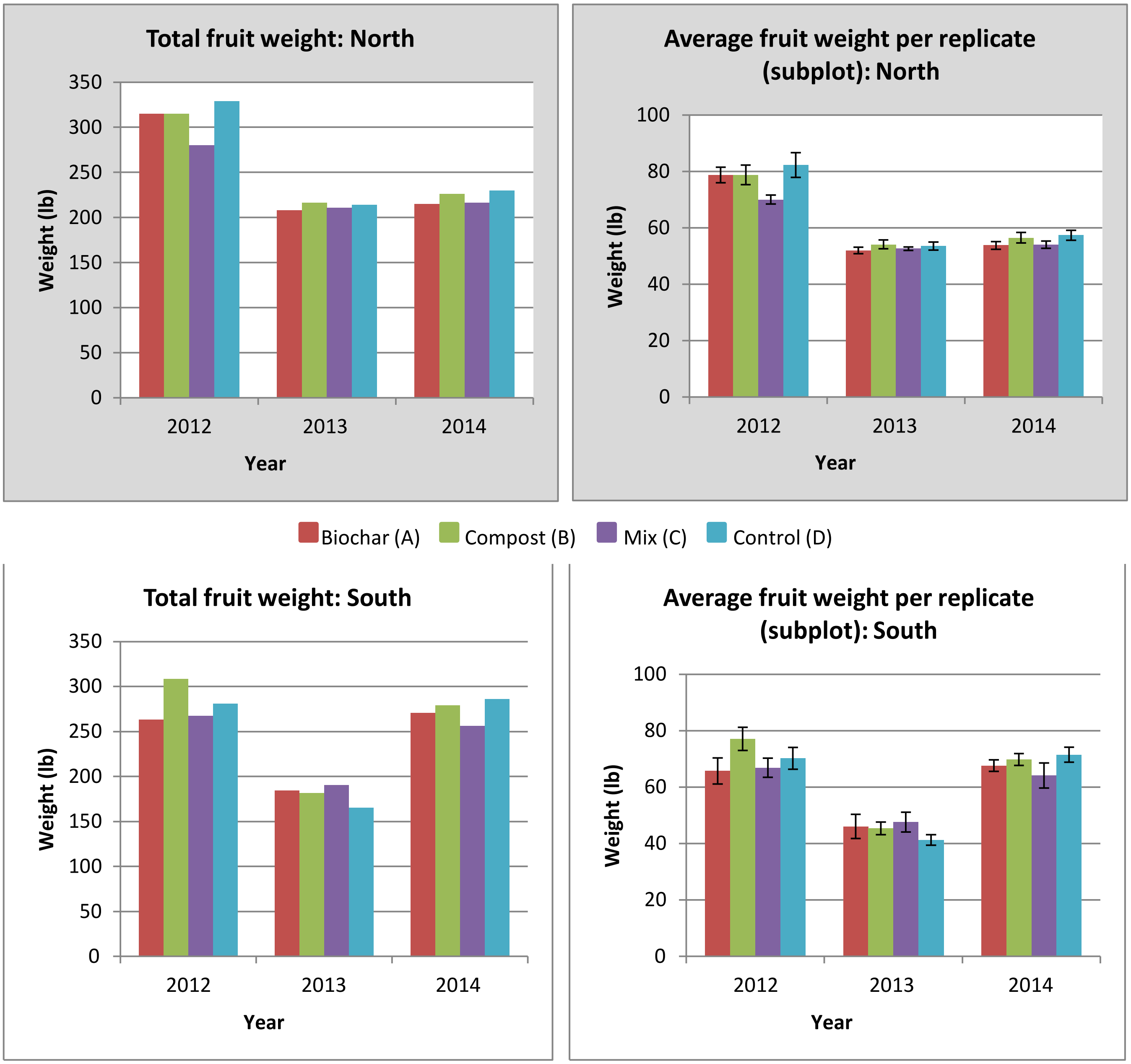

Figure 2. Fruit weights from treatment samplings

The average biomass (stalk with fruit weight) per stalk for each treatment is shown in Figure 3. In the North plot, the only significant differences between treatments and the control occurred in 2014; both the compost and mix resulted in significantly lower biomass than the control. Over the three-year study, the biomass results for all of the treatments except for the control declined, with the 2014 weights being significantly lower than in 2012.

In the South plot, the compost treatment resulted in significantly higher biomass than the control in 2012 and 2013. Compared with the control, the biochar and mix treatments resulted in significantly higher biomass in 2013 but significantly lower biomass in 2014. Over time, the control and compost treatment results followed a similar pattern; dropping off significantly in 2013 (from 2012 biomass) then returning back up to levels comparable with 2012. The biomass results for biochar and mix declined over the three years and 2014 results were significantly lower than in 2012.

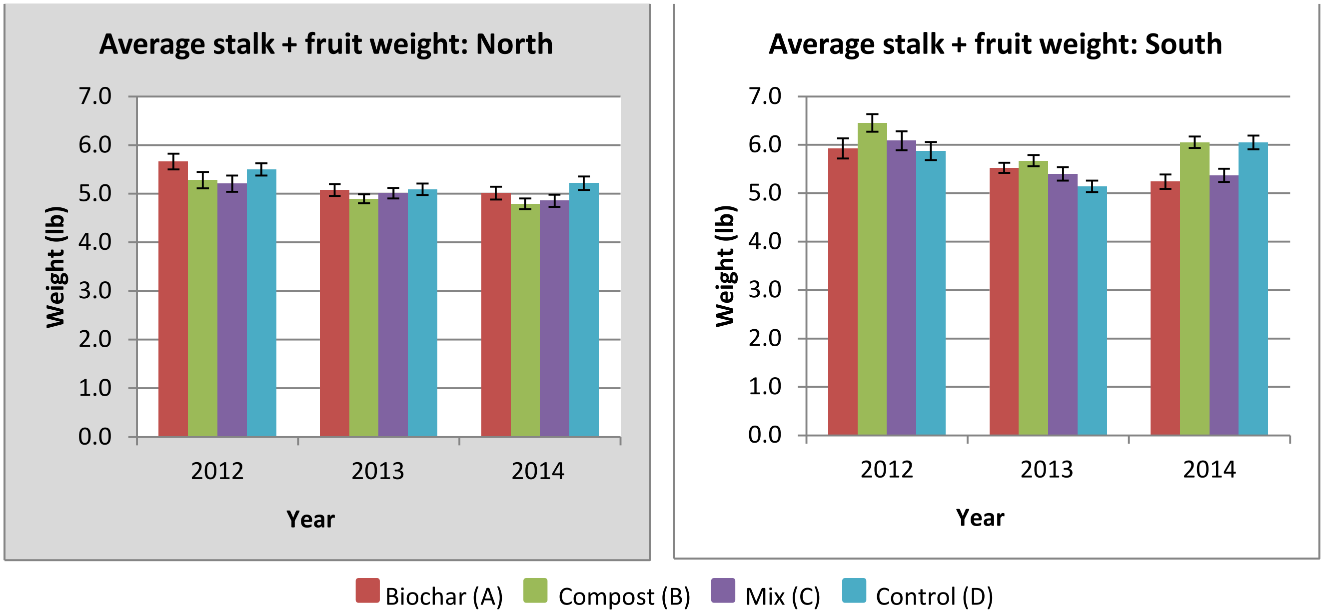

Figure 3. Average biomass (stalk with fruit weight) per stalk

When considered together, the fruit yield and biomass results show that the declines in overall biomass production (i.e., stalk with fruit weight) that occurred across all treatments and control in the North and South plots were not proportional to the declines in fruit yield. The per plant fruit yield to total biomass ratios in Table 4.1c indicate that the stalk weights increased in 2013 in both plots and in the North plot in 2014 when compared with 2012 results.

Table 10. Ratio of average fruit weight per stalk to average to stalk + fruit weight (biomass/ stalk). [7]

	NORTH			SOUTH		
Treatment	**2012**	**2013**	**2014**	**2012**	**2013**	**2014**
Biochar	0.7	0.5	0.5	0.5	0.4	0.6
Compost	0.7	0.5	0.6	0.6	0.4	0.5
Mix	0.6	0.5	0.5	0.5	0.4	0.6
Control	0.7	0.5	0.5	0.6	0.4	0.6

b. Soil Health

i. Bulk Density

Results from the analysis of bulk density for the soil sampling cores taken in fall of 2012, 2013 and 2014 are shown in Figures 4.3a and 4.3b. For shallow and mid depths in both plots, none of the treatments or control resulted in bulk densities that exceeded the recommended threshold of 1.6 g/cm^3 , above which root growth can be affected in loams and clay loams, the soil textures in the North and South plots respectively (USDA, 1999b, p 57).

In the North plot shallow depth, the control resulted in increasing bulk density over time, whereas in the mid depth, bulk density declined. The compost treatment resulted in significantly higher bulk density that the control in the 2012 shallow depth. The control bulk density in the shallow depth in 2014 resulted in the highest bulk density measured for the North plot (approaching 1.5 g/cm^3), and was significantly higher than the biochar and mix treatments bulk densities. At the mid depth in 2012 and 2013, the compost treatment resulted in bulk densities greater than 1.4 g/cm^3 , as did the mix treatment in 2013. For the loam and clay loam soil textures present in the North and South fields ideal bulk density for root penetration is <1.40 g/cm^3. (USDA, 1999b, Section II, Page 57). With the exception of the control mid depth sample in 2013, all of the average bulk densities in the South plot in the shallow and mid depths were within this ideal range (i.e., <1.4 g/cm^3) for the loam or clay loam soil textures found at these depths.

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[7] The stalk + fruit weights were calculated from the 84 plants sampled per treatment per plot (i.e., 21 plants sampled per replicate, four replicates per plot). The average fruit weight per stalk for each treatment was determined by dividing the treatment fruit weight sums (above) by 84.

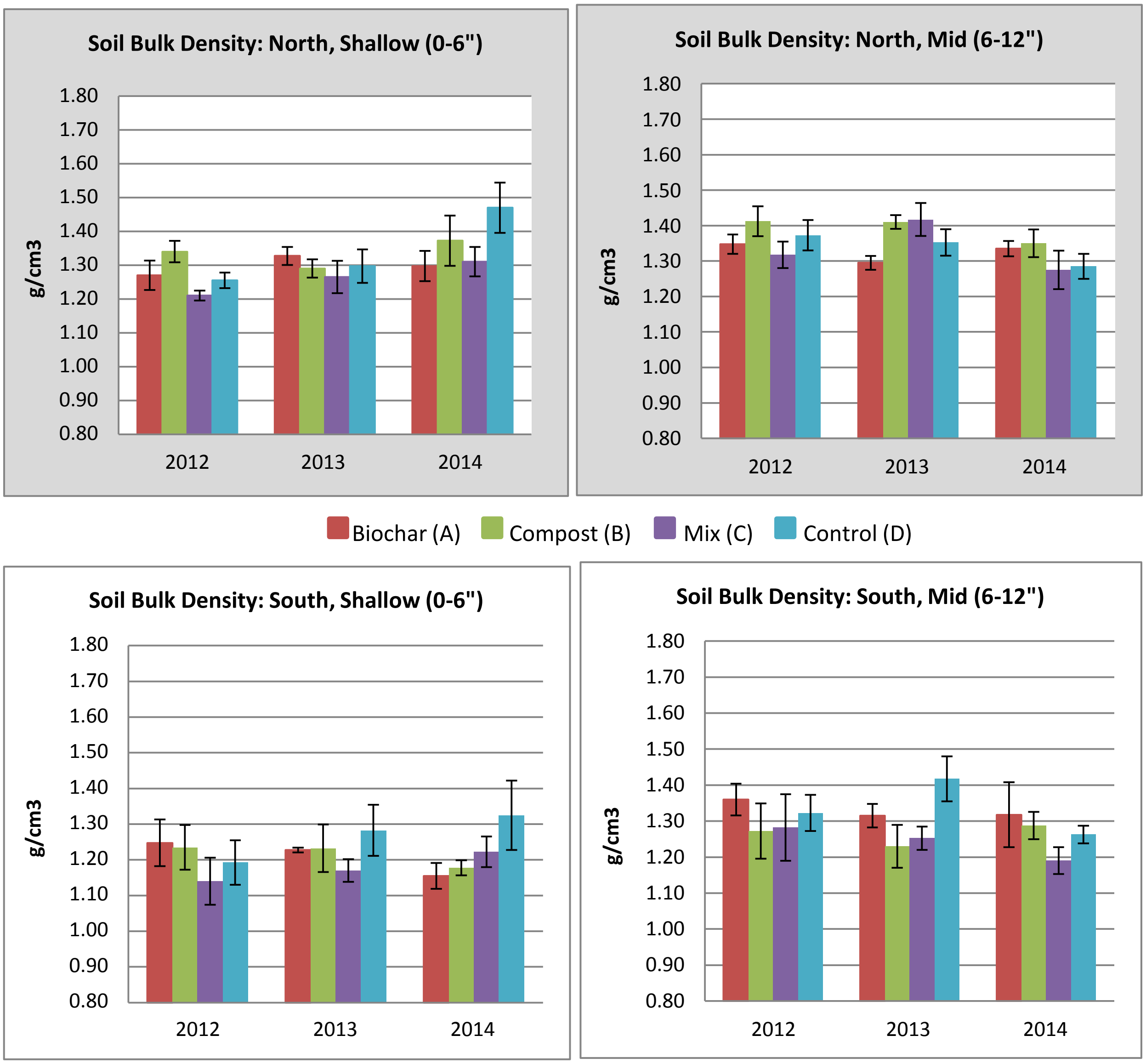

Figure 4. Soil bulk densities (g/cm3) in shallow (0-6”) and mid (6-12”) depths

Bulk densities in for the low and deep layers are shown in Figure 5. For low depth samples in the North plot all bulk densities exceeded 1.4 g/cm^3 in 2012 and 2013, but declined significantly in 2014. Overall, the South plot average bulk densities at this same low depth were less than in the North plot; only the biochar treatment in 2013 resulted in a bulk density greater than the 1.4 g/cm^3 threshold.

The deep (>24”) samples, soils were as dense as or more dense than the upper limit of the ideal range (1.4 g/cm^3), and likely less permeable (Ken Oster, Pers. comm., August 18, 2015).

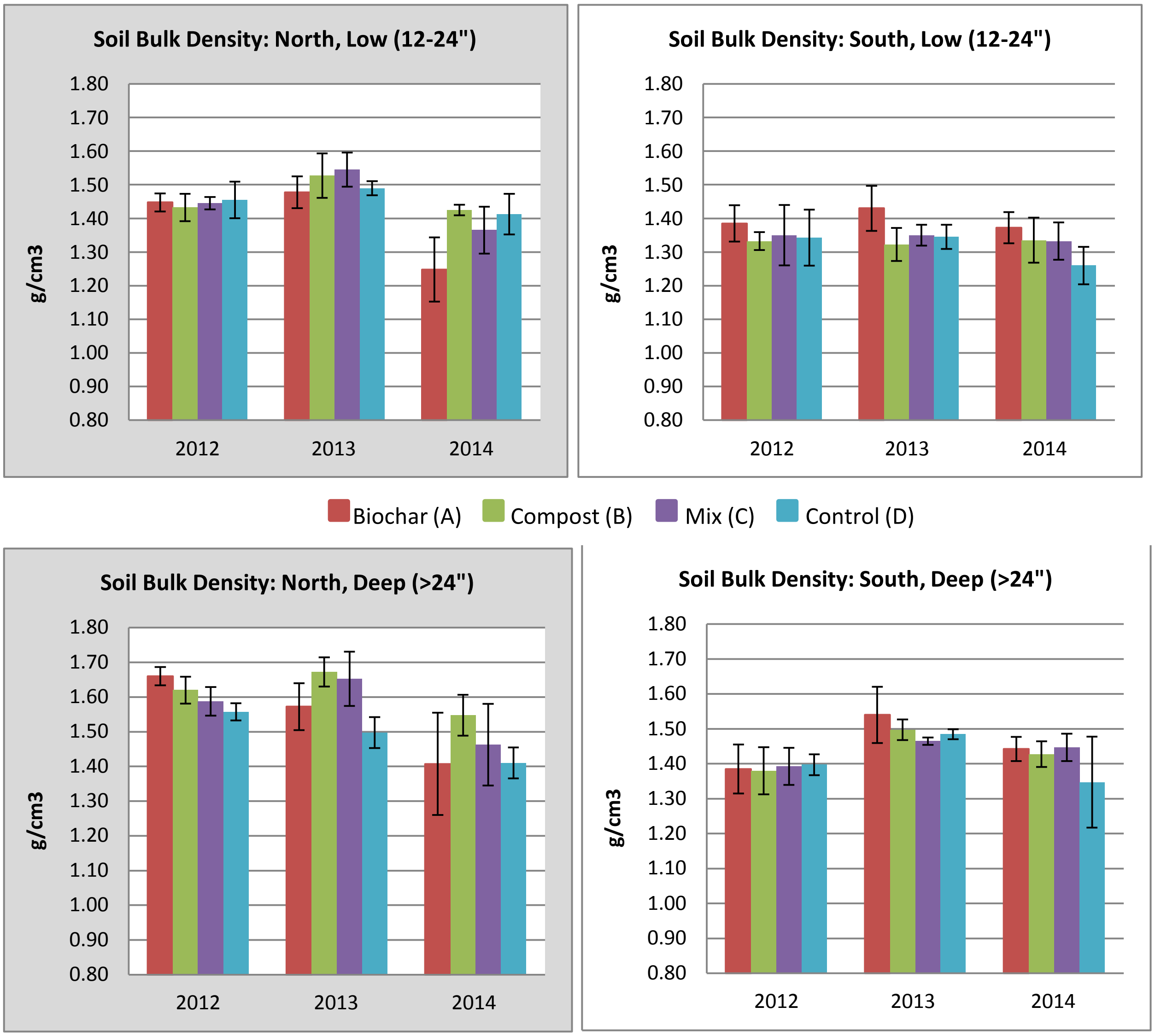

Figure 5. Soil bulk densities (g/cm3) in low (12-24") and deep (24-36") depths

ii. Soil Porosity

Table 11 summarizes percent soil porosity below 24". The percent porosity was both more and less than 50%, a lower threshold for supporting good plant growth. Soil porosity below 40% may inhibit leaching.

Table 11. Percent soil porosity below 24" depth

	North Plot			South Plot		
Year	Low	Ave	High	Low	Ave	High
2012	34	39	45	42	48	62
2013	31	40	48	35	44	59
2014	32	45	63	40	47	61

iii. Pre-treatment Soil Composition

Chemical analysis (by Soil Control Lab, Watsonville, CA) of soil samples taken prior to application of treatments in spring 2012 are shown in Table 12. Soil concentrations of nitrogen as nitrate (nitrate-N) and nitrogen as ammonium (ammonium-N), potassium (K) and boron (B) were insufficient for optimal growth based on recommended ranges (Soil Control Lab; Mills, 2001). Other soil health indicators including soil organic matter (SOM), phosphorus (P), pH, electrical conductivity, cation exchange capacity (CEC) and soil adsorption rate (SAR)) were within recommended ranges.

