Impact of Urban Residuals-Based Amendments on Soil Health, Crop Yield, and Nutritional Quality

Anna Beebe

A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Science

University of Washington

2021

Committee:

Sally Brown, Chair

David Butman

Program Authorized to Offer Degree:

School of Environmental and Forest Sciences

University of Washington

Abstract

Impact of Urban Residuals-Based Amendments on Soil Health, Crop Yield, and Nutritional Quality

Anna Beebe

Chair of the Supervisory Committee:

Professor Sally Brown

School of Environmental and Forest Sciences

Biosolids and food scraps are highly prevalent in urban waste streams and can be stabilized for beneficial use as soil amendments. The impact of these amendments on soil health and crop response was tested for two urban soils. One soil was collected from the Tacoma Wastewater Treatment plant and was likely a remnant from plant construction. The second soil, a sandy loam, was classified as part of the Woodinville series (Fine-silty, mixed, super active, nonacid, mesic Aeric Fluvaquents) and collected from a farm located at the King County South treatment plant. Kale (*Brassica oleracea* 'Winterbor') and Swiss chard (*Beta vulgaris* 'Fordhook Giant') were grown in succession in a replicated pot trial. Pots were amended with high rates (220 mg ha^{-1}) of two food scrap-based amendments; bokashi and vermicompost, and two biosolids-based materials; a potting soil (Tagro), and a sawdust/biosolids compost (GroCo). A soil-only control and an inorganic N-P-K (24-25-4) fertilizer control (224 kg N ha^{-1}) were included. Soils were analyzed for total C and total N, pH, electrical conductivity (EC), mineralizable (min C), oxidizable carbon (POXC), and Mehlich-III (M-III) extractable nutrients. Plant response was measured via yield and foliar mineral concentrations (Ca, K, Mg, P, Cu, Fe, Mn, and Zn). Across both soils, organic amendments increased total C and total N, and reduced bulk density in comparison to both controls. In general, amendments increased soil available (M-III extractable) K, Mg, and S, and decreased Cu. Changes to soil C:N, pH, and M-III nutrients were mostly consistent with amendment characteristics. Measures of active C demonstrated positive changes to soil biological indicators but were not predictive of differences in plant yield.

In the kale and chard, soil and amendment were highly significant factors for plant yield. Of the amendments tested, the Tagro and vermicompost resulted in dramatic improvements in plant yield and measured soil properties. Differences in yield as a result of amendment addition were more pronounced in the Tacoma soil and significantly higher than both controls. GroCo had positive effects on yield in both soils but was similar to the fertilized control in the Renton soil. The only case where bokashi germinated was for chard in the Renton soil. However, after successful germination, the yield was significantly higher than both controls and had the second-highest yield after vermicompost. This suggests further research should investigate the use of bokashi.

Crops grown in the Tacoma soil had select foliar concentrations (P, S, Cu, Mn, and Zn) that were higher than in the Renton soil. Amendment impacts on yield in this soil would improve nutrients provided for an urban gardener relative to crops grown in amended soils in the initially higher-yielding soil (Renton). Overall, vermicompost, GroCo, and Tagro had similar or increased foliar macronutrients relative to the fertilized controls. Vermicompost had particularly large increases in crop K concentrations. Biosolids-based amendments had notably large increases in crop foliar concentrations of Mn and Zn in the chard. The results from this study suggest that food scrap-based residuals have the potential to improve urban soils and increase yields for urban agriculture.

Table of Contents

Acknowledgements

Many people have contributed in one way or another to make this project possible. I am deeply grateful for everyone who has taken the time to help shape my understanding of soils and compost.

First of all, I want to thank my advisor Dr. Sally Brown. She provided the opportunity for me to work at the University of Washington and learn soil science. I cannot express how valuable this experience and her continued support have been. I also want to thank Andy Bary. He helped guide my education and provided essential hands-on learning for compost and soils. I also want to thank my committee member, David Butman, for his invaluable advice and support.

Special thanks go to Dr. Deirdre Griffin LaHue for all of her wisdom. She went above and beyond to mentor me as a soil scientist. Her students, Toby U. and Molly M. inspired me with their friendship and their soil science research and spent many hours in the lab to help me.

This research would not have been possible without the logistical and financial support of King County and the Northwest Biosolids Association. In particular, I highly appreciated the immense kindness from Ashley Mihle, Erika Kinno, and Cat Gowan.

Graduate school would have been entirely different without my SEFS friends; Jalene W., Nastassia B., Don R., Katie B., and Ande N., who as scientists and recreation companions, kept me sane.

This work would not have been possible without the support of my family and the unconditional love from my mom and dad. Keyla, thank you for growing with me and staying passionate about regenerative agriculture. Lastly, Alex, your unwavering support and endless patience for the past five years has gotten me farther than I knew was possible.

List of Tables

List of Figures

Chapter 1. Literature Review

Soil health considers physical, chemical, and biological aspects of soils (Bünemann et al., 2018; Stewart et al., 2018) and focuses on soils as functioning ecosystems. The concept of soil quality stems from the observations that dynamic and inherent soil properties influence the health of animals and humans via the quality of crops (Warkentin, 1995). Soil fertility has been recognized for more than a century (McCarrison, 1921) as a key source of essential and beneficial elements for plant and human health (Steffan et al., 2018). The impact of different agricultural practices on soil health has yet to be fully quantified and there remain gaps in the understanding of soil health indicators as predictors of plant response and nutritional quality across soil types (Bünemann et al., 2018).

The use of soil organic amendments (OAs) to improve soil health is not a new concept. The use of residual-derived OAs in agriculture has been extensively researched. Beneficial impacts following the use of OAs have been observed across well-defined sets of physical, chemical, and biological properties used as soil health indicators (Brown et al., 2011; Chen et al., 2018; Diacono & Montemurro, 2010; Ozores-Hampton et al., 2011). However, amendments are highly variable depending on feedstock and processing methods, and their effect on soil health depends on local environmental and soil factors. These materials include a range of organic wastes from food production and consumption. Examples include municipal biosolids, which are the solid residuals from wastewater treatment, and processed food scraps. There is a range of methods to stabilize food scraps so that they can be used as soil amendments. These include composting (Brewer & Sullivan, 2003), vermicomposting (Nurhidayati et al., 2018; Singh et al., 2011), and bokashi, a type of fermentation (Yamada & Xu, 2001).

Organic amendments from urban waste streams can be inexpensive, accessible, and essential tools to improve urban soil quality (Cogger, 2005). Food waste-based composts and biosolids-based products offer high fertilizer value (Kelley et al., 2020) compared to yard-waste compost (Barbarick & Ippolito, 2007; Cogger et al., 2016).

1.1 Soil Response to Organic Amendments

Soil health is defined as “the capacity of a soil to function within an ecosystem and land-use boundaries, to sustain productivity, maintain environmental quality, and promote plant and animal health” (Doran & Zeiss, 2000). For some, the term soil quality is often used interchangeably with soil health (Bünemann et al., 2018) and for others, soil health focuses on the soil’s continued capacity to maintain function and living systems (Pankhurst et al., 1997) while soil quality refers to a soil’s capacity to meet defined human needs such as the growth of a particular crop.

There is a range of tools used to improve soil health. A considerable amount of research has demonstrated beneficial effects from OAs on soil properties in the long term (Diacono & Montemurro, 2010; Ozores-Hampton et al., 2011). Much of this work has focused on OAs created from urban residuals (Beniston & Lal, 2012; Beniston et al., 2016; Cogger, 2005; Larney & Angers, 2012; McIvor et al., 2012).

Understanding the impacts of OAs and other practices on soil health and quality is often a combined effort, using tools to measure changes in the soil’s biological, chemical, and physical properties. The impact of OAs from urban residuals on each of these three soil properties as well as tools for measuring changes are described below.

1.1.1 Biological

Soil organic matter (SOM) is central to any soil health assessment and can be assessed by measuring total C and total N. SOM is crucial to soil function and soil quality for agriculture (Doran & Zeiss, 2000; Weil & Brady, 2017). In a review of organic cropping systems, OAs improved soil chemical and nutrient indices most notably soil organic C (SOC) and N, which were the most significant drivers of changes in soil properties (Norris and Congreves, 2008).

Traditionally, extractions have been used to quantify the humic and fulvic acid fractions of total SOM. Total C depending on the type of soil can contain carbonates which are inorganic C, that need to be accounted for (and removed) to determine SOC levels (Nelson & Sommers, 1996). Soil science has moved away from chemical lab extractions for describing stable SOM as recalcitrant due to its form and rather an assessment of the soil environmental factors (Kleber et al., 2007). More recently, SOM is considered dynamic and on a spectrum of decomposition. Scientists have moved towards methods of characterizing different components of SOM to determine its origins as plant-derived particulate organic matter (POM) or microbial necromass from minerally associated organic matter (MAOM) (Cotrufo et al., 2019; Lavallee et al., 2020). The depth within the soil profile and spatial availability (occluded, adsorbed, or freely accessible to microbes) are important for understanding SOM dynamics (Collins and McQuire, 2019). Some soil scientists consider that no measures of soil health are complete without an analysis of the active SOM fraction. Active pools of SOC are a fraction of overall SOM. Two methods that indicate active carbon are mineralizable carbon (min C) and permanganate oxidizable carbon (POXC), respectively (Hurisso et al., 2016).

1.1.1.1 Soil organic carbon (SOC)

Soil organic carbon (SOC) is a ubiquitous soil quality indicator. Increasing SOC is the primary method to enhance soil function and net primary productivity (Doran & Smith, 2015; Doran & Zeiss, 2000). Small changes in SOC can result in changes to soil physical, biological, and chemical properties, especially those relevant to ecosystem functioning and crop growth (Powlson et al., 2011). SOC and soil organic matter (SOM) although referred to interchangeably are not equivalent terms (require a conversion factor of approximately 2) (Pribyl, 2010).

Within SOM pools of carbon are divided by the length of C turnover in the soil. Active carbon can be comprised of easily decomposable simple sugars, organic acids, and microbial products, whereas slow carbon pools are typically comprised of plant residues or physically stable C compounds. The slow carbon pool is approximately 40-50% of SOC and can take years to turnover. Soil texture is highly influential on SOM dynamics (Grandy et al., 2009), and needs to be considered when investigating the effects of management on SOC.

Studies have shown both long- and short-term increases in SOC following the use of organic amendments (Francioli et al., 2016; Nicholson et al., 2018; Ozores-Hampton et al., 2011; Wuest & Gollany, 2013). Higher increases in SOC have been reported from OA application to degraded soils, high rates of OA addition, or soils with low initial SOM (Beniston et al., 2016; Evanylo et al., 2008; Sullivan et al., 2003). Long-term (>10 years) application of biosolids and compost to sandy soil significantly ($p<0.01$) increased SOM by almost 3x's compared to non-amended controls (Ozores-Hampton et al., 2011) which were similar to the rate of increase found in another study (Sullivan et al., 2003). High increases of SOC (6% by mass) have been documented from compost treated soil compared to unamended controls, but this may have been due to the initially degraded nature of the soil and high application rates (Beniston et al., 2016). In a degraded soil in grain-fallow plots, medium rates of biosolids (6.9 Mg ha^{-1}) increased SOC from compared to anhydrous ammonia control from 1.69 to 9.4 g kg^{-1} (0-10 cm), respectively (Cogger et al., 2013). In a survey across multiple cropping systems in WA state by Brown (2011), SOC increased the most from compost and biosolids in soils with the lowest initial C (r^2=0.37, $p<0.001$). Amendments increased SOC from 8 to 72 Mg ha^{-1} compared to the controls. An application rate of 50 Mg ha^{-1} would be expected to increase SOC from 7 to 33 Mg C ha^{-1} depending on the region and soil type (Brown et al., 2011).

SOC increases from OAs depend on soil type, soil depth, and application rate (Brown et al., 2011; Powlson et al., 2011). In a study of digested biosolids, the increases in SOC ranged from 90 to 290 kg C ha^{-1} yr^{-1} t^{-1} (mean=180 ± 24), with the lower rate in soils that were low clay (8%) and the higher rate for soils that were high clay (23 or 30%). SOC increases seem to have diminishing returns and a maximum limit, which is dependent on soil type and other edaphic factors (Aksakal et al., 2016; Powlson et al., 2011). SOM increases from high rates of vermicompost (Aksakal et al., 2016) eventually reached a saturation point with additional applications having limited effect.

In a long-term (19-year) study by Tautges et al., (2019) SOC increased at depth (2 m) from composted poultry manure (4 t ha^{-1}) but not winter cover crop alone. Winter cover crop increased SOC by 3.5% (1.44 Mg C ha^{-1}) in at the soil surface (0-30 cm) but decreased at depth (30-200 cm) by 10.8% (14.86 Mg C ha^{-1}). Two studies have found that higher nutrient amendments including manure and alfalfa were highly effective at increasing SOC in comparison to high C plant residues (Wuest & Gollany, 2013; Wuest & Reardon, 2016). In a conventional wheat system, biosolids amendments increased persistent SOC compared to plant-based amendments after seven years from the last application when applied at similar C rates (1250 g C m^{-2} total over 5 years). C sequestration efficiencies from additions of biosolids, manure, and alfalfa were 49%, 21%, and 14% that of the unamended control, while plant-based residues were lower (3-11%) (Wuest & Reardon, 2016). Biosolids were suggested to have the highest increase in SOC, as the amendment with the largest total N, P, and S (Wuest & Gollany, 2013). A one-time application of food waste-based compost at a high rate (155 Mg ha^{-1}) had significant positive effects on SOC measurements that lessened for the 7-year study (Sullivan et al., 2003). In a 12-year study, biosolid compost (175 kg N ha^{-1}) increased SOC (14.3 g kg^{-1}) compared to urban, green waste, and manure compost (Ros et al., 2006). In all of these studies, the highest increases to SOM are likely consistent with higher total C, total N, organic S, and P of the amendment (Kirkby et al., 2014).

Studies have consistently shown that OAs can increase SOC relative to unamended or fertilized controls. A global review of the literature on long-term (>10 years) use of OAs by Chen et al., (2018) found that the SOC content of soils amended with OAs alone or with inorganic fertilizer increased by 49% and 29%, respectively compared to a mix of non-fertilized and inorganic fertilized controls. Specifically in urban systems, SOC increased by 10-15 g kg^{-1} from annual or biannual compost applications (Evanylo et al., 2008). Meanwhile, in a turfgrass system, SOC increased from 1.74 g kg^{-1} in the unamended control to 16.6-21.3 g kg^{-1} depending on the biosolid amendment type over 5 years, which was higher than the synthetic fertilizer treatment (13.7) (Badzmierowski et al., 2020). In an urban garden, soils amended with Tagro and GroCo (200 Mg ha^{-1} dry) increased SOC values from 41.0 (soil only control) to 51.6 and 80.2 g kg^{-1}, respectively (McIvor et al., 2012b). Vermicompost increased SOM (2.00%) compared to the soil only control (1.64%), vermicompost + mineral fertilizer (1.87%), and fertilizer alone (1.69%) (Masciandaro et al., 2000).

An important note is that additional SOC storage occurs from OA application indirectly due to increased crop productivity. In Brown et al., (2011), farm soils applied with compost or biosolids had higher C in sampled soil than the total C applied from the amendments themselves, which was likely from improvements to plant growth.

1.1.1.2 Total nitrogen

Soil total N is an essential component of any soil health assessment. Total N includes inorganic and organic forms of soil N. Total N has important relevance to specific soil properties and correlates with biological processes that are highly affected by soil texture (Grandy et al., 2009).

Soil response to organic amendments depend on the type, rate, and soil characteristics (Kallenbach & Grandy, 2011) especially for the microbial portions of C and N. Total N can help provide an estimate of potentially mineralized N which is available for crops is highly variable based on amendment type (Gale et al., 2006).

Increases in total N from OA application are consistent and well documented (Nicholson et al., 2018; Norris & Congreves, 2018; Ros et al., 2006). In field studies, the increases in total N from compost and biosolids were above inorganic fertilized controls (Brown et al., 2011; Nicholson et al., 2018; Warman, 2005). In degraded urban soil, compost (175 Mg ha^{-1}) applied in the short-term (< 3 years) increased total N by 4x's compared to unamended control (Beniston et al., 2016). In a long-term (20-year) field study, biosolids increased soil total N (0.16-0.17%) compared to inorganic NPK fertilized controls (0.14%) (Nicholson et al., 2018). In sandy loam, five plots cropped with different vegetables had an average total N that was significantly higher ($p<0.006$) when treated with compost (manure, food waste, and grass clippings) than fertilizer (1.3 vs. 0.9 g kg^{-1}, respectively) (Warman, 2005).

While OAs consistently increase total N, the magnitude of the effect depends on OA type (Masciandaro et al., 2000; Ros et al., 2006). In a 12-year field study in silt loam soil, OA treatments (food waste, manure, urban waste, and biosolids composts) applied at 175 kg N ha^{-1} increased total N compared to the fertilized and unamended control (1.40 and 1.48 g kg^{-1}, respectively) to a range from 1.53 to 1.68 g kg^{-1}. However, only the increase from urban waste compost (1.68 g kg^{-1}) was significant ($p<0.05$) (Ros et al., 2006). A field study in sandy-clay soil found significant increases from mineral fertilizer alone and vermicompost with mineral fertilizer, relative to the unamended control but the effects were not significant for vermicompost alone (Masciandaro et al., 2000).

1.1.1.3 Mineralizable carbon (min C)

Mineralizable carbon (min C) represents 1-3% of the total SOC (Morrow et al., 2016) and reflects the ability of the soil to cycle nutrients via microbial activity. Min C correlates with soil microbial biomass, particulate organic matter, and nutrient mineralization (Franzluebbers et al., 2000; Haney et al., 2001). Min C represents increases in microbially available carbon and is highly sensitive to management (Hurisso et al., 2016). Across a variety of cropping systems, OAs have consistently shown increases in soil respiration relative to fertilized controls (Brown & Cotton, 2011; Sciubba et al., 2014). Soil respiration rate can also be measured via alkaline absorption (AA) which typically uses NaOH traps or gas analyzers, both of which can measure CO_2 produced from lab incubations, but the latter is useful for field studies.

In lab incubations, OAs consistently increase soil min C (Flavel & Murphy, 2006; Tognetti et al., 2008) and are highly related to nitrogen mineralization (NMIN), SOC, and total N ($p<0.03$) (Franzluebbers, 2020; Haney et al., 2001). Min C also has been shown to increase along with the extractable P content of the amendment (Tognetti et al., 2008). In lab incubations, manure-based composts have typically had higher positive effects on min C rates than MSW-based composts or mineral fertilizer (Flavel & Murphy, 2006; Tognetti et al., 2008). A lab study that used coarse soil with low initial respiration rates (< 2 mg CO_2-C kg^{-1} day) OAs (poultry manure, two green waste composts, straw-based compost, and vermicompost) increased soil respiration rate. Over the 142-day incubation, the amount of C evolved from the amount of C added was highest for the manure, intermediate, or the plant-based composts, and lowest for the vermicompost (Flavel & Murphy, 2006).

In field studies, OAs increase soil min C with differences associated with amendment type and site (Hurisso et al., 2016; Ros et al., 2006; Sprunger et al., 2019). Compared to OAs, inorganic fertilization has been shown to suppress soil min C (Ros et al., 2006; Sprunger et al., 2019). Min C increased over time (3 years) in organic N systems and decreased or remained the same for high inorganic N (< 60 mg kg^{-1}) in both annual and perennial wheat. In a silt loam soil, increased respiration rates (µg CO_2 - C g^{-1} soil h^{-1}) were reported from biosolid compost (0.76), green waste compost (0.57), and mineral fertilizer (0.48) applied at 80 kg N ha^{-1} (Ros et al., 2006). In a review of 13 agricultural soils, min C ranged from 2 to 2,259 mg C kg^{-1}. The site studied that had the highest mean min C was an urban garden in Ohio (1,029 ± 511) that had been applied with compost and had high SOC (56 ± 31 g C kg^{-1}) compared to the rest of the sites, which had average SOC values that ranged from 6 ± 1 to 23 ± 5 g C kg^{-1} (Hurisso et al., 2016).

1.1.1.4 Permanganate oxidizable carbon (POXC)

Permanganate oxidizable carbon (POXC) represents approximately 1-4% of total SOC (Hurisso et al., 2016). POXC has been suggested to be more sensitive to SOM stabilization than other soil health indicators such as SOC, microbial biomass carbon (MBC), or particulate organic carbon (POC) (Culman et al., 2012; Hurisso et al., 2016). Higher values of POXC indicate higher levels of a relatively more processed and stabilized pool of biologically active carbon. Changes in POXC may reflect management that can indicate potential SOC sequestration.

POXC as a result of different management practices has been observed and appears to relate to differences in total C (Hurisso et al., 2016; Morrow et al., 2016; Sprunger et al., 2019). No-till sites had consistently higher POXC than conventionally tilled sites, and high POXC was highly correlated with SOC and total N (Morrow et al., 2016).

Studies suggest POXC is related to both the small (53 to 250-µm) and dense fraction of particulate organic carbon (POC) which have a low C:N ratio and high microbial biomass. This is why scientists suggest POXC measures a more processed fraction of active C (Culman et al., 2012). POXC was highly related to soil microbial biomass carbon (MBC) at some sites (r^2=0.97) and only minimally related at others (r^2=0.11) (Culman et al., 2012). In a review across 13 agricultural sites in the U.S., POXC values ranged from 87 to 1,450 mg C kg^{-1}. The study found that the largest average POXC (mg C kg^{-1}) was in a crop/pasture system (813 ± 411) and was closely followed by an Ohio urban garden that had been applied with compost and cover crop (803 ± 375) (Hurisso et al., 2016).

1.1.2 Chemical

Effects from OA on chemical indicators such as pH, EC, and plant-available nutrients are highly dependent on process parameters. The nutritional value of amendments is highly affected by the amendment feedstocks and process (Nurhidayati et al., 2018; Quiroz & Céspedes, 2019; Steel et al., 2012). Following OA addition, Gómez-Sagasti et al., (2018) concluded that the key benefits to the soil after increased SOC stock and microbial activity were enhanced available nutrients including N, P, K, Ca, and Mg.

1.1.2.1 Soil available nutrients

Soil OA application affects soil available plant nutrients (García-Gil et al., 2004; Ros et al., 2006b; Weber et al., 2007; Kaur et al., 2008). Measurements of soil available nutrients are chemically determined by extractants which are calibrated to measure plant-available nutrients according to soil properties. The Mehlich-III (M-III) extractant has been used as a universal extractant for plant-available nutrients across a range of soil types and elements (Antonious et al., 2014; Brown et al., 2011; Culman et al., 2020; Zbíral, 2016).

Depending on OA type, previous studies have shown increases in plant-available nutrients (Ca, K, Mg, P, Cu, Fe, Mn, and Zn) following the use of OAs (Beniston et al., 2016; Brown & Cotton, 2011; Bulluck et al., 2002; Ozores-Hampton et al., 2011).

Biosolids increased M-III extractable Ca, P, and Zn relative to soil only control but had lower K and Mg (Antonious et al., 2014). Increases to soil M-III Ca from biosolids were higher than the effects from poultry manure. A review of biosolids applied in Pennsylvania (5 to 156 Mg ha^{-1}) found that biosolids increased M-III P by approximately 50 mg kg^{-1} relative to the control (0-10 cm depth), increased M-III Ca, and decreased M-III K relative to controls (Shober et al., 2003).

M-III extractable nutrients (Ca, P, K, Mg, Fe, Mn, and Zn) have been shown to significantly increase due to compost applications (Beniston et al., 2016; Warman, 2005). In degraded urban soil, high rates of compost (150 Mg ha^{-1}) increased P, K, Ca, Mg, S, Al, and Fe. There were no significant differences in concentrations of Zn (Beniston et al., 2016).

Compared to hardwood vegetative compost, biosolids typically have larger increases to soil M-III P, Cu, Fe, and Zn, and similar effects on Mn (Basta et al., 2016). In multiple studies, compost but not biosolids increased M-III K (Antonious et al., 2014; Basta et al., 2016; Brown et al., 2011). Depending on the site (orchard or field), compost amended soils increased M-III K, P, Mg, Cu, Fe, Mn, and Zn (Brown & Cotton, 2011).

1.1.3 Physical

OAs can improve soil structure by lowering bulk density, reducing erosion, increasing soil aggregation and water holding capacity (Brown et al., 2011; Khaleel et al., 1981). Water-stable aggregation and stability help reflect the functional capability of soil and limits wind and water erosion (Franzluebbers, 2016). Aggregate stability as well as many physical soil properties are correlated with SOC (Albiach et al., 2001). Studies show that OAs significantly increase aggregate stability in the short-term (< 2 years) (Beniston et al., 2016; Leroy et al., 2008). OAs have been well-studied with regards to their ability to improve soil physical properties by reducing soil bulk density (Beniston & Lal, 2012; Evanylo et al., 2008; Norris & Congreves, 2018; Ozores-Hampton et al., 2011).

A review of 25 urban soils applied with compost made from various feedstocks at different application rates, study durations, and soil types, found that compost reduced bulk density, enhanced infiltration rate, and increased hydraulic conductivity and plant available water compared to control soils. The authors reported that research of the long-term effects from one-time addition and amendment rate comparisons was lacking in the literature (Kranz et al., 2020).

1.1.3.1 Bulk density

Bulk density is a measure of the dry mass of soil per specific volume. Reduced bulk density is an indicator of improved soil health. A decrease in bulk density is typically associated with increased water infiltration rates, water holding capacity, and improved aggregation. A review of long-term changes from OAs to soil physical properties found that they reduced bulk density due to improved soil aggregation (Khaleel et al., 1981). OA application results in larger decreases in bulk density when amendments have higher C inputs (Cogger et al., 2016; Evanylo et al., 2008).

Single applications of OAs at high rates significantly decrease bulk density (Beniston et al., 2016; González et al., 2010). The magnitude of the reduction is directly related to the application rate (Aksakal et al., 2016) and persists over time (Evanylo et al., 2008; Ozores-Hampton et al., 2011). In a long-term (>10 years) study in sandy soil, bulk density reduced from 1.6 to 1.4 g cm^{-3} from OA application (Ozores-Hampton et al., 2011).

OAs have positive effects on bulk density in urban soils. In an urban soil, low rates (31 Mg ha^{-1}) of biosolids-compost applied annually or biennially, decreased bulk density, and increased porosity compared to the fertilized and control plots over time. However, improvements were much faster at high rates (144 Mg ha^{-1}) which reduced bulk density (1.11 to 1.05 g cm^{-3} in amended soils) compared to fertilized and control treatments (1.32 and 1.27 g cm^{-3}, respectively) (Evanylo et al., 2008). In an urban garden, Tagro and GroCo (200 Mg ha^{-1} dry weight) reduced the soil bulk density (g cm^{-3}) from the unamended control (1.01 ± 0.01) to 0.77 ± 0.03 (Tagro) and 0.51 ± 0.08 (GroCo) (McIvor et al., 2012a).

1.2 Plant Response to Organic Amendments

This section aims to investigate the effect of OA application on plant health as measured by crop yield and nutritional density. Soil function is enhanced by OAs which impacts subsequent crop nutritional quality and yield (Diacono & Montemurro, 2010). Soil properties can be predictive indicators for yield and crop quality and conversely, yield and nutritional quality can offer insights into the cumulative effect of OAs on soil quality. The use of organic residuals to improve yield can avoid the unsustainable use of inorganic fertilizers (Powlson et al., 2011).

Changes in soils have frequently been associated with changes in yield and plant quality. For example, liming is a well-established method to increase crop yield from increased macronutrient availability (Holland et al., 2018). While yield and nutritional density are discussed in separate sections below, it is clear that balanced soil nutrients can help improve yield, especially in degraded soils (Lal, 2009). Low-quality soils tend to have a lower nutrient status and may result in nutrient deficiencies that reduce yield (Brevik, 2013). Other factors that influence crop nutritional quality are genetic, environmental, and management (i.e. agricultural or post-harvest handling and storage) factors (Hornick, 1992).

1.2.1 Crop yield

Reviews of long-term trials indicate beneficial effects on yield from OAs in agronomic systems (Chen et al., 2018; Diacono & Montemurro, 2010). Multiple studies indicate that OAs are highly beneficial to crop yield in urban soils (Alvarez-Campos & Evanylo, 2019b; Beniston et al., 2016). In a review of the literature (n=60) regarding vegetable cropping systems, the application of OAs was the main driver for increases in soil health and crop yield (Norris & Congreves, 2018).

The impact from OAs on crop yield depends on material type and rate of application (Diacono & Montemurro, 2010; Ros et al., 2006), cropping system management (Cogger et al., 2016; Norris & Congreves, 2018), and crop type (Alvarez-Campos & Evanylo, 2019b; Warman, 2005).

Impacts associated with OAs may be more pronounced when soils are initially degraded (Beniston et al., 2016). In degraded urban soil, a single high rate of compost maintained increased tomato yield relative to an unamended control for two years, with similar trends for Swiss chard. OA applications increased sweet potato yield 10-15xs compared to the control plot in the second year after application (Beniston et al., 2016). A review of long-term field experiments (> 3 to 60 years) found that repeated applications of high rates of MSW-based compost increased yield and were highest from frequent applications (Diacono & Montemurro, 2010). In a field study that applied biosolids and chicken manure (15 t acre^{-1}), the yield was 6x's higher for collard and 4x's higher for kale compared to the unamended control (Antonious et al., 2014).

Literature shows larger relative yield increases compared to controls are common in sandier soils (Chen et al., 2018; Nicholson et al., 2018; Ozores-Hampton et al., 2011). A meta-analysis of 132 long-term (>10 years) publications worldwide, found that yields were significantly higher for OAs (green waste, manure, and biosolids) relative to no addition, but were not higher relative to inorganic fertilizer. OA plots had a greater yield compared to inorganic fertilizer when applied to soils with certain characteristics (sandy, degraded, and neutral pH). The final yield in the reviewed experiments increased for OAs alone (81 ± 15%) and OA with fertilizer (102 ± 27%) compared to unamended controls (Chen et al., 2018).

Amendment quality and characteristics may be predictive of the OA effect on yield in the short term (< 3 years). In sandy loam soil, the potato yield was lower in MSW compost than NPK treatments after 3 years. The authors suggested that N mineralization from the MSW compost was too low for the potato crop requirement (Warman et al., 2011). The C:N ratio was likely too high (> 25) and immobilized soil available N. In these cases, compost and inorganic fertilizer can have higher yields than the N treatment alone (Larney & Angers, 2012; Ros et al., 2006).

Additional mineral fertilization is likely not required with the use of biosolids-based or food-based OAs which have high total N and available nutrients (Kelley et al., 2020). An exception being biosolids products which may require additional K depending on the crop and material (Badzmierowski et al., 2020). In urban soil, high biosolids applications showed greater potential to increase vegetable yield than lower rates and inorganic fertilizer. Cabbage and kale yields were higher with biosolids amendments than inorganic fertilizer (Alvarez-Campos & Evanylo, 2019).

Increases in yield from OAs relative to inorganic fertilizer depend on crop type in addition to soil type. In a 12-year field study in sandy loam soil, the increases in yield from compost (animal manure, food waste, yard waste, straw, and manure) amended vs. NPK fertilized plots were significantly higher for yellow beans (7.7 vs. 5.0 kg plot^{-1}) and green beans (6.2 vs 3.9 kg plot^{-1}), respectively. The yield was numerically higher but not significant for compost plots vs. NPK fertilized plots for carrot, pepper, onion, and tomato yield. The NPK fertilizer increased crop yield more than compost amendments for cauliflower and Brussel sprouts (Warman, 2005). Vermicompost (household solid waste, horse manure, and chicken manure) applied at 20 Mg ha^{-1} increased lettuce but not for broccoli yield relative to the control (Ferreras et al., 2006).

Benefits to yield depend on OA application rate and typically increase with higher doses of OA (Cogger et al., 2013; Ferreras et al., 2006; Speir et al., 2004). A long-term field study for 2-year wheat-fallow rotation demonstrated the benefits of from biosolids applied at medium and high rates (6.9 and 9.0 Mg ha^{-1} dry) increased grain yield (3.63 and 6.60 Mg ha^{-1}, respectively) relative to the anhydrous ammonia (3.13 Mg ha^{-1}) (Cogger et al., 2013). In a pot trial, beet yield increased with higher applications of compost from a variety of feedstocks (biosolids, wood waste, green waste-based) applied annually for four years (Speir et al., 2004). Vermicompost (household solid waste, horse manure, and chicken manure) applied at 20 Mg ha^{-1} had a higher lettuce yield than a low rate of 10 Mg ha^{-1} (1.93 vs. 1.3 kg m^{-2} lettuce, respectively) (Ferreras et al., 2006).

Low rates of OA addition have demonstrated improved crop yield (Ninh et al., 2015) with more pronounced impacts in the short term. In a field study, poultry manure when applied at low rates (1.54 Mg C ha^{-1}) to a potato-corn cropping system increased yield by 17% compared to the urea-fertilized control. The resulting yield was similar to higher application rates which increased yield by 23% compared to the control (Ninh et al., 2015). These results were likely from the fertilizer value of the manure which had a positive effect. For more stable materials such as compost, there are fewer effects from low rate applications (Evanylo et al., 2008; Suddick & Six, 2013). A low rate of compost (31 Mg ha^{-1}) improved bulk density and porosity but did not affect yield, soil C, or N mineralization relative to an unamended control (Evanylo et al., 2008). In this 3-year study, compost amended at high rates (144 Mg ha^{-1}) increased crop yield, but low rates did no have an impact. In a small-scale vegetable system, lettuce or bell pepper yield was not impacted with low compost additions (5 t ha^{-1} applied biannually) (Suddick and Six, 2013).

1.2.2 Crop nutritional density

There are 17 elements considered essential to crop growth (Havlin, 1999). Except for H, O, and C, the remaining 14 essential elements for plants are mainly sourced from the soil. Soil to plant transfer of trace elements is controlled by soil master variables: pH, redox potential, texture, organic matter—quantity and quality, mineral composition, temperature, and water (Kabata-Pendias, 2004). Even though the total content of trace elements in soils is typically very low (mg kg^{-1}), the soil-plant-person pathway is a significant source of mineral nutrition (Steffan et al., 2018). However, total concentrations of trace elements in the soil don't necessarily reflect their availability to plants (Antonious et al., 2013).

Crop nutrient concentrations are categorized as deficient, sufficient, or toxic (Havlin, 1999). Critical levels are the nutrient concentrations in a plant below which a yield response occurs from added nutrients. Deficient levels occur when concentrations are low enough to reduce yields. Sufficient levels do not have improved effects from increased yield but may increase nutrient concentrations. A phenomenon termed "luxury uptake" describes nutrient uptake that does not influence yield (Havlin, 1999). Excessive or toxic levels have nutrient concentrations that are high enough to reduce yield. Critical concentration ranges are specific to crop type.

Many studies have found that use of OAs resulted in increased mineral concentrations of K, P, Ca, and Mg (González et al., 2010; Neilsen et al., 1998; Sáinz et al., 1998). Vermicompost increased N and P in beets (González et al., 2010) and biosolids increased N, P, and S in grain compared to synthetic fertilizer (Nicholson et al., 2018). A study using degraded soil from topsoil removal found that vermicompost increased cucumber tissue concentrations of P, Ca, Mg, and Zn (Sáinz et al., 1998). In a field study in sandy loam soil, organic amendments from local wastes (including two biosolid composts, yard waste, and biowaste) increased chard leaf concentrations of N, P, Cu, and Zn relative to minerally fertilized controls (Neilsen et al., 1998).

