2015

ORGANIC WASTE AMENDMENTS AS SOURCES OF CARBON AND FERTILITY FOR VEGETABLE

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Recommended Citation

Long, Rebecca, "ORGANIC WASTE AMENDMENTS AS SOURCES OF CARBON AND FERTILITY FOR VEGETABLE" (2015). *Open Access Master's Theses.* Paper 531.
https://digitalcommons.uri.edu/theses/531

ORGANIC WASTE AMENDMENTS AS SOURCES OF CARBON AND FERTILITY FOR VEGETABLE PRODUCTION

BY

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
BIOLOGICAL AND ENVIRONMENTAL SCIENCES

UNIVERSITY OF RHODE ISLAND
2015

MASTER OF SCIENCE THESIS

OF

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ABSTRACT

Waste amendments, such as food or yard waste, are abundant potential sources of C for soil organic matter and nutrients for crop production. A number of amendments, like gelatin waste and dehydrated food waste, remain relatively unstudied. For those amendments that have been extensively studied, like biosolids and paper waste, the conclusions about their effects on soil and crops are often conflicting, likely due to the varying experimental conditions. To address this gap in knowledge, I compared six waste amendments and their effects on soil quality and vegetable crop production to a mineral fertilizer control.

In a two-year field trial (2013 and 2014) I compared the effects of paper fiber sludge/chicken manure (PF), biosolids/yard waste co-compost (BS), multi-source compost (MS), yard waste compost (YW), dehydrated food waste (FW), and gelatin waste (GW) against a mineral fertilizer (20-20-20). Three crops were included in the study: sweet corn (*Zea mays* cv. Applause and Brocade (2013) and Applause and Montauk (2014)), butternut squash (*Cucurbita moschata* cv. JWS 6823), and potatoes (*Solanum tuberosum* cv. Eva) for their physiological diversity and importance to the local economy. The experiment was conducted at the University of Rhode Island's Greene H. Gardiner Crop Science Field Laboratory in Kingston, RI, and was laid out in a randomized block design (n=4). Waste amendments were applied to supply 10,000 kg C/ha over two seasons.

Amendments were analyzed for pH, electrical conductivity (EC), total C, N and P content, organic matter (OM) content, moisture, density and heavy metals. Amendment effects on soil quality were assessed based on soil OM levels, bulk

density, pH, and moisture. Soil samples were also tested for EC and heavy metals, two of the potential limiting factors for the use of waste amendments. Levels of inorganic N and potentially mineralizable N (PMN) were used to assess effects on soil fertility. Crop quality was assessed based on emergence and early growth, nutrient and heavy metal concentrations of tissue samples, and yield quantity and quality.

Waste amendment properties, including pH, moisture, density, and OM content, varied between wastes, and year-to-year for the same waste, however none had problematically high EC or heavy metal levels. The nutrient (N, P, K) density of amendments was generally low, although GW contained considerable amounts of both N and P. Unique characteristics, like the presence of seashells in MS, affect estimates of carbon inputs and effects on soil pH, and are therefore important to note.

Amendments did not significantly alter soil moisture or heavy metal concentrations, or increase EC to potentially problematic levels. Only MS significantly increased pH compared to the control, likely due to the presence of $CaCO_3$ from seashells. Only FW produced a significant decrease in bulk density, compared to the control. Amendment with YW and BS significantly increased OM compared to the control, although effects were not consistent across crops.

The organic N in waste amendments must be converted to inorganic forms to be plant-available. Waste amendment application was not a reliable way to increase late season inorganic N, or potentially mineralizable N (PMN), a measure of the organic N mineralized to inorganic forms, in comparison to the control. Although PF was the only amendment with a C:N ratio above 25:1, the threshold above which N immobilization is likely; inorganic N levels in plots amended with PF were not always significantly lower than the control.

Potatoes from plots amended with PF had significantly lower emergence (2014) and were significantly shorter (2013 and 2014) compared to the control, indicating inhibition of early growth, although the same was not observed for corn or squash. Nutrient levels in plant tissue varied among treatment, but not consistently with application rates. Tissue levels of N, P, Ca, Mg, Mo, Cu, and Fe were all adequate for plant growth although concentrations of K, Mn, B, and Zn were deficient for some or all crops and treatments. There were no significant differences in corn cob tissue heavy metal levels among treatments (2014), indicating that short-term application of waste amendments does not increase corn ear heavy metal concentrations. Gelatin waste, BS, and FW produced yields comparable to the control for all crops. While YW, PF, and MS underperformed the control for corn and/or squash production, they performed as well as the control for potatoes. Paper fiber/chicken manure enhanced potato quality significantly in 2014.

All waste amendments studied showed promise as effective replacements for mineral fertilizers, although not consistently for all crops. Although benefits to soil quality from application of waste amendments were limited, their application did not appear to be harmful or contribute problematic levels of salinity or heavy metals. Lastly, some waste amendments provided unique benefits such as increasing pH (MS) or improving potato quality (PF).

ACKNOWLEDGMENTS

I would like to acknowledge my co-advisors: Dr. José Amador and Dr. Rebecca Brown for all their assistance with research, writing, conferences, advising, and too many other things to name. I would also like to thank Dr. Amador for countless hours he spent helping a Philosophy major learn to write like a scientist.

I would also like to acknowledge my committee members, Dr. Steven Alm and Dr. Caroline Gottschalk Druschke for their time and input on my thesis.

Without Dr. Cheryl Foster, I would likely not be in this program. She has encouraged me along every step of the way and always been an amazing and generous resource.

I appreciate all of the time Robert Bercaw spent assisting me in the field and the laboratory, and just generally putting up with my nonsense.

I am thankful for all the help I received from the Agronomy Farm staff, especially Tim Sherman and Carl Sawyer who spent countless hours helping me keep my plants alive. I would also like to acknowledge all the undergraduates who helped me in the field, especially Lauren Breene and Emma Chilabato. Without Andy Radin's assistance, bugs would have probably eaten all my crops.

I would like to acknowledge the graduate students who began work on my project before I arrived; Angela Possinger and Eddy Fava as well as my lab mates and fellow grad students; Noah LeClaire-Conway and Ashley Waggoner, and especially Jen Cooper, who spent hours of her own time training me.

Finally I should acknowledge my parents (this is your fault) and my husband, Randy Stevenson, who kept me fed and caffeinated and put up with the strange habits that come along with graduate school, like dead bugs in our freezer.

Funding was provided by the Rhode Island Agricultural Experiment Station and a University of Rhode Island Enhancement of Graduate Research Award. I would like to thank the manufacturers and distributors who donated the amendments for this study.

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INTRODUCTION

Conventional farming relies heavily on mineral fertilizers for the plant nutrients necessary for intensive production. The advantage of these fertilizers is that the nutrients can be balanced to meet crop needs and their release is predictable and reliable. However, synthetic sources of N (fixed by the Haber-Bosch process) are energy intensive to produce, prohibited by all organic certifying agencies and do not provide a source of carbon to build soil organic matter (Crews and Peoples, 2004). Alternative sources of nutrients, including carbon-based materials like composts and manures, have historically been used for agriculture and new types of wastes are being considered for their potential as fertilizer replacements. These wastes can be from industrial processes like the manufacturing of paper or gelatin, or municipal sources such as sewage sludge, food waste, or yard waste.

The advantage of waste amendments as an alternative to mineral fertilizers is that, in addition to plant nutrients, they also provide carbon, a major component of soil organic matter. Soil organic matter is the key to soil quality because it controls moisture and nutrient retention and the density of the soil, all factors which can promote plant growth. In addition, waste amendments may be inexpensive and many are locally available, cutting down on the expense and environmental impacts of transportation. The use of wastes as agricultural amendments prevents the need to landfill or incinerate them, sequesters carbon in the soil and recycles nutrients that would otherwise be lost. Finally, unlike synthetic sources of nitrogen, these wastes have the potential to be approved for use in USDA Certified Organic agriculture (with the exception of biosolids which are prohibited) (USDA, 2015b).

Despite the advantages of their use in agriculture, many waste streams are not being taken advantage of. In the case of more novel amendments, such as gelatin and dehydrated food waste, this may be due to lack of data. In other cases it may be due to a stigma, as in the case of biosolids (processed human waste). Finally, unlike mineral fertilizers, the mineralization of N from organic wastes is less predictable and requires further study to ensure it meets crop needs and provides optimal yields.

Background

Amendment Sources

Waste amendments originate from industrial (manufacturing processes) and municipal (sewage, yard waste) sources and represent a significant waste stream, only a portion of which is being recovered for beneficial use. For example, the U.S. paper industry generates 5.8 million tons of wastewater solids each year (Scott et al., 2000). In addition, 6.9 million tons of biosolids were generated in the U.S. in 1998, and only 60% were used beneficially (Ozores-Hampton and Peach, 2002). An additional 33.8 million tons of yard waste (leaves and grass) and 36.4 million tons of food scraps were generated in the U.S. in 2012, only 21.3 million tons of which were recovered (EPA, 2014). Because of varying inputs and treatment methods, waste amendments differ in composition and consistency from year to year. Many of these characteristics, including nutrient content and ratios, pH, electrical conductivity and heavy metal content, impact their use as agricultural amendments.

Biosolids. Sewage sludge is a byproduct of centralized treatment of wastewater originating from households, industry and storm water runoff. Because it comes from human waste, it must be treated, stabilized, and disinfected by anaerobic or aerobic digestion, composting, or heat treatment before it can be used. The end product of these processes, referred to as biosolids, has a low C:N ratio (~10:1), and is therefore often co-composted with carbon-rich materials, including yard trimmings, to increase its C content (Ozores-Hampton and Peach, 2002), as is the case for the biosolids used in this study. Class A biosolids, as defined by EPA's 40 CFR Part 503 rule, contain no detectable level of pathogens and can be used for agricultural production (U.S. EPA, 1994).