Table 12. Initial soil sample results for spring 2012 before treatments applied.[8]

Indicator	Soil Org Matter (SOM) %	Soil Org Carbon (SOC) %	Nitrate -N ppm	Ammo-nium-N ppm	P ppm	K ppm	B ppm	pH	EC dS/m	CEC m_{eq}/ 100g
Recommended range or threshold	*NA*	*NA*	*10-50 (†)*	*5-25 (†)*	*22-65 (†)*	*246-409 (†)*	*1-4 (†)*	*6.5-7.5 (†)*	*<1.4 (◊)*	*>10 (^)*
North 0-6"	3.5	2	3.9	4.4	120	120	0.38	7	0.6	21
North 6-12"	3.7	2.1	5.8	3	130	110	0.32	7	0.64	18
North 12-24"	3.5	2	3.1	4.4	87	82	0.47	6.9	0.6	16
North 24-36"	3.2	1.8	4.8	4.6	36	78	0.24	6.7	0.65	20
South 0-6"	3.7	2.1	8.9	4.8	160	110	0.25	6.9	0.59	22
South 6-12"	3.4	2	6.3	5.1	170	93	0.25	6.9	0.54	21
South 12-24"	2.2	1.3	6.3	3.8	100	75	0.13	6.9	0.54	21
South 24-36"	0.78	0.46	4.2	2.2	48	39	<0.05	6.8	0.43	10

**Note these samples were taken at one location within the North plot and one location within the South plot.*

***Recommended ranges for soil health indicators are shown in the second row. Sources: (†) Soil Control Lab; (◊) USDA, 1999b; (^) Mengel, 1993*

iv. Soil Organic Matter (SOM)

Results from the analysis of SOM levels are shown in Figure 6. For the spring 2012 shallow sampling, the SOM results for biochar, compost and mix were adjusted as described in Section 3.f.ii.1. Soil Organic Matter (SOM).

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[8] Additional recommended thresholds that were identified for electrical conductivity (EC) and cation exchange capacity are presented in the results sections for these indicators.

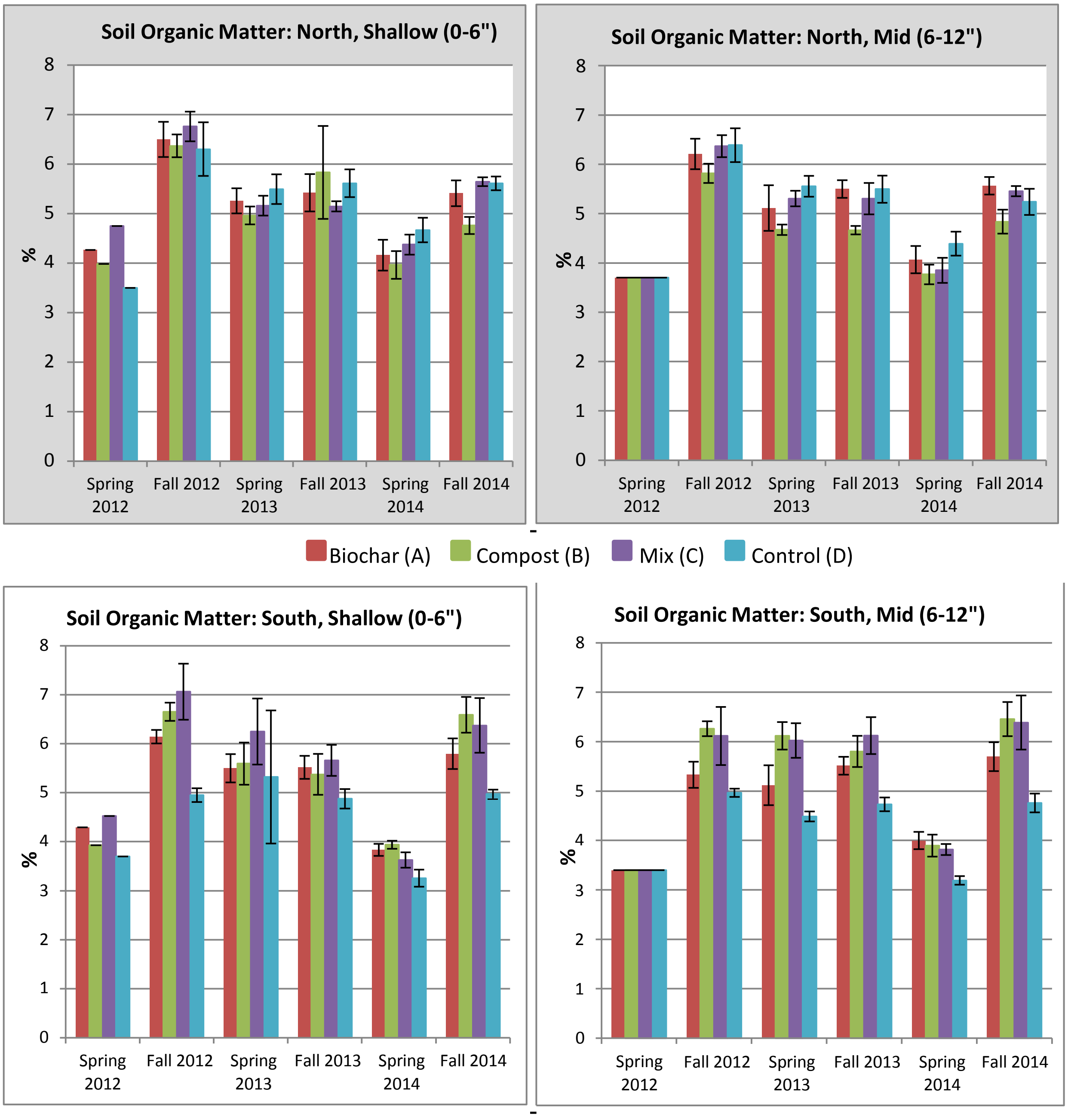

Figure 6. Percent soil organic matter (SOM)

In the South plot the biochar, compost and mix treatments resulted in higher SOM relative to the control. This effect was not apparent in the North plot, where the control resulted in SOM that was not significantly different than biochar and mix treatments, and significantly greater than compost in some cases. In both plots and at both sampling depths, SOM levels were lowest for all treatments and control in spring 2014. However, by fall 2014, the SOM amounts in both plots were comparable to the previous fall (2013) for each treatment and the control.

In the North plot, the treatments and control resulted in the highest levels of SOM in fall 2012 at both depths, and declined over time to the final sampling in fall 2014 (both depths). Throughout the trials biochar, mix and the control resulted in SOM levels that were not significantly different at either depth. However, compost resulted in significantly lower SOM than the control in spring 2013 and spring 2014 at both depths, and the fall 2014 shallow, and fall 2013 mid depths.

In the South plot, compost and mix resulted in the greatest SOM overall. With the exception of spring 2013 (shallow depth), biochar, compost and mix treatments all resulted in significant SOM increases in comparison to control at both sampling depths across all sampling events. Unlike in the North plot, no overall decline in SOM levels occurred over time (i.e., from fall 2012 to fall 2014).

v. Nitrogen as nitrate (Nitrate-N)

Nitrogen as nitrate (nitrate-N) concentrations in the soil samples are shown in Figure7. Over the growing season in 2013 and in 2014 there was an overall order of magnitude drop in concentrations of nitrate-N. (Note the different scales on the y-axis between spring and fall results.) The recommended range for nitrate-N for Brussels sprouts crops in this location is 10-50 ppm (Soil Control Lab, 2014). In both the North and South plots, the spring 2013 and 2014 soil samples had concentrations of nitrate-N that were within this range for all treatments. In the fall of each year, concentrations across all treatments fell below 10ppm.

In the spring samples from the North plot, all treatments results for nitrate-N concentrations were comparable (i.e. no significant differences occurred between treatment and control results). However, in the fall, biochar treatment resulted in significantly higher concentrations of nitrate-N than control in shallow and mid depths for 2012, and in the shallow depth in 2014. Mix treatment also resulted in significantly higher concentrations than the control in the 2012 shallow depth, and in the 2013 mid depth.

In the South test plot, concentrations of nitrate-N from all treatments and the control were significantly higher in spring 2013 at the shallow depth compared with all other samplings from this plot. However, it is not possible to compare this result with the spring 2012 sampling which took place prior to treatments. In spring 2013, biochar treatment resulted in significantly lower nitrate-N concentrations than other treatments (including control), but there were no significant differences in concentrations with respect to the control in spring 2014 at either sampling depth. For fall mid depth results in all three years, the mix treatment resulted in greater nitrate-N concentrations than other treatments (significantly greater than control in 2013 and 2014). But from fall 2012 to spring 2013, and fall 2013 to spring 2014, concentrations in mix treatment samples return to comparable levels with other treatments (i.e. spring samples do not have this difference).

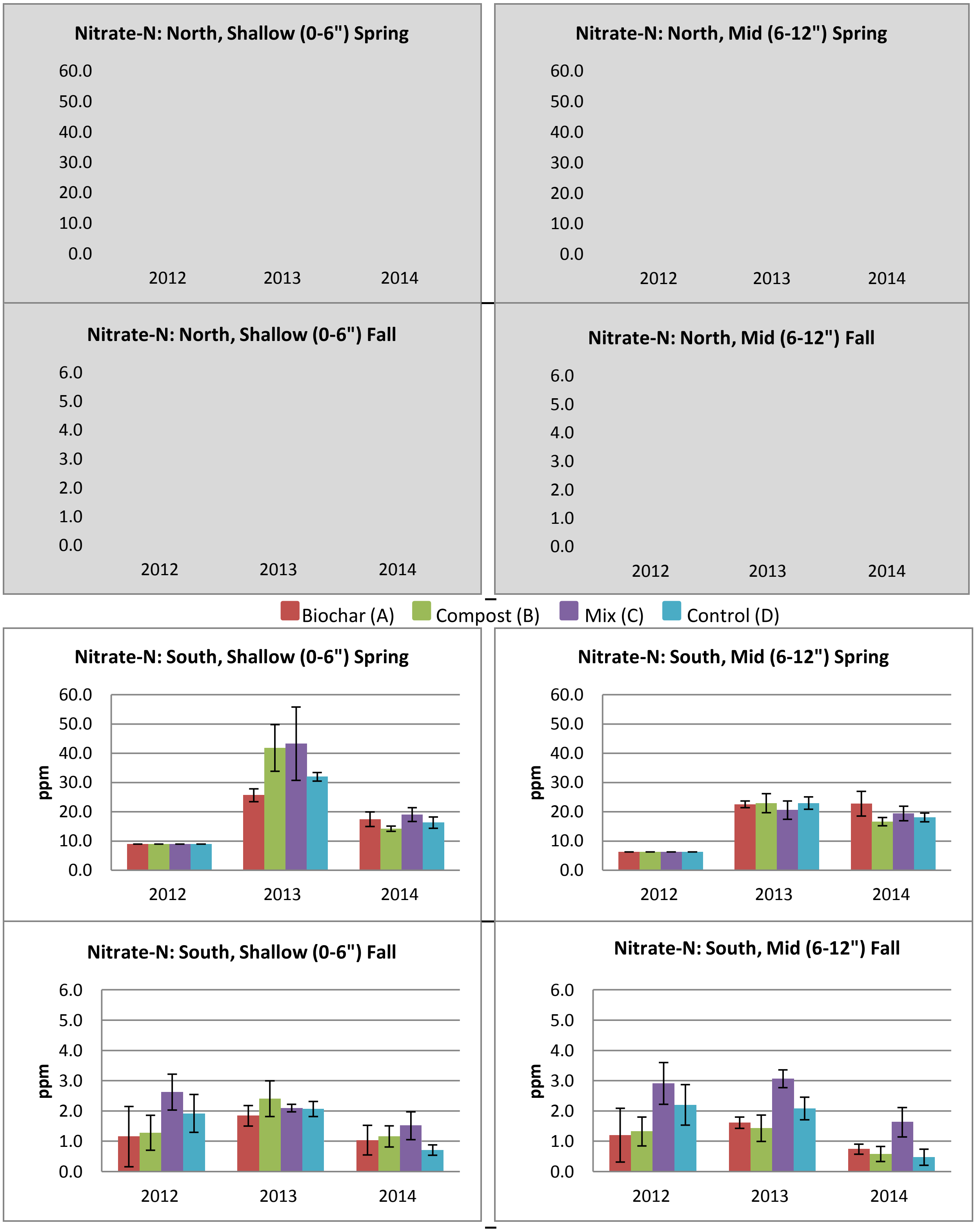

Figure 7. Nitrate-N concentrations (ppm)[9] in shallow (0-6”) and mid (6-12”) depths

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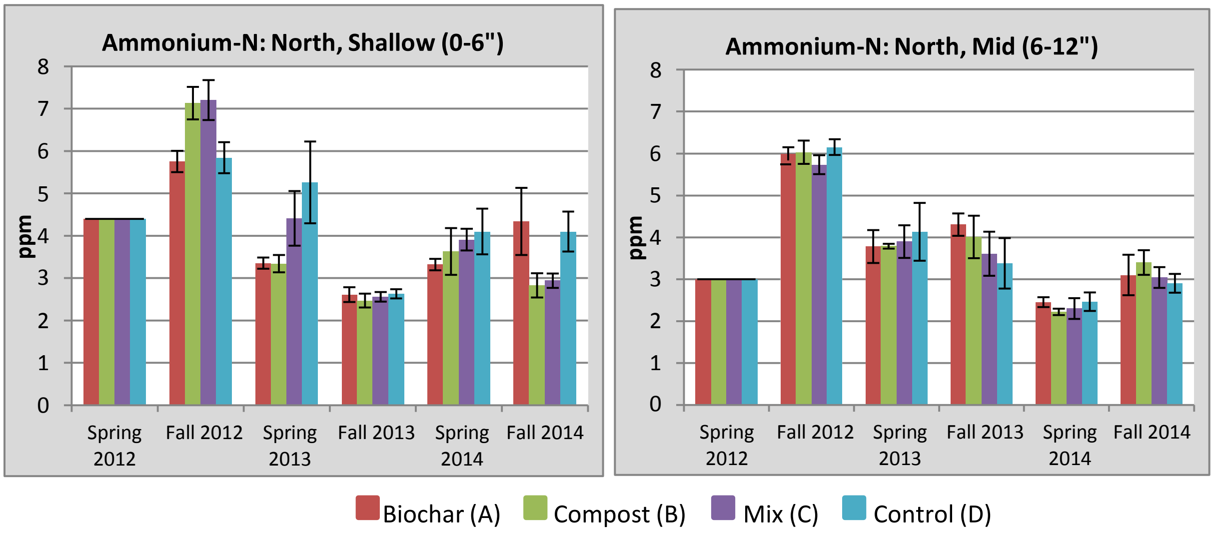
[9] *Note the different scales on the y-axis between spring and fall results*

vi. Nitrogen as ammonium (Ammonium-N)

Nitrogen as ammonium (ammonium-N) in the soil samples is shown in Figure 8. Overall, the ammonium-N concentrations were at the low end of the recommended range of 5-25 ppm or below it (Soil Control Lab, 2014).

In the North plot, ammonium-N concentrations in the shallow depth samples varied considerably within and between treatments. When compared with the control, compost and mix treatments resulted in significantly higher concentrations in fall 2012, but significantly lower concentrations in fall 2014. Biochar treatment resulted in significantly lower ammonium-N concentrations than the control in spring 2013 and 2014. Ammonium-N concentrations for all treatments dropped significantly in fall 2013. At the mid depth, results were more consistent, with no significant differences resulting between treatments and the control in any sampling.

In general, ammonium-N concentrations in the South plot samplings fluctuated much less than in the North plot, and were above the lower limit of the recommended range. However, at both depths in fall 2013, a significant drop (>50%) occurred in all treatment sample concentrations. In spring 2014, concentrations in all treatment samples had increased significantly, and by fall 2014 had returned to levels comparable to 2012. Compared with the control, biochar resulted in significantly higher ammonium-N concentrations at both depths in spring 2014, as did the compost and mix treatments at the mid depth.



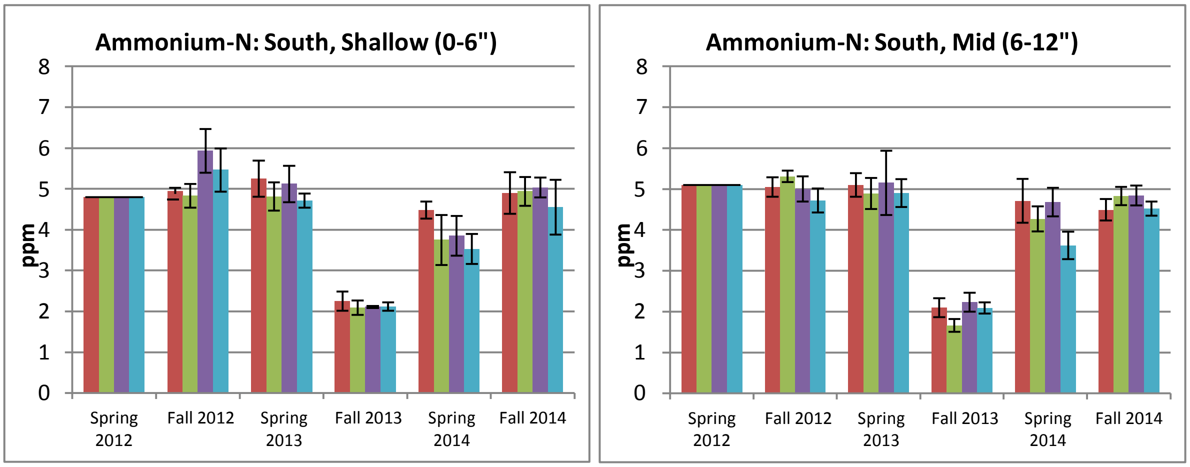


Figure 8. Ammonium-N concentrations (ppm)

vii. Potassium (K)

Concentrations of potassium (K) in spring and fall soil samplings from both plots (Figure 9) were significantly less than the suggested K soil concentration range (246-409 ppm) for growing Brussels sprouts in this location.

In the North plot, K concentrations were highly variable; no trends occurred over the course of the field trial as a result of the treatments or the control. The biochar treatment resulted in K concentrations that were significantly lower than the control in spring and fall of 2013 in the shallow depth sampling. Compost resulted in significantly lower K concentration in fall 2013 as well. The mix treatment, however, resulted in significantly higher K concentration than the control and other treatments in fall 2012 in the shallow depth. In the mid depth sampling, neither the biochar and mix treatments were significantly different that the control throughout the field trial. Compost however resulted in significantly lower K concentrations in fall of 2012 and 2013.