In comparison with clear demonstrations of increased yield due to OA applications, changes to nutritional density are much more variable in the literature. Some studies show no effect on crop nutritional density even with soil available nutrient changes (Alvarez-Campos & Evanylo, 2019; Mkhabela & Warman, 2005; Warman, 2005). A study in urban soil found that EQ biosolids products had no nutritional content benefit compared to inorganic fertilizer despite improving soil physical properties, soil fertility, and yield (Alvarez-Campos & Evanylo, 2019). In a 12-year field study, compost amended plots increased Mehlich-III (M-III) soil available nutrients P, Ca, Mg, Mn, and Zn, but did not significantly increase the nutrient concentration in vegetable crop tissue (Warman, 2005). In sandy loam soil, three rates of MSW compost did not increase soil M-III extractable P or potato P concentration compared to an NPK fertilizer (Mkhabela & Warman, 2005). In a two-year field study in Canada, soil M-III extractable K was much higher in compost plots in comparison to inorganic fertilizer, but there were no detectable differences in strawberry K concentrations (Hargreaves et al., 2008). Similarly, manure compost increased soil available (M-III extractable) P and Zn but did not change strawberry fruit nutrient content. In addition, despite the lack of differences in available Mn between treatments, inorganic fertilizer increased strawberry fruit Mn concentrations compared to manure and manure tea (Hargreaves et al., 2008).

Residuals-based amendments have different characteristics and potential differences in associated benefits to both soils and plants. For this trial, we tested two types of biosolids-based materials; biosolids/sawdust compost (GroCo) and potting soil (Tagro) made by blending biosolids with aged bark. We also tested amendments made from food scraps from a single location, stabilized through vermicomposting and bokashi fermentation. Results from peer-reviewed literature regarding the characteristics of these materials and the subsequent soil and plant response following their use will be summarized.

1.3 Characteristics and Impact of Biosolids-Based and Food Scrap-Based Organic Amendments

Urban residuals-based amendments made from food scraps and biosolids have high nutrient content and can increase soil fertility. Food waste is highly variable and typically has high carbohydrate, low cellulose and lignin, high protein (15-25%), and high lipid (13-30%) content (Olle, 2020). Food waste has low C:N, high macronutrients, and a full balance of micronutrients. Biosolids have high organic C and total N and typically provide all plant available macronutrients and micronutrients (Cogger et al., 2006).

1.3.1 Anaerobic, food scrap-based bokashi

Bokashi is a product of anaerobic fermentation and offers an alternative tool for sustainable soil management (Quiroz & Céspedes, 2019). Anaerobic bokashi is created using an inoculation of beneficial microorganisms. A common commercial inoculant is called effective microorganisms (EM) and is a mix of lactic acid bacteria (LAB) populations, yeasts, photosynthetic bacteria, filamentous fungi, and actinomycetes (Yamada & Xu, 2001). One method to create bokashi is outlined briefly in Christel (2017). First, a starter culture is created usually using an inoculated mix of grain or wheat bran that is fed with a labile carbon source (typically molasses) and kept in an anaerobic environment at least for two weeks. Then, the starter culture is mixed with the desired feedstock (food waste) and packed tightly to keep in anoxic conditions for at least three weeks. The final stage is for product stabilization and requires burial or mixing with soil for at least two weeks. The entire process varies but can take approximately two months. Bokashi quality is dependent on the initial water content, molasses additions, and the microbial inoculant used (Yamada & Xu, 2001).

There are benefits and drawbacks to the use of bokashi as an amendment. Benefits include a shorter process retention time, lower mechanical mixing, and less stringent feedstock composition requirements along with reduced nutrient loss relative to aerobic composting. However, bokashi can also have properties that make it difficult to use. Bokashi is considered semi-stabilized, has high ammonium (due to lack of conversion to nitrate without oxygen), high salts, and is acidic, which makes using the material potentially phytotoxic without further stabilization (Quiroz & Céspedes, 2019).

1.3.1.1 Typical amendment characteristics

1.3.1.1.1 Biological characteristics

Anaerobic fermentation of bokashi propagates *Lactobacillus* sp. which produce lactic acid and suppress less acid pH tolerant microorganisms. The microbes used as a beneficial inoculum change the resulting physicochemical characteristics of the bokashi (Yamada & Xu, 2001). Bokashi may have higher microbial biomass in the product than in the initial mixture or other types of OAs. Microbial biomass carbon (mg C kg^{-1} dry weight) was much higher in bokashi (4,000) than vermicompost (2,000) and other manure-based composts (Epelde et al., 2018). Bokashi retains a higher C:N ratio during the process due to a reduction in evolved carbon to CO_2 which increases C mineralization from stimulated microbial activity once used (Olle, 2020).

1.3.1.1.2 Chemical characteristics

Total C, total N, and C:N ratio

A comparison of two food scrap-based bokashi batches made identically by Christel (2017) had slightly varied total N, OM, and C:N ratio (2.45 and 3.54 % total N; 81.4 and 84.3 % OM; C:N ratio of 18 and 13). Results were similar in a review by Quiroz & Céspedes, (2019) bokashi produced from a large range of feedstocks had a large range of total N content from 1.09% to 3.50%. The highest total N was from food scrap-based feedstocks. There was also a very large range in the C:N ratios (7 to 40) for bokashi from a variety of materials. In a review of 9 farm-based bokashi products the mean total C and total N were 44.5 ± 2.7% and 4.5 ± 0.6%, respectively (Xu, 2001).

pH and electrical conductivity (EC)

Two different food scrap bokashi batches by Christel (2017) had a pH of 4.5 and 4.2, and an EC of 5.1 dS m^{-1}. Bokashi produced a variety of methods (n=9) and had a mean pH of 5.5 ± 0.8 (Yamada & Xu, 2001) and a mean EC (dS m^{-1}) of 4.9 that ranged from 2.5 to 6.5**.**

The pH has been suggested as a reliable indicator of quality for bokashi as it shows whether the LAB has fully acidified the product (Yamada & Xu, 2001). The variation in the material pH has been suggested to be from the microbial populations present and/or the moisture content during fermentation. The population of *Lactobacillus* sp. was much higher in EM-bokashi vs. non-EM bokashi (10^7 vs. 10^3 CFU g^{-1}) potentially contributing to the pH difference between EM vs. non-EM (4.8 vs. 6.0, respectively). Moisture content was found to be a key variable that determined pH. Material that was drier (20% moisture content) had a pH > 6 over 21 days but dropped to < 5.5 when more hydrated (25% moisture content) (Yamada & Xu, 2001).

Nutrient content

Bokashi has high nutrient content (Quiroz & Céspedes, 2019) that is quickly available to plants (Christel, 2017). Values for inorganic N in the material ranged from 416 – 2498 mg kg^{-1} NO_3 and 0.2 – 571 mg kg^{-1} NH_3 (Quiroz & Céspedes, 2019). EM-bokashi had high ammonium and low nitrate N (1007 ± 600 and 85 ± 76 mg kg^{-1}) as well as high available P (9.93 ± 1.53 g kg^{-1}) (Yamada & Xu, 2001). Food scrap bokashi by Christel (2017) had high K (0.63 and 0.82%) measured in two separate batches.

1.3.1.1.3 Physical characteristics

Physical characteristics of bokashi may be more consistent than chemical ones. In a review, bokashi materials had high porosity and water holding capacity, and low bulk density (Quiroz & Céspedes, 2019). In general, the literature regarding the physical characteristics of bokashi is limited.

1.3.1.2 Changes to soil properties following use

Bokashi is much faster to produce than thermophilic compost (< 2 vs. 3-12 months, respectively) and should be considered a semi-stabilized product that may have phytotoxic effects from high ammonium or organic acids from the continued degradation of the material (Quiroz & Céspedes, 2019). There are gaps in the literature regarding the effects of bokashi on soil carbon, physical properties, and microbial indicators. This review will emphasize areas where information is available.

1.3.1.2.1 Fertility

The addition of bokashi to soil demonstrates increased soil N and improved soil chemical properties by degrading quickly and releasing plant-available nutrients (Boechat et al., 2013;

Christel, 2017). Bokashi increased the rate of mineralization of PAN more than 5 other organic wastes (pulp mill, dairy manure, biosolids, and compost) in the first 7 days of a 91 incubation and remained higher for 70 days. The material C:N ratio appeared to help determine the use of bokashi (Boechat et al., 2013).

In a greenhouse study using anaerobic bokashi (food waste, wheat bran, and EM-1) pots amended with bokashi had higher soil nitrate when applied at 112 kg N ha^{-1} relative to compost and vermicompost (both bark, manure, food waste-based). In a similar field experiment, bokashi provided a prolonged supply of inorganic N from higher initial amounts of ammonium which transformed to nitrate over 10 weeks, likely from aerobic nitrifying bacteria. For the spinach crop, Bokashi added sufficient soil available P and K and increased Mn and Fe availability (Christel, 2017).

1.3.1.3 Plant response following use

The variability of the results of bokashi on plant growth could be from the fermentation process or material stabilization differences. Many studies do not indicate the amount of bokashi stabilization before use (Daiss et al., 2008; Ghanem et al., 2017; Xavier et al., 2019). The overall fermentation process can be short (7-15 days) (Daiss et al., 2008; Ghanem et al., 2017; Xavier et al., 2019) while other studies have a longer duration (21-30 days) (Álvarez-Solís et al., 2016; Christel, 2017) and can also be aerobic instead of anaerobic (Álvarez-Solís et al., 2016; Maass et al., 2020). It has been suggested that bokashi should undergo an anaerobic process with aerobic final stages to end with a more stable finished product (Yamada & Xu, 2001). The positive effects to plant response from bokashi may be related to longer processing times or aerobic stabilization where there was no indication of phytotoxic effects (Christel, 2017; Maass et al., 2020). In a study that increased yield the days of fermentation were 30 and was aerobic (Álvarez-Solís et al., 2016). In the few reviews that have been published on bokashi, the fermentation and stabilization processes are not summarized in the literature (Olle, 2020; Quiroz & Céspedes, 2019).

1.3.1.3.1 Yield

Most often yield increases due to bokashi amendments are suggested to be from increased plant-available nutrients (Olle, 2020). Bokashi has demonstrated increased yield of cabbage

(Xavier et al., 2019), lettuce (Ghanem et al., 2017), onion and jalapeño (Álvarez-Solís et al., 2016), spinach (Christel, 2017), but not tomato or peppers (Álvarez-Solís et al., 2016), relative to controls.

The initial yield of tomato fruit was lower in bokashi treatments compared to unamended soils but increased at later stages (4 weeks later). This suggests a limitation in immediate nutrient release followed by higher nutrient mineralization (Xu et al., 2001). Bokashi that was made from rice bran, rapeseed, and fish waste when added to chicken manure with and without inoculation, using EM-1 showed that inoculation of both treatments prior to fermentation increased tomato fruit yield. In all the treatments fruit yield was highest in the latest week (8) than the previous weeks (1-7) (Xu et al., 2001).

A field study using anaerobic bokashi (food waste, wheat bran, and EM-1) applied at high rates (112 kg N ha^{-1}) significantly ($p<0.05$) increased yield at the second harvest of spinach compared to vermicompost, compost, and the unamended control (1.42 compared to 0.47, 0.23, and 0.20 t ac^{-1}, respectively). The researchers attributed higher yield from the second harvest of spinach due to higher soil nitrate mineralization from the bokashi. Spinach yield was significantly ($p<0.05$) higher for food scrap vermicompost and bokashi, compared to the compost (bark, manure, and food waste-based) (Christel, 2017). In their study, grain was inoculated for 2 weeks, followed by a 3-week fermentation process and an additional anaerobic, 2-week stabilization period.

In a field study by Xavier et al., (2019) higher doses of bokashi increased yield. Rates of bokashi applied at 0.5, 7.5, 10, and 12.5 t ha^{-1} were evaluated for effect on cabbage yield found that the best rate was 10 t ha^{-1} and not the highest rate (Xavier et al., 2019). In a study in Chiapas, Mexico, bokashi (30-day plant and manure-based aerobic fermentation) significantly increased onion yield vs. an unamended control (21.0 vs. 6.4 t ha^{-1}). Pepper yield from bokashi treatments were numerically higher (1.6 ± 0.8 t ha^{-1}) but not significantly different than the control (0.9 ± 0.5 t ha^{-1}) (Álvarez-Solís et al., 2016). The highest dose of bokashi (kitchen waste) in a pot study increased lettuce yield compared to the mineral fertilized control (716 vs. 498 g fresh, respectively) (Ghanem et al., 2017).

1.3.1.3.2 Nutritional density

Bokashi has demonstrated the potential to increase foliar concentrations of N, K, P, Mg, Mn, and Zn (Christel, 2017; Daiss et al., 2008; Maass et al., 2020) relative to unamended controls. In a field study spinach leaf concentrations of N, K, Mn, and Zn increased from food scrap bokashi (Christel, 2017), which corresponded with increased soil available Mn and Zn. In a pot study, three rates of bokashi were applied to parsley with varying treatments of rock phosphate added either during the process, to the pot, or omitted as a control. The highest chlorophyll index was seen in the highest BK rate applied with rock phosphate to the pot. All treatments with the highest amount of BK had the highest foliar and soil available P (Maass et al., 2020). This study had positive effects on parsley growth, even with a short fermentation duration (8 days) which may have been from aerobic fermentation due to turning.

In a field study, chard treated with EM-bokashi had higher tissue P and Mg than the unamended control. However, chard nutritional quality (P, Na, K, Ca, Mg, and Fe) did not increase significantly from bokashi (EM, wheat bran, and manure) compared to product applications of Greengold® (minerals, salts, organic acids, and polysaccharides) (Daiss et al., 2008).

1.3.2 Biosolids-based blends or composts

Exceptional quality (EQ) biosolids are class A biosolids that meet additional requirements of pathogen reduction as well as vector attraction reduction (VAR) and pollution concentration limits (USEPA, 2018). Class A biosolids must have non-detectable levels of pathogens and are regulated via process-based (processes to further reduce pathogens) and numerical (fecal coliform or Salmonella *sp.*) standards.

Class A biosolids can be produced in a variety of ways to assure pathogen kill and VAR. A common method for creating class A biosolids is composting to 55°C or 15 days in windrows or 5 days in aerated static piles. Once EQ standards are met site restrictions and management practices such as permitting or pollutant tracking is no longer required (USEPA, 2018).

1.3.2.1 Typical amendment characteristics

Biosolids can be composted or blended with other feedstocks to create a finished product with acceptable pH, EC, and N characteristics that increase suitability for home gardening (Alvarez-Campos et al., 2018; Badzmierowski et al., 2020; Batjiaka & Brown, 2020). Biosolids have high total organic C, total N, and P as well as an active microbial abundance and diversity (Medina-Herrera et al., 2020). Biosolids are composed of both labile and recalcitrant carbon sources such as hemicellulose, cellulose, and lignin. Biosolids can vary in nutrient concentration, organic matter, and pH based on wastewater treatment processes (Rigby et al., 2009). Aerobic thermophilic composting can take 3 months to 1 year.

1.3.2.1.1 Biological characteristics

Relative to fertilized controls and other OAs, biosolids have high fungal and bacteria abundance and activity (Cogger et al., 2013; Kurzemann et al., 2020; Ros et al., 2006). Medium and high rates of biosolids (7 and 9 Mg ha^{-1}) increased gram-negative bacteria, anaerobic bacteria, and bacteria: fungi ratios compared to anhydrous ammonia when applied in a 2-year wheat-fallow rotation (Cogger et al., 2013). Additions of biosolids at rates above 50% (v/v) in green waste compost increased fungal communities (according to ITS-RNA markers) compared to compost without biosolids (Belyaeva et al., 2012).

In a 27-year field trial, applications of biosolids-based compost (175 kg N ha^{-1}) increased soil microbial biomass and activity but did not affect microbial diversity compared to mineral N fertilizer treatments. Biosolids-based compost also increased soil β-glucosidase activity (an enzyme responsible for carbon mineralization) (Kurzemann et al., 2020). Microbial biomass and respiration were higher for soils amended with biosolids-based compost than mineral fertilizer, manure compost, or green waste compost (Ros et al., 2006).

1.3.2.1.2 Chemical characteristics

Total C, total N, C:N ratio

Biosolids-based amendments have high total C and total N (Alvarez-Campos et al., 2018; Batjiaka & Brown, 2020). Characteristics depend on the method of stabilization. Commercial products made from Class A cake (Tagro) from Tacoma, WA had different total C depending on the recipe. Tagro Mix (biosolids, sawdust, and sand) had a total C of around 7% and Tagro potting mix (biosolids, aged bark, and sawdust) had a total C of 20.3% (Batjiaka & Brown, 2020). In the same study, the total N for Tagro Mix and Tagro Potting Soil was 0.64% and 1.16%, respectively. Compared to four EQ products a biosolids-based compost had a higher C:N ratio (12.0) than thermally- and air-dried biosolids (7.8 and 8.1) (Alvarez-Campos et al., 2018).

pH and EC

Typical pH ranges for EQ products range from 6.5 to 9 (Alvarez-Campos et al., 2018). A variety of composts made from biosolids, and wood waste had a $pH_{1:5}$ were more alkaline than the peat-perlite control (5.5) from 5.8 to 6.8. The $EC_{1:5}$ was slightly higher than the control (0.9) with a range from 1.0 to 1.6 dS m^{-1} (Hummel et al., 2014).

Seven commercially available EQ products when used as an amendment had low EC (< 2.5 dS m^{-1}). When used as 100% of the growing media EC ranged from 3.0 to 7.5 dS m^{-1} which likely reduced germination emergence of soybeans (Alvarez-Campos et al., 2018).

Tagro Potting Soil and Tagro Mix had a higher pH (7.77 and 9.00 pH; saturated paste) (Alvarez-Campos et al., 2018) than Tagro Mix in another study (pH of 6.57 and EC of 0.98 dS m^{-1}(Batjiaka & Brown, 2020). The $pH_{1:5}$ and $EC_{1:5}$ of GroCo and Tagro were 6.1 and 6.2, and 2.1 and 1.2 dS m^{-1}, respectively, and similar to a peat-perlite control (Krucker et al., 2010).

Nutrient content

Non-composted biosolids have high concentration ranges of N 20-80 g kg^{-1}, P 15-20 g kg^{-1}, K 1-6 g kg^{-1}, S 6-13 g kg^{-1}, Ca 10-40 g kg^{-1}, and Mg 4-8 g kg^{-1} (Cogger et al., 2006). Six commercial EQ biosolids that were blended or composted had slightly lower macronutrient concentration ranges of P 5.1 to 17.0 g kg^{-1}, K 0.9 to 4.0 g kg^{-1}, S 2.5 to 14.1 g kg^{-1}, Ca 8.5 to 29.3 g kg^{-1}, and Mg 1.8 to 3.5 g Mg kg^{-1}. Micronutrients ranged from Fe 15,500 – 58,300 mg kg^{-1}, Mn 248 – 514 mg kg^{-1}, Cu 93 – 241 mg Cu kg^{-1}, and Zn 217 – 535 mg kg^{-1}. High Fe (> 50,000 mg kg^{-1}) in two products were from the addition of Ferric chloride used to precipitate P (Alvarez-Campos et al., 2018).

1.3.2.1.3 Physical characteristics

Typically, EQ biosolid products had a low bulk density, but this depends on the stabilization method. Six commercial EQ products had low bulk density from 0.26 to 0.36 g cm^{-3}. Another product that was thermally dried had a much higher bulk density of 0.71 (Alvarez-Campos et al., 2018). Tagro Mix (which contains sand) had a bulk density of 0.43 g cm^{-3} (Batjiaka & Brown, 2020).

A pot study that used Tagro Mix (2:1:1 class A cake and sawdust and sand, by volume) and GroCo (3:1 biosolids from King County with sawdust, by volume) either with or with 50% bark (by volume) found that Tagro and GroCo had initially higher aeration porosity (22 and 25%) compared to the peat-perlite (Sungro Mix #2) control (16%). GroCo and Tagro had lower water holding capacity (19% and 29%, respectively) compared to the control (51%), however, additions of bark increased water holding capacity for GroCo (40%) and Tagro (39%) (Krucker et al., 2010).

1.3.2.2 Changes to soil properties following use

Biosolids improve soil health in agronomic systems (Barbarick & Ippolito, 2007; Cogger et al., 2001, 2013; Nicholson et al., 2018). In particular, class A biosolids have been well documented as beneficial to soil quality in urban agricultural systems (Alvarez-Campos et al., 2018; Cogger, 2005; McIvor et al., 2012a).

1.3.2.2.1 SOC and total nitrogen content

Biosolids-based OAs have also been shown to increase SOC content in urban soils (Alvarez-Campos et al., 2018; Basta et al., 2016). Many studies evaluate effects in degraded urban systems (Badzmierowski et al., 2020; Basta et al., 2016), however, positive increases have been demonstrated in healthy urban soils (Brown et al., 2012; McIvor et al., 2012b).

A three-year study in a degraded urban soil that applied yard waste compost (137 Mg ha^{-1}), biosolids (202 or 404 Mg $ha^{-1)}$, and a mix (biosolids at 202 Mg ha^{-1}, biochar at 5.7 Mg ha^{-1}, and drinking water residuals at 10.3 Mg ha^{-1}) were incorporated by rototiller (15.2 cm). Biosolids increased organic C relative to compost in the short term, likely from high total N content (Basta et al., 2016).

In a degraded turfgrass system, biosolids amendments applied at agronomic N rates for five years increased SOC (0-10 cm) from 1.74 to 13.6 7 g kg^{-1} (+682%) relative to a fertilized control (Badzmierowski et al., 2020). In a degraded urban system, four EQ biosolids applied at agronomic N rates (112 kg PAN ha^{-1}) increased C storage to a range of 37%-84% compared to the inorganic fertilized control. After the 2nd year, biosolids-based compost increased SOC (g kg^{-1}) from 7.2 (fertilized control) to 11. Biosolids-based compost increased total N (g kg^{-1}) from 0.7 to 1.6 after the third year (Alvarez-Campos & Evanylo, 2019). In an urban soil that had high initial SOC (41.0%), biosolids products Tagro and GroCo (applied at 200 Mg ha^{-1}) increased total C to 51.6 and 80.2%, respectively (McIvor et al., 2012b). Total N increased from 2.8% (unamended control) from Tagro (3.4%) and GroCo (4.0%).

1.3.2.2.2 Physical properties

Biosolids have beneficial effects on soil physical properties (bulk density, water holding capacity, and porosity), application at high rates are particularly effective. Reclamation rates 5-10x's higher than the recommended agronomic N rate improved soil porosity, bulk density, and water holding capacity at field capacity and permanent wilting point (Alvarez-Campos & Evanylo, 2019). In a turfgrass system, biosolids amendments (applied alone or blended with sand and sawdust) at agronomic N rates reduced soil bulk density (0-5 cm) by 33-53% compared to synthetic fertilizer over 5 years (Badzmierowski et al., 2020).

Urban garden applications (200 Mg ha^{-1} dry) of Tagro Potting Soil (class A cake from Tacoma, WA, and sawdust) and GroCo (biosolids-based compost from King County, WA) increased soil infiltration rate by 5 to 200x's the unamended soil control and decreased soil bulk density (g cm^{-3}) from 1.07 to 0.55 (GroCo) and 0.77 (Tagro) (McIvor et al., 2012b).

EQ products applied at high rates (5x's the agronomic N rate) reduced soil bulk density and increased porosity significantly ($p<0.05$) compared to fertilized controls in two years. The differences were not significant relative to the fertilized control when applied at agronomic N rate (Alvarez-Campos & Evanylo, 2019).

1.3.2.2.3 Fertility

Class A biosolid amendments increase soil plant-available nutrients and nutrient mineralization (Basta et al., 2016; McIvor et al., 2012b; Neilsen et al., 1998). Co-composting MSW with biosolids was the most effective strategy for increasing degradability and nutrient release capacity (highest net N and C mineralization, extractable P release, and microbial biomass N) compared to compost without biosolids. Material extractable P content positively correlated with N mineralization and SOM increase to amended soils, which together explained 83% of the variation in C mineralization (Tognetti et al., 2008).

Biosolids can increase select soil M-III extractable nutrients Ca, P, Mg, Cu, and Zn (Basta et al., 2016; McIvor et al., 2012b). Biosolids amended soils (202 Mg ha^{-1}) had higher M-III soil extractable P, Cu, Fe, Mn, and Zn, with lower K than hardwood vegetative compost (137 Mg ha^{-1}) (Basta et al., 2016).

Biosolids products Tagro and GroCo increased M-III P in urban gardens (McIvor et al., 2012b). Seven EQ products increased M-III P by an order of magnitude compared to fertilizer (Badzmierowski et al., 2020). Biosolids increased M-III P relative to the non-amended control (Basta et al., 2016).

Biosolids are high in K relative to unamended control soils but are typically lower in available K than other organic amendments. Four EQ biosolids used in an urban turfgrass study had low K and required potash application (Badzmierowski et al., 2020). In a field study, biosolid composts increased extractable P, Cu, and Zn, but not K relative to fertilizer and other local wastes (Neilsen et al., 1998).

Composting biosolids helps reduce negative environmental impacts from soil applications of nutrients. A study that investigated a variety of EQ biosolids found that amendments increased P saturation in soil by 20-35% suggesting beneficial and environmentally sound use for urban soils (Alvarez-Campos et al., 2018). Approximately 20% and 15% of amendment organic N were released depending on the product without excessive increases in soil P (Alvarez-Campos et al., 2018). In a separate study, the N released from composted biosolids was half that of non-composted biosolids and the lower PAN in composted biosolids (4.0%-5.9%) did not negatively impact crop growth. Over 2 years, the N released from composted biosolids depended on soil type which was 6% and 12% of the amendment organic N for clay and sandy loam soils, respectively (Oladeji et al., 2020).

1.3.2.2.4 Microbial

Biosolids-based amendments positively impact microbial indicators relative to other organic amendments. Indicators of biological activity, microbial biomass N (MBN), and dehydrogenase (DHase) were significantly higher in soils amended with biosolids-based composts than MSW-based compost. MBN (mg N kg^{-1}) was higher for biosolids vs. MSW compost (22 ± 2 vs. 15 ± 4). Differences in MBN and DHase activity were not significant due to the type of compost (vermicompost or thermophilic) or amendment rate (2:1 or 3:1 by volume) (Tognetti et al., 2008).

In a 27-year field trial, compost made from urban organic waste, green waste, manure, and biosolids (175 kg N ha^{-1}) with 0 or 80 kg ha^{-1} N mineral fertilizer, found that all OAs significantly impacted microbial community composition and activity. However, soil microbial biomass and activity were higher from biosolids-based compost than the other compost types (Kurzemann et al., 2020).

1.3.2.3 Plant response following use

1.3.2.3.1 Yield

Yield in urban systems is consistently improved from biosolids-based amendments relative to unamended or fertilized controls. In Basta et al., (2016) biosolid amended plots had greater plant biomass production than unamended controls and applications of yard waste compost. Higher rates of EQ biosolids have shown higher yield increases (Alvarez-Campos & Evanylo, 2019). EQ biosolids applied at agronomic N rates increased yield by 3x's that of inorganic fertilizer for cabbage (3.1 and 1.1, respectively) and kale (1.0 and 0.4, respectively) (Alvarez-Campos & Evanylo, 2019).

Many pot studies demonstrate increased plant growth from biosolids-based amendments (Alvarez-Campos et al., 2018; Batjiaka & Brown, 2020; Hummel et al., 2014). In a pot study that tested various organic and inorganic residuals treatments made from class A biosolids, Tagro

Potting Soil (62% aged bark, 31% sawdust, and 7% biosolids) had the highest petunia biomass when grown in 100% of the treatment (24.2 g pot^{-1}) (Batjiaka & Brown, 2020). When diluted (50% by volume with sand) TP had a higher yield vs. the potting mix control (18.4 vs. 6.4 g pot^{-1}, respectively). In general, except for TP, most of the other blends had a better growth response when used at 50% by volume than as topsoil alone (Batjiaka & Brown, 2020). In a pot study by Alvarez-Campos et al., (2018) typical field rates (75 mg PAN kg^{-1} soil) of seven EQ biosolids produced excellent biomass in soybean and tall fescue assays that were higher than inorganic fertilized controls. Compared to the biosolid-based amendments the fertilizer treatment had one of the lowest germination emergence rates (42%) compared to the range of 63-88% of the other treatments. The exception was Tagro Mix which had lower germination than the fertilizer when used as 100% of the potting media. Tagro Potting Soil had the highest germination emergence in both conditions (81% and 88% at applications of 50% or 100%, respectively). In the aforementioned study, EQ biosolids products applied at the same N rate had significantly higher soybean dry mass than inorganic fertilizer. This is consistent with research that found, biosolids alone were too reactive to successfully germinate, but Tagro Potting Mix had > 95% germination rates (Batjiaka & Brown, 2020). In another pot study, pepper yields were significantly higher for both biosolids amendments relative to the peat perlite control under low N fertilization, but not significant for high N fertilization (Hummel et al., 2014).

Without dilution or irrigation, there is the potential for negative impacts on seed germination as a result of high soluble salts content (Alvarez-Campos et al., 2018; Batjiaka & Brown, 2020). When used as a soil amendment EC was low and ideal for plant growth (< 2.5 dS m^{-1}) but when used without dilution in potted assays ranged from 3.0 to 7.5 dS m^{-1} and likely inhibited soybean seed germination (Alvarez-Campos et al., 2018). In Batjiaka and Brown (2020) organic and inorganic residuals mixed with class A cake had a very high EC (39.9 dS m^{-1}) when mixed with walnut shell char and thus poor germination. A limit considered acceptable for plant growth is an EC_e of < 4 dS m^{-1} (or < 2 for sensitive crops) (Weil & Brady, 2017) but studies showed limited effects when $EC_{1:5}$ was < 5 dS m^{-1} (Hummel et al., 2014).

1.3.2.3.2 Nutritional density

Crop nutrient concentrations of N, Ca, P, K, Cu, and Zn have been measured in field studies from soils amended with biosolids and biosolids-based compost (Basta et al., 2016; Neilsen et al., 1998). In sandy soil in British Columbia, CA, applications of biosolids-based compost increased chard leaf N, P, Cu and Zn compared to a fertilized control (Neilsen et al., 1998). In an urban soil, plant tissue N, P, and K were directly related to biomass and significantly higher in biosolids amended plots compared to both the yard waste compost and the unamended control soil. Biosolids with biochar and biosolids alone increased plant Zn nutrient concentrations in edible leaf tissue. Ca and S tissue content were similar between biosolid, the compost, and the control soil. Plant tissue analysis showed the concentrations of trace elements were below toxic ranges (Basta et al., 2016). Wheat grain Zn was higher in biosolids than in fertilized plots (McGrath et al., 2012). However, in one study in urban soil, while yield increased from biosolids-based amendments, there was surprisingly little effect on vegetable mineral content (Alvarez-Campos & Evanylo, 2019).

1.3.3 Food scrap-based vermicompost

Vermicomposting is a mesophilic (25°C to < 40°C) process that commonly utilizes epigeic, *Eisenia fetida* (red wriggler) worms. The finished material is referred to as worm castings. Vermicomposting has been well-studied as a sustainable option for urban solid waste (Sim & Wu, 2010; Singh et al., 2011). Vermicompost typically requires 1 to 6 months to generate a finished product.

1.3.3.1 Typical amendment characteristics

1.3.3.1.1 Biological characteristics

Vermicompost exhibits large microbial diversity of bacteria, fungi, and actinomycetes (Neher et al., 2013) likely from microbial communities present in the gut of the earthworm during digestion (Guhra et al., 2020) or from the mucus worms secrete to move easily in the soil (Lee, 1985). Worm mucus contains water, carbohydrates, proteins, lipids, and polysaccharides (Pan et al., 2010) which are likely added to worm casting material.

Commercial vermicompost (manure and silage material) had significantly higher ($p<0.001$) microbial diversity and abundance than aerated static pile and windrow compost made from the same feedstocks (Neher et al., 2013).

Benefits to crop growth from vermicompost are likely from plant growth regulator substances and humic acids. When macronutrients were kept constant, yield increases from vermicompost were considered to be from increases in biological activity (Arancon et al., 2004).

Carbon respiration and DHase activity, which indicate microbial activity and C mineralization, are higher in vermicompost than compost. Higher CO_2 flux (πmol m^{-2} s^{-1}) was found in soils amended with vermicompost from food waste (8.4) than food waste compost (5.6), chicken manure (4.2), and green waste (3.2) compost (Pant et al., 2012). Between vermicompost types, food waste compost had higher microbial measures than vermicompost that was chicken manure-based.

1.3.3.1.2 Chemical characteristics

Total C, total N, and C:N ratio

Typically vermicompost decreases the initial feedstock material TOC and C:N ratio relative to the original feedstocks (Shukla & Singh, 2010). Three types of vermicompost were made from combinations of cow manure, vegetable waste, leaf litter, and spent mushroom waste had ranges for TOC from 17-35% and total N from 2.02-2.28% (Nurhidayati et al., 2018). Specifically, food waste vermicompost had a total C and N of 19.5% and 1.3%, respectively (Arancon et al., 2004), which was in-between the results found for TOC and total N in kitchen vermicompost (10.3% and 0.85%) and vegetable-based vermicompost (23.92% and 2.11%, respectively). (Nurhidayati et al., 2018).

Typically, the C:N ratio for vermicompost is low (< 20). A study of three types of vermicompost had C:N ratios that ranged from 8.5 to 15.2 (Nurhidayati et al., 2018). In an incubation study, vermicompost was the only amendment compared to green waste, poultry manure, and straw compost, which behaved like a mature compost with a C:N ratio of < 12 (Flavel and Murphy, 2006).

A review by Singh et al, (2011) that compared vermicompost and compost processes (16-day) made from the same MSW feedstock found that the volatile solid reduction was 19% for vermicompost and 12% for compost and that the C:N ratio reduced from 21.5 to 16.2 for vermicompost while the compost reduced from 21.5 to 18.8. While these differences appear small, they indicate a potential for larger differences in final material stabilization and C:N ratio over a longer duration (> 2 weeks).

pH and EC

Typically, worm castings from food waste are alkaline (Arancon et al., 2004; Nurhidayati et al., 2018). The pH of three types of vermicompost (cow manure, vegetable waste, leaf litter, and spent mushroom waste) ranged from 7.1 to 7.4 (Nurhidayati et al., 2018). Worm castings had a higher pH (7.59) compared to the peat-perlite mixture (Hidalgo et al., 2006).

Nutrient content

Vermicompost can increase total Kjeldahl N, total Ca, and total K, relative to the initial feedstock material (Shukla & Singh, 2010). Vermicompost has high concentrations of plant-available nutrients (Sing et al., 2011), including nitrates, phosphates, exchangeable Ca, and soluble K (International Symposium on Earthworm Ecology, 2004). Multiple studies have shown higher nutrients in food scrap-based vermicompost than other types (Arancon et al., 2004; Nurhidayati et al., 2018). Three types of vermicompost (combinations of cow manure, vegetable waste, leaf litter, and spent mushroom waste) had nutrient concentrations ranging from 0.73-10.63% P and 0.23–1.05% K (Nurhidayati et al., 2018).