Paper fiber sludge. Pulp and paper production, a major U.S. industry, generates a large amount of wastewater (USEPA, 2002). Treatment of this wastewater produces sludge of varying compositions and properties (Thompson et al., 2001). While most of this sludge is disposed of in landfills, or by surface impoundment, some is used for land application (U.S. EPA, 2002).

Since the major U.S. source of fiber for paper is wood from trees, pulp mill waste sludge reflects the composition of wood fiber (Camberato et al., 2006; Thompson et al., 2001; U.S. EPA, 2002). Unlike pulp mill sludge, paper mill sludge contains only the cellulose portion of wood, along with additives and some heavy metals (Thompson et al., 2001). The growing trend of obtaining pulp from recovered paper requires a deinking stage, and sludge from this stage can contain ink residues

(Camberato et al., 2006; U.S. EPA, 2002). In addition, sludge treatment can affect its composition. Primary sludge, which is treated by clarification, and deinking sludge tend to have high amounts of C but low plant nutrient levels. Secondary sludge, which undergoes further biological treatment, can have significant amounts of essential plant nutrients, including N, P and K (Camberato et al., 2006). The paper fiber used in this study was dewatered primary sludge from a mill that processes recycled paper.

Gelatin. Gelatin is manufactured from the skin and/or bones of pigs, cattle or fish, and used in the manufacture of photographic film, food, and pharmaceutical capsules (Roupas et al., 2007). Manufacturing gelatin involves removing the mineral portion of the bones, leaving behind "ossein", the organic portion, which contains collagen. The collagen is hydrolyzed into gelatin by liming, and filtered out, leaving behind a "filter cake," which is the waste used in this study (Geoff Kuter, pers. comm., Ag Resource Inc., February 27th, 2014). Compared to the other wastes used in this study, the gelatin waste was unique in that it had similar amounts of N and P (49 and 39 g/kg respectively). This could be problematic if the waste was applied to meet plant N needs because of the over application of P, which is discussed later.

Dehydrated food waste. I am not aware of any other published studies that have used this waste as an agricultural amendment although food waste is often used as a component of compost. The food waste used in this study is sourced from a restaurant. It is first ground, then dehydrated, and finally incubated for 18 h in an aerobic reactor, which reduces the waste volume by up to 90% (Global Enviro, 2011). Although the food waste used had a similar N and P content to the biosolids compost used, it is only minimally composted and therefore the N and P may mineralize at a different rate from the more mature biosolids compost. The composition of the waste also reflects the restaurant it originates from and in this case it contained a large amount of mussel shells.

Compost. The two remaining waste amendments used in this study are composed in large part (multi-source compost) or entirely (yard waste) out of grass clippings, leaves, and brush. Many states are moving away from landfilling and incinerating yard waste, with some states outright banning the practice, and instead moving towards aerobic composting (Arsova et al., 2008). Leaves are often incorporated to provide bulk, preventing the composting process from becoming anaerobic (Michel et al., 1993).

While compost characteristics can vary widely depending on inputs and processing, the composts in this study were among the least nutrient dense of the materials used. While the multisource amendment had between 9-16 g/kg of N and 2-3 g/kg of P for 2013 and 2014 samples, the yard waste compost had 15-16 g/kg of N and 2 g/kg of P. Although neither had a high concentration of N, they both had C:N ratios below 15:1, indicating that the N present was unlikely to become immobilized in the soil during decomposition.

Amendment Qualities

i. Heavy Metals

If waste amendments are to be recommended to farmers, we have to be aware of the risks associated with their use, including the potential to contribute heavy metals to the soil. Because heavy metals are toxic to humans and animals at elevated concentrations, the U.S. EPA (1994) has set upper limits for the amount of As, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Se, and Zn permitted in sewage sludge applied to agricultural land. These metals are a concern when any compost is applied to soil, not just those containing sewage sludge. Due to gaseous losses of C and N during the composting process, and retention of heavy metals, the concentration of heavy metals in composts are often higher than soil and can therefore increase soil concentrations when used as amendments (Eklind and Kirchmann, 2000a, 2000b; Smith, 2009).

Because of their long residence time in the soil, repeated additions of heavy metals from waste amendments may lead to their accumulation (Smith, 2009). This is a concern, not only because of contamination of the human food chain, but also because of the toxicity of heavy metals to plants and to soil microorganisms involved in carbon and nitrogen cycling (Giller et al., 1998; Khan et al., 2008).

Heavy metals can be present in soil in numerous forms, with varying levels of solubility and bioavailability. They may be bound in organic matter, or present in carbonates, oxides of iron and manganese, and sulfides (Giller et al., 1998). Soil properties, including pH, can have a strong influence on metal availability. For instance, for each unit decrease in pH, there is an approximate two-fold increase in the concentrations of Zn, Ni and Cd in the soil solution (Giller et al., 1998). The solubility of metals also influences their residence in the soil because, when metals become soluble, they can be lost both by leaching to groundwater and by increased plant uptake and crop removal (when part or all of the plant is harvested).

While aerobic composting of amendments generally increases binding of metals to stable forms of organic matter, which limits their bioavailability, amendments that include soluble organic matter increase metal leaching, possibly due to lowered pH and binding of metals to soluble organic compounds (Schwab et al., 2007; Smith, 2009). Thus, the accumulation of heavy metals in the soil is not just a function of the amount applied in waste amendments, but depends on other properties, including amendment pH, organic matter content and state of decomposition.

The presence and levels of heavy metals in waste amendments varies. A review of municipal solid waste (MSW) compost reported Cu, Zn, Ni, Cr, Cd, Mo, As, and Hg levels below EPA max concentrations but Pb and Se concentrations in some samples exceeded EPA limits (Hargreaves et al., 2008). Studies of sewage sludge reported detectable levels of Cd, Cr, Pb, Cu, Zn, and Ni, although none high enough to restrict land application (Casado-Vela et al., 2007; Da Silva et al., 2010). Similarly, the levels of Cd, Cr, Cu, Zn, and Ni detected in gelatin industry by-product and vegetable waste compost were not high enough to restrict land application (Da Silva et al., 2010).

Despite detectable levels of heavy metals in some waste amendments, they often have little effect on soil concentrations. Studies of soil amendment with sewage sludge and paper mill sludge reported no significant increases in soil concentrations (Aitken et al., 1998; Casado-Vela et al., 2007; Douglas et al., 2003). However, a review of MSW compost found that it can increase the soil concentrations of several heavy metals (Hargreaves et al., 2008).

ii. Salinity

Another concern about the addition of waste amendments to soil is increasing the concentration of soluble salts, which can increase the osmotic potential of the soil, making it harder for plants to obtain water. Furthermore, Na^+ can be toxic to plants at high concentrations, and can compete with K^+ for plant uptake (Sinha, 2004). Salinity problems are more likely in arid and semiarid regions where evaporation is high and there is not enough precipitation to flush out salts. Soil salinity is assessed by measuring the electrical conductivity (EC) of a saturated soil sample. The lower limit for a saline soil (a soil that contains enough soluble salts to adversely affect plant growth) is conventionally set at 4 mS/cm, however, due to varying plant sensitivities , adverse effects can begin as low as 1 mS/cm or as high as 8 mS/cm (Bernstein, 1975; Maas, 1984; Rhoades et al., 1999).

Studies conducted under greenhouse and humid field conditions (Maine and Quebec) have not identified a risk to crop productivity from excess soluble salts in paper sludge (Carpenter and Fernandez, 2000; Levy and Taylor, 2003; Simard et al., 1998). However, a different greenhouse experiment found that application of secondary pulp mill sludge led to significant increases in exchangeable Na, with Na saturation higher in amended soils than the level at which adverse impacts can become evident (Rato Nunes et al., 2008). Under greenhouse conditions salinity problems may be exaggerated by the lack of leaching from precipitation and higher temperatures for longer time periods.

In a review of municipal solid waste (MSW) compost, Hargreaves et al. (2008) reported compost EC levels ranging from 3.69 to 7.49 mS/cm. Application of MSW compost to soil at rates from 40 to 120 Mg/ha increased soil EC and, in some cases, inhibited plant growth. Two studies reported EC values for sewage sludge compost of 5.03 and 2.04 mS/cm (Casado-Vela et al., 2007; Perez-Murcia et al., 2006). A study conducted in a semi-arid region of Spain reported that increasing soil EC correlated with increasing compost application rate, although even at the highest rate (9 kg m^2), soil EC did not exceed 1.2 mS/cm (Casado-Vela et al., 2007). Reported EC levels for leaf compost have been low (0.6 mS/cm) (Maynard and Hill, 2000).

Soil Quality

i. Organic Matter

The concentration of soil organic matter (SOM) is a key determinant of soil quality because it controls many properties, including cation exchange and water-holding capacity, nutrient retention, and bulk density. It is also a source of slow-release plant nutrients as well as food and energy for soil microorganisms. Soil OM is, on average, about 58% carbon by mass (Howard and Howard, 1990).

Most studies have reported that the addition of paper mill sludge to soil increased soil OM levels (Rato Nunes et al., 2008). Douglas et al. (2003) reported a 60% increase in SOM in samples taken over a year after a single application of paper mill sludge (385 tons/ha). Gagnon et al. (2001) conducted a field trial on sandy loam using raw and composted pulp, and found that both similarly increased the total C content and C:N ratio of the soil, which can affect the mineralization of nutrients as discussed later. Finally, Zibilske et al. (2000) conducted a multiyear study on fine sandy loam soil and concluded that paper mill sludge, applied biennially, could compensate for decomposition losses due to conventional tillage, and allow for some C accumulation in soil.

In their review, Hargreaves et al. (2001) found MSW composts were generally high in OM, especially stable forms like humic acid. In addition, repeated application of MSW compost consistently increased soil OM levels. Ozores-Hampton et al. (2011), after eight seasons of organic amendment application (biosolids or biosolids/yard waste co-compost), found that soil OM levels increased more than 200%.