In the South plot, K concentrations dropped over the entire field trial (from 2012 to 2014) across all treatments and depths. From spring to fall (growing season) for all years, concentrations either remained the same or dropped significantly within treatments. One exception was the concentration of K in the mix treatment sample in 2013 which increased significantly from spring to fall. In the first two years of the trail (2012 and 2013) the treatments did not result in K concentrations in the shallow depth that were significantly different that the control. However, in 2014 at the shallow depth, all treatments resulted in significantly lower K concentrations than the control. In the mid depth samples, results varied more. Biochar treatment resulted in significantly lower K concentration than the control in fall 2012, yet significantly greater than the control in the fall of 2013 and following spring. Compost treatment resulted in significantly lower K concentrations in 2013 and 2014 compared with the control.

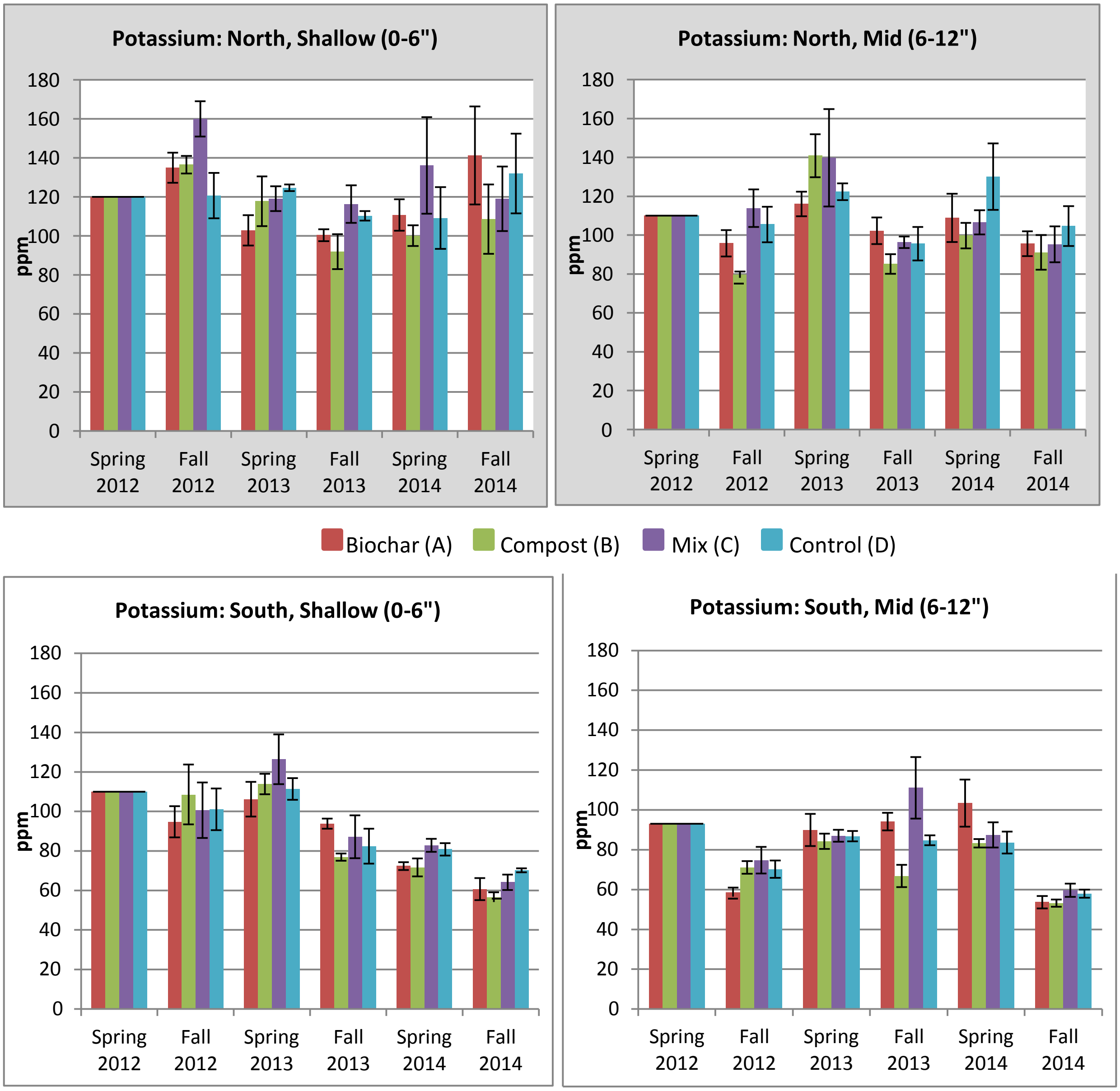


Figure 9. Potassium (K) concentrations (ppm)

viii. Phosphorus (P)

Concentrations of phosphorus (P) (Figure 10) were high in both plots in spring and fall samplings relative to the suggested P soil concentration range (22-65 ppm) for growing Brussels sprouts in this location.

In the North plot, concentrations from the shallow depth samples increased across all treatments from fall 2012 to spring 2014, and then dropped in fall 2014, significantly so as a result of the compost treatment (at both depths). The compost treatment resulted in the significantly lower P concentrations in 2013 and fall 2014 (shallow depth) compared with the control levels. Otherwise, the treatments showed no significant differences than the control at either depth in the North plot.

In the South plot, the overall trend appeared to be opposite to that of the North plot. Overall, the P concentration in the treatment and control samples dropped from the initial spring 2012 sampling, but were higher in fall 2014, returning to spring 2012 levels in the shallow sample. Within spring 2013 samples for shallow and mid depths, biochar treatment resulted in significantly higher P concentration than control whereas mix resulted in significantly lower concentrations than control. In 2012, no significant differences in P concentrations resulted at either depth, but in 2013 (fall and spring), the biochar treatment resulted in significantly higher P concentrations than the control. The only other significant differences from the control were for the mix treatment which had decreased concentrations in spring 2013 (both depths) but showed a significant increase in the mid depth by the following fall (of 2014).

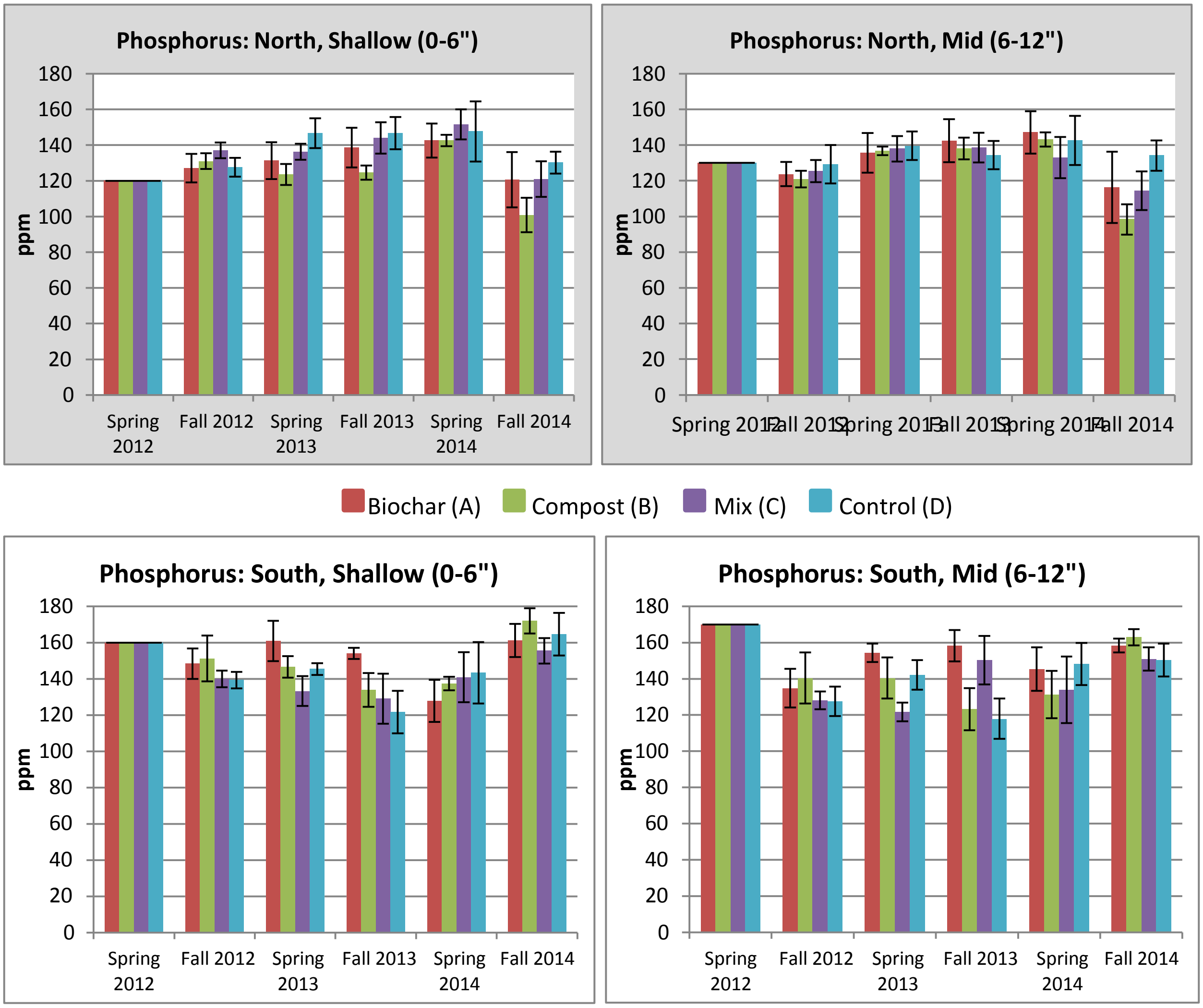


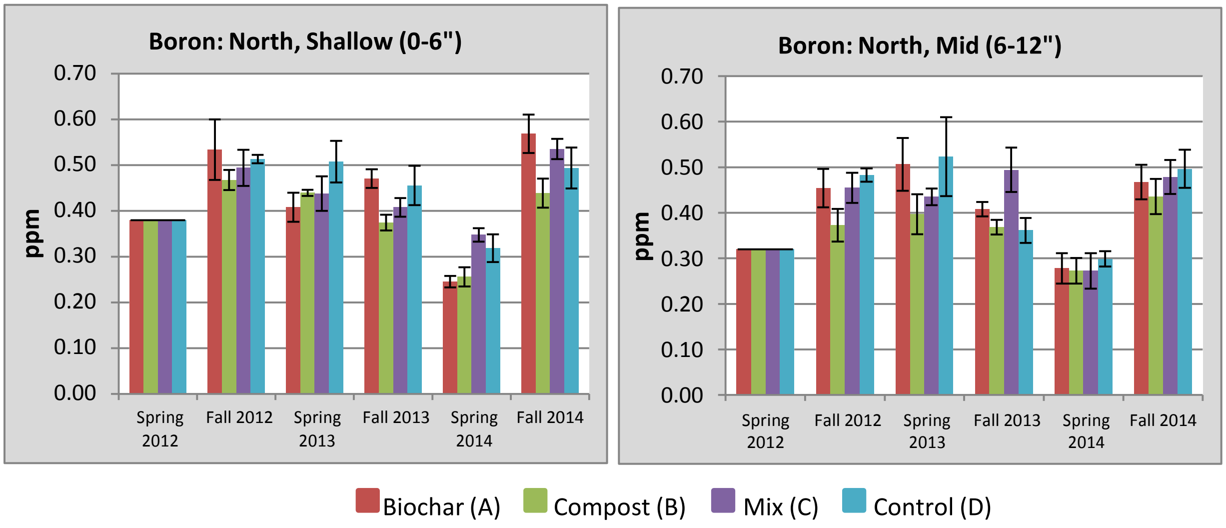
Figure 10. Phosphorus (P) concentrations (ppm)

ix. Boron (B)

Boron (B) concentrations in the soil samples are shown in Figure 11. Throughout the field trial the B concentrations in both plots were significantly lower than the 1-4 ppm range recommended for growing Brussels sprouts in this location (Soil Control Lab, 2014).

In the North plot, shallow depth, control B concentrations did not change significantly, with the exception of the decrease in spring 2014. In the mid depth, control concentrations dropped significantly in fall 2013 and spring 2014, but increased again to previous levels in fall 2014. Compost resulted in lower B concentrations in the shallow depth than the control throughout the field trial, significantly so for fall 2012 through spring 2014. In the mid depth compost samples had less B in fall 2012 and spring 2013, but comparable concentrations as the control for the rest of the samplings. In the shallow layer, biochar treatment resulted in higher fall concentrations that were comparable to the control results, and low spring concentrations that were significantly less than the control results. This pattern was not evident at the mid depth, and biochar treatment did not result in significant differences in B concentration than the control. The mix treatment resulted in B concentrations that were comparable to the control throughout the trial (in both depths) with the exception of fall 2013 where mid depth results were significantly higher than all other results.

In the South plot, samples were not analyzed for B concentrations in fall 2013. Both the biochar and the mix treatments resulted in significantly higher B concentrations (in both depths) than the control in fall 2012 and spring 2013. By spring 2014, this was no longer true, and neither treatment differed significantly from the control. The very large error associated with control results in the shallow depth fall 2014 results makes it difficult to interpret further trends. However, in the mid depth, biochar and mix resulted in significantly higher concentrations than the control, suggesting that the trend seen in earlier in the trial occurred here as well. With the exception of the fall 2014 shallow depth results that are difficult to interpret, the compost treatment resulted in higher average B concentrations than the control, significantly so in the fall 2012 mid depth, and spring 2014 shallow depth samplings.



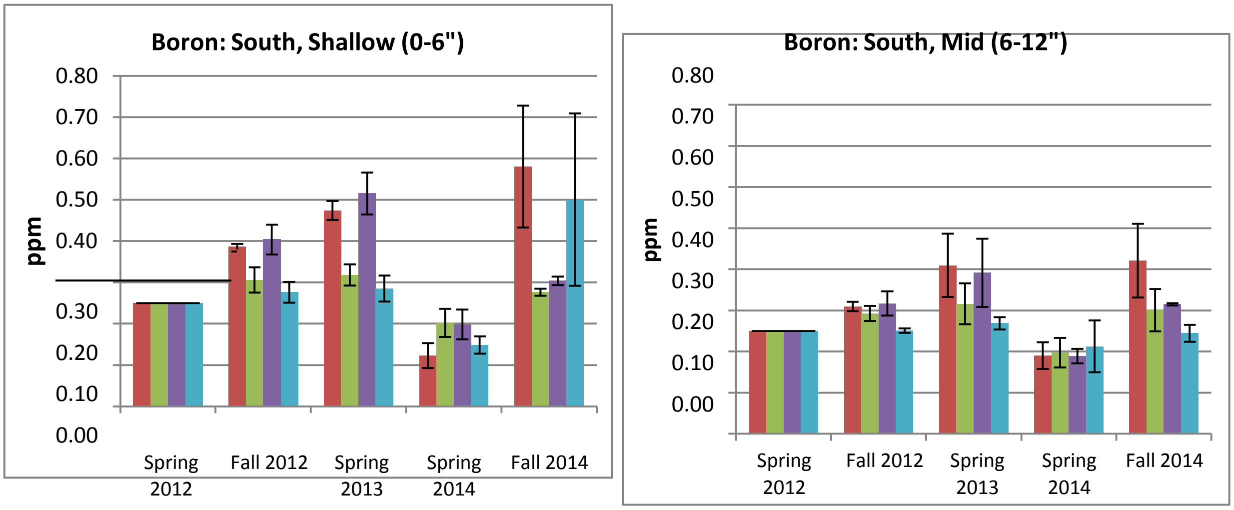


Figure 11. Boron (B) concentrations (ppm)

x. Electrical Conductivity (EC)

Results of the electrical conductivity (EC) measurements for the soil samplings are shown in Figure 12. As stated previously, a general EC threshold for Brussels sprouts growth is 1.4 dS/m, but a range of 0.2-4.0 dS/m has been recommended for the location of the field trial (USDA, 1999b, p. 60; Soil Control Lab, 2014). Measured thresholds for cabbage and broccoli crops, both of which are in the same family, Brassica *oleracea,* as Brussels sprouts are 1.8 and 2.8 dS/m, respectively (Hanson, 2006, p. 20, Table 4.).

In the North plot, average EC results did not exceed the 1.4dS/m threshold. However, in fall of 2013 the mix treatment resulted in significantly higher average EC than the control at both sampling depths that approached 1.4 dS/m. In the South plot, average EC results more than doubled from fall 2012 to spring 2013, with the compost, mix and control shallow depth results all exceeding the 1.4 dS/m threshold. However, the average EC for the biochar treatment samples did not exceed this threshold and was significantly lower than the other treatments and control in the shallow depth. In general, the biochar treatment resulted in higher average EC in the fall samplings than the other treatments and the control, and average EC results in the fall 2013 shallow depth and fall 2014 mid depth exceeded 1.4 dS/m and 1.8 dS/m thresholds, respectively. The average EC of sample results approached 1.4 dS/m in two other instances: control in fall 2013 at the mid depth, and compost in fall 2014 shallow depth.