Food scrap-based vermicompost can have higher macro-and micronutrients than paper or other wastes used for vermicompost (Arancon, et al., 2004; Nurhidayati et al., 2018). Kitchen and vegetable waste vermicompost had macronutrients of 1.96% Ca, 0.80% Mg, and 0.15% P. Vegetable waste vermicompost had Fe, Cu, Mn, and Zn of 412, 57, 98, and 89 mg kg^{-1} (Nurhidayati et al., 2018). Food scrap-based vermicompost had higher nutrients (C, N, Ca, Fe, K, and S) than paper-based vermicompost (Arancon et al., 2004). Both food waste and paper-based vermicompost had similar Mn, Mg, P, Cu, and high levels of nitrates. Food scrap vermicompost had 2.7% P, 9.2% K, 4.4% Mg, 2.6% S, 23.3% Fe, and 609.8% Mn and 50.1 µg g^{-1} Cu (Arancon et al., 2004).

1.3.3.1.3 Physical characteristics

Worm castings are often considered a peat-like material, with a large surface area with high porosity, aeration, drainage, and water holding capacity (Lim et al., 2015).

1.3.3.2 Changes to soil properties following use

Improvements to soil fertility, physical properties, and biological activity from vermicompost have been well documented (Lim et al., 2015).

1.3.3.2.1 SOC content

Carbon content was increased in vermicompost amended soils relative to controls in lab incubations (Aksakal et al., 2016), but larger doses may be necessary for SOM changes in the field (Albiach et al., 2001; Ferreras et al., 2006). In a lab study, applications of 0.5%, 1%, 2%, and 4% (w/w) that vermicompost increased SOM compared to the unamended control by 14.0%, 23.8%, 42.0%, and 90.2% (Aksakal et al., 2016). In a field study, vermicompost (household solid waste, horse, and chicken manure) applied at 10 and 20 Mg ha^{-1} increased SOC compared to nonamended control. However, in the first application increases were significant for just one type of vermicompost at the higher rate only. After a second addition, vermicompost significantly increased SOC at either rate (Ferreras et al., 2006). In a 5-year field study where vermicompost was applied at low rates (2.4 t ha^{-1} yr^{-1}) there was no effect on SOC compared to an unamended control (Albiach et al., 2001)

1.3.3.2.2 Physical properties

Vermicompost has beneficial effects on soil physical properties. A recent study found that worm-secreted mucus assisted in the formation of soil mineral micro aggregates (Guhra et al., 2020). In a field study, the proportion of water-stable soil aggregates in soils amended with vermicompost a rate of 20 Mg ha^{-1} was significantly higher than 10 Mg ha^{-1} (Ferreras et al., 2006).

In a lab study, vermicompost addition improved wet aggregate stability, reduced bulk density, and decreased soil dispersion ratio in a wide range of soil textures. The highest application had the highest total porosity and the lowest bulk density (Aksakal et al., 2016). At the highest rate, vermicompost increased wet aggregate stability from 26.9% to 52.2% compared to an unamended control and was highly correlated (r=0.92) to changes in SOM. Applications of vermicompost at 0.5%, 1%, 2%, and 4% (w/w) decreased soil bulk density (g cm^{-3}) from the unamended control (1.32) to 1.26, 1.24, 1.19 and 1.15 and increased total porosity by 3.5%, 5.1%, 9.1%, and 11.9%, respectively (Aksakal et al., 2016).

1.3.3.2.3 Fertility

Vermicompost has demonstrated increases in soil nitrate compared to fertilizer or manure compost (Christel, 2017; Panicker et al., 2009; Wang et al., 2017). In a greenhouse study, food waste vermicompost had high soil nitrate initially but was identical to the control by the end of the experiment (17 weeks) (Christel, 2017). Concentrations of nitrate N and available P were also found to be higher in vermicompost amended soil than inorganic fertilizer (Panicker et al., 2009). Food and paper waste vermicompost amended soils (5 or 10 t ha^{-1} to top 10 cm) had significantly higher total extractable N and orthophosphates than inorganic fertilizer plots (Arancon et al., 2004). Vermicompost increased soil total N and soil available P and K, compared to a control of 5 t ha^{-1} manure only (Nurhidayati et al., 2018).

1.3.3.2.4 Microbial

Multiple studies demonstrate increased soil microbial diversity and abundance from vermicompost application (Arancon et al., 2004; Neher et al., 2013). Microbial respiration was significantly higher than an unamended control from the application of vermicompost at 2 kg m^{-1}, but not 1 kg m^{-1} (González et al., 2010). Microbial biomass was significantly higher in plots that received 5 or 10 t ha^{-1} vermicompost, compared to inorganic fertilizer (Arancon et al., 2004).

In a field study, vermicompost (household solid waste and manure) applied at low rates (10 or 20 Mg ha^{-1}) increased soil microbial respiration (AA method) but was highly variable depending on vermicompost type (Ferreras et al., 2006).

1.3.3.3 Plant response following use

1.3.3.3.1 Yield

Studies have shown that vermicompost additions have large benefits to yield (Goswami et al., 2017; Sáinz et al., 1998) but reach a point of diminishing returns (Hargreaves et al., 2008). Vermicompost additions of 10%, 50%, and 100% (by volume) significantly ($p<0.05$) increased cucumber shoot yield (dry g pot^{-1}) to 0.8, 1.4, and 1.2, compared a control (0.1) and inoculated soil (0.2) (Sáinz et al., 1998). Vermicompost increased yield and quality for tomato and cabbage (Goswami et al., 2017). In a degraded system, vermicompost increased yield (15-17%) relative to the MSW compost made from the same material (González et al., 2010).

Ideal vermicompost application rates for yield increases likely reach an upper threshold. In a field experiment, vermicompost was applied at four rates (2.5, 5.0, 7.5, and 10.0 t ha^{-1}) with supplemental fertilizer to meet the NPK agronomic requirements. The best results were from the vermicompost application of 7.5 t ha^{-1} compared to the other rates (Hargreaves et al., 2008).

Yield increases from vermicompost differ depending on the feedstock used. A field study tested in a silt-clay soil amended with three different types of vermicompost at four rates (5, 10, 15, and 20 t ha^{-1}) and found that the highest yield was from a spent mushroom compost and coconut husk vermicompost applied at 10-15 t ha^{-1} (Nurhidayati et al., 2018).

In pot studies, vermicompost consistently demonstrates increased plant growth (Arancon et al., 2004; Atiyeh et al., 2000; Christel, 2017; Hidalgo et al., 2006). When used as a portion of the potting media, vermicompost increased plant growth in marigolds (Hidalgo et al., 2006), lettuce (Atiyeh et al., 2000), spinach (Christel, 2017), and chard (Libutti et al., 2020). Vermicompost (pig manure and food waste) mixed in pots at 10% and 20% (by volume), increased lettuce and marigold growth compared to commercial potting mixes (Atiyeh et al., 2000). Applications of manure-based vermicompost (140 and 280 kg N ha^{-1}) increased chard yield in pots compared to unamended soil with higher yields from the higher rates (Libutti et al., 2020).

When nutrients were not limiting across treatments, yield improvements from vermicompost compared to mineral fertilizer suggest that soil physical or biological improvements are responsible for increases in yield, such as plant growth-promoting substances, improved physical structure, and beneficial microorganisms (Arancon et al., 2004). In a pot study with similar nutrients applied, soils that were amended with 40% (by volume) of food waste vermicompost increased pepper fruit yield by 45% compared to commercial potting media without vermicompost addition (Arancon et al., 2004). In a pot study in three soil types, additions of chicken manure (19 t ha^{-1}) and vermicompost (30 t ha^{-1}) improved tomato yield relative to conventional (urea) fertilizer treatment, when applied with similar N and K additions (Wang et al., 2017).

Research has suggested that increased yield from vermicompost may be the result of the humic acids (formed from the breakdown of organic wastes) in worm castings which can act as plant growth hormones from their ability to adsorb to the humates (Arancon et al., 2004) and increase yield (Atiyeh et al., 2002). To test this, pot studies with non-limiting applications of nutrients were applied with extracted humic acid from food waste and pig manure vermicompost. The extracted humic acid significantly increased the growth of tomatoes and cucumbers. In addition, compared to commercially produced phytohormone indole acetic acid (IAA), the humic acids derived from food waste vermicompost (500 mg kg^{-1} dry) significantly increased pepper yield (Arancon et al., 2006).

Field studies of vermicompost demonstrate increased yield compared to inorganic fertilizer and other OAs (Christel, 2017; Panicker et al., 2009; Rashtbari et al., 2020). In clay soil, the blueberry yield was significantly higher in vermicompost plots relative to inorganic fertilizer (Panicker et al., 2009). A lab study, on the yield of canola under drought conditions (moderate and severe stress), found that 4% vermicompost application increased growth attributes significantly compared to compost and a lower (2%) vermicompost rate (Rashtbari et al., 2020). Positive effects of vermicompost relative to NPK were found in strawberry, tomato, and pepper crops (Arancon et al., 2004). Food-based and paper waste-based vermicompost (5 or 10 t ha^{-1}) increased strawberry marketable fruit weight by 35% relative to the NPK treatment. Food waste vermicompost applied (10 t ha^{-1}) significantly ($p<0.05$) outperformed paper waste vermicompost. Pepper yield was the highest at one site, from the higher vermicompost rate, but at another site similar benefits were seen for pepper yield at both rates (Arancon et al., 2004).

1.3.3.3.2 Nutritional density

Crop nutrient concentrations increased from vermicompost but vary depending on crop and nutrient. Vermicompost has shown increased concentration of N and P in beet roots (González et al., 2010), P, Ca, Mg, Cu, Mn, and Zn in cucumber shoots (Sáinz et al., 1998), N and K in Pak-Choi (Nurhidayati, et al., 2018), and Mg, Fe, Zn, and Cu in lettuce leaves (Hernández et al., 2010).

Vermicompost application rates seem to be important for resulting crop nutrient content effects. A higher dose of vermicompost (2 vs. 1 kg m^{-2}) increased N and P concentration in beet tissue. The high rate of vermicompost, both alone and with additional bone meal, had significantly higher N (25.00 and 24.20 g kg^{-1}, respectively) and P (4.50 and 4.76 g kg^{-1}, respectively) than the unamended control, bone meal alone, or the lower rate of vermicompost (González et al., 2010). In Sáinz et al., (1998) vermicompost from urban waste influenced the mineral nutrition of cucumber. Higher doses of vermicompost (10%, 50%, and 100% by volume) increased nutrient content in the shoot tissue for P, Ca, Mg, Cu, Mn, and Zn relative to the unamended control. In contrast, shoot tissue Fe decrease from increasing amounts of vermicompost.

In some cases, there were effects from vermicompost on mineral concentrations of K and P that increased or unchanged depending on the study. In the case of mineral Fe concentrations, the direction of the effect was not consistent between studies. In a silt-clay soil, three types of vermicompost were applied to Pak-Choi (*Brassica rapa* L.) at rates from 5-20 t ha^{-1} increased nutrient uptake for N and K, but not P in the first and second cropping (Nurhidayati et al., 2018). In a 25-week pot study, applications (18.5 t ha^{-1}) of cattle manure-based vermicompost and compost increased leaf Ca and Mg relative to inorganic fertilizer, but did not change P, K, Cu, or Zn. Vermicompost increased leaf Mn, Cu, and Fe, compared to the compost, but Fe was not significantly higher than the inorganic fertilizer (Hernández et al., 2010).

1.3.4 Potential effects of urban residuals-based organic amendments on human health

In general, Americans lack vegetables in their diet regardless of age. The average adult (2,000-calorie diet) should consume 1.5 cups of dark green vegetables per week and 2.5 cups of vegetable equivalents per day (*Dietary Guidelines for Americans, 2020-2025*, 2010). In 2017, a study found that only 1 in 10 adults meet the federal USDA guideline for fruit and vegetable consumption (2-3 cups of vegetables per day depending on age and calorie requirements) (Lee-Kwan, 2017). Almost 90% of the U.S. population does not meet their vegetable recommendations and most adults are only getting half of their recommended vegetable intake (*Dietary Guidelines for Americans, 2020-2025*, 2010).

When vegetables are consumed, they are disproportionate amounts consumed from some categories than others. For example, tomatoes or potatoes are typically consumed more than dark green vegetables. The USDA Dietary Guidelines recommends consuming varied (from five broad categories) and nutrient-dense vegetables. Recommendations for vegetable portions differ based on the method of preparation and water content. For example, two cups of raw leafy salad or dark greens are considered one cup vegetable equivalent (*Dietary Guidelines for Americans, 2020-2025*, 2010).

The use of urban residuals-based OAs that are food scrap and biosolids-based has the potential to fill major gaps in the diet and nutritional intake of the average American when used in home gardening and urban agriculture from improvements to soil and plant health.

Chapter 2. Soil Health Plant Health Pot Study

2.1 Introduction

Urban agriculture can improve food security and sovereignty (Lal, 2020) while increasing the use of highly available local resources as organic amendments (OAs) which are beneficial to soil health and crop yield. Two highly prevalent urban residuals that are valuable as soil OAs once stabilized are food waste and biosolids. Opportunities exist for both these materials to divert large amounts of material from landfills for beneficial end uses. Landfilled material as a percent of the total generated is higher for food waste vs. biosolids (56% vs. 45%, respectively) (*A National Biosolids Regulation, Quality, End-Use & Disposal Survey*, 2007; EPA, 2018).

The U.S. EPA reported in 1998, that 6.9 million tons (dry) of biosolids were produced and 60% were beneficially applied while the remaining 40% were landfilled or incinerated (*Biosolids Generation, Use and Disposal in the United States*, 1999). Most of the land-applied biosolids are permitted for use on agronomic crops and reclamation sites that require further pathogen destruction before use by the general public. This estimate was updated more recently from wastewater flow data was compiled in a report by the Northeast Biosolids, and Residuals Association (NEBRA). In 2004, the number of biosolids produced in the U.S. was 7.18 million tons (dry) of which only 50-55% were beneficially used. The remaining 45% were landfilled or incinerated. Approximately 75% of the biosolids produced that were beneficially used were land applied and the remaining ¼ were class A biosolids (mostly compost or heat-dried pellet fertilizer). Trends for biosolid re-use are increasing. In a survey, 20 out of 43 states responded positively that the beneficial use of biosolids was increasing in their state (*A National Biosolids Regulation, Quality, End-Use & Disposal Survey*, 2007). Methods of stabilization of biosolids include chemical or biological methods such as thermal hydrolysis, lime stabilization, or aerobic composting. Biosolids can be blended or composted with other feedstocks to create a finished product suitable for urban agriculture (Alvarez-Campos et al., 2018; Badzmierowski et al., 2020; Batjiaka & Brown, 2020). For use by the general public, biosolids must be free of pathogens. Exceptional quality (EQ) biosolids are class A biosolids that meet additional requirements of pathogen reduction as well as vector attraction reduction (VAR) along with pollution concentration limits (USEPA, 2018).

According to the US EPA, in 2018, municipal solid waste (MSW) across industrial, residential, and commercial sectors, consisted of significant quantities of food waste (22%) and yard waste (12%) (63 and 35 million fresh U.S. tons, respectively). Large amounts of food waste are landfilled (56%) or incinerated (12%) (35.2 and 7.6 million U.S. tons, respectively) (EPA, 2018). Methods of stabilization of food waste include aerobic thermophilic composting, anaerobic bokashi, and mesophilic vermicomposting.

In this study, amendments were produced using two methods of food scrap stabilization: anaerobic bokashi and vermicompost. Bokashi is a fermentation process that originated in Japan and offers an alternative tool for sustainable soil management (Quiroz & Céspedes, 2019). Typically, bokashi is inoculated with beneficial microorganisms and maintained as anaerobic fermentation. There is a commercially available inoculum called effective microorganisms (EM) which contains a mixture of organisms to start the fermentation process (Yamada & Xu, 2001). Bokashi is a quick process vs. composting (< 2 vs. 3-12 months) but typically requires additional stabilization through soil burial or aerobic composting (Weil & Brady, 2017). Vermicomposting is a mesophilic (< 40°C) process that commonly utilizes epigeic, *Eisenia fetida* (red wriggler) worms. Vermicomposting has been well studied as a sustainable option for urban organics (Sim & Wu, 2010; Singh et al., 2011). Vermicompost generally takes 1-6 months.

In many pot trials or field studies across various systems, the effects on soil quality and subsequent yield to soils from vermicompost and EQ biosolids have been well documented (Aksakal et al., 2016; Alvarez-Campos & Evanylo, 2019, 2019; Beniston et al., 2016; Libutti et al., 2020; McIvor et al., 2012a; Neilsen et al., 1998; Singh et al., 2008), but food scrap bokashi has had limited investigation on soil and plant response. While the concept of 'soil health' has become integrated into agronomic systems, it has yet to be thoroughly tested for urban systems. The impact of soil health on vegetable yield and nutritional quality has had limited investigation in these systems.

Additional research on the impact of OAs on soils with a focus on community gardens and urban agriculture is needed. There have been limited studies that use urban residuals OAs in urban gardens (Alvarez-Campos & Evanylo, 2019; McIvor et al., 2012). Yet, many studies investigate degraded urban soils (Badzmierowski et al., 2020; Basta et al., 2016; Beniston et al., 2016). Urban soils can suffer from degradation due to compaction, pollution, or topsoil removal (De Kimpe & Morel, 2000), however, they can also be even healthier than agricultural fields due to perennial crops, mulching, and irrigation (Brown et al., 2012). It is important to investigate the use of highly available, locally sourced urban residuals for their effects on different urban soils.

Plant and soil impacts urban-derived OAs depend on amendment characteristics as well as soil and environmental factors. We conducted a pot study using OAs made from biosolids and food scraps to answer the following research questions:

- What are the impacts from urban residuals-derived OAs on soil health and are they consistent across different soils?
- How do vegetable yield and foliar mineral concentration compare between crops grown in soils that are traditionally fertilized vs. amended with urban residuals-based products?

2.2 Materials and Methods

2.2.1 Control soils and treatments

A pot study was conducted to test kale (*Brassica oleracea* subsp. *Acephala* ‘Winterbor’) and Swiss chard (*Beta vulgaris ‘*Fordhook Giant’) response to biosolid and food scrap-based soil amendments. Two soils were used as controls. This study was an extension of a field trial. The field trial was conducted at three sites where locally-produced OAs had been used over time. The impact of the OAs on soil health, crop yield, and nutrient concentrations were measured as part of that trial. For this trial, we directly compared each of the amendments from the different field sites on two of the control soils. One control soil was sourced from the City of Tacoma Central Wastewater Treatment Plant in Pierce County, WA (Tacoma). The Tacoma soil was not classified and was likely fill remnant from plant construction. The second was collected from the South Plant Wastewater Treatment in Renton, King County, WA (Renton) which is part of the Woodinville series; Fine-silty, mixed, superactive, nonacid, mesic Aeric Fluvaquents (NRCS Soil Survey Staff, 2021). Control soils were collected at the surface (20 cm) by shovel from random areas at each site. The control soils were sieved moist through a 4 mm sieve and stored fresh prior to use.

The OA treatments were locally sourced near King County, WA. Vermicompost, bokashi, and worm tea were made from food scraps generated at the Monroe Correctional Facility (Monroe, WA). Food scraps collected from the cafeteria were pulped before further processing. For the bokashi, food waste was placed in large barrels, layered with inoculated grain, and stored for at least 6 weeks (Hachney & Brown, 2017). The vermicompost was produced by layering food waste with shredded paper. The worm (vermicompost) tea was prepared by circulating water through the vermicompost for 24 hours and was stored in the refrigerator (4°C) in-between weekly applications throughout the kale pot study (7 weeks). Two commercial biosolids products were included in the study; Tagro and GroCo. GroCo is a biosolid-based compost that is produced using anaerobically digested class B biosolids composted with fir and hemlock sawdust for at least one year (3:1 biosolid:sawdust by volume) (King County, 2021). Tagro Potting Mix is a blend (% by volume) of class A biosolids (8%), aged bark (61%), and washed/screened sand (31%) from Tacoma Central Wastewater Treatment Plant in Pierce County, WA (McIvor et al., 2012a).

2.2.2 Amendment application rates

Amendments were applied at rates of 210 and 220 Mg dry ha^{-1} to the Renton and Tacoma soil, respectively. Dry application rates were calculated after measuring the percent solids and bulk density of each amendment (Table 2.1). Total solids were weighed in triplicate and dried at 60 °C for at least 24 hours to determine gravimetric water content. Initial bulk density was recorded by filling the fresh material into a container of known volume and calculating the dry mass from the total solids content. Below is an example of the calculated dry mass addition from the 1:1 by volume (fresh) addition for bokashi and the dry mass of the control soils. To summarize from the calculation, dry rates of addition were 1.17 kg bokashi to 5.32 kg (Tacoma) and 4.54 kg (Renton) soil. Dry mass additions as a percent of the total mass (% dry) were calculated using Equation 1.

The high rate was chosen to represent two potential scenarios. The first is a community gardener who uses high rates of amendments to rapidly improve the soil. The second represents what cumulative loading rates would be over time. The latter is more in line with the use of amendments in the field component of the study.

Table 2.1 Amendment and control soil total solids, bulk density, fresh volume addition, and dry mass addition.

Amendment or control	Total solids	Bulk density	Volume added (fresh)	Mass added (dry)
	%	g cm^{-3}	g cm^{-3}	kg
Renton soil	79.1 ± 3.0	0.67	6,500	4.54
Tacoma soil	96.0 ± 3.5	0.82	6,500	5.32
Bokashi	21.0 ± 2.9	0.18	6,509	1.17
GroCo	37.6 ± 1.6	0.13	8,970	1.17
Tagro	48.7 ± 4.5	0.22	5,243	1.17
Vermicompost	36.7 ± 11.9	0.21	5,945	1.17

*Mean (n=3) ± standard deviation. Control soils are in grey.

$$\frac{1{,}170\ Bokashi\ (\ dry\ g)}{5{,}320\ Tacoma\ control\ +1{,}170\ Bokashi\ (\ dry\ g)} = 18\%$$

$$\frac{1{,}170\ Bokashi\ (dry\ g)}{4{,}540\ Renton\ control + 1{,}170\ Bokashi\ (dry\ g)} = 20\%$$

Equation 1. Example calculation of percent addition of 18% (Tacoma) and 20% (Renton) soil (dry mass basis) based on bokashi and control soil dry application rates.

Amendments were mixed with the control soils as follows. The bokashi was mixed with the control soils (1:1 by volume fresh) to allow time for the material to stabilize. Bokashi was mixed by setting a bottom layer of each respective control soil on a tarp and evenly spreading bokashi over top. We then mixed thoroughly mixed the material by hand and cured the mixture for 11 weeks in a 19-liter plastic bucket. Bokashi was cured for a longer duration than the other amendments by an additional 6 weeks. When added 1:1 (by fresh volume) approximately ¼ of the dry weight was bokashi which was consistent with the high moisture content of food waste. The process was similar for the rest of the amendments which cured for 5 weeks total in 19-

liter buckets with holes to maintain aerobic conditions. During curing, the amended soil mixtures were turned by hand weekly to ensure even mixing, increase aeration, and allow for stabilization.

The experimental design included a fertilized and unamended control for each soil type. The fertilizer control was an inorganic fertilizer (Scotts® Lawn and Turf Builder, 24-25-4) applied at agronomic N rate (224 kg ha^{-1} or 1.65 g pot $^{-1}$) to the top 5-8 cm of the soil. Worm tea additions in the kale study were added at 250 mL weekly (for 7 weeks total). Before planting kale, aliquots of amended soil mixtures and control soils were set aside for soil analysis and later use in the chard pot study.

2.2.3 Kale pot study

The kale pot study was conducted at the University of Washington greenhouse at the Center for Urban Horticulture (CUH) in Seattle, Washington. The greenhouse was set to a 14-hour daytime photoperiod. Temperatures were typical for summer in the Pacific Northwest with 20-23°C day and 18-20°C night temperatures. Humidity was set to 68% and the light was at 500 µmol photons m^{-2} s^{-1}.

The kale pot study experimental design tested seven treatments added to two soil types with four replicates of each treatment (N=56). The treatments used in each respective soil (Renton and Tacoma) were the following: anaerobically fermented food scrap bokashi, GroCo, Tagro Potting Soil, food scrap vermicompost, worm tea, inorganic fertilizer, and soil only control.

Kale (*Brassica oleracea* subsp. *Acephala* ‘Winterbor’) was grown from direct seed to maturity (52 days). Plants were arranged on greenhouse benches in a randomized complete block design and randomly re-arranged halfway through the study. In each pot (2-liter), three kale seeds were planted (1.3 cm depth). Germination emergence was recorded 1 and 2 weeks after planting. In pots without germination, another round of seeding was attempted and recorded. Kale plants were watered as needed. Plants were harvested at maturity at the stem (2.5 cm above the soil). The kale was stored in paper bags and dried at 55°C for a minimum of seven days for later nutrient analysis.

2.2.4 Swiss chard pot study

Due to COVID-19 restrictions, a second pot study growing Swiss chard (*Beta vulgaris* subsp. *vulgaris* 'Fordhook Giant') was moved outdoors. The material in pots previously used in the kale greenhouse study was also used for this portion of the study. The four replicates for each soil and treatment combination were taken from the pots, combined, and homogenized. After homogenization, the mixtures were supplemented (approximately 25% by volume, fresh) with the previously reserved amendment soil mixture or control soil. The mixture of the combined soil from the kale study with the fresh material was redistributed into four replicate pots per treatment for the chard study. The inorganic fertilizer control received an additional 56 kg ha^{-1} (0.4 g pot^{-1}). The worm tea treatment from the kale pot study was excluded from this second part of the trial as we had no access to the tea during the COVID-19 related lockdown. The chard experiment had six treatments with four replicates in each of the two soils (N=48).

The field location for the chard pot study was near Kingston, WA. During the study, in June and July, the total monthly precipitation was 19.1 and 7.1 mm, respectively. Average monthly air temperatures (°C) were 15.0 and 17.3 for June and July with ranges from 10-21 and 11-24, respectively. Daylight hours were approximately 16 (*Ag Weather Net Map*, 2021). The pot study was conducted in randomized blocks on a 1.2 x 15 m row covered with landscape fabric in an open field.

Swiss chard was grown to maturity (56 days) from direct sow (June 2, 2020, to July 28, 2020). Three seeds were planted per pot. Emergence was recorded after 1 and 2 weeks. The second round of seeding was attempted in pots without germination. The chard seeds being a multigerm seed had very different rates of germination and required thinning to two plants per pot at 3 weeks. The chard pots were watered as needed. Swiss chard yield (g fresh pot^{-1}) was determined by harvesting the plant at the stem (2.5 cm above the soil). Harvested chard was stored in paper bags and dried at 55°C for a minimum of seven days for later nutrient analysis.

2.2.5 Soil analysis

Amendments, control soils, and amended soil mixtures were air-dried for at least one week before being ground and sieved to < 2 mm for analysis. Samples were sent to Kansas State University Soils Testing Lab (Manhattan, KS) for total C and total N using 0.35 g for dry combustion (LECO TruSpec CN combustion analyzer). Sample modifications (0.13-0.25 g) had to be made to measure Tagro and GroCo which had difficulty fitting into the required sample container size due to the low density of the material. Mehlich-III (M-III) extractable K, P, Mg, S, Fe, Mn, Cu, and Zn (mg kg^{-1}) was measured via inductively coupled plasma mass spectrometry (ICP-MS) (Mehlich, 1984). All lab tests included random duplicates for quality assurance. Soil pH was tested in duplicate and EC were tested in triplicate using a portable meter (Milwaukee 2-in-1 portable pH/EC meter MW 802, Rocky Mt, NC) in a 1:2 soil: water slurry at room temperature (25°C) after being suspended for one hour, then lightly stirred. The pH and EC of the amendments were tested using a 1:5 soil:water slurry (Gavlak et al., 2005). Soil analysis specific to the chard study was the final bulk density. Chard final bulk density was measured using the mass and volume of soil left in the pot. The volume was determined by marking the top of the soil at the appropriate height on the pot, removing the soil, lining the pot with a plastic bag, and filling it with water. The dry mass was determined by weighing the fresh soil and converting it to dry mass using the measured material total solids.

Mineralizable carbon (min C) and permanganate oxidizable carbon (POXC) were evaluated on initial amended soil mixes. Min C was also evaluated on the amendments alone. Methods for both tests are described in detail below. Procedures for min C and POXC were adapted from Oregon State University Soil Health Laboratory in Corvallis, OR (Oregon State University, 2021) according to previous studies (Franzluebbers, 2016; Islam et al., 2003). Min C and POXC were conducted at the WSU Soil Health Lab located in the Northwestern Washington Research and Extension Center (Mt. Vernon, WA).

2.2.5.1 Mineralizable carbon

Min C samples were weighed in triplicate to 10 (± 0.01 g) and placed in a condiment container (60 mL) within a 1-liter glass jar. Each batch was run with check soils and blanks. The incubation (25 °C) was initiated by carefully adding deionized water (3 mL) to the surface of each sample. CO_2 concentrations in the headspace after 24 hours were recorded using an LI-870 CO_2/H_2O gas analyzer (Li-Cor Lincoln, NE). The machine was warmed up (15 minutes) and calibrated using < 2, 1,000, and 5,000 ppm gas standards attached to a flow regulator (1-L min^{-1}). The machine records CO_2 concentration every second. Readings for each sample were taken for over 90-

second intervals. The last 30 seconds of the reading were averaged as a final point value for each sample. Raw CO_2 concentrations were adjusted from the baseline (blanks) and calibrated to the standard curve from the known gas concentrations. CO_2 values (ppm) were converted from a volume basis to a mass basis (mg CO_2-C) using ideal gas law and the jar headspace volume. Lastly, values were converted to a daily rate per kg of air-dried soil. All samples with > 15% coefficient of variance were re-analyzed.

2.2.5.2 Permanganate oxidizable carbon

In brief, POXC samples were weighed in duplicate to 2.50 (± 0.01 g) into polypropylene Falcon tubes (50 mL). In the tube with soil, deionized water (18 ml) was added followed by 2.0 mL of 0.2 *M* potassium permanganate ($KMnO_4$) stock solution. Samples were then shaken on a side-to-side shaker (180 rpm for 2 minutes) and left to settle in the dark (10 minutes). After the reaction, 0.5 mL of supernatant was transferred to a 'dilution tube' of DI water while avoiding any organic matter particulates. Subsequently, two samples from the dilution tube are pipetted onto a 96-well plate. A stock solution of 0.2 *M* potassium permanganate ($KMnO_4$) was used to prepare four standard solutions of concentrations 0.005 *M,* 0.01 *M*, 0.015 *M,* and 0.01 *M* that were also plated. Absorbance was analyzed using a spectrophotometer (Synergy LX Multi-Mode BioTek Instruments Inc., Winooski, VT) set at 550 nm to determine the amount of carbon that reacted with the $KMnO_4$. Higher POXC reacts with more $KMnO_4$ making a clearer solution. If the coefficient of variance between replicates was > 10% they were re-analyzed.

2.2.6 Plant analysis

Kale and chard yield was weighed immediately after harvest. Foliar mineral concentrations were analyzed once crops had dried at 55°C for a minimum of seven days and measured at King County Environmental Lab (KCEL; Seattle, WA). The method was slightly adapted from the U.S. EPA method 3050B with 2.5 mL nitric acid, 0.25 mL of 30% hydrogen peroxide, and 0.5 mL of hydrochloric acid to decrease the amount of sample required and reduce waste generation. Then the digestate was analyzed using ICP-MS according to the KCEL standard operating procedure (Sanders, 2019). When yield was limiting, samples from the same treatment were combined for mineral concentration analysis. Mineral concentrations were converted to a dry mass basis (mg kg^{-1} dry) prior to statistical analysis using leaf total solids.

2.2.7 Statistical analysis

Statistical analysis was conducted using *R* statistical software (R Core Team, 2016). A two-way ANOVA was used to test the main effects and interaction of treatment and soil type for soil min C, POXC, crop yield, and foliar mineral concentrations. When an interaction effect or soil effect was found to be significant ($p<0.05$) the main treatment effects were analyzed separately for each soil type and interaction plots were investigated. Pairwise mean comparisons were analyzed using Tukey HSD post hoc analysis. ANOVA assumptions were for normality and homogeneity of variance were tested using Shapiro Wilks test and Levene's test, respectively. Transformations (square, square root, and log10) were applied to the data as needed.

Principal component analysis (PCA) was conducted in *R* using the packages vegan (Okasanene et al., 2020) and factoMineR (Sebastien et al., 2008). A PCA was conducted using only the plant response data for each crop individually. This was because the kale and chard yield and nutritional density data satisfied the rule of thumb (observations > 3 * attribute variables), but the soil data had too few observations. The data were transformed as needed and standardization was not required because the PCA used a correlation matrix. The number of principal component axes with maximal and significant variation explained for the original data were selected to create unconstrained ordination plots for each crop. Scree plots and pseudo-F values from 1,000 random permutations were used to test the significance of the selected principal component axes.

2.3 Results

2.3.1 Control soils, amendment, and amended soil mixture analysis

2.3.1.1 Control soils

The two control soils used in this study (referred to as Renton and Tacoma) are representative of urban soils. The Tacoma soil is unclassified and was collected from landscaped and bare areas within the treatment plant. It may have been a remnant subsoil from treatment plant construction. The texture of the Tacoma soil was loamy sand (74 g kg^{-1} sand, 16 g kg^{-1} silt, and 10 g kg^{-1} clay). The Renton soil was collected from an area that is used as a demonstration farm within the Renton Wastewater treatment plant. It is classified as a part of the Woodinville series; Fine-silty, mixed, superactive, nonacid, mesic Aeric Fluvaquents. The soil was collected from a heavily grassed area. The texture of the Renton soil was a sandy loam (54 sand g kg^{-1}, 32 silt g kg^{-1}, and 14 clay g kg^{-1}) according to data from an unpublished field study of the same soils. Neither soil had any evidence of contamination.

2.3.1.1.1 Chemical properties: control soils

Chemical soil properties were in acceptable ranges for crop growth. The pH, electrical conductivity (EC), total C, total N, and C:N ratio for both control soils can be found in Table 2.2. Total C (2.46% and 4.50% for Renton and Tacoma, respectively) were slightly higher than the typical range of 0.5-2.5% found in most arable mineral soils (Pribyl, 2010). Total N for both soils (0.21% and 0.26% for Renton and Tacoma, respectively) were within the typical range from 0.02-0.5% for mineral soils (Havlin, 1999). The C:N ratio was within the common range for mineral soils 8 – 15 (Weil & Brady, 2017) for the Renton soil (12), but slightly higher for the Tacoma soil (18).

The pH for both control soils (5.90 ± 0.06 Renton and 5.23 ± 0.11 Tacoma) were within acceptable ranges for crop growth (5.5-7.0) (Weil & Brady, 2017). The $EC_{1:2}$ was also low for both soils (0.23 ± 0.03 Renton and 0.07 ± 0.02 Tacoma dS m^{-1}) and below levels of soluble salt that would be detrimental to crop growth ($EC_{1:2} < 2.4$ dS m^{-1}) (Miller & Horneck, 2013).