Once added to soil, the rate at which waste amendments decompose will determine how long they effect SOM levels. The degradation rate of amendments is partly determined by the varying rates at which the organic compounds they are composed of (e.g. carbohydrates, amino acids, fatty acids, lignin) break down. The composting process will also affect the degradation rate of organic C compounds in amendments because labile organic compounds are mineralized during the composting process, leaving behind more resistant compounds (Bernal et al. 1998b). For example, levels of stable organic C were higher for composted food wastes than non-composted wastes (De Neve et al., 2003).

ii. Moisture

Raising the level of soil OM increases the water holding capacity of soil, by creating more small and medium-sized pores, and the amount of water available to plants, thereby reducing water stress during drought (Brady and Weil, 2008). However, an increase in water holding capacity can cause delayed germination or rotting of seed in regions with wet springs (Maynard and Hill, 1994).

Hargreaves et al. (2008) reported that application of MSW compost improved the water holding capacity of soil. Paper sludge also increased volumetric water content of soil (measured at field capacity for those studies that indicated water content); although this effect was short-lived, often disappearing by the second year after application (Aitken et al, 1998; Foley and Cooperband, 2002; Simard et al., 1998). Ozores-Hampton et al. (2011) reported that long-term application of biosolids and biosolids/yard waste compost significantly increased soil moisture at field capacity (-8 to -30 kPa). Water content was also higher at saturation (0 kPa) in amended plots than non-amended plots, although no difference was observed during drainage of gravitational water (-2 to -5 kPa).

iii. Bulk Density

Due to their low density, the incorporation of waste amendments into soil can lower soil bulk density (the dry mass of a unit volume of soil, including pores), at least temporarily. Further, the addition of OM to soil increases aggregation, both by providing the carbon and energy for the biological processes involved in aggregation (e.g. production of polysaccharides), and by supplying organic polymers from decomposition to bind soil particles. Increased soil aggregation lowers bulk density, which allows plant roots to easily penetrate soil and access a greater volume of soil and nutrients (Brady and Weil 2008; Maynard and Hill, 1994).

Amendment with paper sludge increased the total pore space (by % volume) of clay soil and the proportion of macroaggregates (>250 μm), and lowered bulk density (Foley and Cooperband, 2002; Gagnon et al., 2001; Phillips et al., 1997; Zibilske et al., 2000). Long-term application of organic amendments (8 seasons of biosolids or biosolids/yard waste co-compost) also reduced soil bulk density compared to a non-amended control (Ozores-Hampton et al. 2011).

iv. pH

The pH of a soil, a measure of its acidity, is important to crop production because it affects the availability of both nutrients and toxic elements (e.g. aluminum), as well as the rate of microbial process that produce plant-available nutrients. Although maximum nutrient availability differs, a pH of 5.5 to 7.0 is considered optimum for many agronomic crops. Plants also vary in their tolerance for acidity. Due to the inherent acidity of New England soils, and the gradual acidification caused by natural and human-induced processes, local soils often require liming for optimum growth of many crops. Therefore, a waste amendment that could raise pH would provide an added benefit beyond increasing soil OM and fertility.

Since both the pulping and paper finishing processes increase the alkalinity of paper sludge (to a pH higher than 12.5) one would expect it to increase the pH of soil (Camberato et al., 2006; EPA, 2002). Some studies using paper sludge as a soil amendment reported increased pH (Rato Nunes et al., 2008; Aitken et al., 1998), whereas others reported no change (Douglas et al., 2003). The variability in results is likely due to the variability of sludge pH, as well as differences in the pH and buffering capacity of the soil it was applied to. A review of studies of MSW compost found that it increased soil pH, usually in proportion with application rate (Hargreaves et al., 2008).

Soil Fertility

i. Nitrogen

Nitrogen is essential for plant growth, and healthy plant foliage contains 2.5-4.0% N by weight. The C:N ratio of an amendment affects the release of N because microbes incorporate C and N into their biomass in a fixed ratio. Therefore, the application of amendments with a C:N ratio below 25:1 generally leads to the release of excess N into the soil, while addition of amendments with a C:N ratio above 25:1 favors the immobilization of N because soil microbes are forced to scavenge N from their surroundings, which depletes the pool of soluble N available to plants and can last for days to months (Brady and Weil, 2008). Nitrogen immobilization following the addition of composted sewage sludge (12.7:1 and 9:1) or gelatin waste (13.4:1) is unlikely due to their low C:N ratios (Casado-Vela et al., 2007; De Neve et al., 2003; Perez-Murcia et al., 2006).

Because of the low N content of woody plant tissue, the primary input in the paper-making process, pulp and paper-mill sludge are unlikely to contain enough N to satisfy plant needs (Allison and Murphy, 1963). Primary sludge has a C:N ratio ranging from 100 to 300:1 (high enough to cause N immobilization), while secondary sludge can have a C:N as low as 14:1, due to biological treatment (Camberato et al., 2006; Rato Nunes et al., 2008; Thompson et al., 2001). Although the degree of severity varied, studies of combined primary and secondary paper sludge and raw paper sludge application reported evidence of N immobilization in the soil (Carpenter and Fernandez, 2000; Simard et al., 1998).

In waste amendments most of the N is organic, which may not be fully mineralized into plant-available forms within the first season after application, further complicating prediction of N availability. When an amendment is added, soil conditions, including C:N ratio, temperature, and moisture, affect the rate of N mineralization. Immature compost may also have a high C:N ratio, which can cause initial N immobilization (Amlinger et al., 2003). First-year N availability for yard waste compost was 5% to 15%, with another 2% to 8% available the second year, while mean first year N availability of fresh biosolids was 37% (Amlinger et al., 2003; Gilmour et al., 2003). Estimates of first-year availability of N from MSW compost, made up primarily of kitchen and yard waste, ranged from 10 to 21% (Hargreaves et al., 2008). Due to low N availability and low N concentrations (below 40 g/kg), high application rates of MSW compost are often used (>50 Mg/ha) (Hargreaves et al., 2008). The effect of MSW compost on soil N levels varies; Hargreaves et al. (2008) reported that while some studies showed that application of MSW compost increased soil N levels, others found it to be less effective than mineral fertilizers.

When a large quantity of compost with a low N concentration is applied to meet plant N needs, it can lead to the over application of other nutrients, such as phosphorus. While the ratio of plant available N to P in many biosolids composts is 1:2, the ratio of N:P in many crops is between 7:1 and 10:1, leaving excess P to accumulate in the soil (Spargo et al., 2006). If excess P is lost by leaching it can stimulate algal growth in freshwater bodies and lead to eutrophication (Hargreaves et al., 2008).

ii. Phosphorus

Phosphorus is second only to nitrogen in its importance to plant growth. It is a component of nucleic acids, phospholipid membranes and adenosine triphosphate (ATP), the energy source for many biochemical processes. Healthy plant leaf tissue contains between 0.2 and 0.4% P by dry weight. Phosphorus is, however, more problematic than N because when P is added to soil it quickly becomes unavailable to plants due to adsorption to Ca (alkaline soils), or Fe Al (acid soils), and precipitation in association with Fe, Al, Mn, Ca or Mg (Brady and Weil, 2008).

The P content of paper sludge varies depending on its source. While primary sludge can have a P concentration of 1.6 g/kg, deinking sludge may only have ~0.1 g/kg, and secondary sludge can have 4.2 g /kg (Camberato et al., 2006). Application of sludge with C:P ratios of between 943:1 and 6,400:1 appeared to result in P immobilization, leading to reduced crop yields. The application of an organic substrate with a C:P ratio of greater than 300:1 is likely to cause microbial immobilization of soil P (Camberato et al., 2006). While Aitken et al. (2008) found no change in soil levels of extractable P after the addition of deinking sludge, other studies reported increased soil P (Rato Nunes et al., 2008; Simard et al., 1998). Rato Nunes et al. (2008) cautioned that increased pH (as high 7.6) and exchangeable Ca from the sludge may have limited the effects of increased P due to P adsorption.

Application of MSW composts (20 g P/kg) was reported to effectively increase soil P levels, with 10-50% P mineralization the first year. In fact, when MSW compost was applied at a rate of >200 Mg/ha to meet N needs, downward movement of P in the soil profile was reported, indicating a potential risk of leaching (Hargreaves et al., 2008). Ozores-Hampton et al. (2011) reported that after 8 seasons of applying organic amendments (biosolids, alone or co-composted with yard waste) soil P levels increased to more than 10 times the levels in the non-amended control.

Crop Quality

i. Emergence

Rating emergence and initial growth of seedlings is a way to monitor for phytotoxicity and other unfavorable soil conditions caused by the addition of an amendment, such as changes to soil moisture, pH or bulk density. Levy and Taylor (2003) reported strong inhibition of germination for tomato seedlings grown in MSW compost, but no inhibition of seedlings grown in paper pulp mill solids. The inhibitory effect of MSW was observed when applied at very high concentrations, and was possibly due to its high pH (7.4). Douglas et al. (2003) reported poor establishment of ryegrass in plots amended with paper mill sludge, and subsequent significantly lower yields than other amendments, possibly due to the large volume of sludge applied to meet N needs. Perez-Murcia et al. (2006) did not report any reduction in germination of broccoli when composted sewage sludge and peat were used as a greenhouse growth media.

ii. Nutrient Uptake

Although waste amendments may supply plant nutrients in sufficient amounts, rates of mineralization may be too low, or not timed to meet growth needs. Sampling of plant tissue is a way to assess nutrient status and determine fertilizer efficiency. Application of MSW compost increased plant uptake of P in multiple crops, including potatoes (Hargreaves et al., 2008). The use of anaerobically digested liquid sewage sludge increased the uptake of both N and P in rye and sorghum-sudan forage (Kelling et al., 1977). However, Passoni and Borin (2009) found no significant difference in the total N concentration of crop biomass between three different composts made from food processing industry residues and municipal waste (200 kg N/ha) and a control (0 kg N/ha), possibly due to low N mineralization from composts.