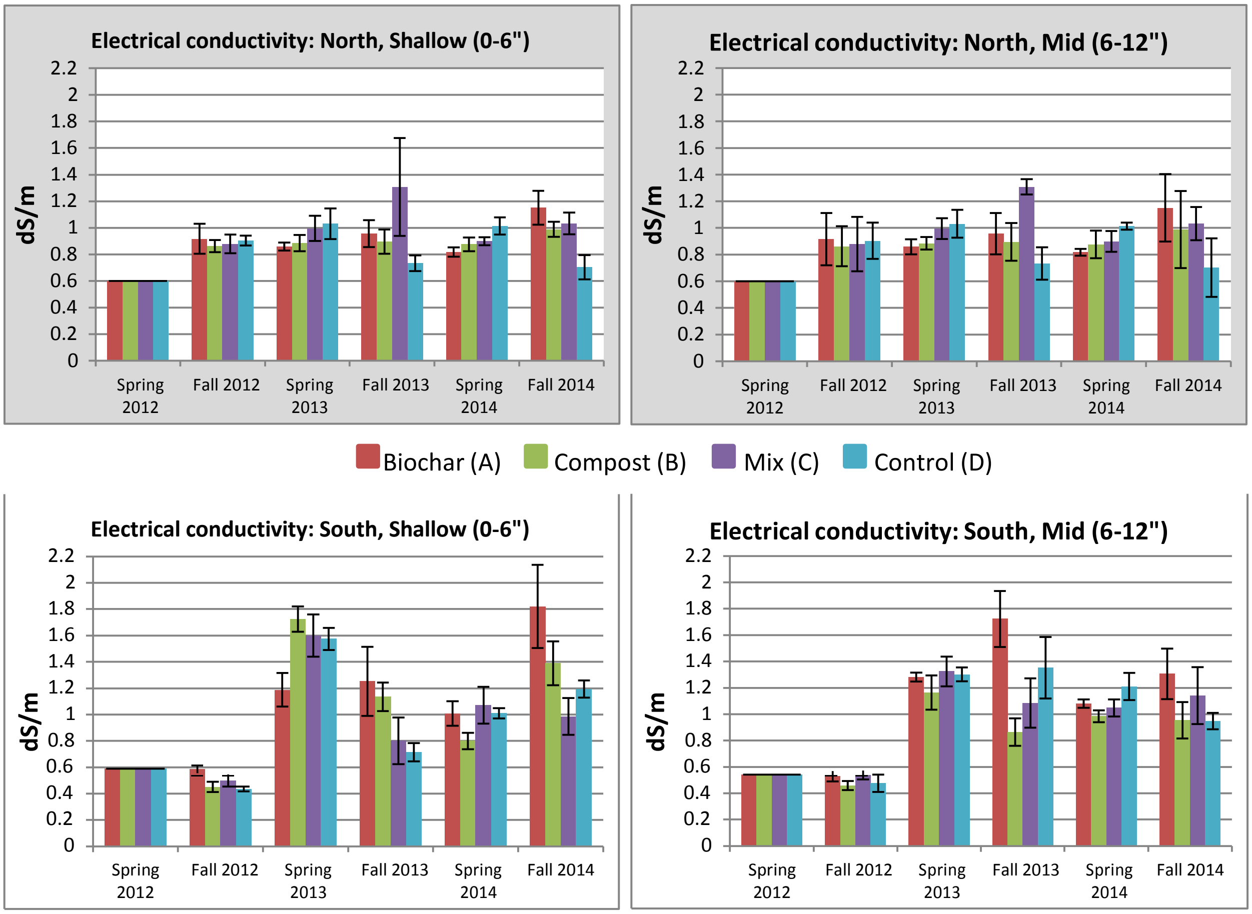


Figure 12. Electrical conductivity (EC) (dS/m)

xi. pH

The results of the pH testing of the soil samples are shown in Figure 13. None of the soil samples from any of the treatments had pH values that fell outside of an acceptable range of 6.5 -7.5 for Brussels sprouts (Soil Control Lab, 2014).

In the North plot, biochar treatments resulted in significantly higher pH values in spring mid depth samples compared with other treatments; the error approaches upper limit of acceptable range in 2014. No significant changes from spring to fall occurred in the North plot, except for the compost 2014. Compost is consistently lowest in fall 2013 and 2014 samples – significantly so in 2014.

In the South plot, opposite trends occurred with values increasing every year in the spring and decreasing every year in fall. Over the 2014 growing season (spring to fall) all treatments and control resulted in significant drops in pH at both shallow and mid depths; biochar and control treatment samples approached the lower limit of the acceptable range (6.5) in fall 2014.

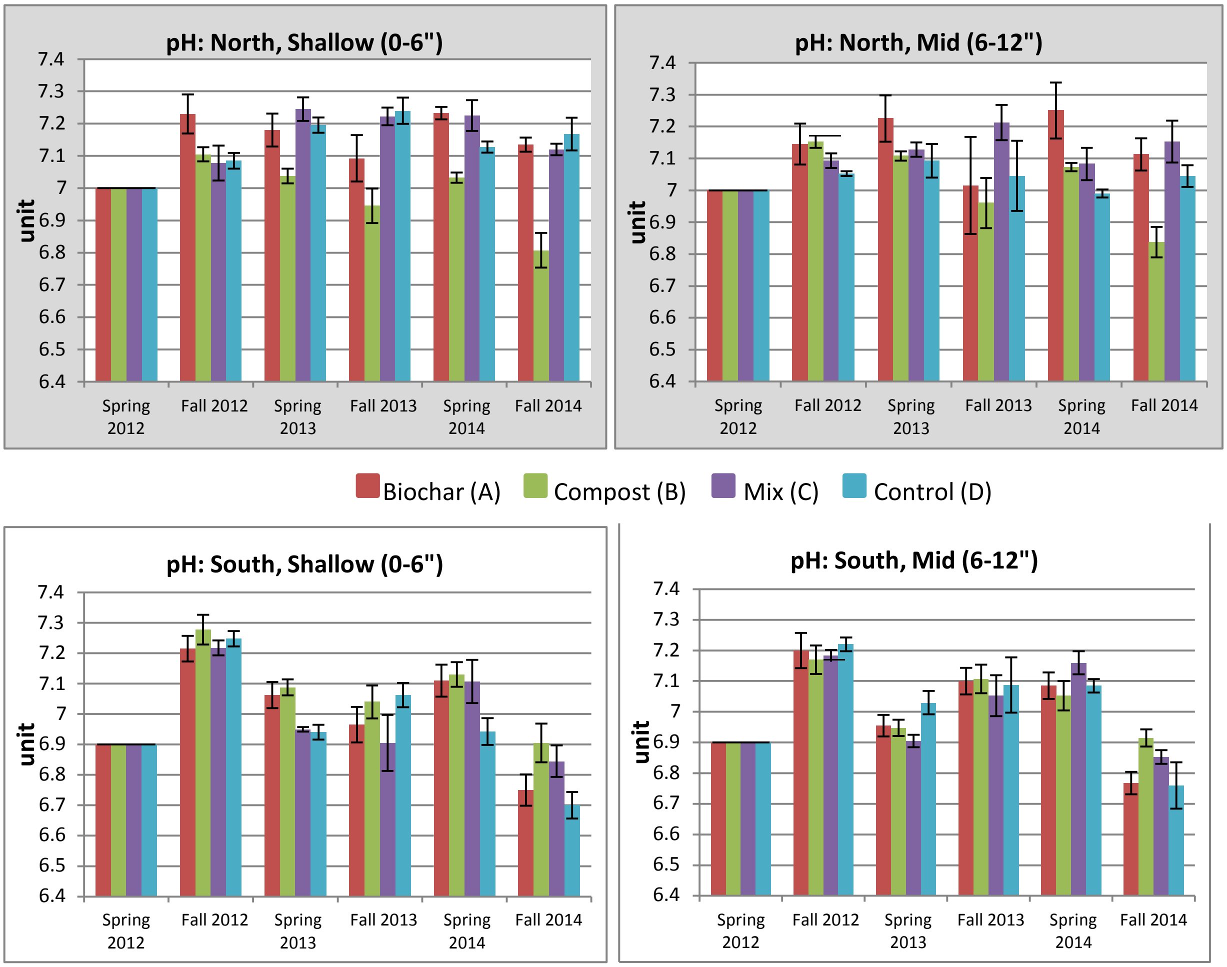


Figure 13. Soil pH values

xii. Cation exchange capacity (CEC)

The results of the CEC analysis are shown in Figure 14. In the North plot, all treatments and the control samples result in average CEC values within an overall range of 10-25 meq/100g that is acceptable for these soil conditions and growth of Brussels sprouts. In the South plot, biochar treatment in fall 2013 (both depths) resulted in a spike in average CEC that exceeded 25 meq/100g, and was significantly higher than the control. In fall 2014 in the South plot at both depths, CEC levels in all treatments and the control were significantly lower (about 15 meq/100g) than in previous samplings.

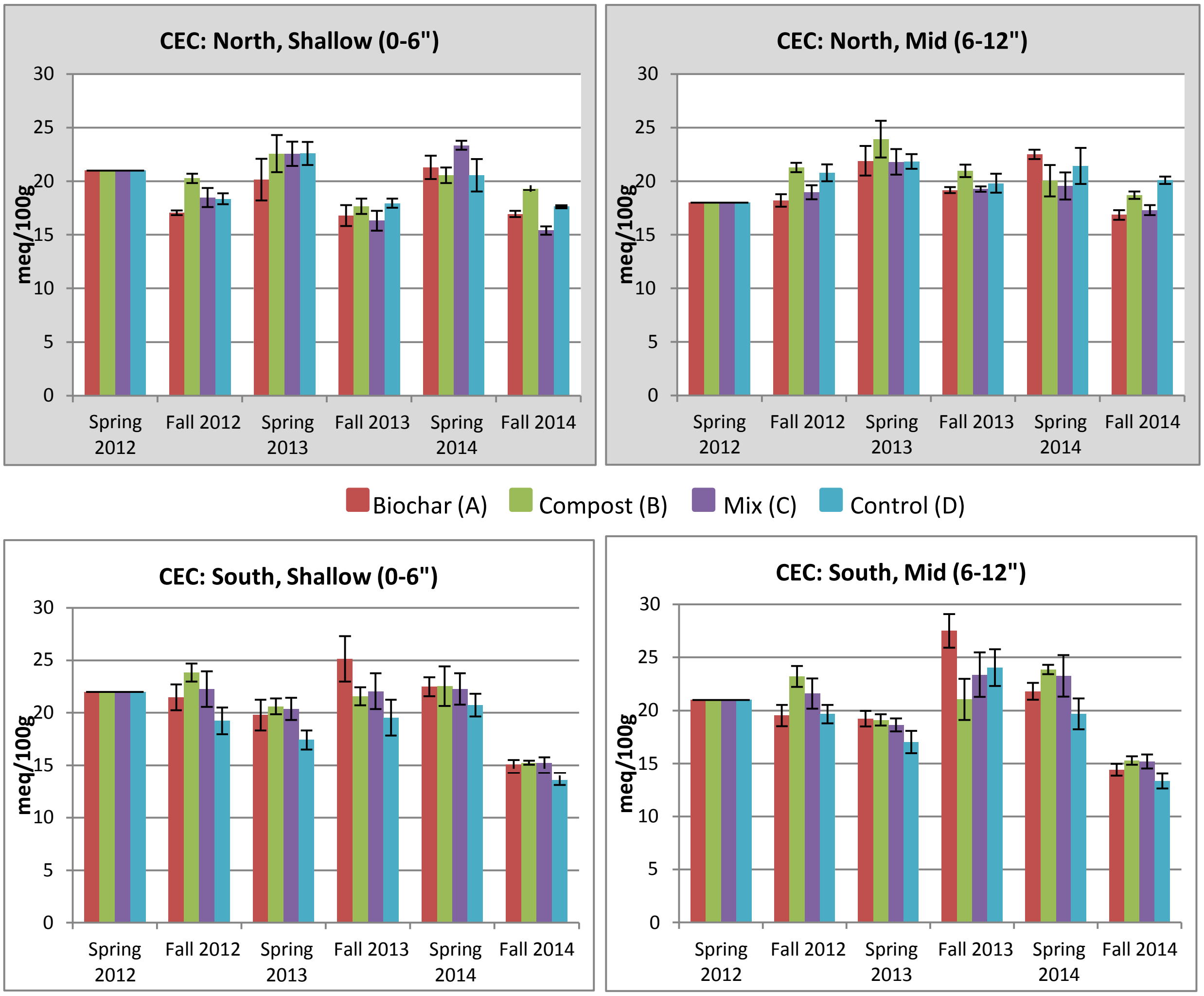


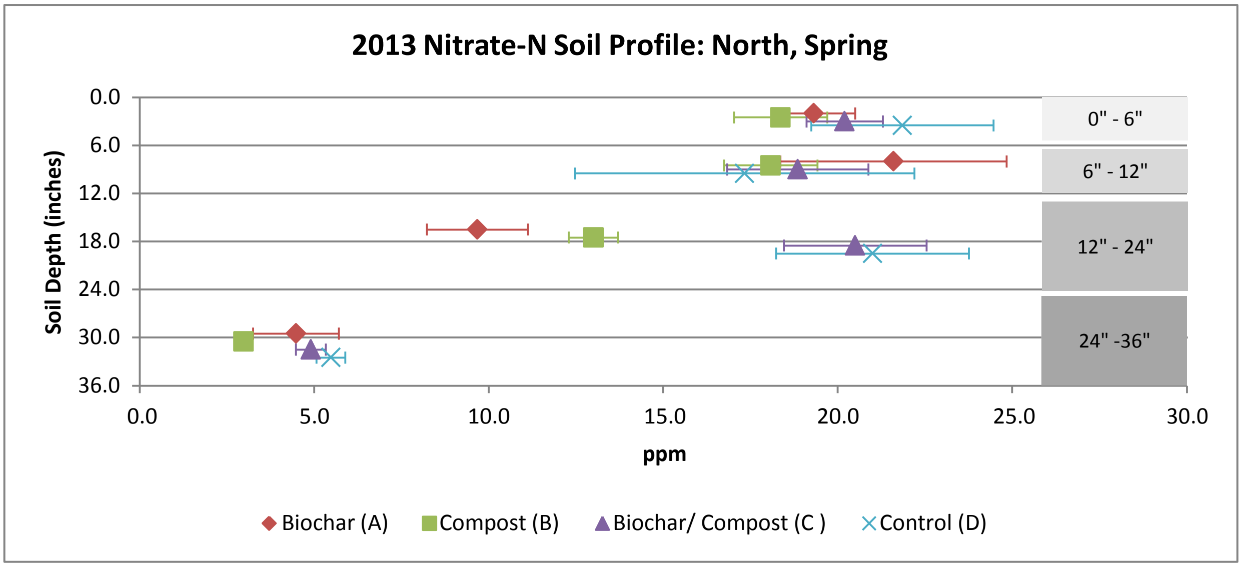
Figure 14. Cation exchange capacity (CEC)

c. Nitrate Leaching/Nitrate-N Soil Profiles

To assess potential effects of biochar, compost and mix treatments on nitrate leaching, soil nitrate profiles were analyzed in both test plots. Overall, there were lower nitrate concentrations in the first year and in the fall soil samples. There was also a slight trend of biochar or mix treatments having the highest nitrate values in the shallow layers and lowest nitrate values in the deeper layers.

Table 12. North plot pre-treatment nitrate-N concentrations in spring 2012

Sample depth	nitrate-N (ppm)
0-6” (shallow)	3.9
6-12” (mid)	5.8
12-24” (low)	3.1
24-36” (deep)	4.8



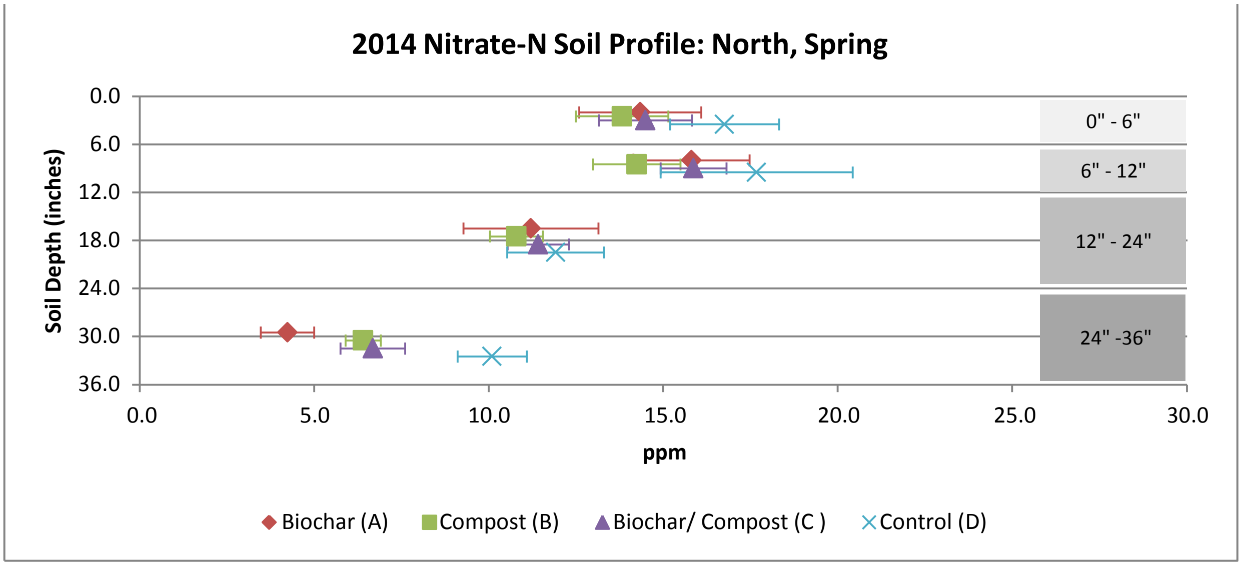
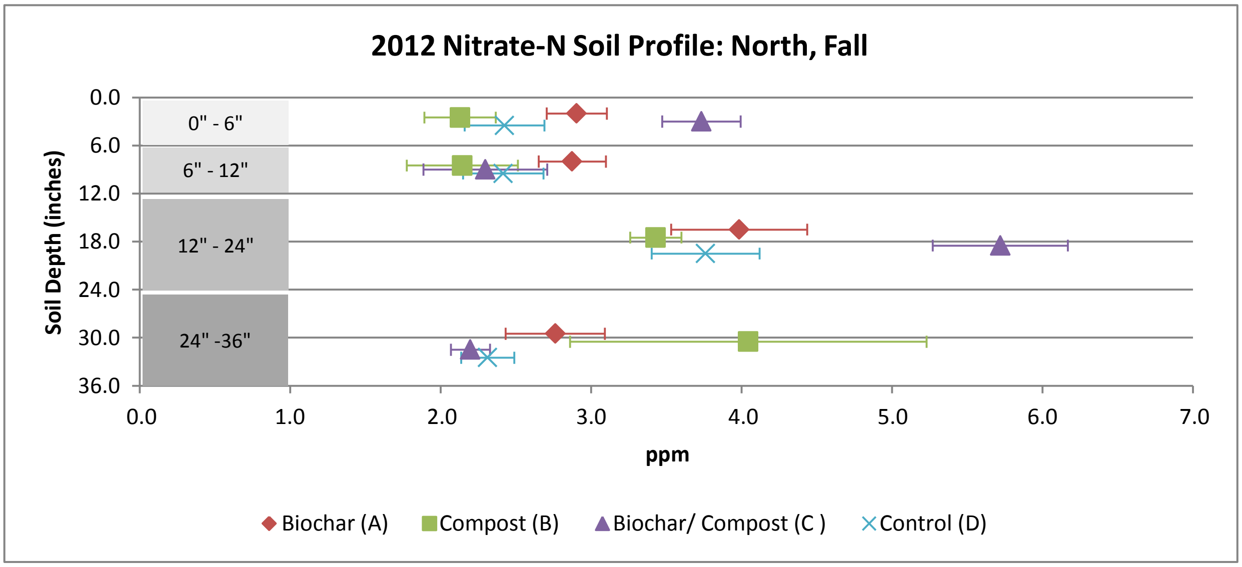


Figure 15. Spring 2013 and 2014 soil nitrate-N profiles for the North plot.

In fall 2012, the mix treatment resulted in significantly higher nitrate-N levels than all other treatments in the shallow and low profile layers (0-6”and 12-24”). In the mid (6-12”) profile layer, biochar resulted in the highest nitrate-N concentration, although not significantly. The compost treatment resulted in the highest nitrate-N concentration in the deep profile layer (24-36”) which was significantly higher than other treatments at this profile layer.