Mehlich-III extractable nutrients

The plant-available nutrients from Mehlich-III (M-III) extraction for both control soils are shown in Table 2.3. Initial M-III extractable nutrients for K, P, Mg, Cu, and Zn appeared to be different between both soils, while concentrations of M-III extractable Fe, Mn, and S were closer to one another. The Tacoma soil had higher M-III extractable Cu, P, and Zn, while the Renton soil had higher K and Mg. The Tacoma soil had nearly 3x's the level of Cu and nearly 7x's the concentration of Zn compared to the Renton soil. The Tacoma soil had M-III extractable P that was an order of magnitude higher compared to the Renton soil (109 vs. 1,059 mg kg^{-1} P). The Renton soil had approximately 3x's the level of M-III extractable K and Mg than the Tacoma control. Higher K and Mg in the Renton soil may have been from a higher cation exchange capacity (CEC) than the Tacoma control (28.1 vs. 13.0 $cmol_c$ kg^{-1}) (unpublished data). The

Tacoma soil had CEC consistent with values for dark-colored sand (10-20 $\text{cmol}_c\ \text{kg}^{-1}$). The Renton soil CEC was consistent for a fine-textured, silt loam (15-25 $\text{cmol}_c\ \text{kg}^{-1}$) (Havlin, 1999).

Total metals

The total metals from EPA 3050B extraction (USEPA, 1996) for the control soils were measured in the field study (unpublished). While there appear to be some differences between the two soils, concentrations of all measured elements are well within reported ranges for soils in the U.S. (Burt et al., 2003).

2.3.1.1.2 Biological properties: control soils

Permanganate oxidizable carbon (POXC) and mineralizable carbon (min C) are shown in Table 2.8. POXC and min C represent active carbon pools but are considered functionally different as representative of SOM stabilization and mineralization, respectively (Hurisso et al., 2016). Min C varied by soil, treatment, and soil*treatment interaction ($p<0.001$) and was higher in the Renton soil vs. the Tacoma soil (98 ± 5 vs. 84 ± 9 mg CO_2-C kg^{-1} day^{-1}). POXC varied by treatment ($p<0.001$) and soil*treatment interaction ($p<0.05$). The baseline POXC values for Renton vs. Tacoma soil were 663 ± 10 vs. 552 ± 28 mg kg^{-1}, respectively. POXC and min C the interaction effect meant that each soil was analyzed separately. Our control soil POXC values were similar to the mean (504 mg kg^{-1}) from a large number of soils (n=1,833) (Wade et al., 2020). Our control soil min C values were within the mean min C values found from 13 agricultural sites across the U.S. that had varied agricultural management and ranged from 46 ± 32 to 1,029 ± 511 mg C kg^{-1} (Hurisso et al., 2016).

2.3.1.1.3 Physical properties: control soils

The two control soils had low initial bulk density. The bulk density of the Renton soil was slightly lower than the Tacoma soil (0.62 vs. 0.82 g cm^{-3}, respectively). The control soils had lower bulk density values compared to typical arable surface soils (approx. 1.2 g cm^{-3}) (Weil & Brady, 2017). Note that in this study the bulk density may be slightly underestimated relative to results from the field study due to methodological differences.

2.3.1.2 Characteristics of the amendments

2.3.1.2.1 Chemical characteristics

Total C

Total carbon in the amendments ranged from 28.3% (vermicompost) to 41.8% (GroCo). Biosolids-based and food scrap-based amendments had consistent values with those found in the literature. In our study, GroCo had a very similar total C (41.8%) compared to previous research (McIvor et al., 2012b). In Batjiaka and Brown (2020) Tagro Potting Soil had a total C (20.3 ± 0.61%) which was lower than the total C in our study (31.0%). The vermicompost in our study had total carbon (28.3%) close to the range found in a review (25.4-27.5% total C) (Singh et al., 2011). Our bokashi (40.5% total C) was similar to the values reported for food scrap-based anaerobic bokashi (81.4-84.3% organic matter) (Christel, 2017).

Total N

Amendment total N was high and ranged from 1.13% (Tagro) to 3.76% (bokashi). Total N for biosolid amendments were consistent with previous research (Batjiaka & Brown, 2020; McIvor, 2011) and reported product information (King County, 2021). In our study, GroCo had a very similar total N (1.23%) compared to previous research (McIvor et al., 2012b). In Batjiaka and Brown (2020) the total N in Tagro Potting Soil (1.16 ± 0.02%) was consistent with the results in our study (1.13%). The total N in the vermicompost in our study (2.69%) was close to the range found in a review (1.2-1.6%) (Singh et al., 2011). Our bokashi (3.76%) had a similar total N to values reported previously for food-based anaerobic bokashi (2.45-3.45%) (Christel, 2017).

C:N ratio

Food-based amendments had low C:N ratios (11 vermicompost; 11 bokashi) while biosolids-based amendments had high C:N ratios (28 Tagro; 34 GroCo). The high C:N ratio for GroCo was similar to the reported product information (King County, 2021). The C:N ratio in our study for Tagro Potting Soil (28) was higher than previously reported (Batjiaka & Brown, 2020; Krucker et al., 2010). In Batjiaka & Brown (2020), Tagro Potting Soil had a C:N ratio of 17.5, and in Krucker et al., (2010) the C:N ratio was 14. This could indicate nitrogen loss from the material, but due to the low pH, volatilization was not likely. The C:N in the biosolids mixes can be controlled by adding more or less high C materials.

The C:N ratio for the bokashi (11) was consistent with values of anaerobic food scrap-based bokashi (Christel, 2017; Olle, 2020). The C:N ratio of our vermicompost (11) was lower than the range (15-18) found in a review by Singh et al., (2011), but higher than the C:N of 9.8 found in Epelde et al., (2018) for vermicompost made from 1:1 manure:straw (by volume).

The C:N ratio of an amendment can impact plant-available N (PAN) depending on the amendment material composition. Amendments with C:N ratio > 20 could immobilize soil N (Havlin, 1999). None of the amendments in the plant growth trial indicated that N immobilization was an issue for crop growth. As C:N ratio decreases, PAN typically increases, but this depends on the amendment and can be highly variable for materials with C:N ratio < 15 (Gale et al., 2006). Higher C:N ratios are frequently indicative of lower PAN, however, if the C is recalcitrant that may not be the case. Food waste-based amendments had a lower C:N ratio than biosolids-based amendments, likely from higher total N.

pH and electrical conductivity (EC)

All amendments were acidic (4.20-4.51) with the exception of vermicompost (6.57 ± 0.07) which is typically alkaline. The pH values in our study for GroCo (4.51 ± 0.08) and Tagro (4.20 ± 0.16) were more acidic than reported in the product information for GroCo (6.8) (King County, 2021) and Tagro (6.7) (*TAGRO Potting Soil*, 2020). Previous studies have reported pH values closer to the product information (Hummel et al., McIvor et al). The measured pH of the bokashi (4.49 ± 0.08) was similar to previous results for anaerobic food scrap-based bokashi (4.2 and 4.5) (Christel, 2017). Bokashi is a fermentation process, and an acidic pH is expected. However, there is a wide range for pH (4.2-8.8) in bokashi that depends on the feedstock and process (Quiroz & Céspedes, 2019).

The electrical conductivity (EC; dS m^{-1}) of the amendments was very different. Measured $EC_{1:5}$ values for bokashi (8.61 ± 0.23) and Tagro (6.84 ± 0.07) were high in comparison to the rest of the amendments and the control soils. The measured $EC_{1:5}$ for GroCo (2.11 ± 0.04 dS m^{-1}) was identical to the value reported in Krucker et al. (2010). Vermicompost had a relatively low EC (0.23 ± 0.03) compared to the other amendments which are consistent with Libutti et al., (2020). The EC in the bokashi in our study was higher than previous anaerobic food waste bokashi (5 dS m^{-1}) but within a wide range (4.2-21.2 dS m^{-1}) for many different types (Quiroz & Céspedes, 2019). Previously reported EC for both Tagro and GroCo have varied. In a pot study the $EC_{1:5}$ for Tagro and GroCo were similar (1.0 and 0.5 dS m^{-1}) (Hummel et al., 2014). Differences in reported EC may be due to the amount of time the material had been left outdoors and exposed to rainfall prior to use. For this study, the EC of the material likely decreased during the growth trial due to thorough watering in the greenhouse.

In a recent study by Batjiaka and Brown (2020), the ideal ranges for suitable residuals-based soil blends were determined as the following: pH 5.5-8.5 and $EC_{1:5} < 5$ dS m^{-1}. For select amendments, slight deviations for the suggested ranges in pH and EC would suggest they may be problematic for plant growth. For example, most of the amendments were slightly acidic according to the acceptable range for plant growth (5.0-8.0) (Weil & Brady, 2017), with the exception of vermicompost. Bokashi and Tagro had greater $EC_{1:5}$ than the acceptable limit for plant growth (< 5 dS m^{-1}) (Weil & Brady, 2017). However, amendments were beneficial to plant response in our study, and any issues with soluble salts were likely not a problem by the end of the study due to leaching from irrigation.

Mehlich-III extractable nutrients

Mehlich-III (M-III) extractable nutrients for amendments and control soils are shown in Table 2.3. The M-III extract has been used as a general measure of plant-available nutrients (Antonious et al., 2014; Basta et al., 2016; Brown & Cotton, 2011).

In general, amendments had high amounts of M-III extractable K, Mg, and S in comparison to both the control soils. Nutrient content for M-III extractable P and Zn were high for all amendments relative to the Renton soil only. Select amendments had higher M-III concentrations than the Tacoma soil which had high initial P and Zn concentrations; GroCo and bokashi had higher P and biosolids-amendments had higher Zn. M-III extractable K was higher in food scrap-based amendments (6,365 Bokashi; 6,384; vermicompost) than biosolids-based amendments (GroCo and Tagro; 1,431 and 1,351 mg kg^{-1}, respectively).

Biosolids-based amendments tended to have high M-III Fe, Mn, and Zn compared to food-based amendments and higher Mn and Zn compared to both control soils. Food scrap-based amendments increased Zn (mg kg^{-1}) (33 – 43) compared to the Renton soil (9), but not the Tacoma soil (58) and had less of an effect compared to biosolids-based amendments (108 to 109). Vermicompost, in particular, had low M-III extractable Cu, Fe, and Mn, relative to control soils and the other amendments, except for Mn which was also low in the bokashi. The bokashi and vermicompost are identical food scrap materials that are reflected in the similar plant-available nutrients for K, Mg, Mn, and Zn. However, bokashi had select available nutrients (mg kg^{-1}) that were higher vs. vermicompost for P (3,367 vs. 1,877), S (754 vs. 564), Cu (8.6 vs. 3.1), and Fe (138 vs. 53).

Select amendments had different nutrient compositions. For the amendments included in this trial, Tagro had higher available S and Cu compared to the other amendments; S (Tagro 1,052 vs. 564 to 772 mg kg^{-1}), and Cu (Tagro 14.8 vs. 3.1 to 8.6 mg kg^{-1}). Meanwhile, GroCo had high Mg (2,334 mg kg^{-1}) and P (4,149 mg kg^{-1}) in particular. The M-III extractable P in bokashi (3,367 mg kg^{-1}) was higher than expected relative to biosolids-based material Tagro (1,556 mg kg^{-1}) and vermicompost (1,877 mg kg^{-1}).

Previous results showed biosolids had higher concentrations of M-III extractable Ca, P, and Zn and lower M-III K than unamended soil (Antonious et al., 2014). When applied biosolids amendments may require additional K fertilization depending on the crop (Badzmierowski et al., 2020), but this was not necessary for our study.

2.3.1.2.2 Biological characteristics

The two measures were used to indirectly evaluate soil biological activity in this study were mineralizable carbon (min C) and permanganate oxidizable carbon (POXC). Amendments could only be tested for min C due to high levels of organic matter which prevented POXC. In this study min C was primarily used to evaluate soil biological activity with higher values used as a surrogate measure for microbial biomass, available C, and N mineralization (Franzluebbers, 2016). Min C tests heterotrophic respiration after the rewetting of air-dried soil.

When used on our amendments, min C is similar to methods used to evaluate compost stability CO_2 respiration (U.S. Composting Council, 2001). Stability here refers to the state of organic matter decomposition. In the context of amendment stability evaluation, a lower rate of respiration is considered to be an indication of a mature material that will be suitable for use as a soil amendment. Higher values can be indicative of highly reactive amendments (Batjiaka and Brown, 2020) which typically is restrictive for the best use of the product and indicates potential phytotoxicity from compounds produced during continued decomposition.

A standard method to test compost CO_2 respiration is the NaOH trap method which is outlined in the Test Methods for Examination of Composting and Composts (TMECC) (U.S. Composting Council, 2001). Results are reported in mg CO_2-C g OM^{-1} day^{-1} or mg CO_2-C g TS^{-1} day^{-1} with values < 8 or between 2-4 considered stable for each unit, respectively) (U.S. Composting Council, 2001). The absolute values from these methods should be comparable (Wade et al., 2018) but it is important to realize that sample pre-processing, preincubation, and moisture adjustment can be highly influential on CO_2 respiration results for either min C or other acceptable methods (U.S. Composting Council, 2001; Wade et al., 2018).

Amendment min C values (mg CO_2-C kg^{-1} day^{-1}) were significantly different ($p<0.05$) from the control soils (98 ± 5 Renton; 85 ± 9 Tacoma) (Table 2.4). The control soils had higher min C than the amendments, with the exception of vermicompost. Min C ranged from (16 ± 3) bokashi to (238 ± 19) vermicompost, with intermediate values for the biosolids-based amendments (51 ± 2 GroCo and 44 ± 1 Tagro).

There are reasons to believe that the biosolids-amendments were stable. Tagro Potting Soil is a successfully bagged commercial product which indicates they are likely stable. In a previous study, Tagro Potting Soil has been demonstrated as stable (1.10 mg CO_2-C g TS^{-1} day^{-1}) according to a NaOH trap method (Batjiaka & Brown, 2020).

It is unclear why the bokashi amendment had the lowest min C. As a fermented product that is semi-stabilized with a shorter process duration (Olle, 2020), we would have expected the bokashi to evolve the highest rate of CO_2. Typically, aerobic compost that is composted for less time has a higher CO_2 evolution rate and is less stable (Griffin and Hutchinson, 2007). In a 10-day lab incubation in sandy loam soil, found that 51-day compost had higher respiration rates than 109-day compost (35 and 15 mg CO_2-C g TS^{-1} day^{-1}, respectively) via the NaOH trap method.

2.3.1.2.3 Physical characteristics

All amendments had low bulk density (g cm^{-3}) that ranged from 0.13 (GroCo) to 0.22 (Tagro) (Table 2.2). These values were much lower than the bulk density of the control soils (0.70 and 0.82, Renton and Tacoma, respectively). In a pot study that used Tagro Potting Soil the reported bulk density was 0.28 g cm^{-3} (Batjiaka & Brown, 2020), which was similar to our findings. The bokashi in our study had a lower measured bulk density (0.18 g cm^{-3}) than found in farm-based bokashi (0.46 g cm^{-3}) (Quiroz & Céspedes, 2019), but physical properties are likely highly variable between different types of bokashi.

Table 2.2 Physicochemical properties of amendments and control soils.

Amendment or control	**Bulk density**	**Total N**	**Total C**	**C:N ratio**	**$pH_{1:5}$**	**$EC_{1:5}$**
	g cm^{-3}	%				dS m^{-1}
Renton soil	0.67	0.21	2.46	12.0	5.90 ± 0.06	0.23 ± 0.03
Tacoma soil	0.82	0.26	4.50	17.7	5.23 ± 0.11	0.07 ± 0.02
Bokashi	0.18	3.76	40.51	10.8	4.49 ± 0.08	8.61 ± 0.23
GroCo	0.13	1.23	41.77	34.1	4.51 ± 0.08	2.11 ± 0.04
Tagro	0.22	1.13	30.95	27.5	4.20 ± 0.16	6.84 ± 0.07
Vermicompost	0.21	2.69	28.32	10.5	6.57 ± 0.07	0.23 ± 0.03

*C:N ratio = total C divided by total N. Bulk density is dry mass over volume. Control soils have a grey background. $pH_{1:5}$ and $EC_{1:5}$ mean (n=3) ± standard deviation.

Table 2.3 Mehlich-III extractable nutrients (K, Mg, P, S, Cu, Fe, Mn, and Zn; mg kg^{-1} dry) for amendments and control soils.

Amendment or control	K	Mg	P	S	Cu	Fe	Mn	Zn
				mg kg^{-1}				
Renton soil	389	359	109	39	9.7	385	31.5	8.6
Tacoma soil	117	128	1,059	45	27.1	449	32.4	58.2
Bokashi	6,365	1,008	3,367	754	8.6	138	23.8	33.4
GroCo	1,431	2,334	4,149	772	8.1	441	149.5	107.6
Tagro	1,351	1,288	1,545	1,052	14.8	399	89.4	108.6
Vermicompost	6,384	1,396	1,877	564	3.1	53	21.0	42.9

*Control soils are in grey.

Table 2.4 Mineralizable carbon (min C; mg CO_2-C kg^{-1} day^{-1}) for the amendments and control soils.

Amendment or control	**Min C**
	mg CO_2-C kg^{-1} day^{-1}
Renton soil	98 ± 5 c
Tacoma soil	85 ± 9 c
Bokashi	16 ± 3 a
GroCo	51 ± 2 b
Tagro	44 ± 1 b
Vermicompost	239 ± 19 d

*Letters that are not shared in the column indicate differences according to Tukey HSD pairwise mean comparison ($p<0.05$). Control soils are in grey.

2.3.1.3 Amended soil mixtures

2.3.1.3.1 Chemical properties

Total C

Amendments increased soil total C in both control soils (Table 2.5). In general, vermicompost and GroCo increased total C more than Tagro and bokashi. Control soils had different baseline levels of total C (Renton 2.5%; Tacoma 4.5%) but the increases from amendments were generally similar across the two soils. One exception was that vermicompost addition resulted in a more pronounced increase in total C in the Renton vs. the Tacoma soil (19.9% vs.11.3%). Increases were similar in magnitude to both soils from additions of Tagro (7.9% Renton; 9.3% Tacoma) and bokashi (4.6% Renton; 7.0% Tacoma). The highest increase was from amendments in the Renton soil (2.5%) was from vermicompost (19.9%) while the highest increase in the Tacoma soil (4.5%) was from GroCo (17.4%). In both soils, the lowest increase in total C was from bokashi.

Previous work has shown that adding high nutrient organic amendments can increase long-term SOM storage compared to low C plant residues, especially for amendments high in total P and total S, as is the case for biosolids (Wuest & Reardon, 2016). The observed increases here would likely decrease in magnitude over time in a field application. However, previous studies have shown persistent increases relative to conventionally managed soils (Brown et al., 2012). If additional amendments were added annually— as was done in the field component of this study, it higher soil C would likely persist over time.

Total N

Amendments increased total N compared to the control soils (0.21% and 0.26%, Renton and Tacoma, respectively) (Table 2.5). In both soils, the treatment effect was similar with the exception of vermicompost amendments in the Renton soil, with had a more pronounced effect. In the Renton soil, increases in total N ranged from 0.44% (Tagro) to 1.60% (vermicompost). In the Tacoma soil, increases in total N ranged from 0.48% (Tagro) to 0.78% (vermicompost). In both soils, total N increased the least from additions of Tagro and increased the most from additions of vermicompost. Total N increased similarly in soils amended with GroCo (0.63% Renton and 0.69% Tacoma) and bokashi (0.56% Renton and 0.69% Tacoma, respectively).

C:N ratio

In both soils, Tagro and GroCo increased the soil C:N ratio, and bokashi and vermicompost decreased the soil C:N ratio. The C:N ratio in the Renton soil (12.0) decreased from bokashi (8.2) and vermicompost (12.5) and increased from Tagro (18.1) and GroCo (22.2). The C:N ratio in the Tacoma soil (17.2) decreased to 10.1 (bokashi) and 14.4 (vermicompost) and increased to 19.5 (Tagro) and 25.4 (GroCo). Changes to soil C:N ratio was consistent with the measured amendment C:N ratio which was higher in biosolids-amendments and lower in food scrap-based amendments.

pH and electrical conductivity (EC)

Amendment additions change the pH in both of the control soils (5.90 ± 0.06 and 5.23 ± 0.11, Renton and Tacoma, respectively) (Table 2.5). These changes were generally consistent with the amendment pH values. Adding vermicompost and bokashi increased pH in both soils. Adding the biosolids-based products decreased pH in both soils. For example, vermicompost addition increased soil pH (6.41 ± 0.04 and 6.01 ± 0.16 in Renton and Tacoma soils, respectively). Soil pH decreased from the addition of GroCo (5.19 ± 0.16 Renton; 4.76 ± 0.13 Tacoma) and Tagro (4.86 ± 0.06 Renton; 5.09 ± 0.65 Tacoma). The exception to this pattern was seen with the bokashi amendment. Bokashi addition increased soil pH (7.59 ± 0.5 Renton; 6.72 ± 0.23 Tacoma) even though the amendment was acidic. Bokashi is a product of anaerobic fermentation and potentially still retained products of high energy (Weil & Brady, 2017). Bokashi is semi-stabilized (Quiroz & Céspedes, 2019) and continued decomposition in an aerobic environment may have caused the observed increase in pH (Weil & Brady, 2017).

Mehlich-III extractable nutrients

The Mehlich-III (M-III) extraction was used to estimate plant-available nutrients of the amended soils (Table 2.6). Some M-III extractable nutrients (K, Mg, and S) were higher in the Renton soil while others (P, Cu, Fe, and Zn) were higher in the Tacoma soil. When applied to meet the N levels for a crop, the high nutrient content of food-based and biosolids-based amendments would be expected to meet nutrient at most of the nutrient needs for K, Mg, P, S, Cu, Fe, Mn, and Zn (Alvarez-Campos et al., 2018; Brown & Cotton, 2011; Kelley et al., 2020). Both soil types had medium to high levels of M-III extractable Cu, Fe, Mn, and Zn (Zbíral, 2016). M-III extractable nutrients varied by soil type and amendment, but certain trends were identifiable.

All amendments increased M-III K (mg kg^{-1}) compared to both soils (389 and 117; Renton and Tacoma, respectively) and the increases appeared to be higher in the Renton soil than the Tacoma soil. Larger increases in M-III extractable K were from vermicompost (2,650 and 1,801 in Renton and Tacoma, respectively) and bokashi (2,094 and 1,655 in Renton and Tacoma, respectively) than from biosolids amendments which also increased M-III K.

All amendments increased M-III Mg (mg kg^{-1}) compared to the Renton (359) and Tacoma soil (128), with larger increases in the Renton soil. In both soils, M-III Mg increased the most from GroCo and vermicompost with respective increases to 864 and 827 in the Renton soil and 384 and 415 in the Tacoma soil. To a lesser extent, bokashi and Tagro also increased M-III Mg.

In general, all amendments increased M-III extractable P (mg kg^{-1}). Amendments had much larger effects on M-III P in the Renton soil than the Tacoma soil due to lower initial amounts (109 Renton; 1,059 Tacoma). In both soils, effects to M-III P were higher from GroCo, followed by vermicompost, and then Tagro amendments. In the Renton soil, GroCo had a very large increase (1,244), followed by vermicompost (748), Tagro (505), and then bokashi (307). These trends were similar in the Tacoma soil but lower in magnitude, with the exception of bokashi which decreased M-III P from 1,059 to 822 in the Tacoma soil.

All amendments increased M-III extractable S (mg kg^{-1}) compared to Renton (39) and Tacoma (45). The increases were higher in the Renton soil compared to the Tacoma soil. Vermicompost, Tagro, and GroCo had similar positive effects on extractable S in each soil, but larger increases in the Renton soil (232, 245, and 233, respectively) than the Tacoma soil (157, 158, and 148, respectively).

Amendments generally reduced M-III extractable Cu with the most pronounced effects in the Tacoma soil. This was likely because the Tacoma soil had higher extractable Cu than the Renton soil (27.1 Tacoma; 9.7 Renton).

Amendments had different impacts on M-III extractable Mn (mg kg^{-1}) with increases from Bokashi, GroCo, and Tagro and a decrease from vermicompost in both soils. The magnitude of the effects from amendments was similar in both control soils which also had similar baseline M-III Mn (31.5 and 32.4, Renton and Tacoma, respectively). One exception was the large increase from bokashi in the Renton soil from 31.5 to 122.5 compared to 32.4 to 70.9 in the Tacoma soil.

Amendments had different impacts on M-III Fe (mg kg^{-1}). Food waste-based amendments decreased extractable Fe in both control soils, with larger effects from vermicompost relative to bokashi. Biosolids-based amendments increased soil Fe in the Renton soil only, likely from the lower concentration of Fe in the Renton soil vs. the Tacoma soil (449.1 vs. 385.3). M-III Fe (mg kg^{-1}) increased in the Renton soil from 385 to 428 from Tagro and 480 from GroCo. There were no comparable changes in the Tacoma soil.

Biosolids-based amendments increased M-III Zn in both soils while all amendments increased soil M-III extractable Zn (mg kg^{-1}) in the Renton soil only. These effects were likely from the high baseline M-III Zn the Tacoma soil (58.2) compared to the Renton soil (8.6). In the Renton soil, GroCo (48.7) had a large effect relative to the increases from the other amendments which ranged from 23.9 (vermicompost) to 27.1 (bokashi). In the Tacoma soil, biosolids-based amendments Tagro and GroCo increased M-III Zn (63.2 and 73.1, respectively).

2.3.1.3.2 Biological properties

The active pool of SOM typically represents a very small (5-20%) but highly influential fraction of the total (Weil & Brady, 2017). We used two methods to measure the active carbon fraction: POXC and min C. Min C is approximately 1-3% and POXC is about 1-4% of SOC (Hurisso et al., 2016). While indicating a biologically relevant soil process, POXC is a chemical method that oxidizes carbon. POXC is designed to measure a relatively processed portion of active C. Min C is designed to indirectly measure microbiological activity via CO_2 respiration from aerobic heterotrophic organisms. For both procedures, higher values are interpreted as indications of improved soil biological health. A high min C value means high nutrient release from SOM mineralization. A high POXC value means potential indications of SOM stabilization. Both indicators when used in combination may better assess SOM dynamics than each individually. A review of studies found that the results of the two measures do not always mirror each other even when conducted on the same soils. However, some of the sites that had higher SOC had close correlations between the two measures (Hurisso et al., 2016).

Mineralizable carbon (min C)

Mineralizable carbon varied by treatment, soil type, and interaction effects ($p<0.001$). Therefore, the min C in the Renton vs. Tacoma soil (98 ± 5 vs. 85 ± 9 mg CO_2-C kg^{-1} day^{-1}) were analyzed separately (Table 2.8). Bokashi, vermicompost, and GroCo increased min C significantly ($p<0.05$) relative to controls in both soils (Figure 2.1). In the Renton soil, the increase was very pronounced for the addition of bokashi (811 ± 36), followed by intermediate effects from vermicompost (288 ± 17) and GroCo (144 ± 17) (Table 2.8). A similar pattern was seen for increases in the Tacoma soil. Tagro had a notably different impact compared to the other amendments. In the Tacoma soil, the reduction in min C from Tagro (54 ± 8) was significant ($p<0.05$) compared to the control. In the Renton soil, Tagro (79 ± 6) also decreased min C, but the effect was not significant.

The high value for min C in the bokashi amended soils suggests it may be an outlier. However, very high increases have also been reported in the literature. A review by Hurriso et al., (2016) reported an increase in min C from 354 to 1,184 mg C kg^{-1} in an Ohio urban garden following compost addition (Hurriso et al., 2016). While an outlier in our study, the magnitude of the increase we saw in bokashi was closer to the large effects from amendment addition in the urban garden study. The control soils in our study were much lower, but bokashi and vermicompost demonstrated the large effects closer to the results seen in the urban garden study.

Measured changes to min C from the GroCo amendments in our study were lower in magnitude and closer to the changes in agronomic sites reported from the same review (Hurriso et al., 2016). In an organic tomato system, amendments increased min C (mg kg^{-1} soil) from 359 to 462 and 462 for compost and manure, respectively. At Russel Ranch, a research farm in California compost and cover crops increased min C from 69 in a minerally fertilized control to 89.

Permanganate oxidizable carbon (POXC)

POXC varied by treatment ($p<0.001$) and soil*treatment interaction ($p<0.05$). The effect on POXC from treatments depends on soil type and therefore results were analyzed separately (Table 2.7). The differences in POXC between treatments were significant in the Renton soil but not the Tacoma soil (Figure 2.1). The increases were the highest from GroCo and vermicompost. In the Renton soil, amendments significantly ($p<0.05$) increased POXC (mg kg^{-1} soil) relative to the control (663 ± 10). POXC increases were significantly higher from GroCo (1,231 ± 21) and vermicompost (1,118 ± 87) amendments than Tagro (849 ± 10) and bokashi (915 ± 3). Amendment additions did not have significant effects on POXC values in the Tacoma soil (522 ± 28) although they showed increasing trends.

The results from our study are within the range of values previously reported for a review of POXC from a variety of agronomic sites (87 to 1450 mg kg^{-1} soil) (Hurisso et al., 2016). In the review, an urban garden and crop-pasture site had higher POXC values compared to a variety of agricultural systems. The mean POXC (mg kg^{-1} soil) across treatments in an urban garden was 803 ± 375 with a range from 142 to 1,257. The POXC in the control soil (172) was much lower than the control soils in our study, but the values for amended soils from compost, compost + biochar, and compost + cover crop (913, 1,041, and 913, respectively) were close to the range of POXC values from amendments we saw in the Renton soil and slightly higher than the Tacoma soil. That being said, because of the high POXC in our control soils, the magnitude of the increases in our study as a result of amendments were much lower. Our results are closer to findings from agronomic sites in the same review.

In an organic tomato system, compost and manure additions increased POXC from 557 in an unamended control to 498 and 615 for compost and manure, respectively. At Russel Ranch, POXC increased from 450 in a mineral fertilized control to 507 from compost and cover crop additions (Hurisso et al., 2016). Our study had measured POXC closer to the control soil values in these systems. However, we observed changes in POXC from amendments were much larger in magnitude compared to these agronomic systems.

2.3.1.3.3 Physical properties

Bulk density

In general, amendments reduced the initial soil bulk density compared to the control soils (0.70 and 0.82, Renton and Tacoma) immediately following amendment addition (Table 2.5). The reduction in bulk density was the most pronounced of all amendments in the Tacoma soil. Of the amendments tested, the largest decreases in bulk density (g cm^{-3}) were observed following GroCo addition (0.22 Renton; 0.23 Tacoma). The impacts from vermicompost and Tagro were less than GroCo. Bokashi showed the lowest reduction soil bulk density (0.44 Renton; 0.50 Tacoma) compared to the other amendments.

Bulk density was also measured at the end of the trial. Throughout the experiment, the soil in pots tended to increase bulk density. The final bulk density from amended soils remained lower than the control soils and was generally consistent with initial amendment effects. Adding fertilizer did not change the bulk density compared to the control soils or over time. Increases in SOC from organic amendments across a variety of soil types have been demonstrated to be highly significant and related ($r^2 = 0.69$) to percent reduction in bulk density (Khaleel et al., 1981). In an urban soil, Tagro and GroCo decreased ($p < 0.05$) bulk density (g cm^{-3}) compared to the unamended control soil from 1.07 to 0.77 (Tagro) and 0.51 (GroCo) (McIvor et al., 2012). These results are consistent with the observed decreases in our study.

Table 2.5 Initial amended soil mixes and control soil physicochemical properties (bulk density, total N, total C, C:N, pH, and EC). Final bulk density of amended soil mixes and control soils after kale and chard growth.

	Bulk Density			**Total N**	**Total C**	**C:N**	**$pH_{1:2}$**	**$EC_{1:2}$**
	Kale initial	Kale final (Swiss chard initial)	Swiss chard final					
	g cm^{-3}			%		ratio		dS m^{-1}
R Control	0.70	0.72	1.02	0.21	2.5	12	5.90 ± 0.06	0.23 ± 0.03
R Fertilizer	0.70	0.71	0.94					
R Bokashi	0.44	0.69	1.00	0.56	4.6	8	7.59 ± 0.50	0.38 ± 0.01
R GroCo	0.22	0.44	0.60	0.63	14.0	22	5.19 ± 0.16	0.78 ± 0.02
R Tagro	0.34	0.60	0.78	0.44	7.9	18	4.86 ± 0.06	1.18 ± 0.04
R Vermicompost	0.31	0.53	0.68	1.60	19.9	13	6.41 ± 0.04	0.25 ± 0.09
T Control	0.82	0.72	0.91	0.26	4.5	18	5.23 ± 0.11	0.07 ± 0.02
T Fertilizer	0.82	0.76	1.04					
T Bokashi	0.50	0.58	0.84	0.69	7.0	10	6.72 ± 0.23	0.25 ± 0.08
T GroCo	0.23	0.35	0.51	0.69	17.4	25	4.76 ± 0.13	0.25 ± 0.01
T Tagro	0.35	0.57	0.69	0.48	9.3	20	5.09 ± 0.65	0.72 ± 0.06
T Vermicompost	0.32	0.57	0.63	0.78	11.3	14	6.01 ± 0.16	0.45 ± 0.04

*R=Renton and T=Tacoma soil types. Kale initial bulk density was calculated from amendment dry mass additions of 1.17 kg divided by the actual volume of addition. C:N=total C divided by total N. EC=electrical conductivity. $pH_{1:2}$ and $EC_{1:2}$ is presented as mean (n=2) and (n=3) respectively, ± standard deviation. Control soils are in grey. Bulk density measurements were not replicated.

Table 2.6 Mehlich-III extractable nutrients in amended soil mixtures and control soils for K, Mg, P, S, Cu, Fe, Mn, and Zn (mg kg^{-1}).

	K	Mg	P	S	Cu	Fe	Mn	Zn
				mg kg^{-1}				
R Control	389	359	109	39	9.7	385.3	31.5	8.6
R Bokashi	2,094	601	307	195	8.9	374.9	122.5	27.1
R GroCo	595	864	1,244	233	8.8	479.3	55.2	48.7
R Tagro	562	550	505	245	10.4	427.8	57.1	25.7
R Vermicompost	2,650	827	748	232	6.8	259.9	29.2	23.9
T Control	117	128	1,059	45	27.1	449.1	32.4	58.2
T Bokashi	1,655	291	822	161	16.7	270.3	70.9	56.9
T GroCo	250	384	1,343	148	20.1	445.4	59.8	73.1
T Tagro	305	306	1,097	158	23.1	426.2	54.4	63.2
T Vermicompost	1,801	415	1,182	157	21.4	375.0	29.9	57.8

*R=Renton and T=Tacoma. Control soils are in grey.

Table 2.7 Soil biological indicators: mineralizable carbon (min C) and permanganate oxidizable carbon (POXC) for amended soil mixtures and control soils.

	Min C	**POXC**
	mg CO_2-C kg^{-1} day^{-1}	mg kg^{-1}
R Control	98 ± 5 a	663 ± 10 a
R Bokashi	811 ± 36 d	915 ± 3 b
R GroCo	144 ± 17 b	1,231 ± 21 c
R Tagro	79 ± 6 a	849 ± 10 b
R Vermicompost	244 ± 25 c	1,118 ± 87 c
T Control	85 ± 9 b	522 ± 28 a
T Bokashi	388 ± 10 e	805 ± 19 a
T GroCo	120 ± 14 c	711 ± 179 a
T Tagro	54 ± 8 a	631 ± 46 a
T Vermicompost	288 ± 17 d	603 ± 110 a

*Mean ± standard deviation for min C and POXC measured in triplicate and duplicate respectively except for TG, TV, and RV treatments which were re-analyzed for POXC (n=5). Letters that are not shared in columns indicate results from pairwise mean comparisons using Tukey HSD post hoc analysis ($p<0.05$).