Tissue analysis can also be used to monitor plant uptake of heavy metals. A review by Hargreaves et al. (2008) reported that amendment with MSW compost was associated with increased plant uptake of Cu, Zn, Mo, and Pb in some crops, while other crops showed no increase. Although Casado-Vela et al. (2007) did not find any evidence of increased uptake of heavy metals from composted sewage sludge in the shoots, leaves or tissue of sweet peppers, Perez-Murcia et al. (2006) detected increases in heavy metals in the aerial parts of broccoli grown in greenhouse media made from composted sewage sludge and peat. Sloan et al. (1997) reported increased uptake of Cd by romaine lettuce more than 15 years after application of high-Cd biosolids. They also found that tissue concentrations of Cd, Zn, Cu, Ni and Cr were positively correlated with soil concentrations of these metals.

iii. Yield

Although the main goal of applying a fertilizer is to ensure sufficient plant nutrients to optimize crop yields, carbon-rich waste amendments have the potential to provide additional benefits which can improve yields. Because the nutrients in waste amendments must first be mineralized into plant available forms, their release may be slower and better timed to meet crop needs than the immediately available forms found in inorganic fertilizer, which are also prone to loss by leaching. In addition, if waste amendments increase soil OM levels, this may provide further benefits, including increased nutrient and moisture retention. Maynard and Hill (2000), in a study of onions grown with leaf compost, reported increased yields for some varieties.

In a different, long-term study, these authors reported yields in plots amended with leaf compost, lime, and fertilizer that were 25% higher than those amended with fertilizer and lime alone (Maynard and Hill, 1994). On the other hand, Chellemi and Rosskopf (2004) reported inconsistent yield responses to the addition of yard waste for pepper production.

Ozores-Hampton and Peach (2002), in a review of studies of biosolids and biosolid co-composts, found that, while co-composts generally increased vegetable yields, several studies showed no response, and others reported decreased yields. Many studies have reported negative or neutral yield responses to application of paper sludge, including reduced yields on a commercial cereal farm and reduced barley yields, both after application of deinking sludge (Aitken et al., 1998; Simard et al., 1998). Foley and Cooperband (2002) found that there was no effect on potato yields the first year after paper mill sludge was applied. Yields of potatoes, sweet corn, and squash were lower in soil treated with MSW compost compared to fertilizer treated soils. However, studies of ryegrass, alfalfa, tomatoes, and strawberries, with application rates of 40 Mg/ha and higher, obtained equivalent or improved yields compared to controls (Hargreaves et al., 2008).

Waste amendments are abundant and a potential source of both nutrients and carbon for crop production. However, some amendments, like gelatin waste and dehydrated food waste, remain relatively unstudied. For those amendments that have been extensively studied, like biosolids and paper waste, the conclusions about their effects on soil and crops are often conflicting, likely due to the varying conditions of experiments. My project went beyond the scope of previous studies by comparing six waste amendments, both familiar and novel, to a mineral fertilizer control, and their effects on soil quality and crop production. Potatoes, sweet corn and winter squash were chosen as the crops for this study because of their importance to Rhode Island's economy (over $4.5 million/yr in sales), the quantity grown (over 1,300 acres), as well as their physiological diversity (USDA, 2013).

Objectives

The objective of this project was to study the use of waste amendments for crop production. Their success as sources of carbon and nutrients for crops was assessed based on their effects on soil quality and fertility as well as crop yield and quality. In a two-year field trial I studied the effects of (1) paper fiber sludge/chicken manure, (2) biosolids/yard waste co-compost, (3) multi-source compost, (4) yard waste compost, (5) dehydrated food waste and (6) gelatin waste on production of sweet corn, winter squash and potatoes.

Hypotheses

Soil quality

i. Organic matter, moisture, bulk density.

Amendments will increase SOM and moisture retention relative to the control and decrease bulk density. Large additions of C-rich amendments have been shown to increase the C content of soil, a major component of SOM, which in turn increases water holding capacity and reduces bulk density (Gregorich et al., 1994; Haynes and Naidu, 1998; Khaleel et al., 1981).

ii. pH

Amendments with a high pH will raise soil pH. Paper fiber sludge and municipal solid waste compost have been reported to increase soil pH (Aitken et al., 1998; Hargreaves et al., 2008; Rato Nunes et al., 2008).

Amendments high in organic C and N will lower soil pH. Sources of acidity from C and N cycles include decomposition of organic matter which releases CO_2 which, when combined with soil water, can form carbonic acid (H_2CO_3), and oxidation of ammonia which releases H^+ (Bolan and Hedley, 2005).

iii. Electrical conductivity

Amendments with high EC will raise soil EC temporarily but the effect will be short lived. Due to the large quantities added, amendments with high EC could raise soil EC but this effect will be only temporary as salts are leached out by rain and irrigation.

iv. Heavy metals

Amendments that contain heavy metals will raise soil heavy metal levels. When added to the soil, heavy metals will be retained by binding to OM or associating with carbonates, oxides of iron and manganese or sulfides. This increase, however, may not be significant enough to be detectable by my analysis method.

Soil fertility

i. Ammonium, nitrate

Early season inorganic N levels will be lowest in plots amended with materials with a C:N ratio >25:1. Application of amendments with a C:N ratio >25:1

causes immobilization of N by soil microbes, which can last for days to months (Brady and Weil, 2008).

Later season soil inorganic N levels will be higher in waste amended plots than fertilizer amended plots due to dynamics of organic N mineralization. Because N applied in mineral fertilizer is subject to plant uptake and loss by leaching or volatilization soon after application, side-dressing with additional N later in the season is often recommended (Hazard and Howell,2007) . However, organic N in wastes is slowly mineralized as organic matter decomposes, leading to a slower release of N and higher later season N levels, which may be better timed to meet crop needs and eliminate the need for side-dressing.

ii. Potentially mineralizable N

PMN will be higher in waste amended plots than control plots. PMN represents organic N mineralized under ideal conditions. Addition of organic N in waste amendments provides a larger pool of N available for mineralization than is present in control plots.

Crop quality

i. Emergence/initial growth

Emergence and initial growth will be delayed in plots amended with high (>25:1) C:N ratio materials relative to the control. The addition of wastes with a high C:N ratio leads to N immobilization by soil microorganisms, which can in turn lead to an insufficient supply of N needed for early plant growth.

Emergence/initial growth in waste amended plots will be higher than control plots. Provided they are a source of sufficient N, waste amended plots will have higher seedling emergence and early growth due to soil conditions favorable for seedling emergence (e.g. increased moisture and lower bulk density due to increased SOM).

ii. Tissue nutrient levels

Adequate levels of plant nutrients will be present in tissue samples for plots that received recommended nutrient application rates. Nutrients from amendment application will be sufficient for plants to reach tissue nutrient levels associated with normal plant growth.

Tissue levels of heavy metals will not reflect increases in soil heavy metal levels (from the addition of wastes) due to low bioavailability. Plants can absorb non-essential elements from the soil, some of which are toxic (Peralta-Videa et al., 2009). However, heavy metals bind to organic matter, both in the soil and waste amendments themselves, as well as from associations with carbonates, oxides of iron and manganese or sulfide, all of which reduces their bioavailability (Giller et al., 1998; Shober et al., 2003).

iii. Yield

Waste amended plots will achieve yields comparable to control plots. The waste amendments in this study have sufficient plant nutrients and are added at a high enough rate to achieve comparable yields to mineral fertilizers.

Project Overview

I conducted a two-year field experiment, at the University of Rhode Island's Greene H. Gardiner Crop Science Field Laboratory in Kingston, RI during the growing seasons of 2013 and 2014, to study the suitability of municipal and industrial waste amendments as sources of carbon and nutrients for sustainable vegetable production. I evaluated 6 waste amendments against a mineral fertilizer control: (1) paper fiber sludge/chicken manure, (2) biosolids/yard waste co-compost, (3) multi-source compost, (4) yard waste compost, (5) dehydrated food waste, and (6) gelatin waste. I collected data on soil fertility, soil quality and crop quality for three crops: sweet corn (*Zea mays* cv. Applause and Brocade (2013) and Applause and Montauk (2014)), butternut squash (*Cucurbita moschata* cv. JWS 6823), and potatoes (*Solanum tuberosum* cv. Eva*).* Amendments were applied at a rate sufficient to supply 10,000 kg organic C/ha over two seasons.

Amendments were analyzed for pH, EC, total C, N and P content, OM content, moisture, and total elements/heavy metals. Amendment effects on soil quality were assessed based on determination of OM levels, bulk density, pH, and soil moisture. Soil samples were also tested for salinity (EC) and heavy metals (As, Cd, Cr, Cu, Pb, Hg, Mo, Ni, Se and Zn), two of the potential limiting factors for the use of waste amendments. Soil fertility effects were evaluated by measuring levels of ammonium, nitrate, and potentially mineralizable N (PMN). Crop quality was assessed based on tissue levels of macro and micro nutrients as well as heavy metals, ratings of crop emergence and early growth, and yield.