In fall 2013, the mix treatment resulted in significantly higher nitrate-N levels than all other treatments in the shallow and mid profile layers. In the low and deep profile layers the nitrate-N concentrations were highest under the control conditions, although no significant differences occurred between any treatments. Due to laboratory error, results from the low and deep depth fall 2014 soil samples from the North plot were not considered in this analysis.



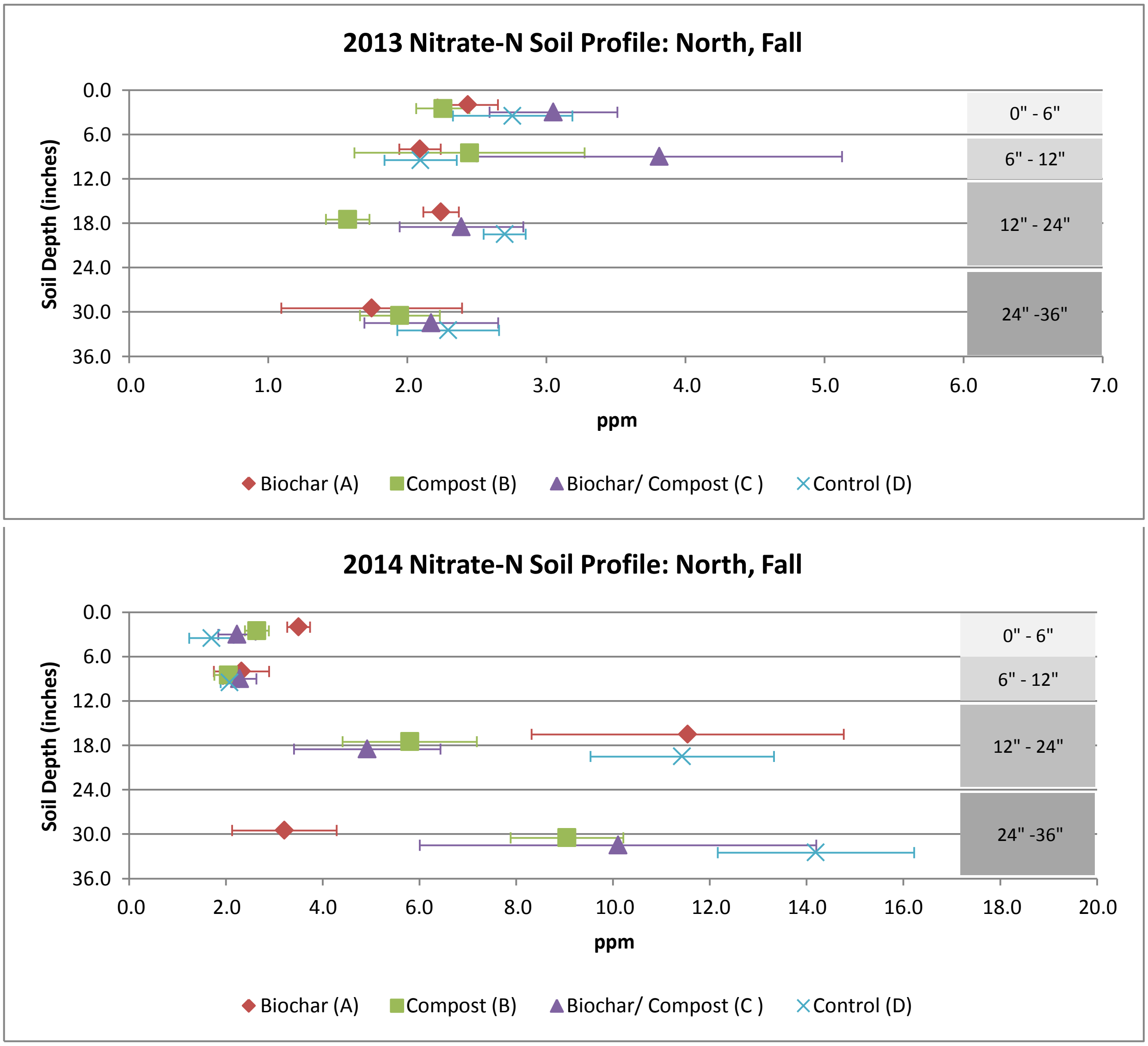


Figure 16. Fall soil nitrate-N profiles for the North plot10

In the South plot, the spring 2013 and spring 2014 nitrate-N profiles were very different (Figure 17). With the exception of the biochar profile, spring 2013 nitrate-N concentrations dropped significantly with each (deeper) profile layer. All treatments except biochar resulted in nitrate-N concentrations in the shallow layer that were significantly higher than all other soil samplings throughout the field trial. In the mid layer, these nitrate-N concentrations dropped off to levels comparable to the other South and North spring samplings at this depth. With the exception of lower nitrate-N concentration resulting from biochar treatment in the shallow depth, no significant differences among treatments and the control occurred at any of the soil depths.

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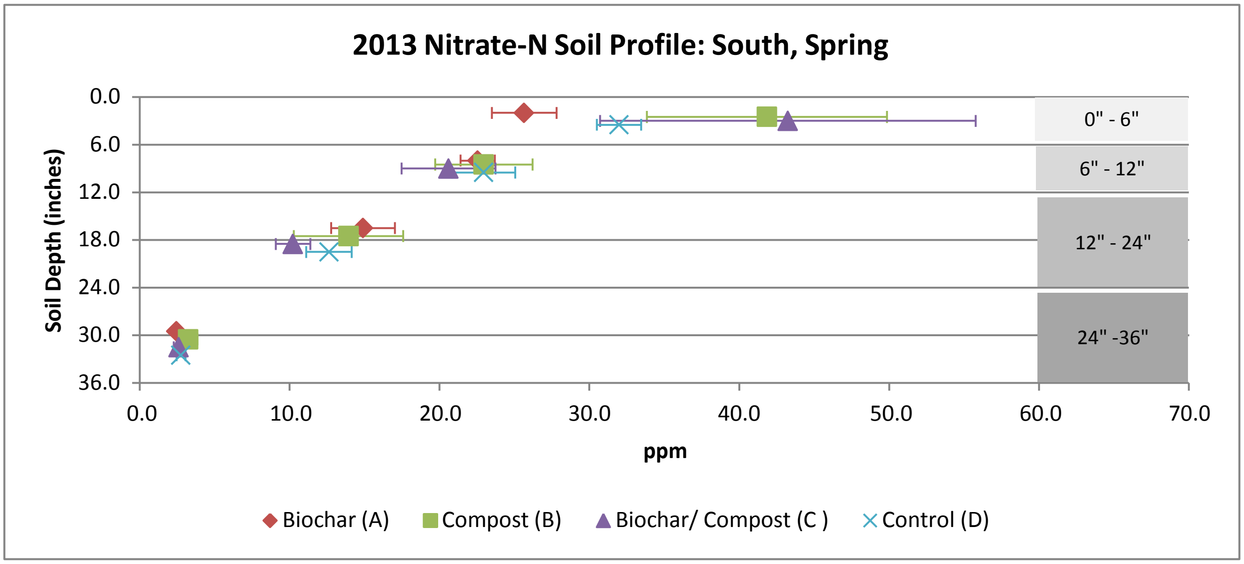
[10] **Note that an error occurred in sampling handling during laboratory analyses of the Fall 2014 low (12-24”) and deep (24-36”) soil samples.**

In 2014, nitrate-N concentrations were significantly lower in the shallow layer, and remained much more uniform throughout the profile, such that the deep layer concentrations were all significantly greater than corresponding samples in spring 2013. The only significant differences within treatments in the profile layers resulted from compost and mix treatments. Compost resulted in significantly lower nitrate-N concentration (compared with all other samples) in the deep profile layer, and mix resulted in significantly higher concentration than the control in the low profile layer.

Table 13. South plot pre-treatment NO3--N concentrations in spring 2012

Sample depth	nitrate-N (ppm)
0-6" (shallow)	8.9
6-12" (mid)	6.3
12-24" (low)	6.3
24-36" (deep)	4.2



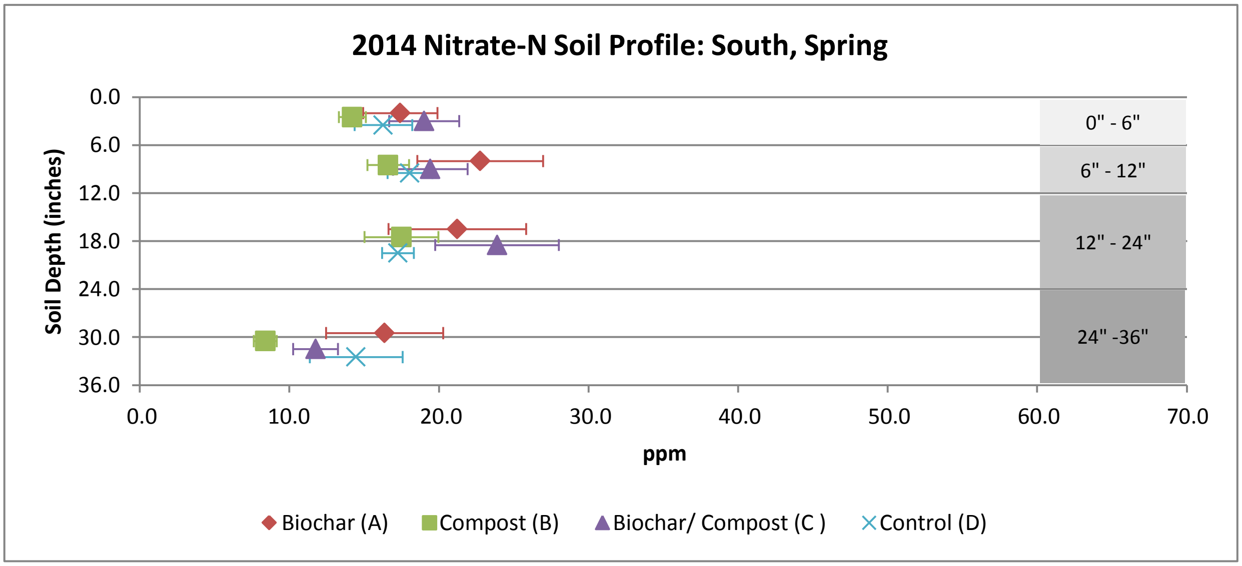
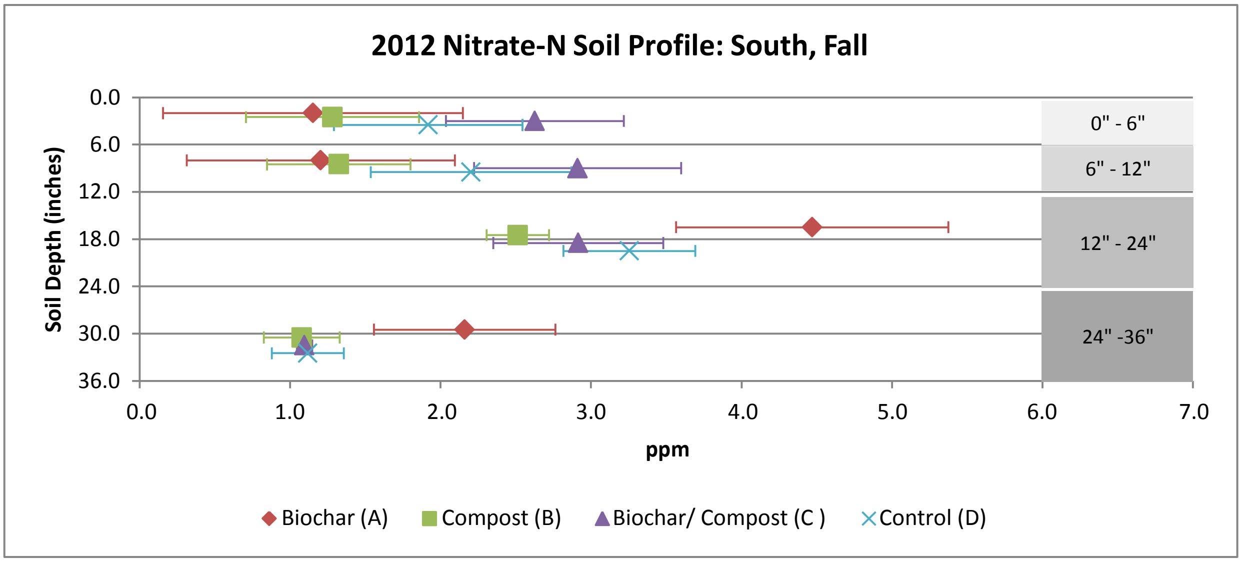
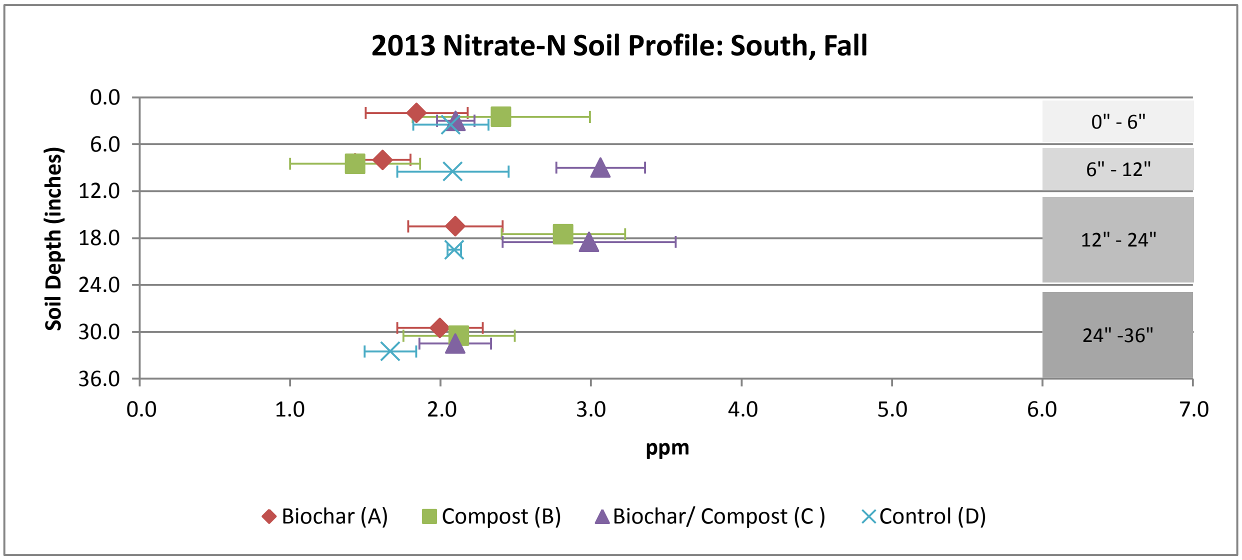


Figure 17. Spring 2013 and 2014 soil nitrate-N profiles for the South plot.

In fall 2012 in the South plot, the low profile layer showed a spike in nitrate-N concentration for the biochar treatment compared with the upper two profile layers as well as the deep profile layer. In fall 2013, nitrate-N concentrations in the mid, low and deep mix treatment samples were significantly higher than control concentrations. In fall 2014, the mix treatment in the upper two profile layers resulted in a higher nitrate-N levels than all other treatments but was significantly higher in the mid profile layer. In the low and deep profile layers, nitrate-N concentrations in the biochar samples were significantly higher than all other treatments.





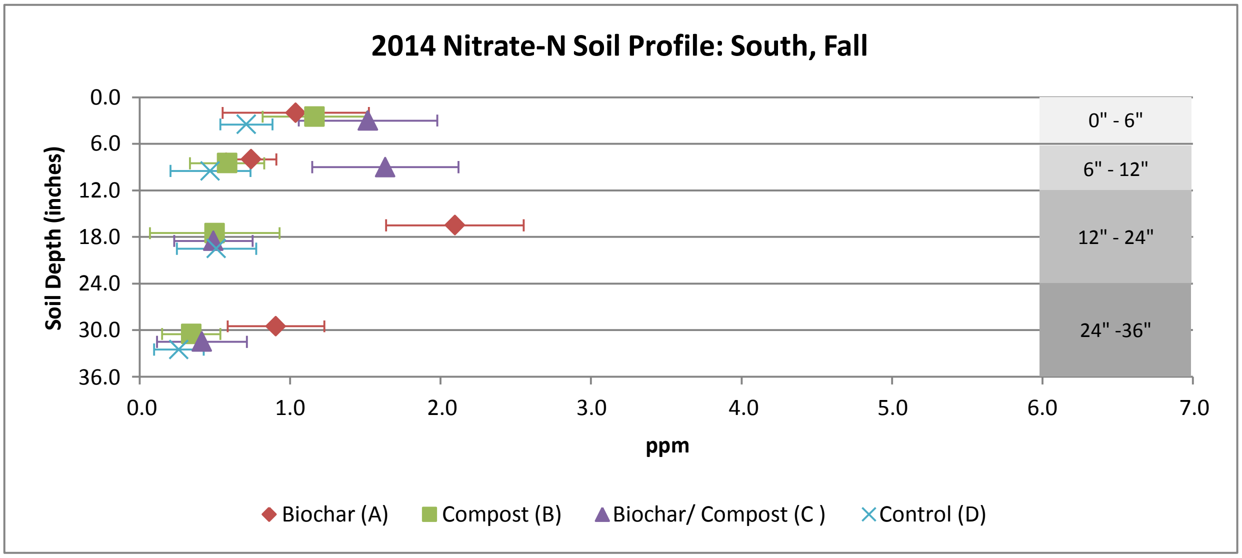


Figure 18. Fall soil nitrate-N profiles for the South plot.

d. Carbon Sequestration/Soil Organic Carbon

The biochar, compost and mix treatments added 6.0, 2.3 and 8.3 tons/acre (respectively) of organic carbon to the soils.

Soil organic carbon (SOC) levels in tons/acre-6” were estimated from the measured percent SOC levels for fall samples when corresponding bulk density data was available (see Section 4.b.i). These results are shown in Figure 19. After the application of organic carbon in the treatments in spring 2012, samples from all three treatments continued to have higher SOC than the control in fall 2012 (in both test plots). It should be noted that in the North plot control samples, the SOC was only slightly lower that the treatments, whereas in the South plot it was much lower.

SOC from the treatments and the control plots decreased in fall 2013 in the North plots, with the mix treatment having much lower SOC than the other treatments and the control. These were all at approximately 33 tons/acre-6”. In the South plot, SOC in the treatment samples also decreased in fall 2013 to about 30 tons/acre-6”. SOC in the control increased, but was still lower than in the treatments. In fall 2014, the control conditions had the highest and lowest SOC in the North and South plots, respectively. The North plot compost treatment had the lowest SOC, but in the South plot the compost treatment along with the mix treatment had the highest levels at almost 35 tons/acre-6”. Also, in the South plot SOC biochar samples were almost as low as the control at slightly less than 30 tons/acre-6”.