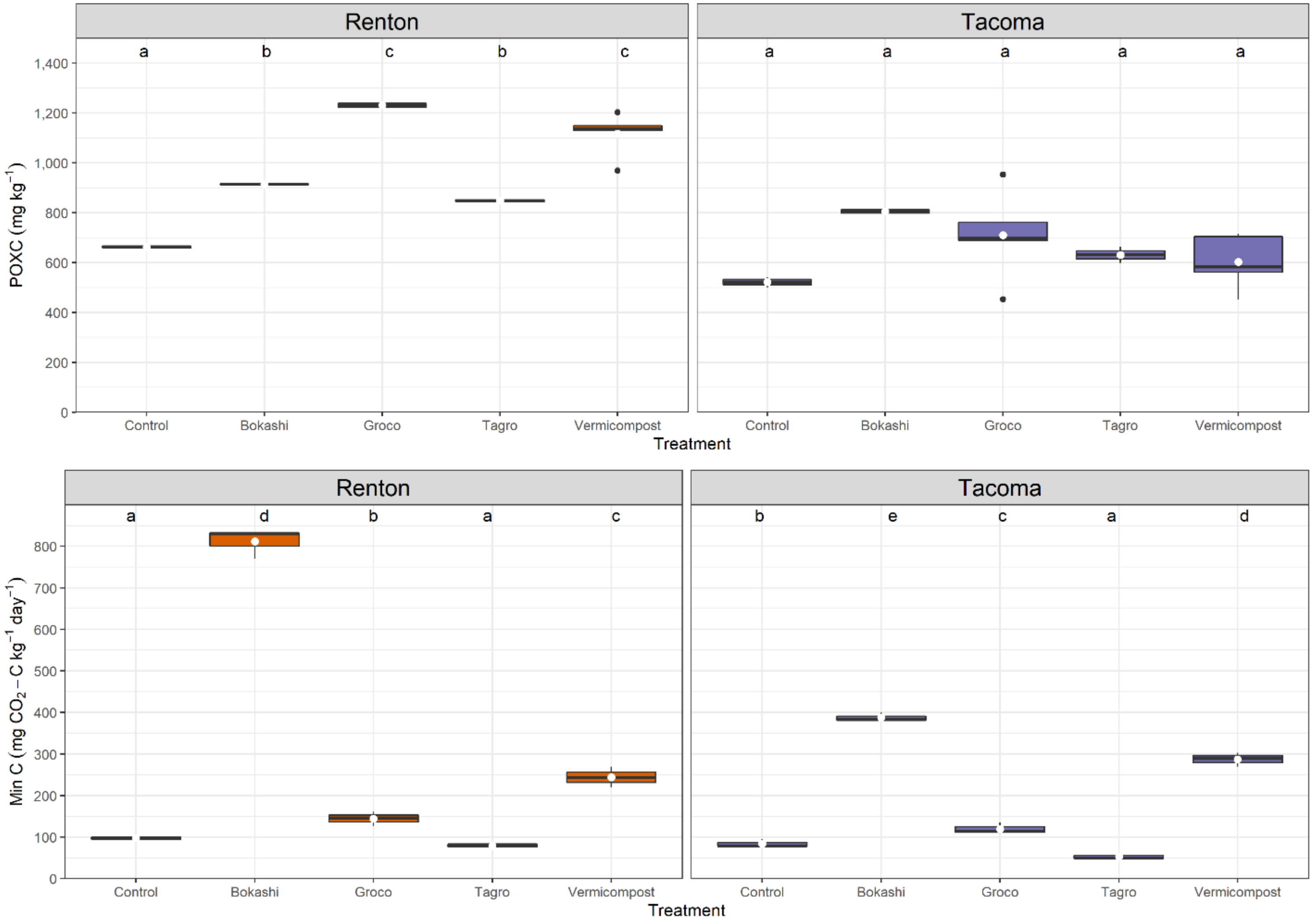

Figure 2.1 Amended soil mixture and control soil permanganate oxidizable carbon (POXC; mg kg^{-1}) and mineralizable carbon (min C mg CO2-C kg^{-1} day^{-1}). Boxes represent the interquartile range (IR). Whiskers include data points above and below 1.5x's the IR. Lines in the boxes represent the median and dots represent the mean. Letters that are not shared above the treatments indicate differences according to Tukey HSD post hoc mean comparison ($p<0.05$). Soils were analyzed separately by soil type.

2.3.2 Plant response

2.3.2.1 Germination

Both soil type and amendment type impacted kale germination (Table 2.8). In the kale, there was no germination in the bokashi amended soils potentially as a result of the high amendment EC (> 8.61 dS m^{-1}). Kale germinated in all other treatments in the Renton soil. In the Tacoma soil, both the control and fertilizer treatments had poor germination (17% and 0%, respectively). Germination in the GroCo, Tagro, and vermicompost was 92% in the Renton soil and 100% in the Tacoma soil.

Table 2.8 Kale germination emergence (%) recorded from three seeds.

	Emergence
	%
R Control	92 ± 14
R Fertilizer	92 ± 14
R Bokashi	0.0
R GroCo	92 ± 14
R Tagro	92 ± 14
R Vermicompost	92 ± 14
T Control	17 ± 17
T Fertilizer	0.0
T Bokashi	0.0
T GroCo	100 ± 0.0
T Tagro	100 ± 0.0
T Vermicompost	100 ± 0.0

*R=Renton and T=Tacoma soil types. Treatments without any germination in the first seeding were reseeded and germination from both attempts was recorded. Control soils are in grey.

2.3.2.2 Kale yield

Comparison of yield across both soils

Kale yield varied by soil, treatment, and soil*treatment interaction ($p<0.001$) (Table 2.9; Figure 2.4). The yield (fresh g pot^{-1}) in the unamended Tacoma soil was much lower than the Renton soil only control (1.3 ± 1.9 and 34.9 ± 8.3, respectively). Overall yield (fresh g pot^{-1}) across all the treatments was higher in the Renton soil was higher vs. the Tacoma soil (45.8 ± 32.7 vs. 30.2 ± 41.4). Considering yield across both soils, the highest yields were observed in the vermicompost amended soils, followed by Tagro amended soils. Yield from GroCo additions significantly increased yield compared to both soils when unamended, but only in the Tacoma soil did yield increase from GroCo relative to the fertilized control. There was no germination for kale plants in the bokashi amended soils. Our results were consistent with the increased effect from organic amendments on yield in sandier soils (Ozores-Hampton et al., 2011). The soil*treatment interaction was significant which meant results were considered for each soil separately.

Renton soil

In the Renton soil, the yield (fresh g pot^{-1}) from additions of vermicompost (92.8 ± 24.1) and Tagro (73.1 ± 9.3) was higher than both fertilized and unamended controls (62.1 ± 6.9 and 34.9 ± 8.3, respectively) but increases were significant ($p<0.05$) compared to the unamended control only. The yield in the GroCo amended soil (45.1 ± 11.7) was similar to the unamended control (34.9 ± 8.3) and numerically lower but statistically similar to fertilized control (62.1 ± 6.9). Bokashi did not germinate.

Tacoma soil

In the Tacoma soil, yield did not increase from fertilizer vs. the soil only control (1.5 ± 2.9 fertilizer vs. 1.3 ± 1.9 control). Germination in both the fertilizer and unamended control soils was poor. All amendments increased ($p<0.05$) yield compared to both controls, with the exception of bokashi which did not germinate. Large increases from vermicompost (104.1 ± 24.7), Tagro (72.9 ± 21.8), and GroCo (30.9 ± 4.9) were observed relative to both controls. The soil health improvements from amendment addition were likely key for successful crop yield in this soil (Figure 2.2; Table 2.9).

Figure 2.2 Kale photos at harvest (52 days from direct sow). Top and bottom: Renton and Tacoma soils, respectively. Left to right: GroCo, Tagro, vermicompost, soil control, fertilizer, worm tea, and bokashi.

Table 2.9 Kale and Swiss chard yield (fresh g pot^{-1}) and percent (%) change relative to soil only or fertilizer controls.

	Absolute yield				**% change relative to control or fertilizer**			
	Kale		Swiss chard		Kale		Swiss chard	
	g fresh pot^{-1}				control	fertilizer	control	fertilizer
R Control	34.9 ± 8.3	c	14.9 ± 7.8	a				
R Fertilizer	62.1 ± 6.9	de	9.2 ± 2.8	a	78%		-38%	0%
R Bokashi	0	a	33.8 ± 7.0	bc			127%	269%
R GroCo	45.1 ± 11.7	cd	18.1 ± 7.1	ab	29%	-27%	22%	97%
R Tagro	73.1 ± 9.3	e	15.2 ± 3.7	a	109%	18%	2%	65%
R Vermicompost	92.8 ± 24.1	e	47.9 ± 12.6	c	166%	49%	222%	422%
T Control	1.3 ± 1.9	a	6.0 ± 3.5	b				
T Fertilizer	1.5 ± 2.9	a	15.2 ± 2.5	c	20%		153%	
T Bokashi	0	a	0	a				
T GroCo	30.9 ± 4.9	b	23.1 ± 3.6	c	2320%	1923%	285%	52%
T Tagro	72.9 ± 21.8	c	54.8 ± 19.4	d	5620%	4682%	813%	260%
T Vermicompost	104.1 ± 24.7	c	56.2 ± 6.2	d	8067%	6728%	836%	270%

*R=Renton and T=Tacoma soil. Mean (n=4) yield ± standard deviation. Means that share the same letter in a column are not significantly different according to pairwise mean comparisons using Tukey HSD ($p<0.05$). Renton and Tacoma soils were analyzed separately. Yield was measured 52 and 56 days from direct sow for kale and chard, respectively.

2.3.2.3 Swiss chard yield

Comparison of yield across both soils

Soil, treatment, and soil*treatment interaction were highly significant ($p<0.001$) factors in chard yield. Vermicompost addition had significant ($p<0.05$) effects in both soils relative to both controls, with an increased effect in the Tacoma soil. The chard yield from the unamended control was higher in the Renton soil than in Tacoma soil (Renton; 14.9 ± 7.8, Tacoma; 6.0 ± 3.5 g pot^{-1}). In the chard trial, the overall yield across all treatments was slightly higher in the Tacoma soil vs. the Renton soil (25.9 ± 23.9 vs. 23.2 ± 15.2).

The impact from soil additions of vermicompost and Tagro on chard yield likely would have been even higher in both soils. However, a small amount of damage from deer browse near the end of the trial resulted in losses from treatments of approximately ½ a leaf from Tacoma Tagro, 4.5 leaves from Tacoma Vermicompost, and 6 leaves from the Renton Vermicompost.

Renton soil

In the Renton soil, yield (fresh g pot^{-1}) from additions of vermicompost (47.9 ± 12.6) and bokashi (33.8 ± 7.0) was higher ($p<0.05$) than both controls (9.2 ± 2.8 fertilizer; 14.9 ± 7.8 control). Yields in chard grown in the GroCo (18.1 ± 7.1) and Tagro (15.2 ± 3.7) amended soils were similar to both controls.

Tacoma soil

In the Tacoma soil, the fertilizer treatment increased chard yield above the soil-only control (15.2 ± 2.5 fertilizer; 6.0 ± 3.5 control). However, chard yield from additions of both the Tagro (54.8 ± 19.4) and vermicompost (56.2 ± 6.2) was significantly higher ($p<0.05$) than both controls. Increases in yield from GroCo (23.1 ± 3.6) were significant ($p<0.05$) compared to the unamended control, but similar to the fertilized control. There was no yield in the bokashi treatment which did not germinate (Figure 2.3).

Figure 2.3 Swiss chard photos at harvest (56 days from direct sow). Top and bottom: Renton and Tacoma soils, respectively. Left to right: vermicompost, Tagro, GroCo, fertilizer, control, and bokashi treatments, respectively.

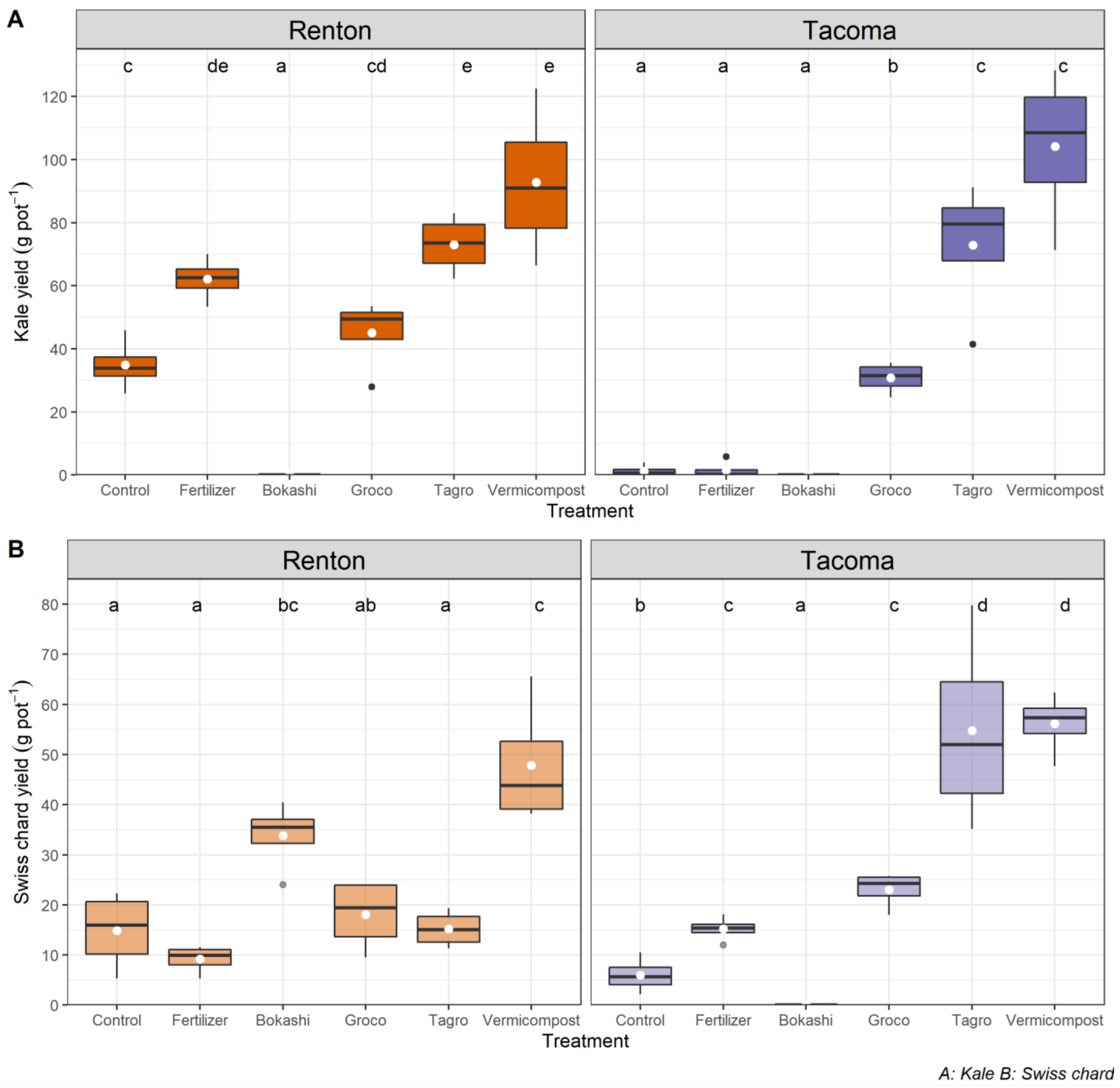

Figure 2.4 Kale and Swiss chard yield (g pot^{-1}) boxplot. Boxes represent the interquartile range (IR). Whiskers include data points above and below 1.5x's the IR. Lines in the boxes represent the median and white dots represent the mean. Letters that are not shared above the treatments indicate differences according to pairwise mean comparisons using Tukey HSD ($p<0.05$) analyzed separately by soil and crop type.

2.3.3 Kale foliar mineral concentrations

Kale foliar mineral concentrations were near or within concentrations found in previous studies (Cornforth et al., 1978; White & Broadley, 2009) and were sufficient for crop growth (White et al., 2012). Foliar concentrations are shown in Table 2.10 and Table 2.11. Results for macronutrients (Ca, Mg, P, and S) analyzed separately by soil type are shown in Figure 2.5, while analysis of kale K concentrations, combined by soil type is shown in Figure 2.6. Results for kale foliar micronutrients (Cu, Fe, Mn, and Zn) analyzed separately for each soil type, are presented in Figure 2.7.

2.3.3.1.1 Calcium (Ca)

Calcium concentrations (g kg^{-1}) in the edible portion of the kale highly varied ($p<0.001$) based on soil, treatment, and the soil*treatment interaction. The mean Ca concentration across all treatments was higher in the Tacoma soil (30.1 ± 10.8) than in the Renton soil (20.5 ± 6.1). Foliar Ca concentrations ranged from 10.9 (Tacoma Vermicompost) to 45.4 (Tacoma Tagro).

In the Renton soil, a significant ($p<0.05$) increase in foliar Ca was observed from the Tagro (27.9 ± 6.6 g kg^{-1}) relative to the unamended control (16.2 ± 3.8 g kg^{-1}) but not the fertilized control (21.3 ± 4.3 g kg^{-1}). In the Tacoma soil, kale grown in the vermicompost (15.3 ± 4.3 g kg^{-1}) had lower Ca than kale grown in both controls (36.3 ± 1.7 unamended; 38.2 ± 0.2 fertilizer g kg^{-1}). Kale in the GroCo (26.6 ± 1.3 g kg^{-1}) amended soil also had lower Ca than in the unamended control.

2.3.3.1.2 Potassium (K)

Potassium concentrations (g kg^{-1}) in the edible portion of the kale varied by treatment ($p<0.001$). The mean foliar K concentrations across all treatments were similar in the Renton and Tacoma soils (43.2 ± 12.3 and 35.6 ± 12.3, respectively). Kale foliar K ranged from 20.0 (Tacoma Fertilizer) to 62.5 (Renton Vermicompost). Kale K concentrations did not vary ($p>0.05$) according to soil or soil*treatment interaction. Therefore, data from both soils were combined for further analysis and are presented below.

Across both soils, positive effects to kale K concentrations (g kg^{-1}) were significant ($p<0.05$) when grown in vermicompost (57.6 ± 2.8) relative to both controls (27.9 ± 6.5 soil only; 34.7 ±

11.0 fertilizer). Significant ($p<0.05$) increases in K from additions of Tagro (38.9 ± 6.4) were above the soil-only control, but similar to the fertilized control. Concentrations of K for kale grown in GroCo (35.7 ± 10.4) were similar to both controls.

2.3.3.1.3 Magnesium (Mg)

Magnesium concentrations (g kg^{-1}) in the edible portion of the kale varied by soil*treatment interaction ($p<0.001$). Soil type and treatment were not significant ($p>0.05$). The significant interaction means that kale Mg concentrations did not respond to the different treatments the same way in both soils. The Mg concentrations across all treatments were similar in the Renton and Tacoma soil (5.34 ± 0.8 and 6.5 ± 1.8 g kg^{-1}, respectively). Foliar Mg concentrations ranged from 4.1 (Tacoma Control) to 10.0 (Tacoma Tagro).

In the Renton soil, leaf tissue Mg (g kg^{-1}) significantly increased ($p<0.05$) for kale grown in GroCo (6.2 ± 0.9 g kg^{-1}) in comparison to the fertilized control (4.7 ± 0.6) but was similar to the unamended control (5.0 ± 0.3). In the Tacoma soil, significant increases ($p<0.05$) to kale foliar Mg occurred from additions of Tagro (9.0 ± 1.0 g kg^{-1}) in comparison to both controls (4.7 ± 0.9 soil only; 6.0 ± 0.1 fertilizer).

2.3.3.1.4 Phosphorus (P)

Phosphorus concentrations (g kg^{-1}) in the edible portion of the kale varied by treatment ($p<0.001$), soil type ($p<0.01$), and soil*treatment interaction ($p<0.01$). The average foliar P across all treatments was lower in the Renton soil compared to the Tacoma soil (6.67 ± 1.40 and 7.69 ± 1.25, respectively). Kale foliar P concentrations ranged from 4.9 (Renton Control) to 10.1 (Renton GroCo).

In the Renton soil, significant increases ($p<0.05$) in leaf P (g kg^{-1}) resulted from additions of GroCo (9.0 ± 1.0) compared to both controls (5.1 ± 0.2 soil only; 6.2 ± 0.7 fertilizer). While similar to the fertilizer treatment, additions from Tagro (6.7 ± 0.5), and vermicompost (6.4 ± 0.1) were higher ($p<0.05$) than the unamended control. In the Tacoma soil, foliar P concentrations increased ($p<0.05$) from GroCo amendment (9.3 ± 0.2) relative to the control (6.6 ± 1.0) but were similar to the fertilizer treatment (8.3 ± 1.3). Leaf P concentrations from additions of vermicompost (6.4 ± 0.1) decreased ($p<0.05$) relative to the fertilized control but were similar to the soil alone.

2.3.3.1.5 Sulfur (S)

Sulfur concentrations (g kg^{-1}) in the edible portion of the kale varied highly ($p<0.001$) from treatment, soil, and soil*treatment interaction. The mean S concentration across all treatments was lower in the Renton soil vs. the Tacoma soil (9.6 ± 6.5 vs. 16.0 ± 2.9). Kale leaf S concentrations ranged from 1.8 (Renton Control) to 22.1 (Tacoma Tagro).

In the Renton soil, increases in leaf S were significant ($p<0.05$) for kale grown in GroCo (16.4 ± 3.4 g kg^{-1}), Tagro (14.8 ± 2.5), and vermicompost (12.2 ± 1.8) compared to both controls (2.0 ± 2.1 control and 2.9 ± 4.7 fertilizer). In the Tacoma soil, Tagro (19.6 ± 1.7) increased ($p<0.05$) tissue S concentrations relative to the fertilizer treatment (12.1 ± 0.0) but was similar to the control (16.3 ± 1.7).

2.3.3.1.6 Copper (Cu)

Copper concentrations (mg kg^{-1}) in the edible portion of the kale varied highly ($p<0.001$) from treatment, soil, and soil*treatment interaction. The mean foliar Cu concentration across all treatments was lower in the Renton vs. Tacoma soil (7.2 ± 2.2 vs. 14.5 ± 6.5). Kale leaf Cu concentrations ranged from 4.31 (Renton Vermicompost) to 30.61 (Tacoma Fertilizer).

In the Renton soil, increases ($p<0.0.5$) in leaf Cu occurred in kale grown with fertilizer (8.7 ± 1.5 mg kg^{-1}), GroCo (9.2 ± 1.7 mg kg^{-1}), and Tagro (8.5 ± 0.8 mg kg^{-1}) compared to the unamended control (5.0 ± 0.5). GroCo and Tagro were similar to the fertilized control. In contrast, kale grown in the vermicompost amendment had decreased ($p<0.05$) leaf Cu concentrations (3.7 ± 0.4 mg kg^{-1}) relative to both controls. This decrease was significant ($p<0.05$) in the Tacoma soil as well. Additions of vermicompost (6.0 ± 1.4 mg kg^{-1}) relative to both controls (15.8 ± 2.6 control; 24.8 ± 8.2 fertilizer). In the Tacoma soil, the kale grown in the rest of the amendments all had similar Cu concentrations.

2.3.3.1.7 Iron (Fe)

Iron concentrations in the edible portion of the kale varied by treatment ($p<0.001$) and soil*treatment interaction ($p<0.01$) but did not vary based on soil type ($p>0.05$). Large outliers for kale Fe concentrations (mg kg^{-1}) from the Tacoma fertilizer (637) and Tacoma control (161) treatments were removed prior to analysis. The mean Fe concentration across all treatments was similar for kale grown in the Renton vs. the Tacoma soil (58 ± 12 vs. 58 ± 14). Kale leaf Fe concentrations (mg kg^{-1}) ranged from 38 (Renton Control) to 91 (Tacoma Fertilizer). The interaction between soil and treatment indicates that kale Fe concentrations did not respond similarly in both soils. Therefore, kale Fe concentrations were analyzed separately for both soil types.

In the Renton soil, treatments increased ($p<0.05$) foliar Fe from additions of Tagro (67 ± 7 mg kg^{-1}) and vermicompost (66 ± 6 mg kg^{-1}) in comparison to the unamended control (41 ± 5 mg kg^{-1}), but not the fertilized control (57 ± 11 mg kg^{-1}). In the Tacoma soil, there was a large increase from fertilizer (91) in comparison to the unamended control (46). However, these results did not have replication and were not significant ($p<0.05$). High variability of the kale leaf Fe may be the result of soil contamination for which large outliers were removed.

2.3.3.1.8 Manganese (Mn)

Manganese foliar concentrations (mg kg^{-1}) in the edible portion of the kale varied highly ($p<0.001$) from treatment, soil, and soil*treatment interaction. The mean foliar Mn across all treatments was higher for kale grown in the Tacoma vs. the Renton soil (251 ± 218 vs. 56 ± 32). Kale foliar Mn concentrations ranged from 17.4 (Tacoma Vermicompost) to 655.5 (Tacoma Fertilizer).

In the Renton soil, increases in leaf Mn (mg kg^{-1}) were significant ($p<0.05$) from additions of Tagro (75 ± 11) and GroCo (51 ± 3) compared to the unamended control (28 ± 5), but similar to the fertilized control (101 ± 30). Leaf Mn (mg kg^{-1}) decreased ($p<0.05$) from additions of vermicompost (24 ± 3) relative to both controls. In the Tacoma soil, increases in leaf Mn were significant ($p<0.05$) from additions of fertilizer (597 ± 82) and Tagro (451 ± 100) which were similar to one another but above the unamended control (127 ± 98). Foliar Mn was similar for kale grown in GroCo (168 ± 22) and the soil only control, but lower than the fertilized control. Leaf Mn decreased ($p<0.05$) from additions of vermicompost (22 ± 5) relative to both controls.

2.3.3.1.9 Zinc (Zn)

Zinc foliar concentrations (mg kg^{-1}) in the edible portion of the kale varied highly ($p<0.001$) from treatment, soil, and soil*treatment interaction. The mean foliar Zn concentration across all treatments was lower in the Renton vs. the Tacoma soil (94 ± 47 vs. 223 ± 107). Kale leaf Zn concentrations ranged from 31 (Renton Vermicompost) to 356 (Tacoma Fertilizer).

In the Renton soil, leaf Zn (mg kg^{-1}) decreased from additions of vermicompost (34 ± 3) relative to both controls (127 ± 15 soil only; 129 ± 76 fertilizer). In the Tacoma soil, leaf Zn was lower in the kale grown in vermicompost (54 ± 11) than both controls (287 ± 24 soil only; 348 ± 11 fertilized). In the Tacoma soil, GroCo (244 ± 27) decreased leaf Zn compared to additions of fertilizer but was similar to the unamended control.

In brief, in both soils, vermicompost significantly decreased leaf Zn compared to both controls, with a larger effect in the Tacoma soil. Most amendments did not impact leaf Zn in either soil, but GroCo had a slight decrease in the Tacoma soil. Foliar Zn concentrations in our study were consistent with the range (100-700 mg kg^{-1} dry) found in a review of a variety of kale cultivars that were being evaluated for agronomic biofortification of Zn (White & Broadley, 2011).

Table 2.10 Kale foliar macronutrient concentrations (g kg^{-1} dry).

Treatment	Ca	K	Mg	P	S
			g kg^{-1} dry		
R Control	16.2 ± 3.8	28.2 ± 6.9	5.0 ± 0.3	5.1 ± 0.2	2.0 ± 2.1
R Fertilizer	21.3 ± 4.3	40.9 ± 6.5	4.7 ± 0.6	6.2 ± 0.7	2.9 ± 4.7
R GroCo	19.6 ± 2.6	42.5 ± 10.9	6.2 ± 0.9	9.0 ± 1.0	16.4 ± 3.4
R Tagro	27.9 ± 6.6	43.5 ± 4.3	5.2 ± 0.7	6.7 ± 0.5	14.8 ± 2.5
R Vermicompost	17.5 ± 6.2	60.9 ± 1.6	5.7 ± 0.6	6.4 ± 0.1	12.2 ± 1.8
T Control	36.3 ± 1.7	27.4 ± 8.5	4.7 ± 0.9	6.6 ± 1.0	16.3 ± 1.7
T Fertilizer	38.2 ± 0.2	22.2 ± 3.1	6.0 ± 0.1	8.3 ± 1.3	12.1 ± 0.0
T GroCo	26.6 ± 1.3	28.9 ± 3.3	6.7 ± 1.0	9.3 ± 0.2	14.6 ± 2.0
T Tagro	41.1 ± 4.7	34.4 ± 4.4	9.0 ± 1.0	7.7 ± 0.4	19.6 ± 1.7
T Vermicompost	15.3 ± 4.3	54.4 ± 1.7	4.9 ± 0.5	6.4 ± 0.1	15.5 ± 1.8

*R=Renton and T=Tacoma soil types. Mean (n=4) ± standard deviation, except for Renton Control (n=2), Renton GroCo (n=2) and Tacoma Vermicompost (n=3).

Table 2.11 Kale foliar micronutrient concentrations (mg kg^{-1} dry).

Treatment	Cu	Fe	Mn	Zn
		mg kg^{-1} dry		
R Control	5.0 ± 0.5	41 ± 5	28 ± 5	127 ± 15
R Fertilizer	8.7 ± 1.5	57 ± 11	101 ± 30	129 ± 76
R GroCo	9.2 ± 1.7	58 ± 1	51 ± 3	93 ± 14
R Tagro	8.5 ± 0.8	67 ± 7	75 ± 11	87 ± 9
R Vermicompost	4.7 ± 0.4	66 ± 6	24 ± 3	34 ± 3
T Control	15.8 ± 2.6	46	127 ± 98	287 ± 24
T Fertilizer	24.8 ± 8.2	91	597 ± 82	348 ± 11
T GroCo	15.0 ± 1.0	46 ± 2	168 ± 22	244 ± 27
T Tagro	16.8 ± 2.8	67 ± 4	451 ± 100	277 ± 19
T Vermicompost	6.0 ± 1.4	56 ± 11	22 ± 5	54 ± 11

*R=Renton and T=Tacoma soil types. Mean (n=4) ± standard deviation, except for Renton Control (n=2), Renton GroCo (n=2) and Tacoma Vermicompost (n=3). Prior to analysis, outliers were removed for Fe (T Control and T Fertilizer) and do not have replicates for standard deviation.

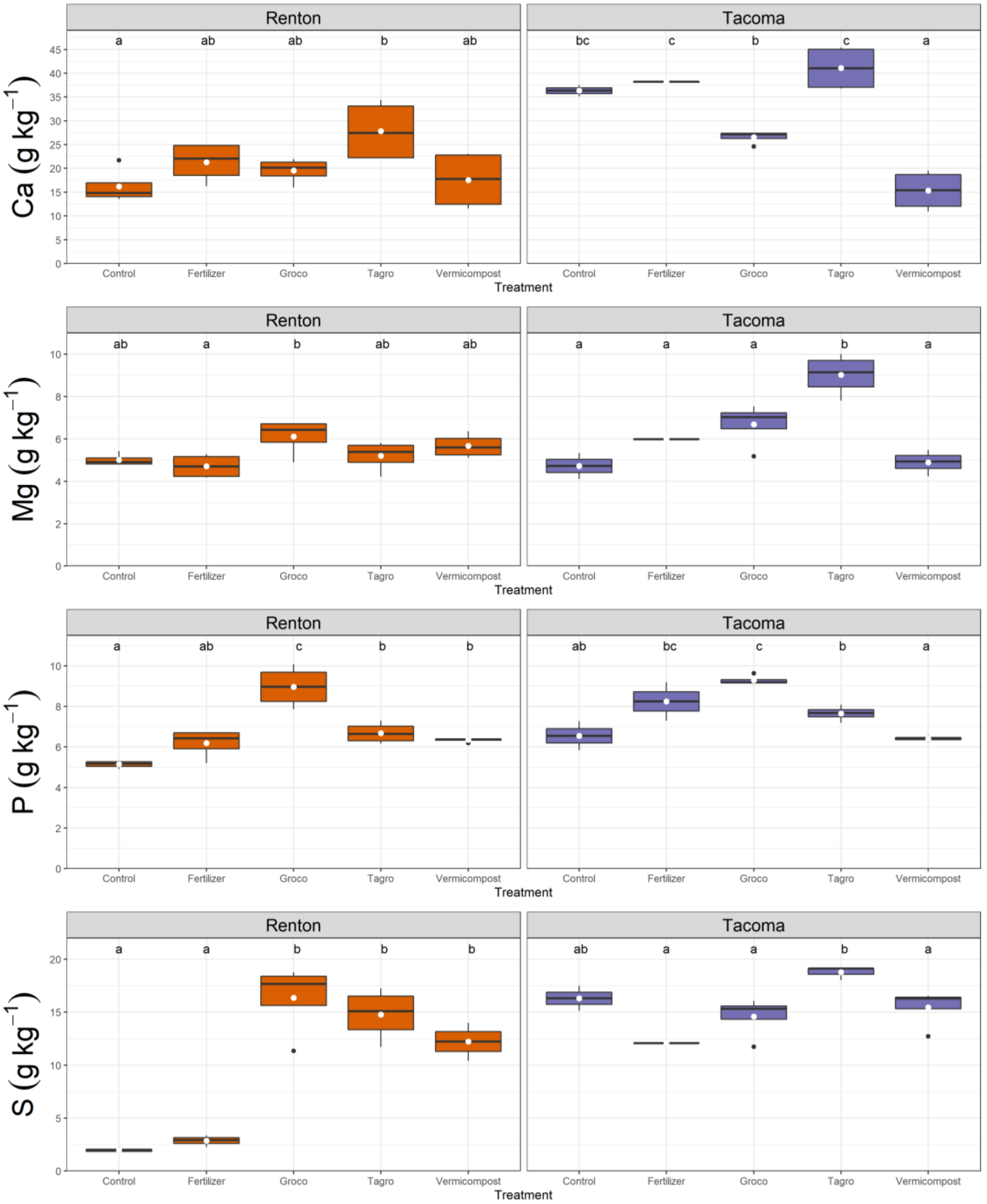

Figure 2.5 Kale leaf macronutrient concentrations (Ca, Mg, P, & S; g kg^{-1}) boxplot. Boxes represent the interquartile range (IR). Whiskers include data points above and below 1.5x's the IR. Lines in the boxes represent the median and white dots represent the mean. Letters that are not shared above the treatments indicate differences according to pairwise mean comparison using Tukey HSD (p<0.05). Kale mineral concentrations were analyzed separately by soil type.