CHAPTER 2

METHODOLOGY

Site Description

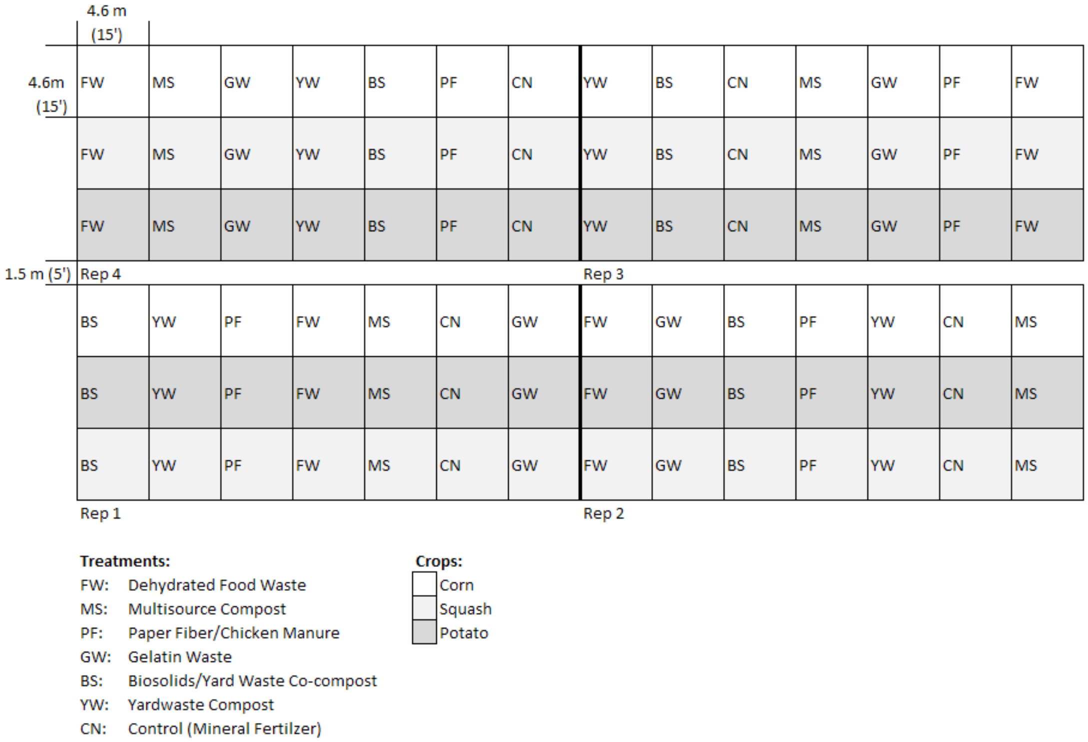
The experimental plots were established in April of 2013 at the University of Rhode Island's Greene H. Gardiner Crop Science Field Laboratory in Kingston, RI. The soil in this part of the farm is a mixture of Bridgehampton silt loam and Enfield silt loam, 0 to 3% slope, with mean annual precipitation of 114-127 cm and a mean annual air temperature of 10 ^{o}C (Soil Survey Staff, 2013). There were 2,548 growing degree days in 2013 and 2,605 in 2014 (May 1st to October 1st, base 10 C) (Weather Channel, 2014). The field was used for vegetable production and then planted with trees (*Acer rubrum, Liriodendron tulipifera, Quercus alba, Q. montana, Q. phellos, and Q. rubra*) inter-sown with creeping red fescue (*Festuca rubra*) from 2006 until the fall of 2012, when the trees were pulled out and the field planted with a cover crop of winter rye (*Secale cereale*) and hairy vetch (*Vicia villosa*) up to the beginning of the experiment in April 2013.

The field was prepared by mowing the cover crop and then incorporating the residue by disc harrow. The 84 experimental plots, measuring 4.6 m × 4.6 m, were laid out with crops and amendments arranged in a randomized block design (n=4) (Figure 1). Amendments were applied in late-April 2013 and late May 2014, at a rate sufficient to supply 10,000 kg organic C/ha over two seasons (Table 1). Application rates were determined using the total C (dry wt.) and moisture content of each amendment to determine the wet weight need to supply the specified rate of C. Wet weights were then converted to volume using amendment bulk density to determine the number of 5-gallon buckets needed per plot. Buckets of amendments were spread on the surface of each plot, evenly distributed with rakes and incorporated by disc harrow within several days of application. The control (20-20-20) mineral fertilizer was applied to provide 112 kg N/ha. The fertilizer was 3.5% N-NH_4, 5.5% N-NO_3 and 11% urea N.

Crops were seeded by hand the last two weeks of May 2013 and last week of May through the second week of June 2014. All crops were planted in six rows per plot, 76 cm (30") between rows. Corn and potatoes (cv. Eva) were planted at 12" (30 cm) in-row spacing and butternut squash (cv. JWS 6823) was planted at 24" (61 cm). Corn varieties (Applause and Brocade in 2013; Applause and Montauk in 2014) were planted in alternating rows.

Management followed typical practices for local production. Crops were irrigated with an overhead sprinkler when rainfall was insufficient and weeds were managed by tractor cultivation and by hand. Potatoes were hilled several times and mowed once senescence began. Corn ear worm (*Helicoverpa zea*) was managed with foliar sprays of Dipel (*Bacillus thuringiensis*) (Valant BioSciences Co., Libertyville, IL) in 2013 and 2014. Ears were also treated directly with injections of Bt in 2013 but this method was not used in 2014 because it was only minimally effective and caused a higher incidence of unfilled ear tips. Pyganic (MGK Co., Minneapolis, MN), a pyrethrin spray, was used for control of cucumber beetles (*Acalymma vittatum*) on squash and Colorado potato beetles (*Leptinotarsa decemlineata*) on potatoes in both

2013 and 2014. In addition a spinosad spray, Entrust (Dow AgroSciences, Indianapolis, IN), was used for Colorado potato beetles in 2014. While most practices adhered to the standards of Rhode Island's Organic certification, it was necessary to use Sevin (Tessenderlo Kerley, Inc., Phoenix, AZ), a carbaryl insecticide not approved for Organic production, in 2014 to control cucumber beetles on squash.



Rep 4							Rep 3						
FW	MS	GW	YW	BS	PF	CN	YW	BS	CN	MS	GW	PF	FW
FW	MS	GW	YW	BS	PF	CN	YW	BS	CN	MS	GW	PF	FW
FW	MS	GW	YW	BS	PF	CN	YW	BS	CN	MS	GW	PF	FW

Rep 1							Rep 2						
BS	YW	PF	FW	MS	CN	GW	FW	GW	BS	PF	YW	CN	MS
BS	YW	PF	FW	MS	CN	GW	FW	GW	BS	PF	YW	CN	MS
BS	YW	PF	FW	MS	CN	GW	FW	GW	BS	PF	YW	CN	MS

Treatments:
FW: Dehydrated Food Waste
MS: Multisource Compost
PF: Paper Fiber/Chicken Manure
GW: Gelatin Waste
BS: Biosolids/Yard Waste Co-compost
YW: Yardwaste Compost
CN: Control (Mineral Fertilzer)

Crops:
☐ Corn
░ Squash
▒ Potato

Figure 1. The experimental plot was laid out in a randomized block design of 7 treatments (6 waste amendments and a mineral fertilizer control) (n=4). Crops were planted in strips and the same plots were used in 2013 and 2014 to monitor the cumulative effects of waste amendment addition. Diagram is to scale.

Table 1. Waste amendment application rates.

	Application Rate (dry kg/ha)		
Amendment	2013	2014	Cumulative
Dehydrated Food Waste	11712	9617	21329
Multi-Source Compost	82174	15722	97895
Paper Fiber/Chicken Manure	12116	15199	27315
Gelatin Waste	23158	0	23158
Biosolids/Yard Waste Compost	11322	19035	30356
Yardwaste Compost	20379	29201	49580
Control: 20-20-20 Mineral Fertilizer	560	560	1120

Amendment Characterization

Amendment were delivered or picked up in the spring of 2013 and 2014. The biosolids/yard waste, yard waste and multisource compost were from Rhode Island. The dehydrated food waste was from a restaurant in New York, the gelatin waste was from a Massachusetts facility and the paper fiber was from a resource management company based in New Hampshire. Amendments were stored in piles under tarps until application. All amendments were applied as delivered with the exception of the gelatin waste which arrived in large filter cakes and had to be broken up through a screen by hand before application.

For both 2013 and 2014 amendments, three subsamples were collected from each amendment pile, combined and analyzed for pH, EC, total C, N and P content, OM, moisture, bulk density and macro and micro nutrients/heavy metals. The 2014 amendment samples were also analyzed for NH_4, NO_3 and P_2O_5.

pH. Amendment pH was measured using a 1:2 soil to water ratio with a Denver Instrument Ultrabasic UB-10 pH meter (Denver Instrument, Bohemia, NY) (Hendershot and Lalande, 1993).

Electrical conductivity. The electrical conductivity (EC) of the amendments was measured using a 1:2 soil to water ratio with a Fisher Scientific Model 06-662-61 Conductivity Meter (Thermo Fisher Scientific Inc., Waltham, MA) (Gartley, 2011).

Total C, N and P. The total C and N content of the amendments was measured by solid phase analysis with a Carlo Erba NC2100 Elemental Analyzer (Brown University, Providence RI, 2013) and an EA1108 CHN Analyzer (URI Graduate School of Oceanography, Narragansett RI, 2014) (CE Instruments, Inc., Wigan, Ireland). Total P was measured by the dry ash method and HCl digestion with a Thermo Scientific iCAP 6000 ICP-OES (Thermo Fisher Scientific Inc., Waltham, MA) by the Maine Soil Testing Service (University of Maine, Orono ME) (Chapman and Pratt, 1961; Kalra and Maynard, 1991).

Organic matter. Amendment organic matter content was measured by loss-on-ignition at 550°C for 5 hours (Gugino et al., 2009).

Moisture. The gravimetric water content of the amendments was determined by drying at 105°C for a minimum of 24 hours. Results were reported as mass of water per mass of dry amendment (Topp, 1993).

Bulk density. Amendment bulk density was determined from the dry weight of amendment samples (dried at 105°C for a minimum of 24 hours) taken with a 1,006 cubic centimeter corer (Culley, 1993). Bulk density measurements were based on one sample per amendment.

Elemental analysis. Amendment macro and micro nutrients and heavy metals were measured by X-ray fluorescence with a Niton XL3r600 XRF Analyzer (Thermo

Fisher Scientific Inc., Waltham, MA). Prior to analysis samples were dried at 105°C for a minimum of 24 hours, ground, and sifted to 0.25 mm.