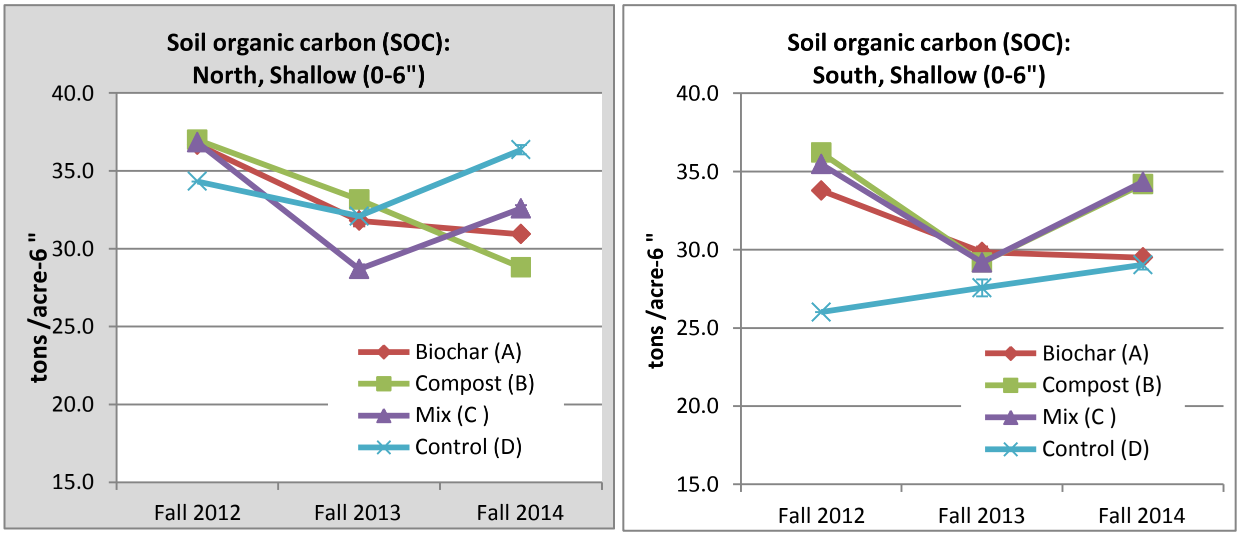


Figure 19. Estimated SOC (tons/acre-6”) in the shallow (0-6”) depth

For the North plot mid (6-12”) depth layer (Figure 20), SOC results for all three treatments and the control were highest (> 35 tons/acre-6”) in fall 2012, and declined over the course of the field trial. The control had in the highest levels in fall 2012 and 2013 but dropped below levels resulting from the biochar and mix treatments in 2014. Compost treatment resulted in the lowest levels at this depth throughout the field trial.

In the South plot mid depth, control SOC levels were lower than all treatment levels throughout. In contrast to the shallow depth results for the control, SOC levels declined in the control soils in fall 2014. In fall 2012, compost treatment resulted in the highest SOC (~ 36 tons/acre-6”) while mix and biochar treatments were about the same (~34 tons/acre-6”). Over time, SOC levels in the biochar and mix treated soils showed a slight increase and slight decline (respectively) with both having about 33 tons/acre-6” in 2014. The compost SOC levels, however, declined in 2013 and then increased substantially in 2014 to the highest SOC level (~37 tons/acre-6”) seen in the South plot mid depth.

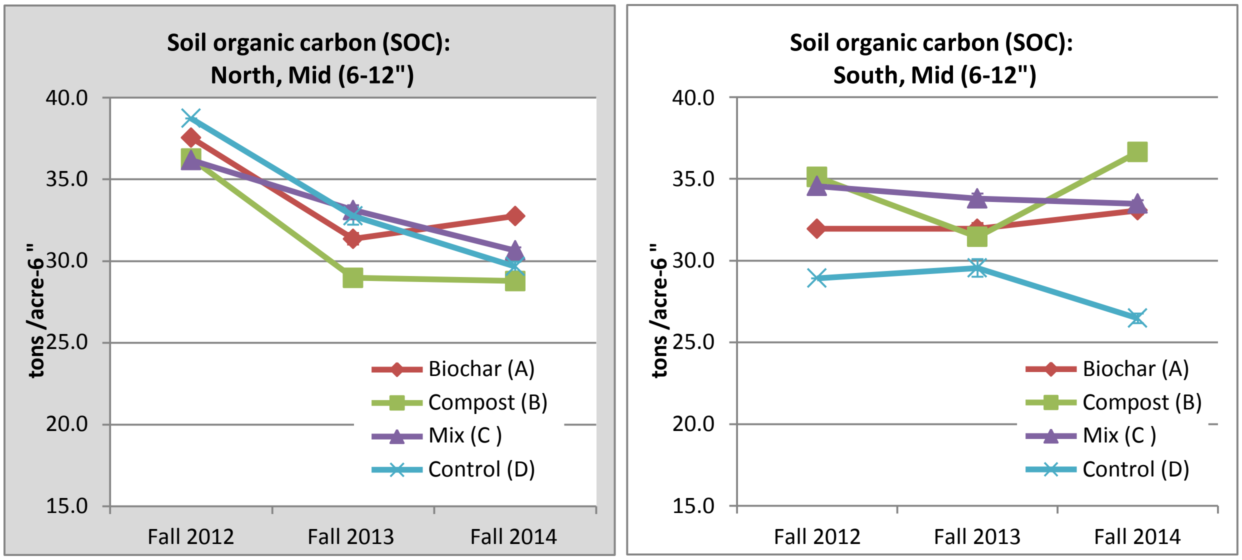


Figure 20. Estimated SOC (tons/acre-6”) in the mid (6-12”) depth

5. DISCUSSION

a. Crop Yield

Results from the three-year field trial suggest that the biochar-only and biochar-compost mix soil amendments had neutral or negative effects on crop yields for conventionally-grown Brussel sprouts in coastal San Mateo County. The compost-only treatment had a neutral or positive affect on crop yields. A variety of factors are discussed here to identify potential causes of these outcomes.

A meta-analysis by Jeffrey et al (2011) of biochar effects on the yields of other row crops from both field and lab studies, suggests a few mechanisms that lead to the greatest positive effects on crop yield. Biochar can increase soil pH which has been identified as potential cause for crop yield increases in acidic soils. Maintaining a soil pH greater than 6.5 is important for Brussels sprouts growth in this location. But in the field trial, the pre-planting lime application likely precluded this benefit of the biochar-containing soil amendments. Biochar particles are negatively charged and can improve nutrient retention and availability in soils with low CEC. However, the field trial soils had sufficient CEC levels, and this specific benefit of biochar was unlikely for this location.

Improved water holding capacity is another potential mechanism for increased crop yields due to biochar use. Water holding capacity is a function of the soil texture and SOM content. Soils in the field trial were loams (North plot to 24”, South to 6”) and clay loams (North >24” and South >6”) which have a relatively high water holding capacity. SOM increases during the field trial could have further improved water holding capacity. However, SOM did not increase in the North plot as a result of the biochar-only and mix soil amendments, and may have declined in soils treated with only compost. The South plot had significantly higher SOM levels resulting from the treatments which may help explain why crop yields in the biochar-only and mix-treated soils – were relatively improved compared with the same set of results in the North plot. (See 5.b Soil Health for further discussion of the SOM results.)

Another consideration is that the application of the (raw) biochar-only treatment could have initially resulted in a decrease in bioavailability of nutrients in the soil. Due to it’s negatively charged particles, biochar binds well to positively charged nutrients (e.g., Ca, Mg, K, Na, and ammonium-N). Over time, this effect can enable biochar to act as a slow-release fertilizer, but initially it can limit nutrient availability. This effect would not have occurred in the compost-only treated soils as nutrients in the compost would have initially increased bioavailable levels (particularly that of K and ammonium-N) in the soil. The low crop yields for biochar-only and high crop yield for compost-only in the South plot in the first year suggest that these nutrient dynamics occurred. However, poor yield results for the biochar-compost mix treatment in both plots in the first year do not support this conclusion. When biochar is pre-blended with compost, the negatively charged biochar particles bind nutrients in the compost. The expectation is that this prevents a drop in nutrient bioavailability immediately after application of the soil amendment. Assuming that nutrient availability was a limiting factor for crop growth in this field trial, opposite results would have been expected for the mix treatment. Soils treated with the pre-blended biochar-compost mix should have had higher crop yields than those of the biochar-only treatment and control conditions. Other soil health indicators and associated processes were considered (see Soil Health discussion) but did not offer further explanation for crop yield results.

Other factors that may have influenced crop yield include weather, site specific conditions (i.e., presence of shade etc.), and Brussels sprout type and quality of seedling stock. Overall, crop yields across all three treatments and the control were poor in 2013 which was consistent with the farmer's observations of small fruit sizes at harvest time (Dave Lea, Pers. comm., November 16, 2015). Weather data for the field trial site (see Section 3.a.iii) for 2013 suggest that the very low rainfall (6.38" for the year) combined with above average temperatures in August and September may have contributed to the significant drop in crop yields. In 2014, summer months (July, August and September) had above average temperatures while rain events in late October and November led to very wet conditions at harvest time (CLVI, 2014; Dave Lea, Pers. comm., November 16, 2015). This combination of warm conditions and heavy, late season precipitation at the time of harvest may help explain the low crop yields in the North plot in 2014. In 2014 in the South plot, crop yields were similar to higher yields in 2012. Tall eucalyptus trees shade this site and may have kept temperatures slightly cooler and contributed to the rebound in growth yields. However, if this indeed had a causal effect, it is unclear why the 2013 crop yields were low for both the North and South plots. One possibility is that the Confidant seedlings planted in the North plot in 2014 were of poorer quality, preventing yields in this field from rebounding as they did in the South plot.

b. Soil Health

Results from the analyses of soil health indicators suggest that for certain soil conditions, the addition of the treatments (biochar-only, compost-only or biochar-compost mix) can improve the health of coastal San Mateo soils for agricultural.

The bulk density results suggested a potential soil health benefit resulting from the one-time application and mixing of the biochar-only and biochar-compost mix amendments into the upper soil layer. In both test plots, bulk densities in the control samples from the shallow (0-6") mixing layer increased (significantly so in the North plot) over time. In the North plot, the average bulk density in 2014 exceeded the 1.4 g/cm^3 threshold that is ideal for plant growth (USDA, 1999b, p 57). However, shallow layer bulk densities for soils treated with biochar-containing soil amendments did not similarly increase, and remained significantly below 1.4 g/cm^3 threshold throughout the field trial. This result suggested that within the initial depth of mixing of the soil amendment, biochar may have had a multi-year, stabilizing effect on bulk densities. For heavier soils such as those at the field trial location, this effect would help maintain ideal conditions for root penetration and soil porosity in the upper soil layer.

A similar effect on bulk density did not extend into the mid (6-12") soil layer in the North plot. However, results in the South plot at this mid depth show that the biochar-compost mix treatment reduced bulk densities relative to the control in both 2013 and 2014. Plowing 12-14" deep in the spring of these years would have mixed the soil amendments into this layer in both test plots. Possibly this effect was only seen in the South plot due to the higher clay content of the soil, but it is unclear why the biochar-only treatment did not also reduce bulk densities in the mid soil layer in this plot.

The soil organic matter (SOM) results suggested another potential benefit to soil health from the treatments under certain conditions. Higher SOM content can increase soil health through nutrient retention and availability, as well as water holding capacity, soil structure and stability. In the South plot, treatments resulted in consistent and significantly higher SOM levels than control conditions throughout the three year field trial.

The effects were strongest for the compost and mix treatments. However, no effects on SOM levels from the biochar-only and mix treatments relative to control conditions were seen in the North plot, and the compost-only soil amendment resulted in higher SOM initially, but significantly lower SOM levels in years two and three of the field trial. The inconsistent results between the North and South plots indicate that any potential benefits of biochar and compost treatments on soil nutrient retention were sensitive to differences between these test sites.

Over the course of the field trial, the control conditions generally resulted in SOM levels that were significantly *lower* in the South plot than the corresponding samples in the North plot. Unlike the control conditions, comparison of SOM levels for the treatments showed no significant differences between North and South plots resulting from biochar treatments while compost and mix treatment SOM levels were either the same, or significantly greater in the South plot. This comparison indicates that under control conditions, the SOM levels in the South plot had been depleted, and that the soil amendments addressed this deficiency in SOM levels. In the North plot where SOM levels were already high under control conditions, the treatments did not further increase SOM levels, suggesting that the soils had reached a limit or carrying capacity for SOM.

To understand the cause of this discrepancy between North and South SOM levels under control conditions, multiple factors that could have differentially affected SOM levels were considered. Comparison of soil types in the test plots (see Section 3.a.ii) showed that the South plot soil below a 6” depth had higher percent clay content. In general, SOM increases with clay content of soils, but this relationship was not reflected in the SOM levels in the three South plot soil samples below 6“which each had lower SOM than the corresponding North plot samples.

Agricultural practices such as tillage intensity, crop rotation, use and type of cover crops and fallowing, amounts of organic inputs and amounts of plant residues returned to the soil, also affect SOM levels. With a few exceptions, these agricultural practices were the same for the North and South plots. However, growth of different Brussels sprouts varieties in the two test plots could have indirectly affected SOM levels if more plant residues (biomass) remained after harvest for one variety versus the other. Comparison of the ratios of average fruit weight per plant to average stalk with fruit weight (i.e. biomass) per plant (Table 8) in the North and South plots indicated that for all treatments and the control, the fruits were proportionally less of the total plant biomass in the South plot than in the North plot. This suggested that after harvesting, more plant residue could have remained on the South plot, potentially resulting in greater SOM levels. However, SOM levels were significantly lower for the control conditions suggesting that the different Brussels sprouts varieties likely did not account for differences in SOM levels in the test plots.

One factor that may help explain the lower SOM levels under control conditions in the South plot is drainage. In general, well-drained soils have lower levels of SOM. Although the plots drained similarly, the farmer reported that the South plot tended to drain slightly better, and the cumulative effects of this faster drainage could account for the depleted SOM levels in this plot.

Overall, the field trial results suggested that the one-time application of a biochar-only, compost-only or biochar-compost mix soil amendment to SOM-depleted soils significantly increased SOM levels over multiple years and therefore likely had positive impacts on soil health. However, in soils with high SOM, application of biochar-only and mix soil amendments had no effect. Furthermore, the addition of the compost-only soil amendment under these conditions reduced SOM levels, potentially having negative effects on soil health factors associated with SOM.

The biochar used in the field trial was composed of mainly carbon but also contained a variety of nutrients. The addition of these nutrients through the application of 10 tons/acre of biochar in the biochar-only and biochar-compost mix treatments was likely insignificant compared to pre-treatment concentrations in the surface layer. . Furthermore, as discussed previously (see the Crop Yield discussion), application of raw biochar (which binds well with positively charged nutrients) can initially cause nutrients to be less available for plant uptake, but over time the biochar can act as a slow release fertilizer over time. Application of the biochar-only treatment could have initially reduced the bioavailable nutrients (relative to the other treatments and the control) in the soil at planting time in 2012. High levels of ammonium-N, P and K in the compost could have significantly increased these concentrations in surface soil layer where the compost-only treatment was applied thus having a fertilizing effect. Furthermore, since the mix treatment was pre-blended with biochar and compost, this would be expected to prevent the drop in nutrient bioavailability that could have occurred immediately after application of the biochar-only soil amendment. Without post-treatment spring 2012 soil samples it was impossible to know if these initial effects occurred. But in fall 2012 in the North plot, the compost and mix treatment plots had higher concentrations of ammonium-N, P and K in the surface layer suggesting these effects in the compost-only and mix treatments. The same increase was not evident in the South plot.

Over the course of the three-year field trial, significant differences between treatment and control concentrations of the macronutrients (Nitrate-N, Ammonium-N, P and K) were reported for individual samplings. However with the exception of the nitrate-N results, consistent positive or negative effects were not observed to suggest a long-term effect for any of the treatments.

Nitrate-N concentrations resulting from the biochar-compost mix treatment in the fall samples from the South plot were consistently greater than control conditions (significantly so in 2014 at both depths), suggesting that this treatment increased soil nitrate-N concentrations over the growing season. It is possible that this effect occurred in the shallow soil layer (0-6”) in the biochar and mix-treated soils in the North plot as well, but the results were inconclusive. Ammonium-N results did not show any consistent trends except for a significant drop (>50%) in all sample concentrations in the fall of 2013, when there was also a drop in crop yield indicating that growth was highly dependent on ammonium-N. However, interpretation of the nitrate-N and ammonium-N results was complicated by N-dynamics over the course of a growing season and influence of factors such as uptake by plants, split applications of N-containing fertilizers, and potentially nitrate leaching. Without intermediary samplings and isolation of variables it was difficult to verify effects of the treatments on levels of nitrate-N and ammonium-N, and subsequent effects on soil health.

In general, results for K and P showed that the soil concentrations of these macronutrients were significantly less and greater, respectively, then the recommended ranges for optimal crop growth at the field trial site. However, as previously noted, the treatments did not have consistent, significant effects on these K and P concentrations. Results did not suggest that the biochar- or compost-containing soil amendments had a benefit or detriment to the level of these nutrients in the soil.

Boron (B) has been identified as an important micronutrient for Brussels sprouts, with insufficient levels potentially causing physiological disorders (Mills, 2001). Throughout the field trials, the B concentrations in all samples were significantly below the recommended range of 1-4 ppm for Brussels sprouts growth in this location (Soil Control Lab, 2014). In the South plot, significant increases in B concentrations resulting from the biochar-only and mix treatments in fall 2012 and spring 2013 (at both sampling depths) compared with the compost and control suggested that biochar was retaining B. This effect did not continue in the South plot, nor did it occur over the same period in the North plot. However, in the North plot in fall 2012 and spring 2013, B concentrations resulting from the compost-only treatment and the control were significantly higher than the comparable South plot results. This suggests that biochar possibly had a marginal benefit for B concentrations in severely depleted soils in the South plot. But in the North plot where B concentrations were higher, there was no marginal benefit.

Results for pH, electrical conductivity (EC) and cation exchange capacity (CEC) under control conditions and with the treatments were (with a few exceptions discussed here) within recommended ranges for these soil health factors.

Specific recommended EC range(s) for Brussels sprouts are not reported, but they fall within a "moderately sensitive" classification which corresponds to an average threshold of 1.4 dS/m (USDA, 1999b, p. 60). However, the upper EC threshold for reduced Brussels sprouts yields in this location is likely higher than this. The Soil Control Lab provided a broad EC range (0.2 – 4.0 dS/m) for growth of Brussels sprouts based on knowledge of local conditions and crop yields in coastal San Mateo County. Furthermore, cabbage and broccoli crops, both of which are in the same family as Brussels sprouts, *Brassica oleracea*, have measured EC thresholds of 1.8 and 2.8 dS/m, respectively (Hanson, 2006, p. 20, Table 4).