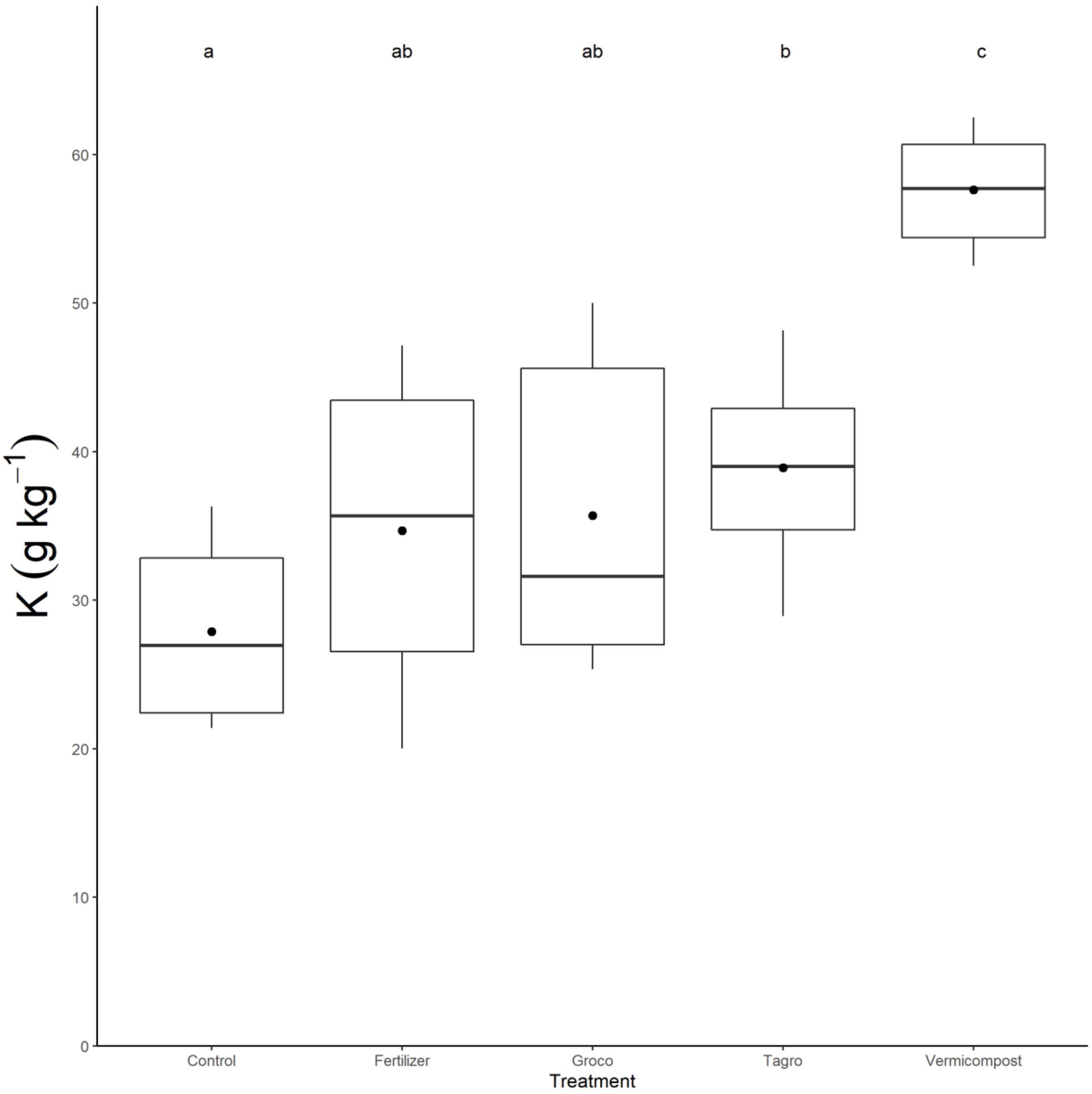

Figure 2.6 Kale leaf K concentrations (g kg^{-1}) boxplot. Boxes represent the interquartile range (IR). Whiskers include data points above and below 1.5x's the IR. Lines in the boxes represent the median and black dots represent the mean. Letters that are not shared above the treatments indicate differences according to pairwise mean comparisons using Tukey ($p<0.05$). Kale K concentrations were combined by soil type prior to analysis.

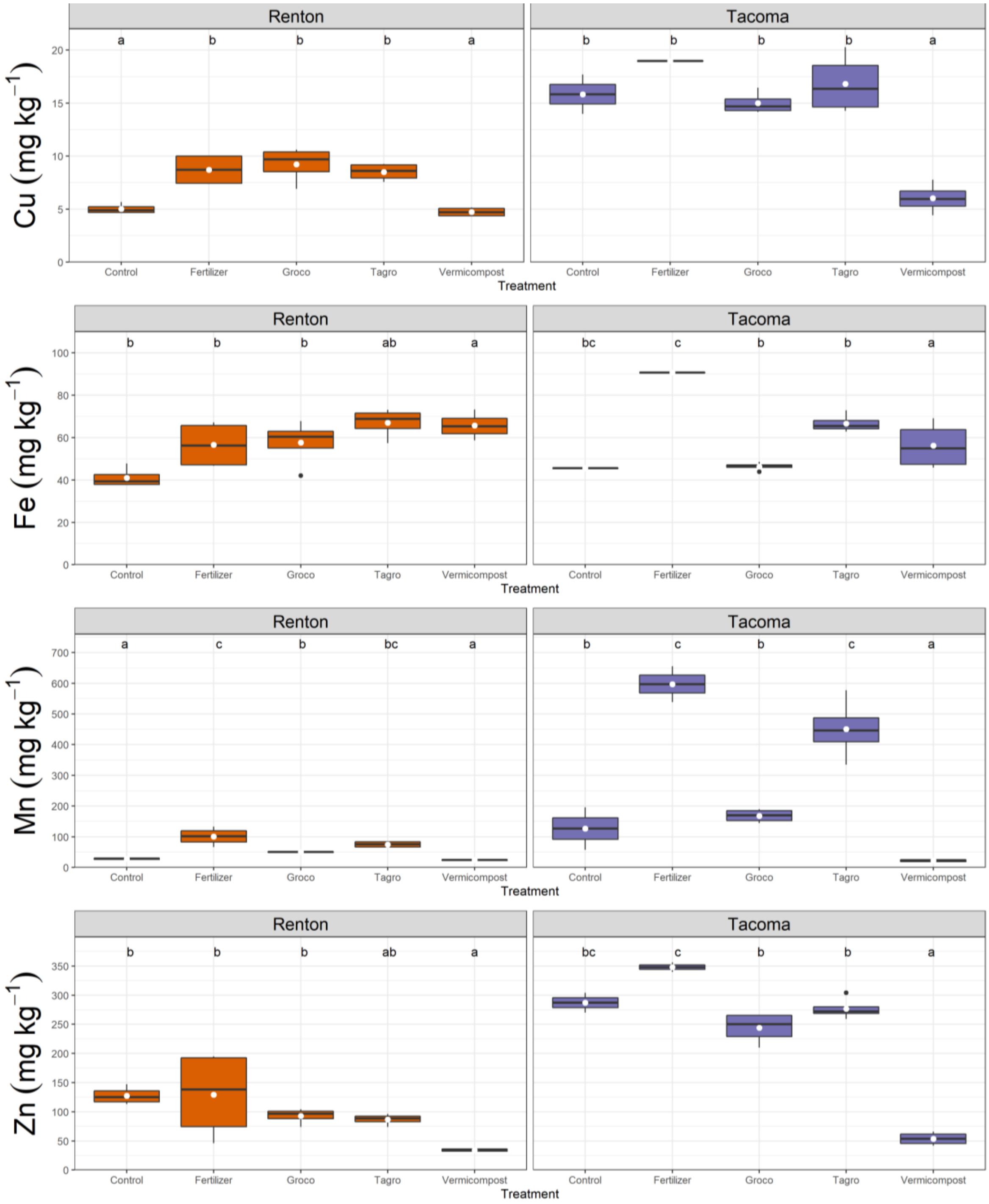

Figure 2.7 Kale micronutrient concentrations (Cu, Fe, Mn, & Zn; mg kg^{-1}) boxplot. Boxes represent the interquartile range (IR). Whiskers include data points above and below 1.5x's the IR. Lines in the boxes represent the median and white dots represent the mean. Letters that are not shared above the treatments indicate differences according to pairwise mean comparisons using Tukey HSD (p<0.05). Kale mineral concentrations were analyzed separately by soil type.

2.3.4 Swiss chard foliar mineral concentrations

Sufficient ranges foliar mineral concentrations were met or exceeded in chard (Havlin, 1999; White et al., 2012) and are shown in Table 2.12 and Table 2.13. Results for chard mineral concentrations (K and P) were analyzed separately by soil type are shown in Figure 2.8. Results for chard mineral concentrations (Ca, Mg, S, and Cu) analyzed with data combined for both soil types are shown in Figure 2.9. Chard mineral concentrations (Fe, Mn, and Zn) were analyzed separately by soil type and are presented in Figure 2.10.

2.3.4.1.1 Calcium (Ca)

Calcium concentrations in the edible portion of chard varied by treatment ($p<0.05$) but did not vary according to soil type or soil*treatment interaction ($p>0.05$). Chard leaf Ca concentrations (g kg^{-1}) ranged from 6.5 (Renton Bokashi) to 48.9 (Tacoma Tagro). The mean foliar Ca concentration across all treatments was similar for both soils (17.6 ± 10.7 Renton; 27.4 ± 11.1 Tacoma). Subsequent results for chard Ca concentrations were analyzed for the effect of treatment using the data for both soil types combined.

Ca concentration increases were significant ($p<0.05$) for chard grown in Tagro (36.2 ± 7.1) compared to unamended and fertilized controls (15.1 ± 5.5 and 22.2 ± 10.3, respectively). Chard Ca concentrations were similar in GroCo (26.1 ± 6.4) and vermicompost (19.8 ± 12.0) amended soils to both controls. Chard grown in the bokashi amended Renton soil (7.2 ± 0.6) appeared to have similar concentrations to controls also. The chard seeded in the bokashi treatment in the Tacoma soil did not germinate.

2.3.4.1.2 Potassium (K)

Potassium concentrations in the edible portion of the chard varied by treatment ($p<0.01$), soil ($p<0.01$), and soil*treatment interaction ($p<0.05$). Chard leaf K concentrations (g kg^{-1}) ranged from 14.7 (Tacoma Fertilizer) to 86.4 (Renton Vermicompost). The mean foliar K concentration across all treatments was higher in the Renton soil (66.4 ± 9.9) than in the Tacoma soil (54.0 ± 21.9).

Amendments did not impact chard K concentrations grown in the Renton soil. In the Tacoma soil, chard K concentrations (g kg^{-1}) increased ($p<0.05$) from additions of vermicompost (76 ± 9) in comparison to both controls (20 control; 15 ± 1 fertilizer) and were significant from GroCo (61 ± 4) and Tagro (54 ± 9) amendments relative to the fertilized control, but not the soil alone.

2.3.4.1.3 Magnesium (Mg)

Magnesium concentrations in the edible portion of the chard varied by treatment ($p<0.001$) but did not vary according to soil or soil*treatment interaction ($p>0.05$). Chard leaf Mg (mg kg^{-1}) concentrations ranged from 6.4 (Tacoma Vermicompost) to 30.3 (Tacoma GroCo). The mean foliar Mg concentration across all treatments was similar for both soils (14.3 ± 5.4 Renton; 17.0 ± 8.15 Tacoma). The results discussed below are analyzed from data for both soils combined.

Chard foliar Mg increases were significant ($p<0.05$) when grown in soils amended with GroCo (25.6 ± 3.7) and Tagro (21.3 ± 2.4) compared to both controls (11.4 ± 2.7 unamended; 10.3 ± 1.24 fertilized control). There was no difference in chard tissue Mg between controls and soils amended with vermicompost (10.4 ± 3.1) and bokashi (11.8 ± 1.0).

2.3.4.1.4 Phosphorus (P)

Phosphorus concentrations in the chard varied highly ($p<0.001$) by treatment, soil, and soil*treatment interaction. Chard leaf P concentrations (g kg^{-1}) ranged from 2.3 (Renton Control) to 81.8 (Tacoma GroCo). The mean foliar P concentrations across all treatments were higher in the Tacoma soil (37.2 ± 24.1) than the Renton soil (14.6 ± 12.1). Both soils had significant ($p<0.05$) increases in tissue P from GroCo and Tagro compared to both controls.

In the Renton soil, increases in leaf P (g kg^{-1}) from additions of GroCo (35.6 ± 7.5) and Tagro (29.7 ± 4.6) were significant ($p<0.05$) compared to both controls (4.4 ± 2.2 soil only; 10.0 ± 2.0 fertilizer) and from vermicompost (17.7 ± 0.5) relative to the unamended control only. In the Tacoma soil, increases to leaf P (g kg^{-1}) were significant ($p<0.05$) from additions of GroCo (72.2 ± 0.4) than from Tagro (36.5 ± 0.1), however, both were significantly above both controls (14.0 unamended; 11.8 ± 4.2 fertilized).

2.3.4.1.5 Sulfur (S)

Sulfur concentrations in the chard varied by treatment ($p<0.001$) and soil ($p<0.001$) but did not vary from soil*treatment interaction ($p>0.05$). Chard leaf S concentrations (g kg^{-1}) ranged from 1.7 (Renton Vermicompost) to 5.0 (Tacoma Tagro). Chard S concentrations across all treatments were higher in the Tacoma soil (3.7 ± 0.8) than in the Renton soil (2.9 ± 0.7). Due to the lack of interaction effect further analysis was conducted on the data for both soil types combined. Almost all treatments had similar S concentrations. Chard S concentrations (g kg^{-1}) increased ($p<0.05$) from amendment of GroCo (4.10 ± 0.6) relative to the fertilized (2.6 ± 0.3), but not the unamended control (2.5 ± 0.4).

2.3.4.1.6 Copper (Cu)

Copper concentrations in the chard varied by treatment ($p<0.001$), and soil ($p<0.01$), but not by soil*treatment interaction ($p>0.05$). Chard leaf Cu concentrations (mg kg^{-1}) ranged from 9.5 (Renton Vermicompost) to 58.0 (Tacoma GroCo). Concentrations of Cu across all treatments were higher in the Tacoma soil (29.6 ± 12.1) than in the Renton soil (19.4 ± 7.0). Due to the lack of interaction effect further analysis was conducted on the data for both soil types combined.

Chard Cu concentrations (mg kg^{-1}) had significant ($p<0.05$) effects from additions of GroCo (38.2 ± 10.0) which increased leaf Cu relative to fertilizer (23.0 ± 2.4) and vermicompost (15.8 ± 4.4) which decreased leaf Cu relative to the unamended control (23.2 ± 3.7). Bokashi in the Renton soil (12.1 ± 1.0) likely decreased chard Cu concentrations but were not analyzed.

2.3.4.1.7 Iron (Fe)

Iron concentrations in the chard varied by treatment ($p<0.001$), soil ($p<0.01$), and soil*treatment interaction ($p<0.001$). Chard leaf Fe concentrations (mg kg^{-1}) ranged from 72 (Tacoma Vermicompost) to 760 (Renton GroCo). Foliar Fe concentrations across all treatments were higher in the Renton soil (202 ± 197) than in the Tacoma soil (154 ± 69).

In the Renton soil, increases in Fe concentrations (mg kg^{-1}) from chard grown in GroCo (1,057 ± 118) were significant ($p<0.05$) compared to both controls (122 ± 43 control; 164 ± 5 fertilizer). In the Tacoma soil, increases from chard grown in Tagro (241 ± 66) were significant ($p<0.05$) compared to the fertilizer (114 ± 16), but similar to the unamended control (212).

2.3.4.1.8 Manganese (Mn)

Manganese concentrations in the chard varied by treatment ($p<0.001$) and soil*treatment interaction ($p<0.001$) but did not vary by soil type ($p>0.05$). Chard leaf Mn concentrations (mg kg^{-1}) ranged from 13 (Tacoma Vermicompost) to 2,041 (Tacoma GroCo). Concentrations of Mn across chard grown in all treatments were similar for both soils (544 ± 237 Renton; 946 ± 736 Tacoma). The effects from amendments on chard leaf Mn were much larger in the Tacoma soil.

In the Renton soil, increases in foliar Mn were significant ($p<0.05$) for chard grown in GroCo (1,057 ± 118) compared to the fertilizer treatment (585 ± 56) but not the unamended control (739 ± 25). In this soil, leaf Mn decreased ($p<0.05$) from vermicompost (95 ± 51) relative to both controls and decreases from bokashi amendment (427 ± 82) relative to the unamended control only. In the Tacoma soil, significant ($p<0.05$) increases in foliar Mn resulted from GroCo (2,387 ± 369) and Tagro (1,430 ± 106) amendments in comparison to both controls (912 control; 827 ± 113 fertilizer). In this soil, decreases in leaf Mn were significant ($p<0.05$) from vermicompost (107 ± 41) relative to both controls.

2.3.4.1.9 Zinc (Zn)

Zinc concentrations in the chard varied by treatment, soil, and soil*treatment interaction ($p<0.001$). Chard leaf Zn concentrations (mg kg^{-1}) ranged from 50 (Renton Vermicompost) to 2,927 (Tacoma GroCo). Concentrations of Zn across all treatments were higher for chard grown in the Tacoma soil (1,218 ± 904) than the Renton soil (257 ± 311).

In the Renton soil, foliar Zn (mg kg^{-1}) for chard increased ($p<0.05$) when grown with GroCo (872 ± 6) than chard grown in both controls (268 ± 20 control; 633 ± 2 fertilizer). Foliar Zn increases from Tagro (690 ± 34) were also higher ($p<0.05$) relative to the unamended control, but not the fertilized control. Chard grown in the Renton soil amended with bokashi (65 ± 8) and vermicompost (85 ± 25) had significant decreases ($p<0.05$) in Zn relative to both controls. In the Tacoma soil, leaf Zn increases were significant ($p<0.05$) from amended soils with GroCo (2,387 ± 369) compared to both controls (912 control; 827 ± 113 fertilizer) and Tagro (1,430 ± 106) relative to the fertilizer only. Decreases in this soil from vermicompost (107 ± 41) were significant compared to both controls. Chard has very high zinc which has been previously found for this variety compared to other vegetable crops (Hamon et al., 1997).

Table 2.12 Swiss chard foliar macronutrient concentrations (g kg^{-1} dry).

Treatment	n	Ca	K	Mg	P	S
				g kg^{-1} dry		
R Control	3	12.3 ± 0.5	61.2 ± 3.1	12.3 ± 0.4	4.4 ± 2.2	2.4 ± 3.1
R Fertilizer	2	13.3 ± 1.6	61.9 ± 9.9	11.3 ± 0.9	10.0 ± 2.0	2.4 ± 0.1
R Bokashi	4	7.2 ± 0.6	60.7 ± 11.0	11.8 ± 0.9	3.5 ± 0.8	3.8 ± 0.4
R GroCo	2	32.4 ± 3.6	72.8 ± 3.6	25.1 ± 0.7	35.6 ± 7.5	3.2 ± 0.1
R Tagro	2	30.9 ± 5.0	72.4 ± 6.3	20.8 ± 2.0	29.7 ± 4.6	3.3 ± 0.1
R Vermicompost	4	20.3 ± 11.7	72.1 ± 13.0	11.1 ± 2.9	17.7 ± 0.5	2.4 ± 0.1
T Control	1	23.3	20.1	8.7	14.0	3.1
T Fertilizer	2	31.1 ± 1.2	15.3 ± 0.8	9.3 ± 0.8	11.8 ± 4.2	2.9 ± 0.3
T GroCo	4	23.0 ± 5.0	60.6 ± 4.3	25.9 ± 4.7	72.2 ± 0.4	4.5 ± 0.2
T Tagro	4	39.0 ± 6.7	53.7 ± 8.6	21.5 ± 2.8	36.5 ± 0.1	3.9 ± 1.0
T Vermicompost	4	19.3 ± 14.2	75.7 ± 8.8	9.7 ± 3.6	21.6 ± 0.4	3.2 ± 0.6

*R=Renton and T=Tacoma soil types. Mean ± standard deviation. Replicates are reported in the “n” column.

Table 2.13 Swiss chard foliar micronutrients (mg kg^{-1} dry).

Treatment	n	Cu	Fe	Mn	Zn
				mg kg^{-1} dry	
R Control	3	21.7 ± 2.6	122 ± 43	739 ± 25	368 ± 20
R Fertilizer	2	24.2 ± 3.2	164 ± 5	585 ± 56	633 ± 2
R Bokashi	4	12.1 ± 1.0	106 ± 40	427 ± 82	65 ± 8
R GroCo	2	31.8 ± 2.3	701 ± 85	1,057 ± 118	872 ± 6
R Tagro	2	20.8 ± 1.0	257 ± 18	827 ± 48	690 ± 34
R Vermicompost	4	15.8 ± 5.7	99 ± 16	95 ± 51	85 ± 25
T Control	1	27.7	212	441	912
T Fertilizer	2	21.8 ± 1.0	114 ± 16	487 ± 25	827 ± 113
T GroCo	4	41.4 ± 11.1	115 ± 9	1,497 ± 376	2,387 ± 369
T Tagro	4	35.8 ± 4.1	241 ± 66	1,649 ± 129	1,430 ± 106
T Vermicompost	4	15.9 ± 3.4	111 ± 31	47 ± 41	107 ± 41

*R=Renton and T=Tacoma soil types. Mean ± standard deviation. Replicates are reported in the “n” column.

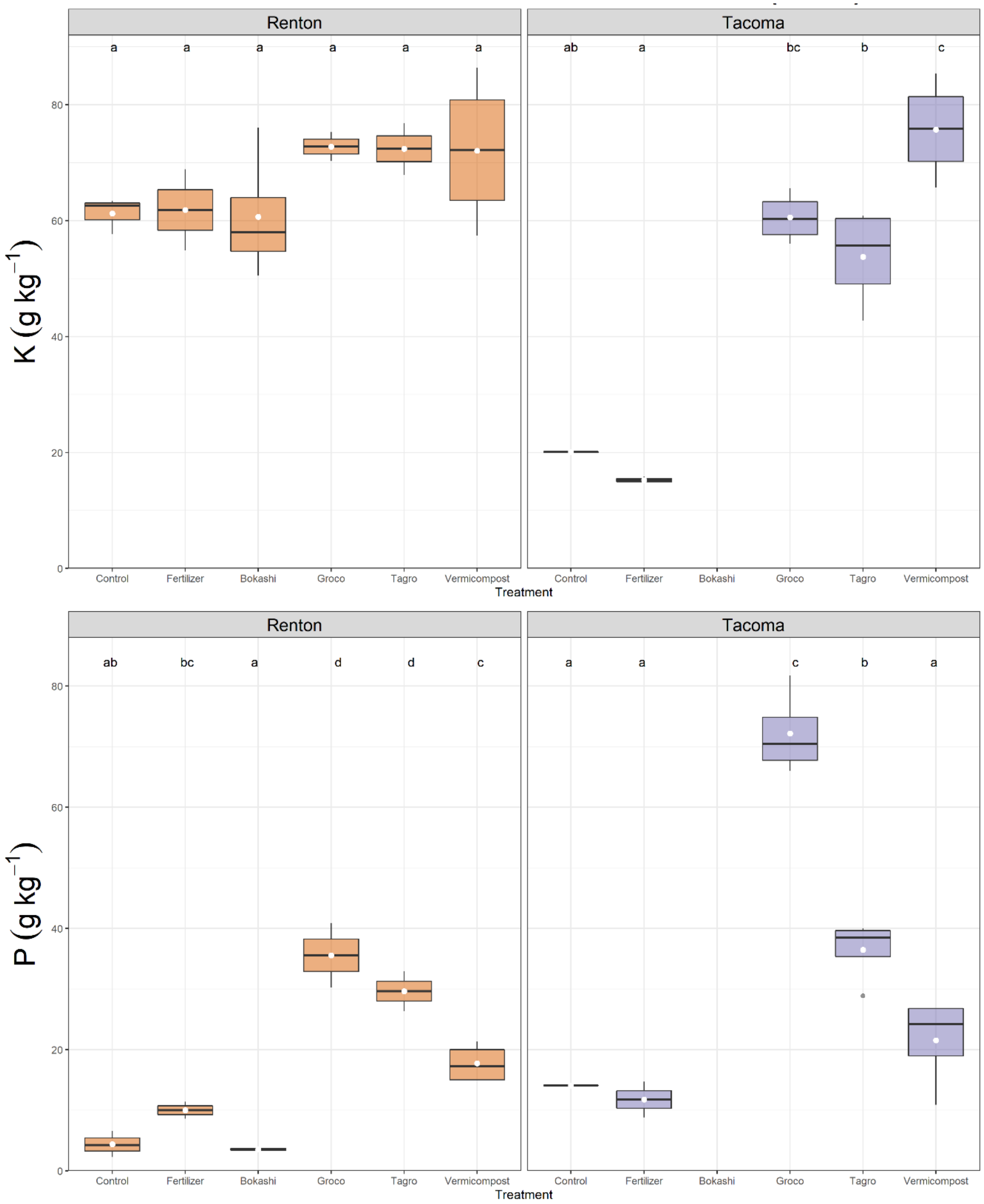

Figure 2.8 Swiss chard leaf macronutrient concentrations (K and P; g kg^{-1}) boxplot. Boxes represent the interquartile range (IR). Whiskers include data points above and below 1.5x's the IR. Lines in the boxes represent the median and dots represent the mean. Letters that are not shared above the treatments indicate differences according to pairwise mean comparison using Tukey HSD ($p<0.05$). Mineral concentrations were analyzed separately by soil type. There was no yield for Tacoma Bokashi.

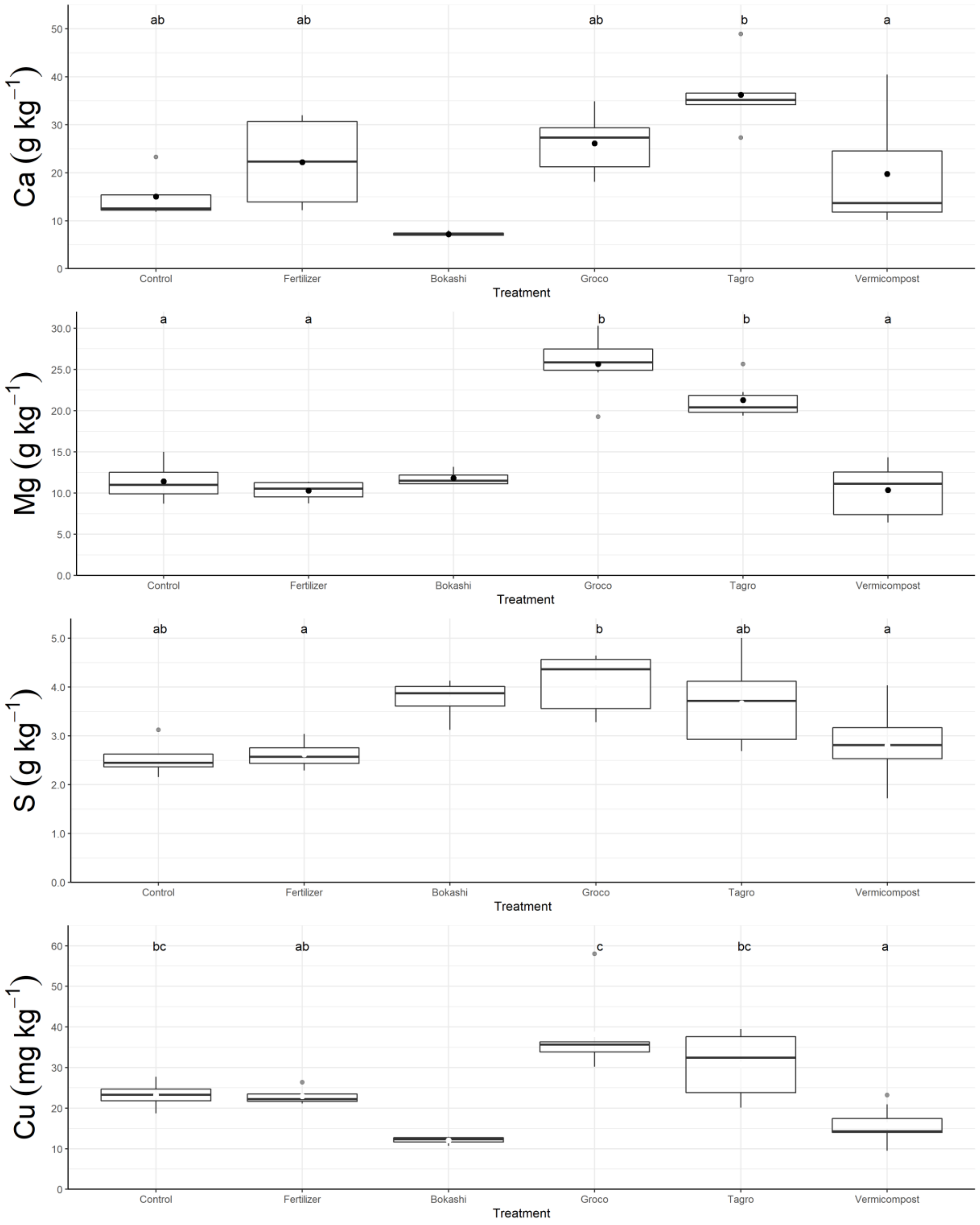

Figure 2.9 Swiss chard leaf mineral concentrations (Ca, Mg, and S; g kg^{-1} and Cu; mg kg^{-1}) boxplot. Boxes represent the interquartile range (IR). Whiskers include data points above and below 1.5x's the IR. Lines in the boxes represent the median and dots represent the mean. Letters that are not shared above the treatments indicate differences according to pairwise mean comparison using Tukey HSD (p<0.05). Mineral concentrations were analyzed for both soil types combined. There was no yield for Tacoma Bokashi.

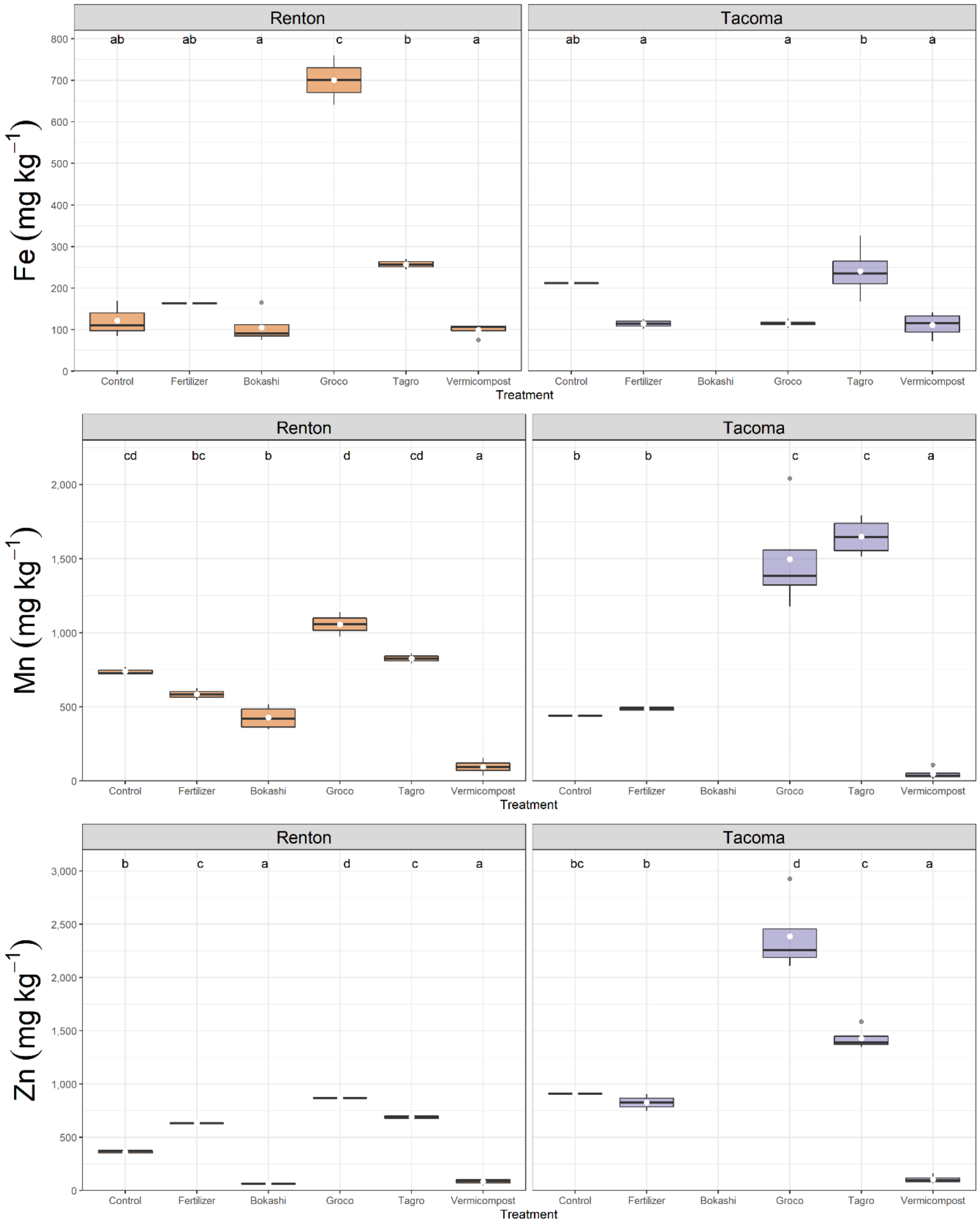

Figure 2.10 Swiss chard foliar micronutrient concentrations (Fe, Mn, & Zn; mg kg^{-1}). Boxes represent the interquartile range (IR). Whiskers include data points above and below 1.5x's the IR. Lines in the boxes represent the median and white dots represent the mean. Letters that are not shared above the treatments indicate differences according to pairwise mean comparison using Tukey HSD ($p<0.05$). Mineral concentrations were analyzed separately by soil type. There was no yield for Tacoma Bokashi.

The kale and chard had different nutritional densities overall, as expected. In general, nutrient concentrations (dry weight basis) were higher in the chard than in the kale. Chard generally had higher concentrations for K, Mg, P, Cu, Fe, Mn, and Zn while kale had higher concentrations of Ca and S.

Foliar tissue concentrations for many elements (Ca, P, S, K, Cu, Mn, and Zn) were higher in one soil than the other. Typically, the Tacoma soil had higher crop mineral concentrations than the Renton soil. For both crops, elements that were higher in the Tacoma soil were P, S, Cu, Mn, and Zn. Specifically in the kale, Ca concentrations were higher in the Tacoma soil while chard leaf concentrations of K and Fe were higher in the Renton soil. The nutritional density of crops grown varied by the main effect of soil type in most cases in the kale with exception of K and Fe concentrations. In the chard most elements varied by the main effect of soil type with the exception of Ca and Mg concentrations. Almost all nutrients had a significant ($p<0.05$) interaction effect between soil and treatment with the exception of a few mineral concentrations in both crops (K concentrations in the kale; Ca, Mg, S, and Cu concentrations in the chard).

Plants grown in the amended soils generally had comparable or increased mineral concentrations than those grown in fertilizer treatments. In both soils, select amendments had an impact on crop mineral concentrations that were significant relative to the fertilized control. In general, relative to controls vermicompost increased crop concentrations of K and kale foliar S concentrations. While not always consistent for both Tagro and GroCo in each soil type, there were many cases where the biosolids-based amendments had higher mineral concentrations than both controls. Biosolids amendments had significant increases in both soils, above both controls in the kale (S) and the chard (Mg and P). In general, both biosolids amendments increased Cu, Fe, Mn, and Zn in the chard.