NH_4, NO_3 and P_2O_5: Available phosphorus was determined by heated neutral ammonium citrate extract and analyzed with a Thermo Scientific iCAP 6000 ICP-OES (Thermo Fisher Scientific Inc., Waltham, MA) by the Maine Soil Testing Service (University of Maine, Orono ME) (Helrich, 1990). Ammonium and nitrate were extracted using a 1:10 ratio of amendment to 1 N KCl and analyzed by ICP (Gugino et al., 2009).

Soil Quality

Amendment effects on soil quality were based on changes to OM levels, bulk density, pH, and soil moisture. Soil samples were also tested for EC and heavy metal content (As, Cd, Cr, Cu, Pb, Hg, Mo, Ni, Se and Zn), two of the potential limiting factors for the use of waste amendments.

The 2013 soil samples were collected on 5/18, 6/24, 8/14, and 9/30 and the 2014 samples were collected 5/14 (pre-amendment), 6/2, 6/30, 8/4, 8/29, and 10/6. One composite sample was analyzed per plot, made up of a minimum of 5 subsamples taken from the 3 m × 3 m center of each 4.5 m × 4.5 m plot, to a depth of 20 cm, using a 2-cm diameter corer.

Testing methods for soil organic matter, pH, moisture, EC and heavy metals were the same as for amendments (see previous section).

Bulk density. Soil bulk density was determined from the dry weight of the soil (dried at 105°C for a minimum of 24 hours) from a 185 cubic centimeter corer (Culley, 1993). Bulk density measurements were based on one 10 cm sample per plot.

Soil Fertility

Soil fertility was assessed by measuring levels of inorganic N (NH_4 and NO_3) and potentially mineralizable N (PMN). The sampling dates were the same as for soil quality testing.

Inorganic N. Ammonium and nitrate were extracted from fresh, sieved soil using a 1:5 ratio of soil to 2.0M KCl (Gugino et al., 2009). Soil and extract were separated by centrifuging at 11,000 RPM for 7 minutes and samples were analyzed colorimetrically on a BioTek PowerWave 340 Microplate Spectrophotometer (BioTek Instruments Inc., Winooski, VT) (Doane and Horwàth, 2003; Weatherburn, 1967).

Potentially mineralizable N. Soil PMN was determined from the difference in soil ammonium concentration before and after a 7-day anaerobic incubation at 30°C (Gugino et al., 2009). Ammonium concentration was determined colorimetrically as described above.

Crop Quality

Crop quality was based on tissue samples levels of macro and micro nutrients as well as heavy metals, crop emergence, early growth, and yield quantity and quality.

Tissue sampling and analysis. Leaf tissue samples were collected on 7/29/2013 and 7/21-8/11/2014. Corn tissue samples were collected from Applause only. They were dried, ground and analyzed for N, P, K, Ca, Mg, Al, B, Cu, Fe, Mn, Mo, Na, Pb and Zn by the dry ash method and HCl extraction with a Spectro Ciros-OES ICP (SPECTRO Analytical Instruments, Kleve, Germany) by the Soil Nutrient Analysis Laboratory (University of Connecticut, Storrs CT) (Miller, 1998).

Critical nutrient levels (the lower limit for adequate growth) were based on Maynard and Hochmuth (2007) for pumpkins (most recent mature leaf, 8 weeks after seeding), sweet corn (most recent mature leaf, just prior to tasseling), and potatoes (most recent mature leaf, 1st blossom stage). These levels represent the closest approximation for the stage of maturity at which tissue samples were taken and although the most recent mature leaf was sampled for potato and squash, corn samples were taken from the 5th leaf down (per Univ. Conn. instructions).

Five Montauk corn ears (including husk and cob) per plot were also collected in 2014 and analyzed for heavy metals by the same method used for soil samples.

Crop emergence and initial growth. Emergence data was collected for corn, squash, and potatoes in 2014. The fraction of seeds planted that emerged was calculated per plot. Measurements of early growth (plant height) were collected for both potatoes and corn in 2013 and 2014. Squash height was not measured because of its horizontal growth habit. The plants were measured from soil level and an average plant height per plot was calculated. All data was collected from the center 3 x 3 m area of each plot.

Yield. Potatoes were harvested from a 3 x 3 m area in the center of each plot. They were washed and sorted into three categories of quality: "A” (marketable), "B" (potentially usable for secondary market like processing) and "C" (culls) based on appearance. The potatoes were weighted by category and total yield (all three categories) was calculated on a per plot basis.

Squash were harvested from a 3 x 3 m area in the center of each plot. They were washed and sorted into marketable and culls based on appearance. Both categories were weighted and counted, and total yield (marketable + culls) was calculated on a per plot basis. The fraction of total yield that was culled was calculated on the basis of weight and number of fruit culled.

Marketable corn was harvested by hand as it ripened from a 3 x 3 m area in the center of each plot. All harvested ears were weighted and counted. Because of varying plant density between plots, yields were calculated on the basis of weight per plant, number of ears per plant, and weight per ear.

Statistical Analyses

SAS® (Statistical Analysis System Inst., Cary, NC) was used to perform one-way ANOVA tests for treatment effect for each crop and date sampled. For tests that passed the F-test for significance, Fisher's least significant difference test was used to perform pair-wise comparisons of means to identify which treatments varied significantly. Wherever significance is indicated $p < 0.05$.

CHAPTER 3

RESULTS AND DISCUSSION

Amendment Qualities

I determined the electrical conductivity (EC), pH and organic matter (OM) content of the amendment samples (Table 2). All amendment EC values were around or below 10 mS/cm with the exception of the mineral fertilizer, which had an EC of 345 mS/cm, and the chicken manure, which had an EC of 41 mS/cm. For those amendments that were sampled both years, EC values were fairly consistent between years.

Amendment pH was less consistent than EC (Table 2). The mineral fertilizer (2014) and gelatin waste (2013) were the most acidic (4.6 and 4.9, respectively), the chicken manure (2014) was neutral (7.0), and the dehydrated food waste was consistently acid in 2013 and 2014 (5.5). The yard waste compost (6.5 and 6.7) and paper fiber (6.9 and 6.4) were only slightly acidic and consistent between years. The pH of the multisource compost hovered right around neutral (6.7 and 7.1). Finally, the biosolids/yard waste co-compost had the least consistent pH, varying from 5.1 in 2013 to 7.9 in 2014.

The organic matter content of the waste amendments varied among amendments and year-to-year for the same amendment (Table 2). In 2013, the OM content of the amendments followed the order: Multisource compost < yard waste compost < dehydrated food waste < biosolids/yard waste co-compost < chicken manure < gelatin waste < paper fiber. The order was the same in 2014, with the exception of dehydrated food waste which had a slightly higher OM content than the biosolids/yard waste co-compost.

Table 2. Electrical conductivity, pH, and organic matter and C content of waste amendment and control treatments used in this study. - indicates no data. BS = biosolids/yard waste co-compost, CM = chicken manure, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber, YW = yard waste.

Amendment	Electrical Conductivity	pH	Organic Matter	C
	(mS/cm)		g/kg	g/kg
	n=1	n=1	n=1	n=2
BS 13	7.3	5.1	612	334
BS 14	7.0	7.9	535	326
CM 14	41.4	7.0	754	368
FW 13	10.2	5.5	539	454
FW 14	10.1	5.5	627	486
MS 13	3.9	6.7	106	94
MS 14	5.3	7.1	194	147
CN 14	344.9	4.6	-	-
GW 13	5.5	4.9	769	477
PF 13	2.4	6.9	823	321
PF 14	4.9	6.4	798	407
PF/CM 13	7.3	-	815	327
PF/CM 14	9.5	-	793	402
YW 13	4.0	6.5	377	210
YW 14	1.8	6.7	344	196

The proportion of C in amendment OM varied, with the lowest values observed for paper fiber and chicken manure (40-50%), biosolids/yard waste co-compost, gelatin waste and yard waste in the middle (50-60%), and the highest values observed for dehydrated food waste and multisource compost (75-85%) (Figure 2).

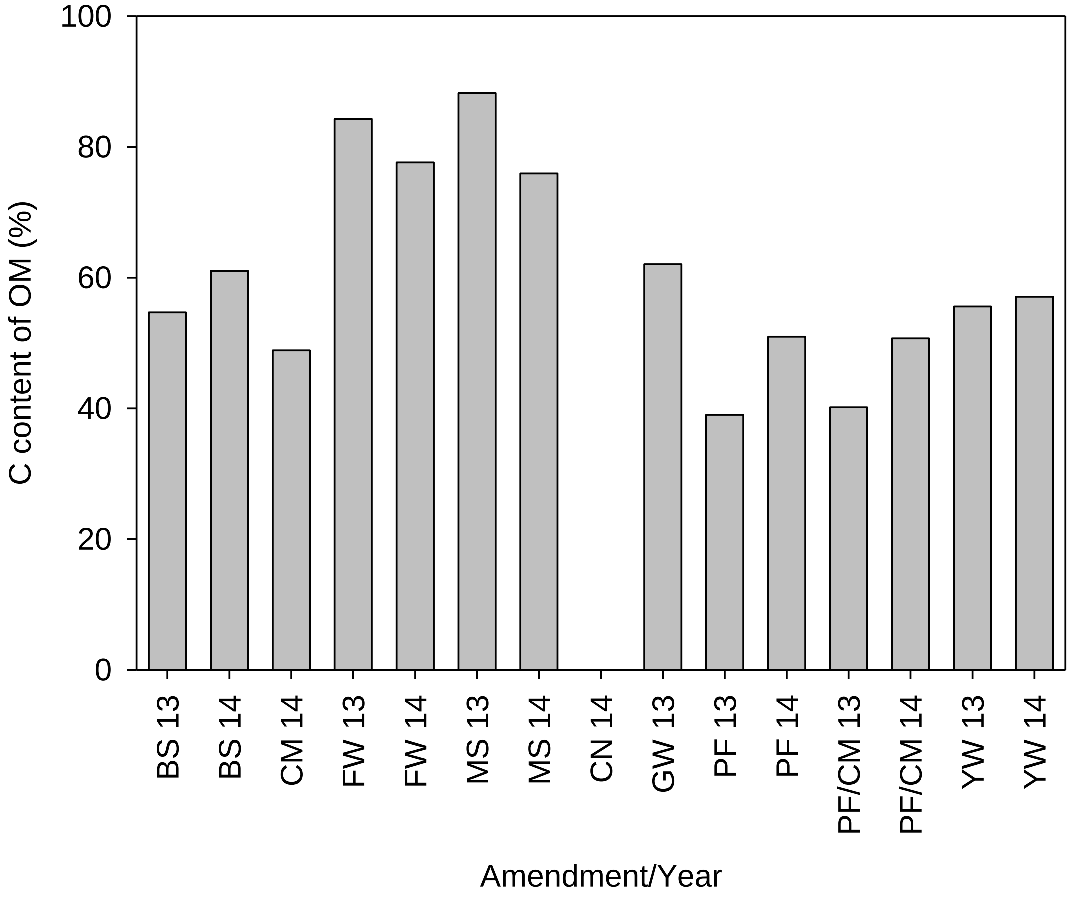


Figure 2. Carbon content of amendment organic matter. BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber, YW = yard waste.