Anomalous spikes in EC levels that approached or exceeded the 1.4dS/m threshold for salt sensitivity in Cole crops (USDA, 1999b, p. 60) occurred in soil samples treated with the biochar-compost in the North plot (fall 2013), and all treatments and the control at different times and depths in the South plot. A variety of factors can cause EC to increase (e.g., the addition of fertilizers and other soil amendments, or low precipitation), but the inconsistency of the results across samplings did not suggest a causal relationship. In general, approaching or exceeding an EC threshold indicates salinity levels can inhibit crop growth. However, as described previously (see Section 3.f.ii. Electrical Conductivity) the actual threshold for Brussels sprouts grown in San Mateo County is likely higher than 1.4dS/m, suggesting that even the highest EC average of about 1.8dS/m did not decrease overall soil health.

All pH results from the field trial (including the pre-treatment spring 2012 levels) were within an acceptable range of 6.5-7.5 for Brussels sprouts growth in this location (Soil Control Lab, 2014). However, the compost-only treatment appeared to have a consistently significant acidifying effect in the surface soil layer (i.e. 0-6") of the North plot relative to the control and the biochar-only and mix treatments. In the South plot, there were no consistent differences between the control and the treatments, but overall, pH levels dropped significantly from fall 2012 to fall 2014. These acidifying effects could be a soil health concern in San Mateo County for the growth of Brussels sprouts where clubroot fungus (*Plasmodiaphora brassicae*) has caused serious economic losses in the past. For the field trials, lime was added to the soil and mixed 6-8" deep prior to the 2013 and 2014 spring soil samples. This was done to keep the soil pH above 7.0 to prevent clubroot disease.

Further interpretation of the pH results was challenged by the timing of the samplings over the course of the field trial. For example, the initial spring 2012 sampling occurred prior to treatment applications and after plowing and disking took place. Subsequent spring samplings (in 2013 and 2014) occurred shortly after lime applications as well as other practices (e.g. fumigation, fungicide) that influence soil pH. The lime application in particular, raises pH of the soil and can increase the availability of positively charged nutrients which likely would have masked any lasting effects of the treatments.

In general, soils with a higher clay content and organic matter, both of which are negatively charged, have higher CEC, and in soils with CEC greater than 10 meq/100g, leaching of cations below the root zone is unlikely (Mengel, 1993). CEC levels in the control soils indicated that this is not a soil health concern for the field trial location. Furthermore, consistent, significant effects on CEC were not observed in the treated soils when compared with the control, suggesting that, under these soil conditions, CEC is not a relevant measure of the effects of the amendments on soil health.

c. Nitrate Leaching Potential

Analysis of the nitrate-N profiles suggested that there is little difference in nitrate leaching potential between the control and the treatments. However, there was a slight trend in the biochar and mix treatment profiles of higher nitrate values in the shallow layers and lower nitrate values in the deeper layers which could reflect positive impacts on nitrate leaching.

To understand potential for nitrate leaching, it is important to understand the various forms of nitrogen (N) and N dynamics within the soil. Nitrate-N and ammonium-N are the inorganic forms of N that can be utilized by plants for growth or leached into groundwater and surface water supplies. Nitrate moves through the soil with water more readily (~10x faster) than ammonium and therefore has a higher leaching potential (Kabir Zahangir, Pers. comm., January 15, 2016). When nitrate or ammonium is converted into organic nitrogen, it is assimilated by other organisms and is unavailable to the plant and for leaching. This process is called immobilization. The opposite of this process is mineralization in which organic nitrogen is converted into ammonium and nitrate that can be used by the plant or leached through the soil profile (Clough, 2010).

The amount of nitrate available for the plant and to be leached is heavily influenced by soil physical properties and conditions. The soil in the test plots were Denison loam soils which have low permeability and leaching potential, and higher lateral runoff potential. The potential for leaching at the test plots based on these soil properties was considered low to moderate. Although, presence of clay in certain locations should be noted as this soil would be more likely to bind to ammonium rather than nitrate since clay is negatively charged. Similarly soil amendments like biochar typically bind well to positively charged ions like ammonium which could indicate that nitrate is more susceptible to leaching.

However, there are several mechanisms by which biochar has shown to decrease nitrate leaching. Biochar can increase SOM which diversifies the microbial assemblage and builds soil health. This can increase water retention and therefore nitrate retention since nitrate moves readily with water through the soil. As found in this study, application of biochar may also help maintain ideal bulk densities and soil porosity in upper soil layers which could further support retention of nitrate in areas where biochar was applied. Immobilization of nitrate can also be stimulated by biochar and therefore reduce potential for nitrate leaching, particularly if the carbon to nitrogen ratio (C:N) of the biochar is high (>30:1).

The type of feedstock used to make biochar as well as the pyrolysis temperature heavily influences the C:N ratio, CEC, and the types of ions that biochar adsorbs to; thereby affecting nutrient retention. Studies suggest that for biochar to have the potential for adsorption of nitrate, temperatures during the pyrolysis process must be at least 600°C (Clough, 2013). The biochar used in the field trial was produced at 575-600°C, suggesting that nitrate adsorption and subsequent reductions in nitrate leaching were possible, but could have been optimized by the biochar being cooked at a higher temperature.

To assess if the biochar-only, compost-only and biochar-compost mix soil amendments affected nitrate retention and leaching, nitrate-N profiles from treated soils were compared with control soil profiles. Overall, analysis of the nitrate profiles indicated little difference between the treatments and control. However, several patterns were identified, such as lower nitrate concentrations in the first year and in the fall soil samples. There was also a general trend of higher nitrate concentrations in the shallow layers and lower concentrations in the deeper layers. This was especially apparent in the fall in the North plot, in the spring in the South plot, and for biochar-only and mix treatments.

In the first year of the study, nitrate concentrations were relatively low (below the recommended range) throughout the soil profile. When these samples were taken, plowing and disking had taken place to integrate crop residues and cover crops. After plowing and disking, the treatments were applied (tilled or disked) within the root zone. In subsequent years, the plots also received lime, fumigant, and fungicide before samples were taken, which undoubtedly influenced soil conditions and nitrate dynamics. Liming can alter the pH of the system while fumigation and fungicide can inhibit mycorrhizal growth and alter microbial assemblages with subsequent effects on soil health and nutrient retention.

Nitrate concentrations were also much higher in the spring than in the fall throughout the soil column. This was likely due to the fact that nitrate was utilized by the plant throughout the growing season and because crop residues and cover crops containing nitrogen were mixed into the soil in the spring. Mixing practices that took place in the spring included tillage which can disturb the upper profile layers and compact deeper layers into a tillage pan, which was often detected during soil sampling events (Joe Issel, Pers. Comm., January 16, 2016). This soil compaction can cause the upper profile layers to form a perched water table that drains laterally into surface water rather than leaching vertically (Plant and Soil, 2001).

The difference in soil conditions between the North and South plots should also be noted as these conditions could account for the differences in trends between the two plots. Soils in the south plot had slightly more clay than in the North plot which could mean less nitrate is adsorbed and more is available for leaching. However, SOM levels increased over time in the South plot as a result of the treatments which can increase water and nutrient retention, and therefore decrease nitrate leaching potential. Increased SOM can also stimulate mineralization of organic N to ammonium and nitrate thereby increasing concentrations of these nutrients that could be taken up by the plant or leached. Lastly, the South plot had higher soil porosity (>24“) so water traveled more readily at least in the deeper layers which could increase potential for nitrate leaching in these areas.

In addition to the soil conditions and on farm practices, the composition of the biochar also likely influenced nitrate leaching potential during the field trials. The biochar had an estimated C:N ratio of 30:1 indicating that it was more likely to induce immobilization rather than mineralization. Immobilization can reduce the amount of nitrate available for leaching, although some studies indicate the effect may be short term. Immobilization can also have a negative impact on crop production since N becomes unavailable. The form of carbon in the soil amendment also affects nitrate leaching potential in addition having climate change impacts. The biochar used in the field trials had a relatively high amount of recalcitrant (unreactive) carbon and lower amounts of labile (reactive) carbon. High amounts of labile carbon in biochar can reduce the amount of nitrate available for the plant and leaching through the process of denitrification. Denitrification through this mechanism often involves conversion of nitrate to N_2 instead of nitrous oxide, thereby reducing the amount of nitrous oxide, a greenhouse gas, released to the atmosphere (Clough, 2013).

Overall, the nitrate profiles did not strongly or consistently show differences between the treatments and the control, or indicate clear trends regarding nitrate leaching. These results demonstrate that biochar-N dynamics are very complex especially in a study where many variables exist within an active farming operation. Defining soil conditions, the composition of biochar and subsequent N interactions are especially important for understanding biochar- N dynamics and implications for nitrate leaching. Soil properties were analyzed during the field trial but less was known about composition of biochar and movement of nitrate and ammonium with water, both vertically and laterally through the soil.

d. Carbon Sequestration Potential

The pyrolysis of organic matter waste to produce biochar, results in the formation of recalcitrant organic carbon which is resistant to microbial decomposition and can persist for hundreds to thousands of years. When biochar is used as a soil amendment, this organic matter waste is effectively sequestered into the soil as carbon (Lehmann et al, 2006). The biochar-only, compost-only and mix treatments added 6.0, 2.3 and 8.3 tons/acre (respectively) of organic carbon to the soil. As discussed previously, direct measurements of the recalcitrant portions of these organic carbon inputs were not possible in this field trial, but studies of biochar composition based on different types of feedstock and production methods suggest that the recalcitrant carbon content was high in the field trial biochar, which was made from wood chips charred at a temperature 575-600°C (Singh et al, 2010; Novak et al, 2009).

Even without measurements of recalcitrant carbon content, consistent, significant increases in SOC over time in soils treated with biochar-only and the biochar-compost mix compared to those treated with compost-only and the control conditions would be strong indicators of soil carbon sequestration due to biochar. However, the SOC results (Section 4.d) did not support the conclusion that a long-term carbon sequestration benefit resulted from the one-time application of the biochar-containing soil amendments at this site. With the exception of the fall mid (6-12") depth North plot samples, SOC was not higher in the soils treated with biochar-only and biochar-compost mix soil amendments relative to the control and the compost-only treatment. Despite these inconclusive results during the three-year field trial, mid depth SOC levels suggested that an effect might have been seen in these sub-surface soils (i.e. below the 6" depth) from the biochar treatment had the field trial monitoring continued for a longer period of time. At this depth for the North plot, the biochar-containing treatments increased SOC relative to the control and the compost treatment. This trend may have become more apparent in subsequent years due to residual biochar which presumably was further mixed into the sub-surface soils. This deeper mixing would help the soils retain biochar and associated carbon sequestration benefits by reducing the exposure of the biochar to surface wind or water erosion.

In addition to the carbon sequestered in the biochar itself, the biochar could have had other climate benefits. As discussed previously, biochar can act as a slow-release fertilizer, thus reducing the need for chemical fertilizers and reducing greenhouse gas emissions caused by manufacturing of fertilizers. Several field studies have shown positive effects of biochar on beneficial microbial activity in the soil which can result in more carbon storage in soils. Although results have been mixed from field studies, some have reported reductions in emissions of certain greenhouse gases (N_2O and C_2O) from agricultural fields treated with biochar (Laufer and Tomlinson, 2013). Certainly the conversion of forestry waste into the biochar used in this field avoided CO_2 and CH_4 emissions that would otherwise have been generated by the natural decomposition or burning of the waste. Monitoring and estimation of these and other climate benefits was beyond the scope of this field trial, but should be considered for future studies of biochar use in coastal San Mateo County.

6. CONCLUSIONS

Biochar use in a conventional agricultural operation in coastal San Mateo County was successfully demonstrated in this project. Overall, biochar had a neutral or negative effect on crop yield, but field trial results pointed to some potential soil health benefits under certain soil conditions. Potential benefits for nitrate leaching and carbon sequestration could not be confirmed from the field trial results. However, monitoring over a longer timeframe was likely needed to see effects on crop yield and trends in nitrate movement as well as carbon storage. Furthermore, beneficial effects from the soil amendments may have been masked or overwhelmed by existing farming practices such as lime application and multiple fertilizer applications.

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APPENDIX 1. Sampling Design Specifics

Coordinate locations of the North and South test plots were as follows:

North coordinates: Corner of subplot 1 (4152330.44N, 544533.06E); corner of subplot 4 (4152718.96N, 544559.36E), corner of subplot 16 (4152692.35N, 544345.14E); corner of subplot 13 (4152704.01N, 544521.26E). South (Plot 1) coordinates: Corner of subplot 1 (4152245.94N, 545090.44E); corner of subplot 4 (4152228.20N, 545113.75E), corner of subplot 16 (4152203.24N, 545101.69E); corner of subplot 13 (4152216.43N, 545077.03E). Randomization values used to assign treatments to subplots following the recommended protocol in “A Guide to Conducting Biochar Trials” by the International Biochar Initiative (pages 7-14) were as follows:

North Plot

Treatment	Randomization value	Plot #
A: Biochar	0.058538197	1
B: Compost	0.129984707	2
B: Compost	0.170511098	3
C: Mix	0.179424153	4
D: Control	0.207966159	5
C: Mix	0.240792167	6
A: Biochar	0.275646499	7
B: Compost	0.318149556	8
B: Compost	0.402465339	9
D: Control	0.423360453	10
C: Mix	0.482475345	11
D: Control	0.566747196	12
C: Mix	0.685675006	13
A: Biochar	0.714655971	14
A: Biochar	0.723580786	15
D: Control	0.979535556	16

South Plot

Treatment	Randomization value	Plot #
C: Mix	0.015138488	1
D: Control	0.027803601	2
A: Biochar	0.082801866	3
D: Control	0.191020247	4
C: Mix	0.269419321	5
B: Compost	0.288828434	6
C: Mix	0.348348708	7
D: Control	0.407743931	8
B: Compost	0.487195113	9
B: Compost	0.648471861	10
C: Mix	0.690980205	11
D: Control	0.815453856	12
B: Compost	0.81903745	13
A: Biochar	0.832785716	14
A: Biochar	0.899427666	15
A: Biochar	0.932510654	16

Appendix B

Biochar Field Trials in San Mateo County, CA

Economic Analysis

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Biochar Field Trials in San Mateo County, CA

ECONOMIC ANALYSIS

Introduction

The use of biochar, a high-carbon charcoal created through pyrolysis of organic materials, as a soil amendment for Brussels sprouts was evaluated in a field trial in San Mateo County, California. This economic analysis estimates the costs (Table 1) for application of a biochar soil amendment on a per-acre basis for a coastal San Mateo County farm. The estimate is representative of the costs to conventional farms in this location to conduct a one-time application of biochar on their fields. Other cost variables that were considered qualitatively include a “convenience cost” to producer (i.e., the degree to which biochar application does or does not interfere with operations), and different application protocols.

Reported benefits of biochar use in agricultural field trials have included improvements to crop yields and profitability (Laufer and Tomlinson, 2013). In the field trial, biochar soil amendments did not increase crop yields over control conditions, but the cost benefit of higher Brussels sprouts yields at this location are considered here. Other benefits of biochar that have been reported from previous studies (Laufer and Tomlinson, 2013; Clough et al, 2013) include improved soil health, reduced nitrate leaching and increased soil carbon sequestration. These were addressed in the field trial, but they were not specifically evaluated in this economic analysis.

Costs

General assumptions about costs are discussed below. Estimated costs per acre (in 2014 dollars) for use of biochar amendments are shown in Table 1, with details of cost factors shown in Table 2.

Materials

For the field trial, biochar, compost and biochar-compost mix were supplied by Energy Anew, Inc. (San Rafael, California) in bags. To estimate an applicable cost per acre for a larger scale application, bulk pricing for raw biochar (i.e., biochar-only) at $210/cubic yard, and a biochar-compost[1] mix at $225/cubic yard (delivered) were used in these calculations. (See Table 2 for details.) It is assumed that the soil amendment is delivered in a pile on site.

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[1] Composition of the mix is approximately 80% biochar and 20% compost.

During the field trial, biochar and compost were each applied at 10 tons/acre (approximately 30 cubic yards/acre) and the mix was applied at 10 tons/acre each of biochar and compost (for a total approximate application of 60 cubic yards/acre). The 10 and 20 tons/acre application rates achieved field coverages of approximately 0.25 and 0.5 acre-inches (respectively) which are less than recommended by the biochar supplier. However, due to practical limitations on application methods (see below), costs are only estimated for 1 and 10 tons/acre to represent what would be feasible within the farmer's field operations.

Application methods and equipment

This cost estimation for application of a biochar soil amendment includes three overall steps: loading (from the starting pile) into the equipment used for broadcasting/spreading; broadcasting onto the field; and incorporation into the surface soil layer (6-8" deep) by disking one time. Hourly costs for equipment operation were based on studies done by the University of California Cooperative Extension (UCCE) faculty at UC Davis of crop production practices and sample costs, and other conservation practices (see UCCE, 2003, 2014a and b). For some operations, the field trial farmer was able to provide labor and equipment use rates (hours/acre). For the others, comparable rates were taken from the noted UCCE reports.

A variety of methods can be used to spread biochar soil amendments onto a field depending on the number of acres covered, moisture level of the amendment and site conditions (Major, 2009). For small applications, manually spreading the biochar with a rake is an effective method. This was the method used to apply treatments to the field trial test plots (which were about one half acre total). However, costs/acre for applying the biochar by hand was not estimated here because this method is impractical at the production scale of the farm (i.e. 295 acres) where the field trial was conducted.

Larger scale methods considered here are broadcasting biochar using a lime drop spreader, and a manure spreader. Farming practices for conventionally grown Brussels sprouts at the field trial site included an annual application (in May) of a dry, gypsum soil amendment (1 ton/acre) prior to planting seedlings. The timing and method – a tractor with a drop spreader – for this lime application would be suitable for application of low-moisture, small particle biochar soil amendments that are similar in consistency to fine solid lime. For the field trial farmer, this method would be relatively easy to incorporate into routine field operation, particularly if the lime and biochar were mixed and then applied in the same operation. However, the farmer would not be able to apply the biochar soil amendments at the rates tested in the field trial (i.e. 10 -20 tons/acre) due to the limited capacity and application rate of the lime drop spreader equipment. To reflect this limitation, the cost/acre estimate for this method assumes a soil amendment application rate of 1 ton/acre.

A manure spreader is also an option for broadcasting moistened biochar soil amendments. Wetting the biochar helps minimize its loss during application due to wind erosion of biochar dust (Major 2009). Presumably, higher application rates would also be feasible with this method. A rate of 10 tons/acre was used for this estimate. Routine field operations at the field trial site did not include manure application, suggesting that in addition to the estimated costs, this method could represent a significant inconvenience cost in a conventional crop system such as this. For example, the farmer did not own the necessary manure spreader equipment, and if the equipment were rented, farm workers might need additional training to use it.

Labor

Hourly wage rates of $11.75 and $9.75 were provided by the farmer for equipment operator labor and non-equipment operator labor, respectively. With a labor overhead cost of 35% for payroll taxes and workers' compensation insurance, these hourly wages were $12.97 and $15.63. This overhead rate is based on a range of reported values for California in 2014 (Rural Migration News, 2014; UCCE, 2014a and 2014b).