For many micronutrients (Cu, Mn, and Zn) vermicompost amendment reduced mineral concentrations relative to both controls. This reduction may be related to the observed yield increase for plants grown in this treatment which could have effectively diluted the available nutrients. Vermicompost decreased foliar Cu concentrations in the kale and concentrations of

Mn and Zn in both crops. This trend may have persisted for bokashi, which is the other food scrap-based amendment. In the Renton soil, bokashi decreased chard concentrations of Cu and Zn relative to both controls. However, because this was the only crop and soil where bokashi germinated further research is necessary.

In a sandy loam soil applied with high applications of biosolids (11.7 Mg ha^{-1} annually for 7 years), mineral concentrations in Canola (*Brassica napus)* increased for leaf concentrations Ca, K, Mg, P, S, Cu, Mn, and Zn relative to an unamended control (Bañuelos et al., 2004) although they did not test Fe concentrations. Similarly, a previous study that evaluated organic amendment applications from local wastes (including two biosolid composts, yard waste, and biowaste) in sandy loam in British Columbia, Canada found increased chard leaf concentrations of N, P, Cu, and Zn relative to minerally fertilized controls (Neilsen et al., 1998).

2.3.5 Principal Component Analysis (PCA)

Principal component analysis (PCA) biplots were produced for the kale (Figure 2.11) and chard (Figure 2.12) using the principal component (PC) axes that described the highest and significant proportions of the variation in the original crop yield and mineral concentration data.

2.3.5.1 Kale PCA: yield and mineral concentrations

Kale crop data had a large amount of cumulative variation (72%) that was described by the two PC axes. A significant and high amount of variation (52%) was primarily explained by the 1st PC for kale mineral concentrations of Ca, Cu, Mn, and Zn. Although PC1 also explained a non-trivial amount of the original variance for other mineral concentrations (Mg, P, Fe, and S). Much less variation from the original variables contributed to the 2nd PC which was primarily comprised of yield and foliar concentrations of S and K.

2.3.5.2 Swiss chard PCA: yield and foliar mineral concentrations

Chard plant data had a large and significant amount of cumulative variation of the original data (68%) that was explained by both PC axes. An intermediate and significant amount of variation (49%) in PC1 was primarily comprised of original variable contributions from chard mineral concentrations of Mg, Cu, Mn, and Zn. Although PC1 also explained a non-trivial amount of variance for other leaf concentrations (Ca, P, Fe, and S). The 2nd PC axis was not significant and was primarily explained by yield and chard foliar concentrations of K and P.

2.3.5.3 PCA results: yield and foliar nutrient concentration

In general, both crops had higher yields from pots with additions of vermicompost, Tagro, and GroCo (Figure 2.11 and 2.12; panel C). In general, foliar mineral concentrations were higher in the Tacoma soil than the Renton soil but were the opposite for crop yield. The differences between plant responses for treatments were much larger in the Tacoma soil in the kale but closer to one another in the chard (Figure 2.11 and 2.12; panel B).

In the chard, the nutritional concentrations were different between the various treatments, then in the kale. While in the kale, the yield seemed to be more different between treatment groups than in the chard. For both crops, yield, and foliar K concentrations were highly correlated, while macronutrients and micronutrients concentrations were closely related to each other (Figure 2.11 and 2.12; panel A).

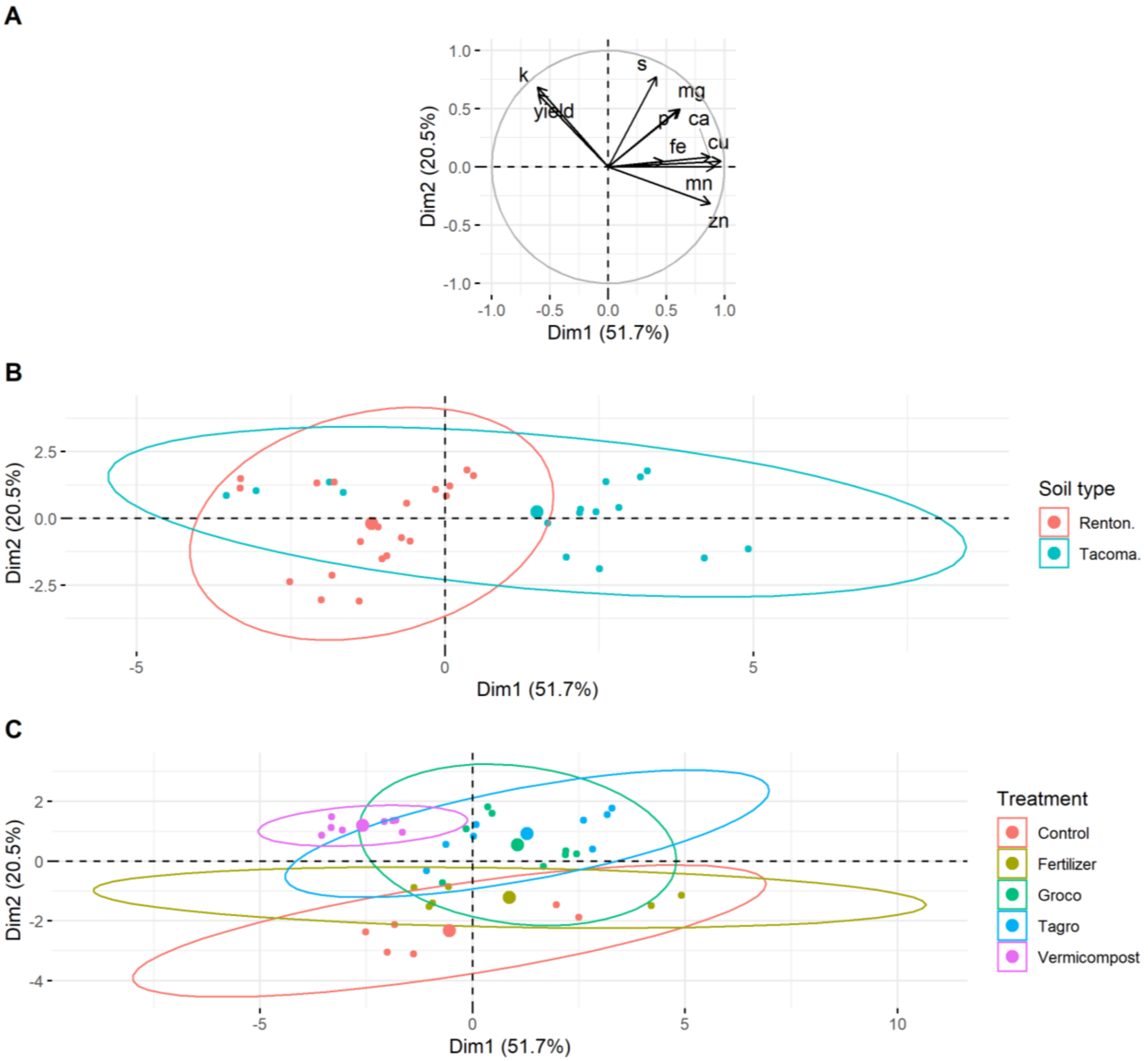

Figure 2.11 Kale PCA biplot: variables alone (A) grouped by soil type (B) or treatment (C) with 95% confidence interval ellipses.

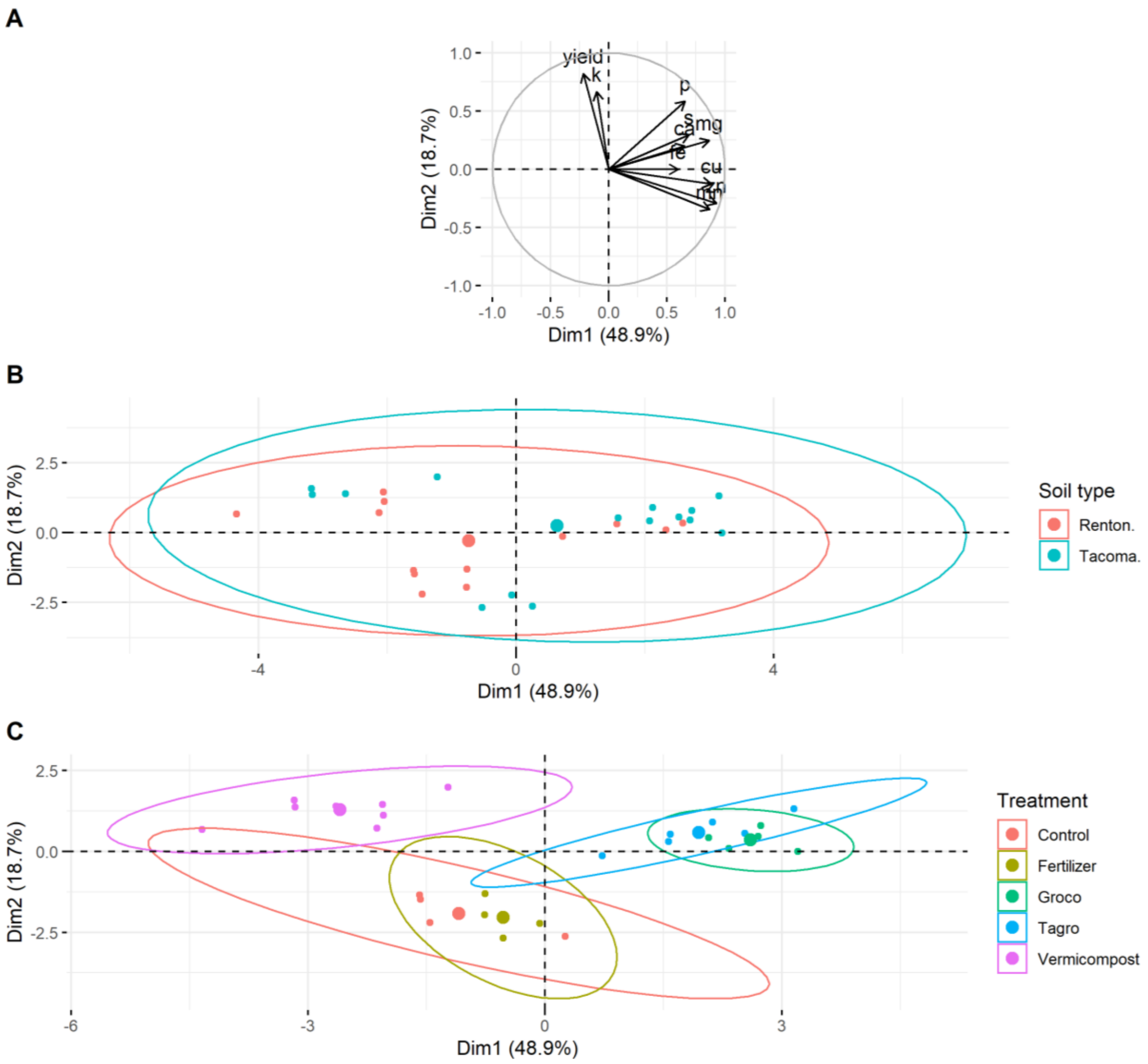

Figure 2.12 Swiss chard PCA biplot: variables alone (A) grouped by soil type (B) or treatment (C) with 95% confidence interval ellipses. The bokashi treatment was removed due to lack of germination in the Tacoma soil.

2.4 Discussion

2.4.1 Soil response to urban residuals-based organic amendments (OAs)

2.4.1.1 Impact from OAs on soil response

Organic amendments (OAs) used in this trial improved soil health according to the indicators used in this study. The most pronounced changes were increased total C, total N, and reduced bulk density. Across all OAs, soil available (M-III extractable) K, Mg, and S increased in both soils, and soil available Cu decreased with the minor exception of Tagro which slightly increased M-III Cu in the Renton soil. In both soils, OAs increased microbial activity according to the two measures used in this trial (min C and POXC) relative to control soils. Again, the exception here was from the Tagro amendment which decreased min C in both soils. In the Renton soil, amendments consistently increased available P and Zn which had lower initial concentrations than the Tacoma soil.

Soil response differed between food scrap and biosolids amendments. The effect on soil C:N and pH differed for food scrap (bokashi and vermicompost) or biosolids-based (Tagro and GroCo) amendments. Food scrap amendments decreased soil C:N and increased soil pH. Biosolids-based amendments increased soil C:N and decreased soil pH. These changes to pH, C:N ratio, and M-III available nutrients were mostly consistent with amendment characteristics, except for the soil pH from the bokashi amendment.

Changes to soil M-III extractable nutrients following amendment addition varied based on amendment type and soil type. Typically, the increases in available macronutrients (K, Mg, P, and S) were greater in the Renton soil than in the Tacoma soil. Amendments mostly had different effect sizes on soil available macronutrients with the exception of S which had similar treatment increases in each respective soil. For example, food scrap amendments increased M-III K much more than biosolids amendments. Meanwhile, GroCo and vermicompost had larger increases to M-III extractable Mg and P. Changes from amendments increased of decreased soil available micronutrients. There were larger decreases in available nutrients in the Tacoma soil. In general, biosolids amendments increased soil available Fe, Mn, and Zn. All amendments increased soil Zn in the Renton soil, but the increases from biosolids amendments were high in both soils. Bokashi had large increases in Mn which were higher than the biosolids amendments. Vermicompost decreased Mn and Fe, and bokashi decreased Fe in both soils.

Our results were consistent with changes in soil M-III extractable concentrations found in a survey of agricultural sites in California by Brown and Cotton, (2011). In that study compost applications increased K, Cu, Fe, Mg, Mn, P, and Zn compared to either unamended or fertilized control soils. In another field study, which was in a silt loam soil applications (37 Mg ha^{-1}) of biosolids increased M-III extractable nutrients Ca and Zn relative to chicken manure and increased M-III P concentrations relative to the unamended soil (Antonious et al., 2014). However, biosolids decreased M-III soil K and Mg, which did not occur in our study. In an urban system, biosolids applications (202 and 404 Mg ha^{-1}) increased soil M-III extractable Fe, Cu, and Zn relative to soil-only controls. Biosolids did not increase M-III K, P, or Mn, relative to compost (hardwood vegetative) applications (137 Mg ha^{-1}).

2.4.2 Plant response to urban residuals-based organic amendments (OAs)

2.4.2.1 Did plants grown in amended soils perform as well as those grown with synthetic fertilizer?

First and foremost, amendment additions of GroCo, Tagro, and vermicompost had positive effects on crop response. For these treatments, the yield response from OAs was much more pronounced in the Tacoma soil than the Renton soil. Of the amendments tested the increases in yield were much higher from applications of vermicompost and Tagro. In the Tacoma soil, in both crops most dramatic increases in yield were from Tagro and vermicompost relative to both controls. In the Renton soil, these amendments were also the most productive for kale but similar to both controls. In this soil vermicompost and bokashi amendments were the most productive for the chard and were higher than both controls. Bokashi did not germinate in the kale or the Tacoma soil. In most cases, GroCo increased plant yield relative to the soil only control but was generally similar to or less than the increase associated with the use of synthetic fertilizer.

Kale and chard are leafy greens with high concentrations of mineral nutrients. These greens are inherently nutrient-dense. Typically, kale has high K and Cu while chard elevated Ca, K, and Mn. Different cultivars will impact nutrient concentration and yield (Broadley et al., 2010; Hamon et al., 1997; Yoder & Davis, 2020). Amendments in our trial had crop responses (yield and foliar mineral concentrations) that were highly dependent on soil and crop type. These changes are summarized for each specific amendment below.

Vermicompost

Across both soils, vermicompost amendments resulted in the highest yielding crops. Crops grown in the vermicompost amended soil had higher tissue concentrations of K than both controls which corresponded to amendment content and amended soil mixture concentrations for M-III extractable K. Response to vermicompost amendments varied for foliar element concentrations with decreases (Ca, Cu, Mn, and Zn) and increases (K and S) observed relative to the fertilizer control. Vermicompost decreased kale tissue Ca and Cu in the Tacoma soil, and decreased crop foliar Mn and Zn for both soil types. In addition to the universal increases in foliar K, vermicompost increase kale concentrations of S relative to the fertilized control. Compared to the Renton soil alone without amendment, the vermicompost addition increased foliar Fe in kale and tissue concentrations of P in both crops.

Tagro

Soils amended with Tagro tended to have higher crop yields than both controls. Of the amendments tested, Tagro generated the 2nd highest yields, with responses lower than the vermicompost amended soils. Plants grown in the Tagro amended soils generally had elevated concentrations of certain nutrients relative to the two controls. When compared to the fertilizer additions Tagro increased foliar nutrients in the kale (Mg and S) and the chard (K, Mg, P, Fe, Mn, and Zn), although chard increases in Fe, Mn, and Zn were only higher than the fertilizer treatment in the Tacoma soil. Relative to unamended controls Tagro generally increased mineral concentrations of Ca in both crops and K, P, Cu, Fe, and Mn in the kale.

GroCo

GroCo tended to have yields in kale and chard that were higher than both controls in the Tacoma soil and similar in the Renton soil. Of the amendments tested, GroCo generated the 3rd highest yields in the Tacoma soil. In the Renton soil, GroCo was the 4th most productive in both crops. Fertilizer yielded higher than GroCo in the kale and after bokashi yielded more in the chard. Crops grown in the GroCo amended soils generally had elevated concentrations of certain nutrient concentrations that were higher than the two controls in both crops (Mg and P) in the kale (S) or the chard (K, Cu, Fe, Mn, and Zn). These changes were typically significant in just one soil type in the kale but were across both soil types for the elements Mg, P, Mn, and Zn in the chard. Compared to the control soils alone, GroCo amendments increased crop levels of Fe and kale tissue concentrations of Cu and Mn. These changes were typically found in one soil type but not both.

Bokashi

In the soils amended with bokashi, there was no germination with the exception of the chard in the Renton soil. When able to germinate, chard yield was the 3rd highest following vermicompost and Tagro, with an increase in yield above both controls. Nutrient analysis of bokashi was only possible for chard grown in the Renton soil which resulted in decreases of chard tissue Cu and Zn relative to both controls and Ca compared to the unamended control.

2.4.2.2 Does soil type impact plant response to OAs?

2.4.2.2.1 Crop yield response from OAs in different soil types

Response to amendments, both in terms of changes in soil properties and plant growth, varied by soil type. Despite having lower initial total C concentrations, the Renton soil supported higher plant germination and yield than the Tacoma soil. The soils and plant response to amendments in the Renton soil likely reflects the response of amendments to generally healthy soil. This soil was derived from alluvial sediments recognized as productive parent material. In contrast, the Tacoma soil was likely to fill material from construction. All amendments that we tested resulted in some (bokashi) or dramatic (Tagro and vermicompost) improvements to plant yield. In both crops, the unamended Renton soil had a higher yield than the unamended Tacoma control but the effect on yield was much higher in magnitude in the Tacoma soil. There was no or close to no yield in the control and fertilizer treatments for the Tacoma soil. Germination was very low in the Tacoma controls (<17%) and increased to 100% from the positive effects of GroCo, Tagro, and vermicompost. In the Renton soil, amendments did not impact germination.

2.4.2.2.2 Foliar mineral concentration response from OAs in different soil types

Soil type had a large effect on the foliar nutrient concentration changes from the amendments we tested. The only foliar mineral concentrations that did not vary by either soil type or interaction effects were K in the kale or Ca and Mg in the chard.

In the Renton soil, which was already highly productive as a gardening soil, vermicompost increased macronutrients (Mg, K, P, and S) typically increased from amendments which were consistent with the larger increases in the same soil M-III extractable nutrients in this soil.

In the Tacoma soil, representative of fill, crops had higher mineral foliar concentrations of P, S, Cu, Mn, and Zn than in the Renton soil, but this soil had higher micronutrient concentrations, to begin with. The decreases in micronutrient concentrations were especially high from food scrap-based amendments in this soil which was consistent with the changes and amendments properties of M-III nutrients from the vermicompost.

Soil response from organic amendments has been shown to impact leaf nutrient concentrations in other studies. In a pot study by Topalović et al., (2018) chard concentrations of Ca, Mg, and P were positively related to their soil available (ammonium lacetate-Ca, P and K) concentrations. In a field study using two biosolids-based composts, soil extractable (DPTA) P, Cu, Fe, and Mn were significantly ($p<0.001$) higher in the soil surface (0-15 cm) than the control which corresponded to increases in chard yield and leaf concentrations of Cu, Fe, and Mn above the fertilized control in the 3-year study (Neilsen et al., 1998). Potential differences from various soil types were not addressed in these studies.

2.5 Conclusion

All of the urban residuals-derived amendments tested in this study indicated increased soil quality via physical, chemical, and biological indicators. Pronounced increases in soil health were seen in changes to total C, total N, and bulk density. Soil physical changes were essential to improve yield in the lower quality soil (Tacoma) based on the lack of germination from both controls. High amendment available nutrients (M-III extractable) were reflected in the increases to the amended soil mixtures for most elements with a few exceptions.

Crop yield was highly increased in soils that were amended with Tagro and vermicompost. A soil with an inherently lower yield (Tacoma) had dramatic increases compared to the unamended and fertilizer controls. Benefits to yield also occurred for an initially healthier soil (Renton) when unamended, but much larger increases from fertilizer were seen in this soil. GroCo had positive effects on yield in both soils but did not increase yield above the fertilized Renton soil. which did not increase relative to the fertilized control. When bokashi was able to germinate which never occurred in the Tacoma soil, and only happened in the Renton soil in the chard the treatment yielded the second-highest after vermicompost. Results suggest further investigation is needed to fully assess the potential use of bokashi as an amendment.

High foliar nutrients (P, S, Cu, Mn, and Zn) across all treatments in crops in the Tacoma soil would not have been realized to an urban gardener without yield due to amendment additions. Mineral concentrations varied by crop and soil type. In general, amendments had similar or increased foliar mineral concentrations relative to the fertilized controls for macronutrients (K, Mg, S, and P). Mineral concentrations of micronutrients in general either increased from biosolids-based amendments or decreased from food-scrap based on the feedstock materials. The results from this study suggest that urban food-based residuals have the potential to improve urban soils and increase yields for urban agriculture.

References

Ag Weather Net Current Conditions Map. (2021). [Map]. https://weather.wsu.edu/

Aksakal, E. L., Sari, S., & Angin, I. (2016). Effects of Vermicompost Application on Soil Aggregation and Certain Physical Properties. Land Degradation & Development, 27(4), 983–995. https://doi.org/10.1002/ldr.2350

Albiach, R., Canet, R., Pomares, F., & Ingelmo, F. (2001). Organic matter components and aggregate stability after the application of different amendments to a horticultural soil. Bioresource Technology, 76(2), 125–129. https://doi.org/10.1016/S0960-8524(00)00090-0

Alvarez-Campos, O., & Evanylo, G. K. (2019). Biosolids Improve Urban Soil Properties and Vegetable Production in Urban Agriculture. Urban Agriculture & Regional Food Systems, 4(1), 190002. https://doi.org/10.2134/urbanag2019.04.0002

Alvarez-Campos, O., & Evanylo, G. K. (2019a). Plant Available Nitrogen Estimation Tools for a Biosolids-Amended, Clayey Urban Soil. Soil Science Society of America Journal, 83(3), 808–816. https://doi.org/10.2136/sssaj2018.11.0441

Alvarez-Campos, O., & Evanylo, G. K. (2019b). Environmental Impact of Exceptional Quality Biosolids Use in Urban Agriculture. Journal of Environmental Quality, 48(6), 1872–1880. https://doi.org/10.2134/jeq2019.04.0181

Alvarez-Campos, O., Evanylo, G. K., & Badzmierowski, M. J. (2018). Development and Assessment of Exceptional Quality Biosolids Products for Urban Gardens. Compost Science & Utilization, 26(4), 232–243. https://doi.org/10.1080/1065657X.2018.1488636

Álvarez-Solís, J. D., Mendoza-Niñez, J. A., León-Martínez, N. S., Castellanos-Albores, J., & Gutiérrez-Miceli, F. A. (2016). Effect of bokashi and vermicompost leachate on yield and quality of pepper (Capsicum annuum) and onion (Allium cepa) under monoculture and intercropping cultures. Ciencia e Investigación Agraria, 43(2), 243–252. https://doi.org/10.4067/S0718-16202016000200008

Antonious, G. F., Silitonga, M. R., Tsegaye, T. D., Unrine, J. M., Coolong, T., & Snyder, J. C. (2013). Elevated concentrations of trace elements in soil do not necessarily reflect metals available to plants. Journal of Environmental Science and Health, Part B, 48(3), 219–225. https://doi.org/10.1080/03601234.2013.730340

Antonious, G. F., Turley, E. T., Hill, R. R., & Snyder, J. C. (2014). Chicken manure enhanced yield and quality of field-grown kale and collard greens. Journal of Environmental Science and Health, Part B, 49(4), 299–304. https://doi.org/10.1080/03601234.2014.868681

Arancon, N. Q., Edwards, C. A., Bierman, P., Welch, C., & Metzger, J. D. (2004). Influences of vermicomposts on field strawberries: 1. Effects on growth and yields. Bioresource Technology, 93(2), 145–153. https://doi.org/10.1016/j.biortech.2003.10.014

Arancon, N. Q., Edwards, C. A., Dick, R., & Dick, L. (2007). Vermicompost Tea production and plant growth impacts. Biocycle, 48(11), 51–52.

Arancon, Norman Q., Edwards, C. A., Atiyeh, R., & Metzger, J. D. (2004). Effects of vermicomposts produced from food waste on the growth and yields of greenhouse peppers. Bioresource Technology, 93(2), 139–144. https://doi.org/10.1016/j.biortech.2003.10.015

Arancon, Norman Q., Edwards, Clive. A., Lee, S., & Byrne, R. (2006). Effects of humic acids from vermicomposts on plant growth. European Journal of Soil Biology, 42, S65–S69. https://doi.org/10.1016/j.ejsobi.2006.06.004

Atiyeh, R. M., Lee, S., Edwards, C. A., Arancon, N. Q., & Metzger, J. D. (2002). The influence of humic acids derived from earthworm-processed organic wastes on plant growth. Bioresource Technology, 84(1), 7–14. https://doi.org/10.1016/S0960-8524(02)00017-2

Atiyeh, Rola M., Edwards, C. A., Subler, S., & Metzger, J. D. (2000). Earthworm-Processed Organic Wastes as Components Of Horticultural Potting Media for Growing Marigold and Vegetable Seedlings. Compost Science & Utilization, 8(3), 215–223. https://doi.org/10.1080/1065657X.2000.10701994

Badzmierowski, M. J., Evanylo, G. K., & Ervin, E. H. (2020). Biosolids amendments improve an anthropogenically disturbed urban turfgrass system. Crop Science, 60(3), 1666–1681. https://doi.org/10.1002/csc2.20151

Bañuelos, G. S., Sharmasarkar, S., & Pasakdee, S. (2004). Utilization of Biosolids as a Fertilizer for Canola. *Compost Science & Utilization*, *12*(1), 61–68. https://doi.org/10.1080/1065657X.2004.10702159

Barbarick, K. A., & Ippolito, J. A. (2007). Nutrient Assessment of a Dryland Wheat Agroecosystem after 12 Years of Biosolids Applications. Agronomy Journal, 99(3), 715–722. https://doi.org/10.2134/agronj2006.0221

Basta, N. T., Busalacchi, D. M., Hundal, L. S., Kumar, K., Dick, R. P., Lanno, R. P., Carlson, J., Cox, A. E., & Granato, T. C. (2016). Restoring Ecosystem Function in Degraded Urban Soil Using Biosolids, Biosolids Blend, and Compost. Journal of Environmental Quality, 45(1), 74–83. https://doi.org/10.2134/jeq2015.01.0009

Batjiaka, R., & Brown, S. (2020). Creating topsoils and soil conditioners from biosolids and urban residuals. Journal of Environmental Quality, jeq2.20067. https://doi.org/10.1002/jeq2.20067

Beesley, L. (2014). Respiration (CO2 flux) from urban and peri-urban soils amended with green waste compost. Geoderma, 223–225, 68–72. https://doi.org/10.1016/j.geoderma.2014.01.024

Beniston, J., & Lal, R. (2012). Improving Soil Quality for Urban Agriculture in the North Central U.S (pp. 279–313). Springer Netherlands. https://doi.org/10.1007/978-94-007-2366-5_15

Beniston, J. W., Lal, R., & Mercer, K. L. (2016). Assessing and Managing Soil Quality for Urban Agriculture in a Degraded Vacant Lot Soil. Land Degradation & Development, 27(4), 996–1006. https://doi.org/10.1002/ldr.2342

Burt, R. M.A. Wilson, D. Mays and C.W. Lee. 2003 Major and Trace Elements of Selected Pedons in the USA JEQ. https://doi.org/10.2134/jeq2003.2109

Boechat, C. L., Santos, J. A. G., & Accioly, A. M. de A. (2013). Net mineralization nitrogen and soil chemical changes with application of organic wastes with 'Fermented Bokashi Compost.' Acta Scientiarum. Agronomy, 35(2), 257–264. https://doi.org/10.4025/actasciagron.v35i2.15133

Brewer, L. J., & Sullivan, D. M. (2003). Maturity and Stability Evaluation of Composted Yard Trimmings. Compost Science & Utilization, 11(2), 96–112. https://doi.org/10.1080/1065657X.2003.10702117

Broadley, M., Lochlainn, S., Hammond, J., Bowen, H., Cakmak, I., Eker, S., Erdem, H., King, G., & White, P. (2010). Shoot zinc (Zn) concentration varies widely within Brassica oleracea L. and is affected by soil Zn and phosphorus (P) levels. The Journal of Horticultural Science and Biotechnology, 85(5), 375–380. https://doi.org/10.1080/14620316.2010.11512683

Brown, S., & Cotton, M. (2011). Changes in Soil Properties and Carbon Content Following Compost Application: Results of On-farm Sampling. Compost Science & Utilization, 19(2), 87–96. https://doi.org/10.1080/1065657X.2011.10736983

Brown, S., Kurtz, K., Bary, A., & Cogger, C. (2011). Quantifying Benefits Associated with Land Application of Organic Residuals in Washington State. Environmental Science & Technology, 45(17), 7451–7458. https://doi.org/10.1021/es2010418

Bulluck, L. R., Brosius, M., Evanylo, G. K., & Ristaino, J. B. (2002). Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. Applied Soil Ecology, 19(2), 147–160. https://doi.org/10.1016/S0929-1393(01)00187-1

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J. W., & Brussaard, L. (2018). Soil quality – A critical review. Soil Biology and Biochemistry, 120, 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030

Carballo, T., Gil, M. V., Calvo, L. F., & Morán, A. (2009). The Influence of Aeration System, Temperature and Compost Origin on the Phytotoxicity of Compost Tea. Compost Science & Utilization, 17(2), 127–139. https://doi.org/10.1080/1065657X.2009.10702411

CFR Title 21, Part 101 Food Labeling Table iv. (2020). Department of Health and Human Services. https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/cfrsearch.cfm?fr=101.9

Chaichi, W., Djazouli, Z., Zebib, B., & Merah, O. (2018). Effect of Vermicompost Tea on Faba Bean Growth and Yield. Compost Science & Utilization, 26(4), 279–285. https://doi.org/10.1080/1065657X.2018.1528908

Chen, Y., Camps-Arbestain, M., Shen, Q., Singh, B., & Cayuela, M. L. (2018). The long-term role of organic amendments in building soil nutrient fertility: A meta-analysis and review. Nutrient Cycling in Agroecosystems, 111(2), 103–125. https://doi.org/10.1007/s10705-017-9903-5

Christel, D. M. (2017). The Use Of Bokashi As A Soil Fertility Amendment In Organic Spinach Cultivation. 162.

Cogger, C G, Forge, T. A., & Neilsen, G. H. (2006). Biosolids recycling: Nitrogen management and soil ecology. Canadian Journal of Soil Science, 86(4), 613–620. https://doi.org/10.4141/S05-117

Cogger, Craig G. (2005). Potential Compost Benefits for Restoration Of Soils Disturbed by Urban Development. Compost Science & Utilization, 13(4), 243–251. https://doi.org/10.1080/1065657X.2005.10702248

Cogger, Craig G., Bary, A. I., Fransen, S. C., & Sullivan, D. M. (2001). Seven Years of Biosolids versus Inorganic Nitrogen Applications to Tall Fescue. Journal of Environmental Quality, 30(6), 2188–2194. https://doi.org/10.2134/jeq2001.2188

Cogger, Craig G., Bary, A. I., Kennedy, A. C., & Fortuna, A.-M. (2013). Long-Term Crop and Soil Response to Biosolids Applications in Dryland Wheat. Journal of Environmental Quality, 42(6), 1872–1880. https://doi.org/10.2134/jeq2013.05.0109

Cogger, Craig G., Bary, A. I., Myhre, E. A., Fortuna, A.-M., & Collins, D. P. (2016). Soil Physical Properties, Nitrogen, and Crop Yield in Organic Vegetable Production Systems. Agronomy Journal, 108(3), 1142–1154. https://doi.org/10.2134/agronj2015.0335

Collins, Doug, M., Andy. (2019). Understanding and Measuring Organic Matter in Soil. 17.

Cotrufo, M. F., Ranalli, M. G., Haddix, M. L., Six, J., & Lugato, E. (2019). Soil carbon storage informed by particulate and mineral-associated organic matter. Nature Geoscience, 12(12), 989–994. https://doi.org/10.1038/s41561-019-0484-6

Cornforth, I. S., Stephen, R. C., Barry, T. N., & Baird, G. A. (1978). Mineral content of swedes, turnips, and kale. *New Zealand Journal of Experimental Agriculture*, *6*(2), 151–156. https://doi.org/10.1080/03015521.1978.10426032

Culman, Steve W., Mann, M., Sharma, S., Saeed, M. T., Fulford, A. M., Lindsey, L. E., Brooker, A., Dayton, E., Warden, R., & Joern, B. (2020). Calibration of Mehlich-III with Bray P1 and Ammonium Acetate in the Tri-State Region of Ohio, Indiana and Michigan.