Both the dehydrated food waste and the multisource compost contained a considerable amount of seashells. Because shells are denser (1.7 g/cm^3) than organic matter, and are primarily $CaCO_3$ (12% C), they could be responsible for the high percent of C in OM for these amendments (Manohara et al., 2014). While the C contribution from shells is reflected in the total C measurement of the amendments due to the high combustion temperature, the $CaCO_3$ from the shells would be unlikely to begin decomposing during heating in the muffle furnace to measure OM. Although the loss-on-ignition procedure heats the samples to 550°C, Mohamed et al. (2012) found that the $CaCO_3$ in cockle shells does not begin to decompose until 700°C. Therefore, the percent of OM that is C is likely overestimated by the methods used here. The C present in the shells as $CaCO_3$ would not function the same as the rest of the C in the waste materials because the large pieces of shell would break down very slowly, therefore very little of this C would initially be available to soil microorganisms.

To determine how seashells affected the C content of amendments, samples of the dehydrated food waste and multisource compost (2014) were treated with 6N HCl. The samples were mixed with the acid, dried (105°C for a minimum of 24 hours), ground, and analyzed for total C and N by solid phase analysis. The total C content of the acid-treated samples was subtracted from the C content of the untreated samples to determine the amount of C lost (from $CaCO_3$). While there was only 15.5% less C in dehydrated food waste samples after acid treatment, there was 47.4% less C in the multisource compost samples. Because C from $CaCO_3$ is not available to microorganisms, the multisource compost will contribute almost 50% less C to microbial processes than total C values indicate. Without shells the C:N ratio of the multisource compost decreases from 9:1 to 5:1, which could result in higher inorganic N availability than expected. This highlights the importance of distinguishing between organic and inorganic sources of C when interpreting amendment test results.

Although they were not determined quantitatively, some textural properties of the amendments were unique. The biosolids/yard waste co-compost was a mixture of very fine organic material and larger pieces that resembled bark mulch. The yard waste compost also resembled bark mulch, although the pieces were consistently larger. The multisource compost was unique from the other composts because it included pieces of clam shells. This is reflected in a higher bulk density than the other two composts (Table 3). The dehydrated food waste was finely ground and contained pieces of mussel shells. Because the paper fiber was not composted, and was made entirely of recycled paper, it had a very different appearnce and texture from the rest of the material: it had a very low density (0.22 g/cm^3) and contained foreign materials, including pieces of plastic. Finally, the gelatin waste arrived in large filter cakes and had the texture of cheesecake. It had to be pushed through a sieve by hand to break it up into smaller pieces before it could be applied.

Physical charactersitics of waste amendments, like texture and moisture, are important for practical and aesthetic reasons. Texture can effect the rate of decomposition: aerobic breakdown of materials depends on both access; the smaller the particle size the more surface area available to microorganisms, and also availability of oxygen; if particles are too small it can lead to compaction and prevent airflow (Ahmad et al., 2007). Particle size also influences the ability of a farmer to spread the materials, while the requirements for specific pieces of equipment vary, a consistent texture is preferable (Alexander, 1997). Although amendments in this study were spread by hand, the gelatin waste could not have been spread by many types of equipment (like a cone spreader) without being first broken up by hand. Amendment moisture content is also a consideration: excess moisture adds unnecessarily to shipping costs but materials that are too dry may be dusty or hydrophobic (Ozores-

Hampton et al., 1998). For this study, the paper fiber that was delivered was over half water by weight, while the other amendments were drier (Table 3). There are also aesthetic considerations: a farmer or gardener might object to materials that contain large quanities of shell (dehydrated food waste and multisource compost) or foreign material (plastic in paper fiber).

Table 3. Bulk density and volumetric water content of amendments. Gelatin waste bulk density as given by manufacturer. - indicates no data.

Amendment	Bulk Density	Gravimetric Water Content
	(g/cm^3)	%
	n=1	n=1
Biosolids/Yard Waste Co-compost 14	0.32	45
Dehydrated Food Waste 14	0.65	3
Multisource Compost 14	0.54	40
Gelatin Waste 13	0.65	-
Paper Fiber/Chicken Manure 14	0.22	102
Yard Waste 14	0.39	78

The amendments were also tested for their heavy metal content (Mo, Pb, Se, As, Hg, Zn, Cu, Ni, Cr and Cd). None of the amendments exceeded the ceiling limits for heavy metal concentrations outlined by the U.S. EPA (1994) for land application of biosolids (Appendix 1). All concentrations were also below the more restrictive levels established for exceptional quality biosolids with the exception of the yard waste compost in 2014, which slightly exceeded the limit for As.

Plant Nutrients

Waste amendments were tested for their total N, P and K content. Several of the amendments studied had N contents comparable to or exceeding commercial organic fertilizers such as chicken manure (Table 4). The gelatin waste had the highest N concentration (49 g/kg), exceeding that for the chicken manure (45 g/kg) used in the paper fiber blend. The dehydrated food waste and biosolids both contained > 30 g N/kg. The multisource compost, paper fiber and yard waste compost all contained < 17 g N/kg.

Although the multisource compost and yard waste compost had low N contents, their C:N ratios were <15:1, while the C:N ratio of the paper fiber was between 57:1 and 74:1, well above the threshold for N immobilization (25:1) (Table 4). Even when blended with a composted chicken manure product (C:N = 8:1) at the rate recommended by the provider of the paper fiber (7 parts paper to 1 part chicken manure), the C:N ratio of the blend (>50:1) was still high enough to result in N immobilization.

Most of the N present in waste amendments is organic N; however, some is present in inorganic forms (NH_4 and NO_3) (Figure 3). Unlike organic N, these forms are available for immediate plant uptake, and nitrate is susceptible to loss by leaching. The paper fiber/chicken manure blend had the highest fraction of N in inorganic forms (4.5%), followed by the biosolids/yard waste co-compost (3%), and the multisource compost (2.6%). The yard waste compost, gelatin waste and dehydrated food waste all had 1% or less of their N content in inorganic forms.

Table 4. N, P, and K content and C:N ratio of waste amendments. Values for fertilizer N, P, and K as given by the manufacturer. - indicates no data. BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber, YW = yard waste.

Amendment	N	C:N	P	K
	g/kg		g/kg	g/kg
	n=2	n=2	n=1	n=2-3
BS 13	33	10	4.6	17.1
BS 14	32	10	5.8	25.2
CM 14	45	8	13.8	61.9
FW 13	37	12	2.9	18.0
FW 14	34	14	3.0	15.4
MS 13	9	10	1.9	11.9
MS 14	16	9	3.0	11.1
CN 14	200	-	87.2	166
GW 13	49	10	39.0	0.3
PF 13	4	74	0.7	4.8
PF 14	7	57	0.3	1.8
PF/CM 13	9	66	2.4	11.9
PF/CM 14	12	51	2.0	9.3
YW 13	17	13	2.3	27.4
YW 14	15	13	2.1	24.3

Most of the waste amendments are not significant sources of P (Table 4). Although the dehydrated food waste, yard waste compost and multisource compost had P concentrations of 2-3 g/kg, the paper fiber had <1 g P/kg. The biosolid/yard waste co-compost had a slightly higher concentration (4-6 g P/kg). The gelatin waste was unique because it had a P content approaching its N content (39 g P/kg), which could lead to over application of P if it were applied to meet crop N needs.