*Table 1. Cost per acre estimations for biochar-only and biochar-compost mix applications.**

Operation **	Labor hrs***	Labor cost	Equipment cost	Material applied (tons)	Biochar-only material cost	Biochar-compost mix material cost
A. Loading (Tractor + front-loader)	0.2	$ 3.17	$ 4.16			
B1. Applying dry soil amendment (Tractor + Lime drop-spreader)	1.2	$ 19.04	$ 36.98	1	$ 599.97	$ 642.83
B2. Applying wet soil amendment (Tractor + Manure spreader)	3	$ 47.59	$ 76.65	10	$ 5,999.70	$ 6,428.25
C. Incorporating: Disking 1X (Tractor with Disk)	0.33	$ 5.23	$ 10.43			
Subtotals: Dry application (A+B1+C)		$ 27.44	$ 51.58		$ 599.97	$ 642.83
Subtotals: Wet application (A+B2+C)		$ 55.99	$ 91.24		$ 5,999.70	$ 6,428.25
TOTALS (per acre)					Biochar-only	Mix
Dry application (1 ton/acre)					$ 678.99	$ 721.84
Wet application (10 tons/acre)					$ 6,146.94	$ 6,575.49

* All costs are per acre, and in 2014 dollars.

** Starting point is a pile of the soil amendment material.

*** Labor time for B1 is based on estimated rate of 3 workers for 1 day (at 10 hour workday) to apply 25 tons of lime at 1 ton/acre lime with this equipment. For C, labor hours are based on estimated rate of 1 worker disking 30 acres/day. (Dave Lea, Cabrillo Farms, Pers. comm., November 19, 2015.) Labor hours for A, B2 are based on similar operations reported in crop production cost studies conducted by the University of California Cooperative Extension at UC Davis (UCCE, 2014b and UCCE, 1994). Labor times for steps in an operation take into account time for equipment set up, moving, maintenance, work breaks, and field repair.

Table 2. Details of cost factors application of the soil amendments.

Labor costs/hour	
Equipment operator hourly wage[1]	$ 11.75
Non-equipment operator hourly wage[1]	$ 9.75
Labor overhead [2]	35%
Equipment operator hourly wage with overhead	$ 15.86
Non-equipment operator hourly wage with overhead	$ 13.16
Equipment costs/hour	
Tractor (75HP) [3]	$ 20.82
Lime drop-spreader [4]	$ 10.00
Manure spreader [5]	$ 4.73
Disk (14' offset) [3]	$ 10.78
Materials costs/ton	
Biochar-only $/cubic yard [6]	$ 210.00
Biochar-Compost mix $/cubic yard [6]	$ 225.00
Cubic yards/ ton [7]	2.857
Biochar-only $/ton	$ 599.97
Biochar-Compost mix $/ton	$ 642.83

[1] Personal communication Dave Lea, Cabrillo Farms, November 19, 2015.

[2] UCCE, 2014b. Labor overhead includes payroll taxes, workers' compensation insurance.

[3] UCCE, 2014b. Table 6. Hourly Equipment Costs.

[4] UCCE, 2009. Table 18. Hourly Equipment Costs. (Converted to 2014 dollars.)

[5] UCCE, 1994. Table 5. Hourly Equipment Costs. (Converted to 2014 dollars.)

[6] Trip Allen, Energy Anew Inc., Pers. comm., January 16, 2016. Raw biochar at $190/yard, and biochar-compost mix at $205/yard, FOB Richmond, CA. Estimated additional transport cost to Half Moon Bay, CA area is $20/yard.

[7] Dry biochar bulk density is about 700lbs/cubic yard. (Trip Allen, Energy Anew Inc, Pers. comm., January 16, 2016.): (1cubic yard/700 lbs)*(2000lbs/ton) = 2.857 cubic yards/ton.

Potential Benefits and Drawbacks

Increased crop yields are one of the most commonly cited benefits of biochar agricultural use in field studies. Over the three-year field trial in San Mateo County, the effect was not observed: the biochar-only and biochar-compost mix resulted in the same or less (respectively) fruit yields compared with control conditions. However, results[2] varied significantly by year and test plot, and in 2013 the biochar-only and biochar-compost treatments increased crop yields by 12% and 16%, respectively, in one of the test plots. To inform the design of future studies, it is worthwhile to consider the degree to which increases in crop yield would have affected the benefits component of this analysis.

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[2] See Table 1., Final Project Report, Biochar Field Trials in San Mateo County, CA.

Using the 2014 reported Brussels sprouts crop yields for San Mateo County (10.17 tons/acre) and the reported price of $1,596/ton, increases of 5%, 10% and 15% in crop yields (over control conditions) would translate to increases in per-acre crop values of $812, $1,623 and $2,424, respectively (Crowder, 2014). This suggests that in one growth season, crop yield increases of about 5% or more with the 1 ton/acre soil amendment application would provide a slight economic benefit to the farmer. Alternatively, if the yields were consistently 1-2% greater than the control yields over two or three seasons, this would also provide a benefit from the one-time biochar application. However, at a higher application rate of 10 tons/acre, a 37-40% single-year crop yield increase (or about 13% greater for all three years) would need to occur for the farmer to begin to receive an economic benefit.

Other benefits of biochar use that were considered in the field trial included improvements to soil health, reduced potential for nitrate leaching from the soil, and soil carbon sequestration. The economic effect of these benefits for coastal San Mateo County farms would be heavily dependent on the specific farming system and conditions, as well as the goals for biochar use. Near the location of the San Mateo County field trial, there have been reports of high levels of nitrate in wells that serve adjacent neighborhoods. As a result farmers and resource managers have a strong interest in reducing the potential for nitrate leaching from the crop soils. Soil carbon sequestration could create another economic benefit of biochar, especially if a California state protocol was adopted for quantifying offset credits for carbon sequestration from applications of biochar soil amendments in agricultural operations.

Overall, this economic analysis suggests that in a conventional farming system, the major drawbacks to using biochar as a soil amendment at the levels tested in the San Mateo County field trial are cost and inconvenience to the farmer which outweigh crop yield benefits.

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Appendix C

Biochar Field Trials in San Mateo County, CA

Outreach Materials

SAN MATEO COUNTY
RESOURCE
CONSERVATION
DISTRICT

PHONE: 650.712.7765

625 Miramontes Street, Ste.103, Half Moon Bay, CA 94019
www.sanmateoRCD.org

Biochar Field Trials in San Mateo County, CA

PROJECT SUMMARY

In Central California and San Mateo County, agriculture is an important component of the local economy and culture. Local farmers and resource managers have shown interest in biochar use as an agricultural soil amendment, and studies have shown that biochar can improve crop yield, soil health, nutrient retention, and have climate change benefits.

The Biochar Field Trial was conducted by the San Mateo County Resource Conservation District (RCD) at a conventional Brussels sprouts farm in coastal San Mateo County over a three year period. The goal of this project was to demonstrate local biochar use and provide a general overview of the effects and feasibility in the region. The project was funded by the USDA-Natural Resources Conservation Service and the California Department of Conservation.

Key findings from the Biochar Field Trials project are summarized below. Please visit our website to access the full report: http://www.sanmateorcd.org/.

- Overall, biochar use in a conventional agricultural operation in coastal San Mateo County was successfully demonstrated
- Biochar and biochar-compost mix soil amendments had neutral or negative effects on crop yields
- The compost-only soil amendment had a neutral or positive affect on crop yields
- All soil amendments (biochar-only, compost-only and biochar-compost mix) significantly increased soil organic matter (SOM) levels in SOM depleted soils with various potential benefits to soil health (nutrient retention and availability, water holding capacity, soil structure and stability)
- There were no consistent or significant trends in nitrate profile data to draw conclusions about nitrate leaching
- There were no consistent or significant trends in total soil organic carbon data to draw conclusions about carbon sequestration
- There was no cost-benefit to the farmer (Note crop yield was the major benefit considered. Benefits from soil health were not included in this analysis)
- Barriers to local biochar use included cost and supply of material & inconvenience costs
- Identified opportunities and solutions including production of biochar on site and potential development of a NRCS practice standard to assist in operationalization if justified
- Key factors that likely influenced results and complicated conclusions included existence of on-farm practices (rototill, lime, fumigation, fertilizer etc.) and short study length

The RCD is YOUR local partner in conservation and agriculture. We are a non-regulatory special district that helps people protect, conserve, and restore natural resources through information, education, and technical assistance programs.

Biochar Field Trial in San Mateo County, California:

RESOURCE CONSERVATION DISTRICT

NRCS

CALIFORNIA CONSERVATION

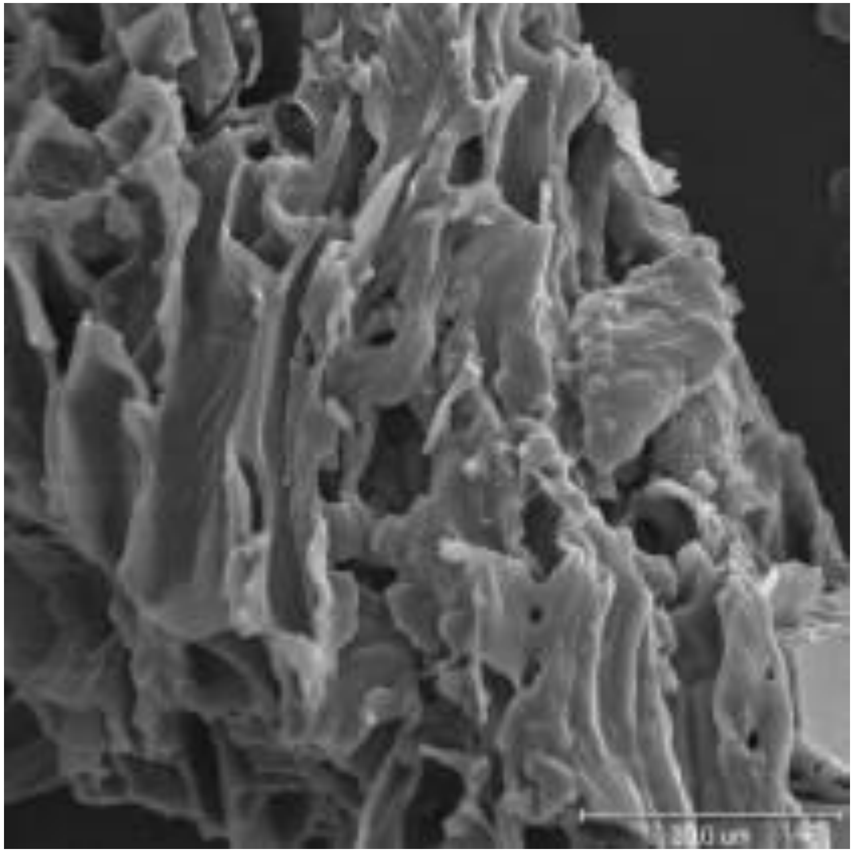
Department of Conservation

What is Biochar?

- Ancient soil amendment technology
- Highly porous charcoal
- Pyrolysis (slow burning in low-oxygen and low temperature)
- Organic biomass is source (wood, bone, crop byproducts, manure, etc.)

Properties of Biochar

- Varies depending on parent material- carbon preserved
- Porous, highly ionized particles
- Highly stable in soil
- Slow decay



When applied as a soil amendment in agricultural operations….

Biochar has been shown to improve crop yield, soil health, nutrient retention and have climate change benefits

How?

- Stable particle can retain nutrients and act as slow release fertilizer
- Can create healthy soil with diversified microbial assemblages
- Can increase water holding capacity
- Can decrease nitrous oxide emissions and nitrate leaching
- Can increase carbon soil content and storage
- Positive feedback loops

RCD Biochar Field Trial Project

The purpose of our study was to demonstrate the use of biochar in conventional row crop operation in the local climatic and soil conditions of coastal San Mateo County

Our specific goals were to assess:

- The effects of biochar on crop yield, soil health, nutrient retention (e.g. nitrate leaching)and carbon sequestration
- The cost benefit to farmers and identifying barriers and opportunities to local biochar use

Project Need

- Agriculture large part of local and statewide culture and economy
- Local benefits to grower and environment unknown
- Feasibility, costs, and barriers unknown
- Local and global signifiance

Project Tasks

- Field trial
  - Crop yield and soil monitoring
- Cost- benefit analysis
  - Labor, materials, crop yield etc.
- Barriers and opportunities analysis
  - Sources, application methods, feasibility, NRCS practice standard etc.
- Report and distribute results

Field Trial

Site Identification

- Conventional row crop site (Brussels sprouts) in Half Moon Bay, CA

Baseline Data

- Quantity of agrochemicals
- Standard soil parameters
- Crop yield

Field Trial Methods

- A Guide to Conducting Biochar Trials (2009): International Biochar Initiative (IBI)
- Spring 2012-Fall 2014 (3 yr. length minimum)
- Two test plots of 16 square subplots: 4 control, 4 biochar, 4 compost, 4 biochar-compost mix
- One-time application at 10-20 tons/acre with rakes
- Existing farming operation and practices preserved

Soil Amendment Application

Field Trial Monitoring

- Crop Yield
  - Weigh Brussels sprouts stalk and fruit in the fall

- Soil
  - Spring and fall samples
    - Composite nutrient analysis (0-6”, 6-12” depths)
      Nitrate-N analysis (12-24”, 24+” depths)
  - Fall samples
    - Bulk density analysis (soil cores)

Crop Yield Findings

- Biochar-only and biochar-compost mix soil amendments had neutral or negative effects on crop yields
  - Lime application may have masked biochar benefits (water holding capacity and nutrient availability)
  - Biochar likely bound to nutrients initially and decreased nutrient availability during the short term of the study
- Compost-only treatment had a neutral or positive affect on crop yields
  - Compost may have increased soil organic matter (SOM) particularly in SOM deficient soils

Soil Health Findings

- All soil amendments significantly increased SOM levels in SOM depleted soils
  - Soil health benefits -nutrient retention and availability, water holding capacity, soil structure and stability

- Bulk density, pH, electrical conductivity, cation exchange capacity, phosphorus, and potassium generally within recommended ranges
- Biochar-compost mix appeared to increase nitrate-N concentrations slightly in the root zone over the growing season
- Biochar treatment appeared to increase Boron concentrations slightly in Boron depleted soils

Nitrate Leaching Findings

- Nitrate soil profiles used to draw inferences
- No consistent or significant effects of treatments
- Slight trend of higher nitrate concentrations in the upper soil layers and lower concentrations in the lower layers, particularly with the biochar and mix treatments
- Biochar-N dynamics are complex especially within an active farming operation
  - Plowing, tilling, disking, lime application, fumigation, fungicide, fertilizer etc.

Carbon Sequestration Findings

- Carbon sequestration from soil amendment biomass:
  - Biochar: 6.0 tons/acre total organic carbon
  - Compost: 2.3 tons/acre total organic carbon
  - Mix: 8.3 tons/acre total organic carbon
- No conclusive trends from total soil organic carbon to show carbon sequestration benefit
- Soil monitoring too short
- Other carbon sequestration benefits not quantified:
  - Higher, more diverse microbial activity → Increased carbon storage?
  - Slow-release fertilizer → reduced need for fertilizer/GHG production?

Cost- Benefit Analysis

- Didn’t see increased crop yield during field trial but in general:
  - If yields 1-2% greater over several years or 5% greater over one year there would be a benefit
- Cost and inconvenience can be major drawbacks (But depends on the rate of application)
- Potential benefits from soil health, nutrient retention and climate change should also be considered

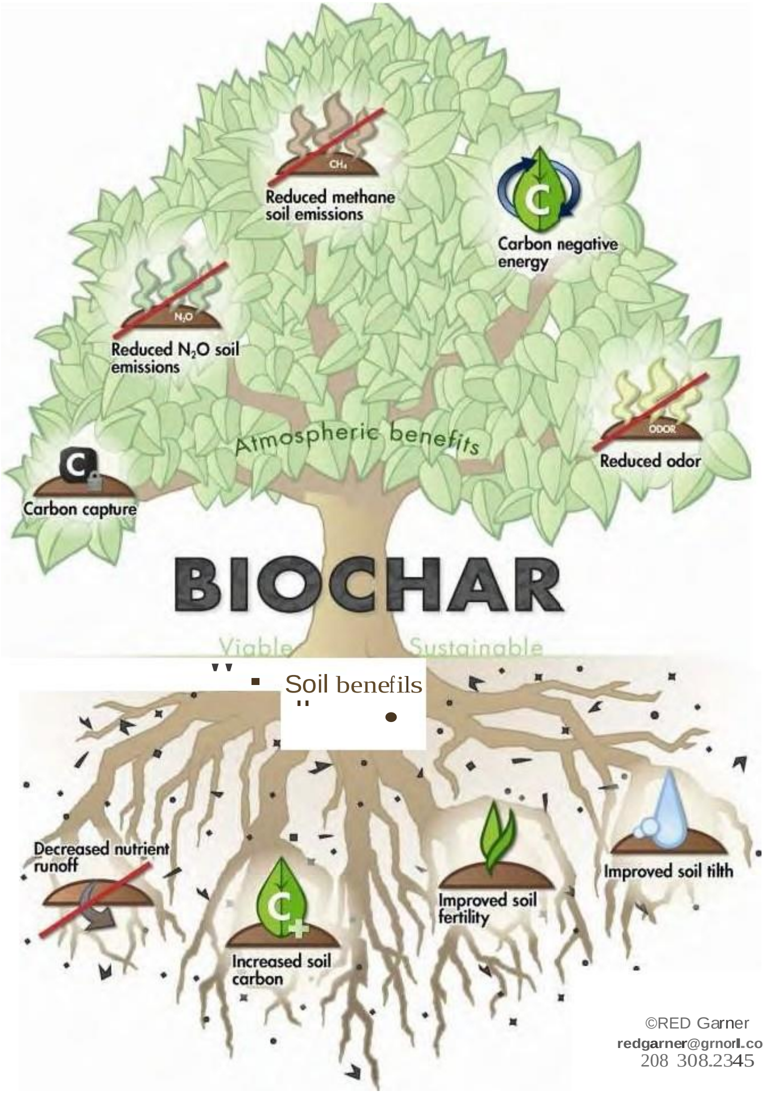
Barriers and Opportunites Analysis

- High cost of material
- Few local suppliers
  - Produce biochar on-site?
- Transport and storage difficulties
- Challenges with application methods and equipment
- Eventually operationalize with NRCS conservation practice standard?

Conclusions and Next Steps

- Biochar use in a conventional agricultural operation in coastal San Mateo County was successfully demonstrated
- Results largely inconclusive besides benefits to soil health
- Potential influencing factors:
  - Extreme weather conditions (heat and drought)
  - Study too short
  - Influence of on-farm practices
- Substantial costs and barriers
- Future studies
  - Rate and timing of application, isolation of variables, longer study

Questions?



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