Communications in Soil Science and Plant Analysis, 51(1), 86–97. https://doi.org/10.1080/00103624.2019.1695825

Culman, Steven W., Snapp, S. S., Freeman, M. A., Schipanski, M. E., Beniston, J., Lal, R., Drinkwater, L. E., Franzluebbers, A. J., Glover, J. D., Grandy, A. S., Lee, J., Six, J., Maul, J. E., Mirksy, S. B., Spargo, J. T., & Wander, M. M. (2012). Permanganate Oxidizable Carbon Reflects a Processed Soil Fraction that is Sensitive to Management. Soil Science Society of America Journal, 76(2), 494–504. https://doi.org/10.2136/sssaj2011.0286

Daiss, N., Lobo, M. G., Socorro, A. R., Brückner, U., Heller, J., & Gonzalez, M. (2008). The effect of three organic pre-harvest treatments on Swiss chard (Beta vulgaris L. var. Cycla L.) quality. European Food Research and Technology, 226(3), 345–353. https://doi.org/10.1007/s00217-006-0543-2

D'Hose, T., Cougnon, M., De Vliegher, A., Vandecasteele, B., Viaene, N., Cornelis, W., Van Bockstaele, E., & Reheul, D. (2014). The positive relationship between soil quality and crop production: A case study on the effect of farm compost application. Applied Soil Ecology, 75, 189–198. https://doi.org/10.1016/j.apsoil.2013.11.013

Diacono, M., & Montemurro, F. (2010). Long-term effects of organic amendments on soil fertility. A review. Agronomy for Sustainable Development (EDP Sciences), 30(2), 401–422. https://doi.org/10.1051/agro/2009040

Dietary Reference Intakes: The Essential Guide to Nutrient Requirements (p. 11537). (2006). National Academies Press. https://doi.org/10.17226/11537

Doran, John W., & Zeiss, M. R. (2000). Soil health and sustainability: Managing the biotic component of soil quality. Applied Soil Ecology, 15(1), 3–11. https://doi.org/10.1016/S0929-1393(00)00067-6

EPA. (2018). 2018 Wasted Food Report. EPA. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/food-material-specific-data

Epelde, L., Jauregi, L., Urra, J., Ibarretxe, L., Romo, J., Goikoetxea, I., & Garbisu, C. (2018). Characterization of Composted Organic Amendments for Agricultural Use. Frontiers in Sustainable Food Systems, 2. https://doi.org/10.3389/fsufs.2018.00044

Evanylo, G., Sherony, C., Spargo, J., Starner, D., Brosius, M., & Haering, K. (2008). Soil and water environmental effects of fertilizer-, manure-, and compost-based fertility practices in an organic vegetable cropping system. Agriculture, Ecosystems & Environment, 127(1), 50–58. https://doi.org/10.1016/j.agee.2008.02.014

Ferreras, L., Gomez, E., Toresani, S., Firpo, I., & Rotondo, R. (2006). Effect of organic amendments on some physical, chemical and biological properties in a horticultural soil. Bioresource Technology, 97(4), 635–640. https://doi.org/10.1016/j.biortech.2005.03.018

Flavel, T. C., & Murphy, D. V. (2006). Carbon and Nitrogen Mineralization Rates after Application of Organic Amendments to Soil. Journal of Environmental Quality, 35(1), 183–193. https://doi.org/10.2134/jeq2005.0022

Fadigas, J. C. (2010). Use of multivariate analysis techniques for the characterization of analytical results for the determination of the mineral composition of kale. Microchemical Journal, 5.

Franzluebbers, A. J. (2016). Should Soil Testing Services Measure Soil Biological Activity? Agricultural & Environmental Letters, 1(1), 150009. https://doi.org/10.2134/ael2015.11.0009

FoodData Central. (2019). U.S. Department of Agriculture, Agricultural Research Service. fdc.nal.usda.gov.

Franzluebbers, A. J. (2016). Should Soil Testing Services Measure Soil Biological Activity? Agricultural & Environmental Letters, 1(1), 150009. https://doi.org/10.2134/ael2015.11.0009

Gale, E. S., Sullivan, D. M., Cogger, C. G., Bary, A. I., Hemphill, D. D., & Myhre, E. A. (2006). Estimating Plant-Available Nitrogen Release from Manures, Composts, and Specialty Products. Journal of Environmental Quality, 35(6), 2321–2332. https://doi.org/10.2134/jeq2006.0062

Gartler, J., Robinson, B., Burton, K., & Clucas, L. (2013). Carbonaceous soil amendments to biofortify crop plants with zinc. Science of The Total Environment, 465, 308–313. https://doi.org/10.1016/j.scitotenv.2012.10.027

Gavlak, R., Horneck, D. A., & Miller, R. O. (2005). SOIL, PLANT AND WATER REFERENCE METHODS FOR THE WESTERN REGION 1.

Ghanem, K., El-Zabalawy, K., Mustafa, A., & Elbanna, B. (2017). Impact of Using Compost Bokashi Resulting from Recycling Kitchen Waste on Head Lettuce (Lactuca sativa var. Capitata L.)Grown Organically at Home. Journal of Soil Sciences and Agricultural Engineering, 8(1), 21–27. https://doi.org/10.21608/jssae.2017.37071

Ghorbani, R., Koocheki, A., Jahan, M., & Asadi, G. A. (2008). Impact of organic amendments and compost extracts on tomato production and storability in agroecological systems. Agronomy for Sustainable Development, 28(2), 307–311. https://doi.org/10.1051/agro:2008003

Gómez-Sagasti, M. T., Hernández, A., Artetxe, U., Garbisu, C., & Becerril, J. M. (2018). How Valuable Are Organic Amendments as Tools for the Phytomanagement of Degraded Soils? The Knowns, Known Unknowns, and Unknowns. Frontiers in Sustainable Food Systems, 2. https://doi.org/10.3389/fsufs.2018.00068

González, M., Gomez, E., Comese, R., Quesada, M., & Conti, M. (2010). Influence of organic amendments on soil quality potential indicators in an urban horticultural system.

Bioresource Technology, 101(22), 8897–8901. https://doi.org/10.1016/j.biortech.2010.06.095

Goswami, L., Nath, A., Sutradhar, S., Bhattacharya, S. S., Kalamdhad, A., Vellingiri, K., & Kim, K.-H. (2017). Application of drum compost and vermicompost to improve soil health, growth, and yield parameters for tomato and cabbage plants. Journal of Environmental Management, 200, 243–252. https://doi.org/10.1016/j.jenvman.2017.05.073

Grandy, A. S., Strickland, M. S., Lauber, C. L., Bradford, M. A., & Fierer, N. (2009). The influence of microbial communities, management, and soil texture on soil organic matter chemistry. Geoderma, 150(3), 278–286. https://doi.org/10.1016/j.geoderma.2009.02.007

Griffin, T. S., & Hutchinson, M. (2007). Compost Maturity Effects on Nitrogen and Carbon Mineralization and Plant Growth. Compost Science & Utilization, 15(4), 228–236. https://doi.org/10.1080/1065657X.2007.10702338

Guhra, T., Stolze, K., Schweizer, S., & Totsche, K. U. (2020). Earthworm mucus contributes to the formation of organo-mineral associations in soil. Soil Biology and Biochemistry, 145, 107785. https://doi.org/10.1016/j.soilbio.2020.107785

Hachney, N., & Brown, S. (2017). Correctional Facility Adopts Multiple Food Scraps Practices. https://www.biocycle.net/correctional-facility-adopts-multiple-food-scraps-practices/

Hamon, R., Wundke, J., McLaughlin, M., & Naidu, R. (1997). Availability of zinc and cadmium to different plant species. Soil Research, 35(6), 1267. https://doi.org/10.1071/S97052

Havlin, J. (1999). Soil fertility and fertilizers: An introduction to nutrient management (6th ed.). Prentice Hall.

Haney, R. L., Hons, F. M., Sanderson, M. A., & Franzluebbers, A. J. (2001). A rapid procedure for estimating nitrogen mineralization in manured soil. Biology and Fertility of Soils, 33(2), 100–104. https://doi.org/10.1007/s003740000294

Hargreaves, J., Adl, M. S., Warman, P. R., & Rupasinghe, H. P. V. (2008). The effects of organic amendments on mineral element uptake and fruit quality of raspberries. Plant and Soil, 308(1), 213–226. https://doi.org/10.1007/s11104-008-9621-5

Hargreaves, J. C., Adl, M. S., Warman, P. R., & Rupasinghe, H. P. V. (2008). The effects of organic and conventional nutrient amendments on strawberry cultivation: Fruit yield and quality. Journal of the Science of Food and Agriculture, 88(15), 2669–2675. https://doi.org/10.1002/jsfa.3388

Hepperly, P., Lotter, D., Ulsh, C. Z., Seidel, R., & Reider, C. (2009). Compost, Manure and Synthetic Fertilizer Influences Crop Yields, Soil Properties, Nitrate Leaching and Crop Nutrient Content. Compost Science & Utilization, 17(2), 117–126. https://doi.org/10.1080/1065657X.2009.10702410

Hernández, A., Castillo, H., Ojeda, D., Arras, A., López, J., & Sánchez, E. (2010). Effect of Vermicompost and Compost on Lettuce Production. Chilean Journal of Agricultural Research, 70(4), 583–589. https://doi.org/10.4067/S0718-58392010000400008

Hidalgo, P. R., Matta, F. B., & Harkess, R. L. (2006). Physical and Chemical Properties of Substrates Containing Earthworm Castings and Effects on Marigold Growth. HortScience, 41(6), 1474–1476. https://doi.org/10.21273/HORTSCI.41.6.1474

Holland, J. E., Bennett, A. E., Newton, A. C., White, P. J., McKenzie, B. M., George, T. S., Pakeman, R. J., Bailey, J. S., Fornara, D. A., & Hayes, R. C. (2018). Liming impacts on soils, crops and biodiversity in the UK: A review. Science of The Total Environment, 610–611, 316–332. https://doi.org/10.1016/j.scitotenv.2017.08.020

Holmes, M. R. J. (1980). Nutrition of the oilseed rape crop. Applied Science Publishers.

Holmgren, G. G. S., Meyer, M. W., Chaney, R. L., & Daniels, R. B. (1993). Cadmium, Lead, Zinc, Copper, and Nickel in Agricultural Soils of the United States of America. Journal of Environmental Quality, 22(2), 335–348. https://doi.org/10.2134/jeq1993.00472425002200020015

Hornick, S. B. (1992). Factors affecting the nutritional quality of crops. American Journal of Alternative Agriculture, 7(1/2), 63–68. JSTOR.

Hui-Lian Xu, Ran Wang, & Mridha, Md. A. U. (2001). Effects of Organic Fertilizers and a Microbial Inoculant on Leaf Photosynthesis and Fruit Yield and Quality of Tomato Plants. Journal of Crop Production, 3(1), 173. https://doi.org/10.1300/J144v03n01_15

Hummel, R. L., Cogger, C., Bary, A., & Riley, R. (2014). Marigold and Pepper Growth in Container Substrates Made from Biosolids Composted with Carbon-rich Organic Wastes. HortTechnology, 24(3), 325–333. https://doi.org/10.21273/HORTTECH.24.3.325

Hurisso, T. T., Culman, S. W., Horwath, W. R., Wade, J., Cass, D., Beniston, J. W., Bowles, T. M., Grandy, A. S., Franzluebbers, A. J., Schipanski, M. E., Lucas, S. T., & Ugarte, C. M. (2016). Comparison of Permanganate-Oxidizable Carbon and Mineralizable Carbon for Assessment of Organic Matter Stabilization and Mineralization. Soil Science Society of America Journal, 80(5), 1352–1364. https://doi.org/10.2136/sssaj2016.04.0106

Ingham, E. R. (2004). The Compost Tea Brewing Manual. 91.International Symposium on Earthworm Ecology. Earthworm ecology (2nd ed.). CRC Press.

Islam, K. R., Stine, M. A., Gruver, J. B., Samson-Liebig, S. E., & Weil, R. R. (2003). Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. American Journal of Alternative Agriculture, 18(1), 3–17. https://doi.org/10.1079/AJAA2003003

Islam, M. K., Yaseen, T., Traversa, A., Ben Kheder, M., Brunetti, G., & Cocozza, C. (2016). Effects of the main extraction parameters on chemical and microbial characteristics of compost tea. Waste Management, 52, 62–68. https://doi.org/10.1016/j.wasman.2016.03.042

Jamroz, E., Bekier, J., Medynska-Juraszek, A., Kaluza-Haladyn, A., Cwielag-Piasecka, I., & Bednik, M. (2020). The contribution of water extractable forms of plant nutrients to evaluate MSW compost maturity: A case study. Scientific Reports, 10(1), 12842. https://doi.org/10.1038/s41598-020-69860-9

Jari Oksanen, F. Guillame Blanchet, Michael Friendly, Roeland Kindt, Pierre Legendre, Dan McGlinn, Peter R. Minchin, R. B. O'Hara, Gavin L. Simpson, Peter Solymos, M. Henry H. Stevens, Eduard Szoexs and Helene Wagner (2020). Vegan: Community Ecology Package. R package version 2.5-7. https://CRAN.R-project.org/package=vegan

Kallenbach, C., & Grandy, A. S. (2011). Controls over soil microbial biomass responses to carbon amendments in agricultural systems: A meta-analysis. Agriculture, Ecosystems & Environment, 144(1), 241–252. https://doi.org/10.1016/j.agee.2011.08.020

Kelley, A., Wilkie, A. C., & Maltais-Landry, G. (2020). Food-Based Composts Provide More Soil Fertility Benefits Than Cow Manure-Based Composts in Sandy Soils. Agriculture, 10(3), NA-NA. https://doi.org/10.3390/agriculture10030069

Khaleel, R., Reddy, K. R., & Overcash, M. R. (1981). Changes in Soil Physical Properties Due to Organic Waste Applications: A Review. Journal of Environmental Quality, 10(2), 133–141. https://doi.org/10.2134/jeq1981.00472425001000020002x

King County, W. (2021). GroCo product information. https://kingcounty.gov/services/environment/wastewater/resource-recovery/loop-biosolids/compost.aspx

Kirkby, C. A., Richardson, A. E., Wade, L. J., Passioura, J. B., Batten, G. D., Blanchard, C., & Kirkegaard, J. A. (2014). Nutrient availability limits carbon sequestration in arable soils. Soil Biology & Biochemistry, 68, 402–409. https://doi.org/10.1016/j.soilbio.2013.09.032

Knežević, M., Đurović, D., Mugoša, B., Strunjaš, M., & Topalović, A. (2014). RELATIONSHIPS BETWEEN PARAMETERS OF SOIL AND CHARD (BETA VULGARIS L. VAR. CICLA L.). 10.

Kranz, C. N., McLaughlin, R. A., Johnson, A., Miller, G., & Heitman, J. L. (2020). The effects of compost incorporation on soil physical properties in urban soils – A concise review. Journal of Environmental Management, 261, 110209. https://doi.org/10.1016/j.jenvman.2020.110209

Krucker, M., Hummel, R. L., & Cogger, C. (2010). Chrysanthemum Production in Composted and Noncomposted Organic Waste Substrates Fertilized with Nitrogen at Two Rates Using Surface and Subirrigation. HortScience, 45(11), 1695–1701. https://doi.org/10.21273/HORTSCI.45.11.1695

Krucker, M., Hummel, R. L., & Cogger, C. (2010). Chrysanthemum Production in Composted and Noncomposted Organic Waste Substrates Fertilized with Nitrogen at Two Rates Using Surface and Subirrigation. HortScience, 45(11), 1695–1701. https://doi.org/10.21273/HORTSCI.45.11.1695

Lal, R. (2009). Soil degradation as a reason for inadequate human nutrition. Food Security, 1(1), 45–57. https://doi.org/10.1007/s12571-009-0009-z

Lal, Rattan. (2020). Home gardening and urban agriculture for advancing food and nutritional security in response to the COVID-19 pandemic. Food Security, 12(4), 871–876. https://doi.org/10.1007/s12571-020-01058-3

Larney, F. J., & Angers, D. A. (2012). The role of organic amendments in soil reclamation: A review. Canadian Journal of Soil Science, 92(1), 19–38. https://doi.org/10.4141/cjss2010-064

Lavallee, J. M., Soong, J. L., & Cotrufo, M. F. (2020). Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. Global Change Biology, 26(1), 261–273. https://doi.org/10.1111/gcb.14859

Leroy, B. L. M., Herath, H. M. S. K., Sleutel, S., Neve, S. D., Gabriels, D., Reheul, D., & Moens, M. (2008). The quality of exogenous organic matter: Short-term effects on soil physical properties and soil organic matter fractions. Soil Use and Management, 24(2), 139–147. https://doi.org/10.1111/j.1475-2743.2008.00142.x

Libutti, A., Trotta, V., & Rivelli, A. (2020). Biochar, Vermicompost, and Compost as Soil Organic Amendments: Influence on Growth Parameters, Nitrate and Chlorophyll Content of Swiss Chard (Beta vulgaris L. var. cycla). Agronomy, 10(3), 346. https://doi.org/10.3390/agronomy10030346

Lim, S. L., Wu, T. Y., Lim, P. N., & Shak, K. P. Y. (2015). The use of vermicompost in organic farming: Overview, effects on soil and economics. Journal of the Science of Food and Agriculture, 95(6), 1143–1156. https://doi.org/10.1002/jsfa.6849

Maass, V., Céspedes, C., Cárdenas, C., Maass, V., Céspedes, C., & Cárdenas, C. (2020). Effect of bokashi improved with rock phosphate on parsley cultivation under organic greenhouse management. Chilean Journal of Agricultural Research, 80(3), 444–451. https://doi.org/10.4067/S0718-58392020000300444

Masciandaro, G., Ceccanti, B., Ronchi, V., & Bauer, C. (2000). Kinetic parameters of dehydrogenase in the assessment of the response of soil to vermicompost and inorganic fertilisers. Biology and Fertility of Soils, 32(6), 479–483. https://doi.org/10.1007/s003740000280

McCarrison, R. (1921). Studies in deficiency disease. HFrowde; Hodder & Stoughton.

McGrath, S. P., Chambers, B. J., Taylor, M. J., & Carlton-Smith, C. H. (2012). Biofortification of zinc in wheat grain by the application of sewage sludge. Plant and Soil, 361(1–2), 97–108. https://doi.org/10.1007/s11104-012-1381-6

McIvor, K., Cogger, C., & Brown, S. (2012). Effects of Biosolids Based Soil Products on Soil Physical and Chemical Properties in Urban Gardens. Compost Science & Utilization, 20(4), 199–206. https://doi.org/10.1080/1065657X.2012.10737049

Medina-Herrera, M. del R., Negrete-Rodríguez, M. de la L. X., Álvarez-Trejo, J. L., Samaniego-Hernández, M., González-Cruz, L., Bernardino-Nicanor, A., & Conde-Barajas, E. (2020). Evaluation of Non-Conventional Biological and Molecular Parameters as Potential Indicators of Quality and Functionality of Urban Biosolids Used as Organic Amendments of Agricultural Soils. Applied Sciences, 10(2), 517. https://doi.org/10.3390/app10020517

Mehlich, A. (1984). Mehlich-III soil test extractant: A modification of the Mehlich 2 extractant.

Miller, D. R. O., & Horneck, D. D. (2013). SOIL, PLANT AND WATER REFERENCE METHODS FOR THE WESTERN REGION. 156.

Mkhabela, M. S., & Warman, P. R. (2005). The influence of municipal solid waste compost on yield, soil phosphorus availability and uptake by two vegetable crops grown in a Pugwash sandy loam soil in Nova Scotia. Agriculture, Ecosystems & Environment, 106(1), 57–67. https://doi.org/10.1016/j.agee.2004.07.014

Morra, L., Pagano, L., Iovieno, P., Baldantoni, D., & Alfani, A. (2010). Soil and vegetable crop response to addition of different levels of municipal waste compost under Mediterranean greenhouse conditions. Agronomy for Sustainable Development, 30(3), 701–709. https://doi.org/10.1051/agro/2009046

Morrow, J. G., Huggins, D. R., Carpenter-Boggs, L. A., & Reganold, J. P. (2016). Evaluating Measures to Assess Soil Health in Long-Term Agroecosystem Trials. Soil Science Society of America Journal, 80(2), 450–462. https://doi.org/10.2136/sssaj2015.08.0308

Neher, D. A., Weicht, T. R., Bates, S. T., Leff, J. W., & Fierer, N. (2013). Changes in Bacterial and Fungal Communities across Compost Recipes, Preparation Methods, and Composting Times. PLoS ONE, 8(11), e79512–e79512. https://doi.org/10.1371/journal.pone.0079512

Neilsen, G. H., Hogue, E. J., Neilsen, D., & Zebarth, B. J. (1998). Evaluation of organic wastes as soil amendments for cultivation of carrot and chard on irrigated sandy soils. Canadian Journal of Soil Science, 78(1), 217–225. https://doi.org/10.4141/S97-037

Nicholson, F., Bhogal, A., Taylor, M., McGrath, S., & Withers, P. (2018). Long-term Effects of Biosolids on Soil Quality and Fertility: Soil Science, 183(3), 89–98. https://doi.org/10.1097/SS.0000000000000239

Ninh, H. T., Grandy, A. S., Wickings, K., Snapp, S. S., Kirk, W., & Hao, J. (2015). Organic amendment effects on potato productivity and quality are related to soil microbial activity. Plant and Soil, 386(1), 223–236. https://doi.org/10.1007/s11104-014-2223-5

Norris, C. E., & Congreves, K. A. (2018). Alternative Management Practices Improve Soil Health Indices in Intensive Vegetable Cropping Systems: A Review. Frontiers in Environmental Science, 6. https://doi.org/10.3389/fenvs.2018.00050

NRCS Soil Survey Staff, N. R. C. S. (2021). Web Soil Survey. United States Department of Agriculture. http://websoilsurvey.sc.egov.usda.gov/

Nurhidayati, N, Machfudz, M., & Murwani, I. (2018). Direct and residual effect of various vermicompost on soil nutrient and nutrient uptake dynamics and productivity of four mustard Pak-Coi (Brassica rapa L.) sequences in organic farming system. International Journal of Recycling of Organic Waste in Agriculture; Isfahan, 7(2), 173–181. http://dx.doi.org/10.1007/s40093-018-0203-0

Oladeji, O., Tian, G., Lindo, P., Kumar, K., Cox, A., Hundal, L., Zhang, H., & Podczerwinski, E. (2020). Nitrogen release and plant available nitrogen of composted and un-composted biosolids. Water Environment Research, 92(4), 631–640. https://doi.org/10.1002/wer.1260

Olle, M., & Williams, I. H. (2013). Effective microorganisms and their influence on vegetable production – a review. The Journal of Horticultural Science and Biotechnology, 88(4), 380–386. https://doi.org/10.1080/14620316.2013.11512979

Olle, M. (2020). Review: Bokashi technology as a promising technology for crop production in Europe. The Journal of Horticultural Science and Biotechnology, 0(0), 1–8. https://doi.org/10.1080/14620316.2020.1810140

Oregon State University. (2021). Soil health lab standard operating procedures. https://cropandsoil.oregonstate.edu/shl/methods-and-equipment

Ozores-Hampton, M., Stansly, P. A., & Salame, T. P. (2011). Soil Chemical, Physical, and Biological Properties of a Sandy Soil Subjected to Long-Term Organic Amendments. Journal of Sustainable Agriculture, 35(3), 243–259. https://doi.org/10.1080/10440046.2011.554289

Pan, X., Song, W., & Zhang, D. (2010). Earthworms (Eisenia foetida, Savigny) mucus as complexing ligand for imidacloprid. Biology and Fertility of Soils, 46(8), 845–850. https://doi.org/10.1007/s00374-010-0494-4

Panicker, G. K., Sims, C. A., Spiers, J. M., Silva, J. L., & Matta, F. B. (2009). EFFECT OF WORM CASTINGS, COW MANURE, AND FOREST WASTE ON YIELD AND FRUIT QUALITY OF ORGANIC BLUEBERRIES GROWN ON A HEAVY SOIL. Acta Horticulturae, 841, 581–584. https://doi.org/10.17660/ActaHortic.2009.841.88

Pant, A. P., Radovich, T. J., Hue, N. V., Talcott, S. T., & Krenek, K. A. (2009). Vermicompost extracts influence growth, mineral nutrients, phytonutrients and antioxidant activity in pak choi (Brassica rapa cv. Bonsai, Chinensis group) grown under vermicompost and chemical fertiliser. Journal of the Science of Food and Agriculture, 89(14), 2383–2392. https://doi.org/10.1002/jsfa.3732

Pant, A. P., Radovich, T. J. K., Hue, N. V., & Paull, R. E. (2012). Biochemical properties of compost tea associated with compost quality and effects on pak choi growth. Scientia Horticulturae, 148, 138–146. https://doi.org/10.1016/j.scienta.2012.09.019

Powlson, D. S., Gregory, P. J., Whalley, W. R., Quinton, J. N., Hopkins, D. W., Whitmore, A. P., Hirsch, P. R., & Goulding, K. W. T. (2011). Soil management in relation to sustainable agriculture and ecosystem services. Food Policy, 36, S72–S87. https://doi.org/10.1016/j.foodpol.2010.11.025

Pribyl, D. W. (2010). A critical review of the conventional SOC to SOM conversion factor. Geoderma, 156(3), 75–83. https://doi.org/10.1016/j.geoderma.2010.02.003

Quiroz, M., & Céspedes, C. (2019). Bokashi as an Amendment and Source of Nitrogen in Sustainable Agricultural Systems: A Review. Journal of Soil Science and Plant Nutrition, 19(1), 237–248. https://doi.org/10.1007/s42729-019-0009-9

Rashtbari, M., Ali, A. H., & Ghorchiani, M. (2020). Effect of Vermicompost and Municipal Solid Waste Compost on Growth and Yield of Canola under Drought Stress Conditions. Communications in Soil Science and Plant Analysis, 51(17), 2215–2222. https://doi.org/10.1080/00103624.2020.1820023

R Core Team. (2016). R: A Language and Environment for Statistical Computing.

Reardon, C. L., & Wuest, S. B. (2016). Soil amendments yield persisting effects on the microbial communities—A 7-year study. Applied Soil Ecology, 101, 107–116. https://doi.org/10.1016/j.apsoil.2015.12.013

Reich, P. (2021). Soil Inorganic Carbon Map [Map]. NRCS USDA. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/worldsoils/?cid=nrcs142p2_054016

Rigby, H., Perez-Viana, F., Cass, J., Rogers, M., & Smith, S. R. (2009). The influence of soil and biosolids type, and microbial immobilisation on nitrogen availability in biosolids-amended agricultural soils – implications for fertiliser recommendations. Soil Use and Management, 25(4), 395–408. https://doi.org/10.1111/j.1475-2743.2009.00240.x

Ros, M., Klammer, S., Knapp, B., Aichberger, K., & Insam, H. (2006). Long-term effects of compost amendment of soil on functional and structural diversity and microbial activity. Soil Use and Management, 22(2), 209–218. https://doi.org/10.1111/j.1475-2743.2006.00027.x

Sáinz, M. J., Taboada-Castro, M. T., & Vilariño, A. (1998). Growth, mineral nutrition and mycorrhizal colonization of red clover and cucumber plants grown in a soil amended with composted urban wastes. Plant and Soil, 205(1), 85–92. JSTOR.

Sanders, D. (2019). Standard Operating Procedure for Preparation of Tissue Samples for Analysis of Total Metals by Inductively Coupled Plasma—Mass Spectrometry (ICP-MS). King County Environmental Laboratory.

Sciubba, L., Cavani, L., Negroni, A., Zanaroli, G., Fava, F., Ciavatta, C., & Marzadori, C. (2014). Changes in the functional properties of a sandy loam soil amended with biosolids at different application rates. Geoderma, 221–222, 40–49. https://doi.org/10.1016/j.geoderma.2014.01.018

Sebastien Le, Julie Josse, Francoi Husson (2008). FactoMineR: An R Package for Multivariate Analysis. Journal of Statistical Software, 25(1), 1-18. 10.18.627/jss.v025.i01

Shober, A. L., Stehouwer, R. C., & Macneal, K. E. (2003). On-Farm Assessment of Biosolids Effects on Soil and Crop Tissue Quality. *Journal of Environmental Quality*, *32*(5), 1873–1880. https://doi.org/10.2134/jeq2003.1873

Shukla, R. C., & Singh, K. (2010). Effect of Vermicompost of Different Organic Wastes on the Germination, Growth and Productivity of Certain Crops. Journal of Solid Waste Technology & Management, 36(3), 170–181. https://doi.org/10.5276/JSWTM.2010.170

Sim, E. Y. S., & Wu, T. Y. (2010). The potential reuse of biodegradable municipal solid wastes (MSW) as feedstocks in vermicomposting. Journal of the Science of Food and Agriculture, 90(13), 2153–2162. https://doi.org/10.1002/jsfa.4127

Singh, R. P., Singh, P., Araujo, A. S. F., Hakimi Ibrahim, M., & Sulaiman, O. (2011). Management of urban solid waste: Vermicomposting a sustainable option. Resources, Conservation and Recycling, 55(7), 719–729. https://doi.org/10.1016/j.resconrec.2011.02.005

Singh, R., Sharma, R. R., Kumar, S., Gupta, R. K., & Patil, R. T. (2008). Vermicompost substitution influences growth, physiological disorders, fruit yield and quality of strawberry (Fragaria x ananassa Duch.). Bioresource Technology, 99(17), 8507–8511. https://doi.org/10.1016/j.biortech.2008.03.034

Speir, T. W., Horswell, J., van Schaik, A. P., Mclaren, R. G., & Fietje, G. (2004). Composted biosolids enhance fertility of a sandy loam soil under dairy pasture. Biology and Fertility of Soils; Heidelberg, 40(5), 349–358. http://dx.doi.org/10.1007/s00374-004-0787-6

Sprunger, C. D., Culman, S. W., Peralta, A. L., DuPont, S. T., Lennon, J. T., & Snapp, S. S. (2019). Perennial grain crop roots and nitrogen management shape soil food webs and soil carbon dynamics. Soil Biology and Biochemistry, 137, 107573. https://doi.org/10.1016/j.soilbio.2019.107573

Steel, H., Vandecasteele, B., Willekens, K., Sabbe, K., Moens, T., & Bert, W. (2012). Nematode communities and macronutrients in composts and compost-amended soils as affected by feedstock composition. Applied Soil Ecology, 61, 100–112. https://doi.org/10.1016/j.apsoil.2012.05.004

Steffan, J. J., Brevik, E. C., Burgess, L. C., & Cerda, A. (2018). The effect of soil on human health: An overview. European Journal of Soil Science, 69(1), 159–171. https://doi.org/10.1111/ejss.12451

Stewart, R. D., Jian, J., Gyawali, A. J., Thomason, W. E., Badgley, B. D., Reiter, M. S., & Strickland, M. S. (2018). What We Talk about When We Talk about Soil Health. Agricultural & Environmental Letters, 3(1), UNSP 180033. https://doi.org/10.2134/ael2018.06.0033

Sullivan, D. M., Peachey, E., Heinrich, A. L., & Brewer, L. J. (2017). Nutrient Management for Sustainable Vegetable Cropping Systems in Western Oregon. 25.

TAGRO Potting Soil. (2020). https://www.cityoftacoma.org/cms/one.aspx?pageId=16884

Tautges, N. E., Chiartas, J. L., Gaudin, A. C. M., O'Geen, A. T., Herrera, I., & Scow, K. M. (2019). Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. Global Change Biology, 25(11), 3753–3766. https://doi.org/10.1111/gcb.14762

Tognetti, C., Mazzarino, M. J., & Laos, F. (2008). Compost of municipal organic waste: Effects of different management practices on degradability and nutrient release capacity. Soil Biology and Biochemistry, 40(9), 2290–2296. https://doi.org/10.1016/j.soilbio.2008.05.006

U.S. Composting Council. (2001). Test Methods for the Examination of Composting and Composts (TMECC). https://www.compostingcouncil.org/

U.S. EPA. 1996. "Method 3050B: Acid Digestion of Sediments, Sludges, and Soils," Revision 2. Washington, DC.

USEPA. (2018). PART 503—STANDARDS FOR THE USE OR DISPOSAL OF SEWAGE SLUDGE. https://www.govinfo.gov/content/pkg/CFR-2018-title40-vol32/xml/CFR-2018-title40-vol32-part503.xml

Wade, J., Culman, S. W., Hurisso, T. T., Miller, R. O., Baker, L., & Horwath, W. R. (2018). Sources of Variability that Compromise Mineralizable Carbon as a Soil Health Indicator. Soil Science Society of America Journal, 82(1), 243–252. https://doi.org/10.2136/sssaj2017.03.0105

Wade, J., Maltais-Landry, G., Lucas, D. E., Bongiorno, G., Bowles, T. M., Calderón, F. J., Culman, S. W., Daughtridge, R., Ernakovich, J. G., Fonte, S. J., Giang, D., Herman, B. L., Guan, L., Jastrow, J. D., Loh, B. H. H., Kelly, C., Mann, M. E., Matamala, R., Miernicki, E. A., … Margenot, A. J. (2020). Assessing the sensitivity and repeatability of permanganate oxidizable carbon as a soil health metric: An interlab comparison across soils. Geoderma, 366, 114235. https://doi.org/10.1016/j.geoderma.2020.114235

Wang, X.-X., Zhao, F., Zhang, G., Zhang, Y., & Yang, L. (2017). Vermicompost Improves Tomato Yield and Quality and the Biochemical Properties of Soils with Different Tomato Planting History in a Greenhouse Study. Frontiers in Plant Science. Gale Academic OneFile. http://link.gale.com/apps/doc/A515188578/AONE?sid=bookmark-AONE&xid=e6a387c9

Warkentin, B. P. (1995). The changing concept of soil quality. Journal of Soil and Water Conservation, 50(3), 226–228.

Warman, P. R. (2005). Soil Fertility, Yield and Nutrient Contents of Vegetable Crops after 12 Years of Compost or Fertilizer Amendments. Biological Agriculture & Horticulture, 23(1), 85–96. https://doi.org/10.1080/01448765.2005.9755310

Warman, Philip R., Vernon Rodd, A., & Hicklenton, P. (2011). The Effect of MSW Compost and Fertilizer on Extractable Soil Elements, Tuber Yield, and Elemental Concentrations in the

Plant Tissue of Potato. Potato Research, 54(1), 1–11. https://doi.org/10.1007/s11540-010-9167-9

Weil, R., & Brady, N. (2017). The Nature and Properties of Soils. 15th edition.

White, P. J., & Broadley, M. R. (2009). Biofortification of crops with seven mineral elements often lacking in human diets—Iron, zinc, copper, calcium, magnesium, selenium and iodine. The New Phytologist, 182(1), 49–84. https://doi.org/10.1111/j.1469-8137.2008.02738.x

White, P. J., Broadley, M. R., & Gregory, P. J. (2012). Managing the Nutrition of Plants and People. Applied and Environmental Soil Science, 2012, 1–13. https://doi.org/10.1155/2012/104826

Willekens, K., Vandecasteele, B., Buchan, D., & De Neve, S. (2014). Soil quality is positively affected by reduced tillage and compost in an intensive vegetable cropping system. Applied Soil Ecology, 82, 61–71. https://doi.org/10.1016/j.apsoil.2014.05.009

WSDOT. (2016). Standard Specifications. Washington Deparment of Transportation. https://www.compostingcouncil.org/page/UnderstandingCTDS

Wuest, S. B., & Gollany, H. T. (2013). Soil Organic Carbon and Nitrogen After Application of Nine Organic Amendments. Soil Science Society of America Journal, 77(1), 237–245. https://doi.org/10.2136/sssaj2012.0184

Wuest, S. B., & Reardon, C. L. (2016). Surface and Root Inputs Produce Different Carbon/Phosphorus Ratios in Soil. Soil Science Society of America Journal, 80(2), 463–471. https://doi.org/10.2136/sssaj2015.09.0334

Yamada, K. & Hui-Lian Xu. (2001). Properties and Applications of an Organic Fertilizer Inoculated with Effective Microorganisms. Journal of Crop Production, 3(1), 255. https://doi.org/10.1300/J144v03n01_21

Yoder, N., & Davis, J. G. (2020). Organic Fertilizer Comparison on Growth and Nutrient Content of Three Kale Cultivars. HortTechnology, 30(2), 176–184. https://doi.org/10.21273/HORTTECH04483-19

Xavier, M. C. G., Santos, C. A. dos, Costa, E. S. P., & Carmo, M. G. F. do. (2019). PRODUTIVIDADE DE REPOLHO EM FUNÇÃO DE DOSES DE BOKASHI. JOURNAL OF NEOTROPICAL AGRICULTURE, 6(1), 17–22. https://doi.org/10.32404/rean.v6i1.2372

Zbíral, J. (2016). Determination of plant-available micronutrients by the Mehlich-III soil extractant – a proposal of critical values. Plant Soil Environ., 62(11), 5.