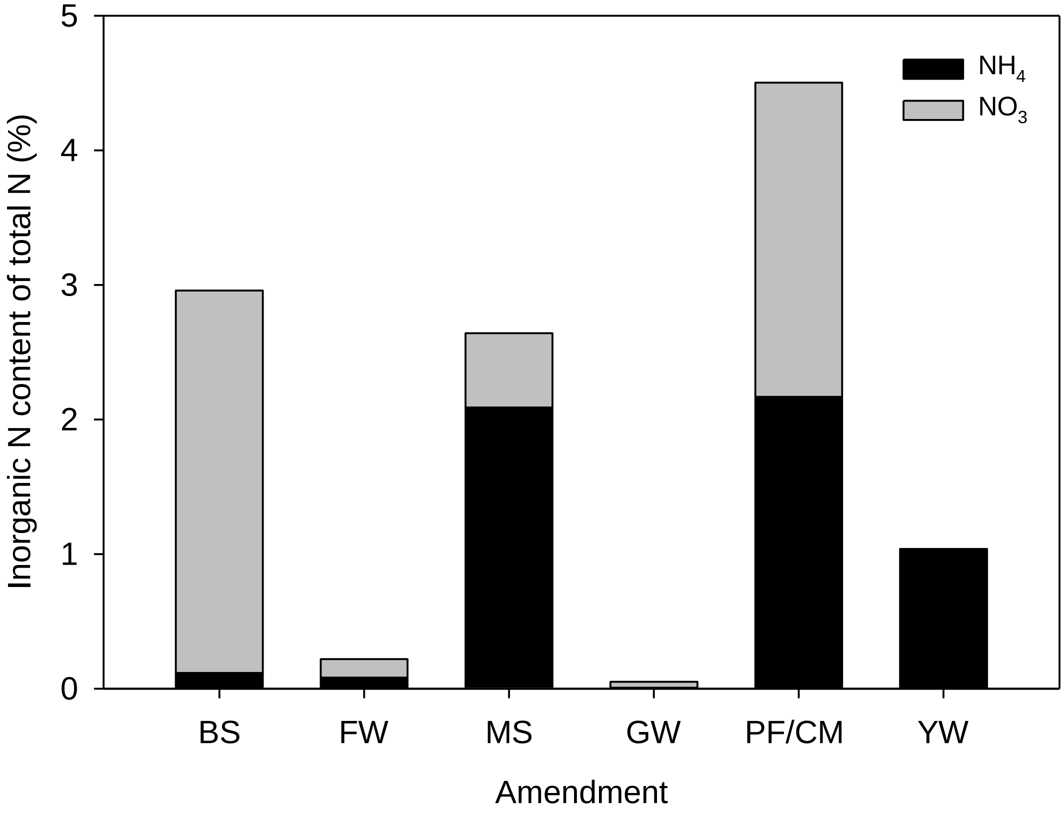


Figure 3. The fraction of amendment total N present as inorganic N (NH_4 and NO_3). Values are for 2014 except GW (2013). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber, YW = yard waste.

Unlike mineral fertilizers, not all of the P in waste amendments is plant-available. For example, the plant-availability of P from biosolids ranged from nearly 0% to 100%, depending on how the wastewater was treated (Elliot et al., 2005). Therefore, a measure of plant-available-P is necessary when applying amendments to meet crop nutrient needs. For this study, the amount of available-P in the waste amendments was measured using a neutral ammonium citrate (NAC) extraction. The portion of the total P that was plant-available (according to this method) varied between 53% (multisource compost) up to 111% (paper fiber/chicken manure mix)

(Figure 4). However, Elliot et al. (2005) reported that, for biosolids, the amount of available-P extracted by the NAC method was not statistically different from the total P extracted by strong acid digestion, and sometimes even exceeded it (as seen in this study). Further, they reported that there was no correlation between plant-availability of biosolids P and the amount extracted by NAC. They concluded that NAC extraction was not useful for testing plant-availability of P in biosolids.

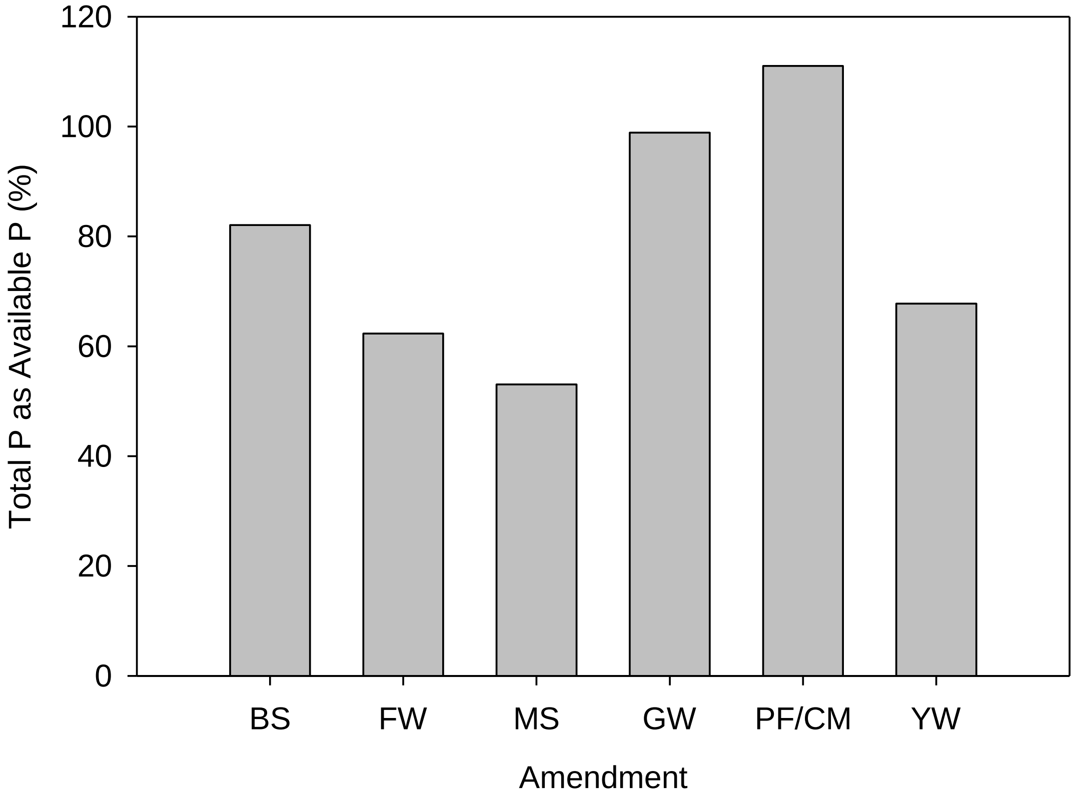


Figure 4. The percent of amendment total P present as available P. All amendment samples from 2014 except gelatin waste (2013). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber, YW = yard waste.

The waste amendments used in this study also contained varying amounts of K (Table 4). The gelatin waste contained almost none (<1 g/kg) and the paper fiber also contained very little (<5 g/kg). The biosolids/yard waste co-compost, dehydrated food waste, multisource compost, and yard waste compost all contained between 10 and 30 g/kg of K. These are all low in comparison to the chicken manure (62 g/kg) and fertilizer (166 g/kg).

Application Rates

Amendments were applied to provide ~10,000 kg/ha of C over the two years of the study, with the exception of the mineral fertilizer control, which was not a significant source of C (Table 5). Gelatin waste was not applied in 2014, as the 2013 application had exceeded the total C required.

Table 5. Application rate of organic matter and C from amendments. Application rates were set to provide a cumulative application of ~10,000 kg C/ha over two years. BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF/CM = paper fiber/chicken manure, YW = yard waste.

Amendment	Carbon			Organic Matter		
	2013	2014	Total	2013	2014	Total
	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
FW	5322	4678	10000	6316	6026	12342
MS	7689	2311	10000	8717	3044	11761
PF/CM	3963	6109	10071	9871	12046	21917
GW	11044	0	11044	17798	0	17798
BS	3786	6214	10000	6923	10185	17108
YW	4270	5730	10000	7684	10039	17723
CN	0	0	0	0	0	0

Because application rates were based on amendment C content, and the nutrient density of the amendments varied, application rates of N, P, and K also varied (Figure 5). The recommended N application rates are 112-146 kg N/ha for sweet corn, 123-157 kg N/ha for winter squash, and 134-202 kg N/ha for potatoes) (Hazzard and Howell, 2014). All application rates met the lowest N requirement (112 kg/ha) in both years, with the exception of the gelatin waste plots, which were not amended in 2014 after a large addition of N in 2013 (1,140 kg/ha N). The control plots (112 kg N/ha) in both 2013 and 2014 did not meet the minimum N recommendations for potatoes and squash. These application rates do not, however, take into account N mineralized from soil OM and previous cover crop, which included hairy vetch, a legume. Based on the average N content and mineralization rate of soil OM, you can expect the release of ~22-45 kg N/ha for each 1% OM in the surface 15-18 cm of soil (Hazzard and Howell, 2014). For soil with an organic matter content of 5%, this would provide an additional 110-225 kg N/ha. Therefore, total N application rates in all plots were likely sufficient to meet all crop needs.

Although enough N was applied in waste-amended plots to meet crop needs, it was applied mostly as organic N (Figure 3), which is not mineralized completely into plant-available forms in the first growing season. Estimates of first-year N availability from yard waste and municipal solid waste composts range from 5-21% (Amlinger et al., 2003; Hargreaves et al., 2008). Although data on inorganic N release is available for many composts, similar data are not available for novel amendments such as gelatin waste and dehydrated food waste. The mineralization rates for these amendments are potentially higher because they have not been composted and likely contain more rapidly decomposable compounds. Because N mineralization rates depend on a wide variety of factors, including soil conditions, it is difficult to predict if the N applied from waste amendments (and N mineralized from existing soil OM) will be sufficient to meet crop needs.

The recommended agronomic P and K application rates vary based on crop needs; however, they are also dependent on existing soil P and K levels. When P is added to acid soil, like the field in this study (pH generally <6.0), it quickly becomes bound in Fe and Al compounds with very low solubility and therefore low plant availability. To compensate for low plant availability, farmers often over apply P, resulting in excess buildup in the soil. Once this buildup has occurred, if soil tests indicate optimum to above-optimum soil P levels, little to no P addition is recommended (Hazard and and Howell, 2014).

Because P uptake is slow in cold soils, a small addition is recommended even for soils with optimum P levels. These rates range from 20 kg P/ha for sweet corn and squash to 29 kg/P ha for potatoes (Hazzard and Howell, 2014). The results of soil tests from March 2013 (UConn Soil Laboratory), before establishment of experimental plots, indicated that soil P levels were already optimum, indicating further additions of P would be unlikely to increase yields (Hazzard and Howell, 2014). All amendment application rates were at least 29 kg P/ha, with the exception of the gelatin waste plots in 2014, which did not receive any additional amendment after a large addition (904 kg P/ha) in 2013.

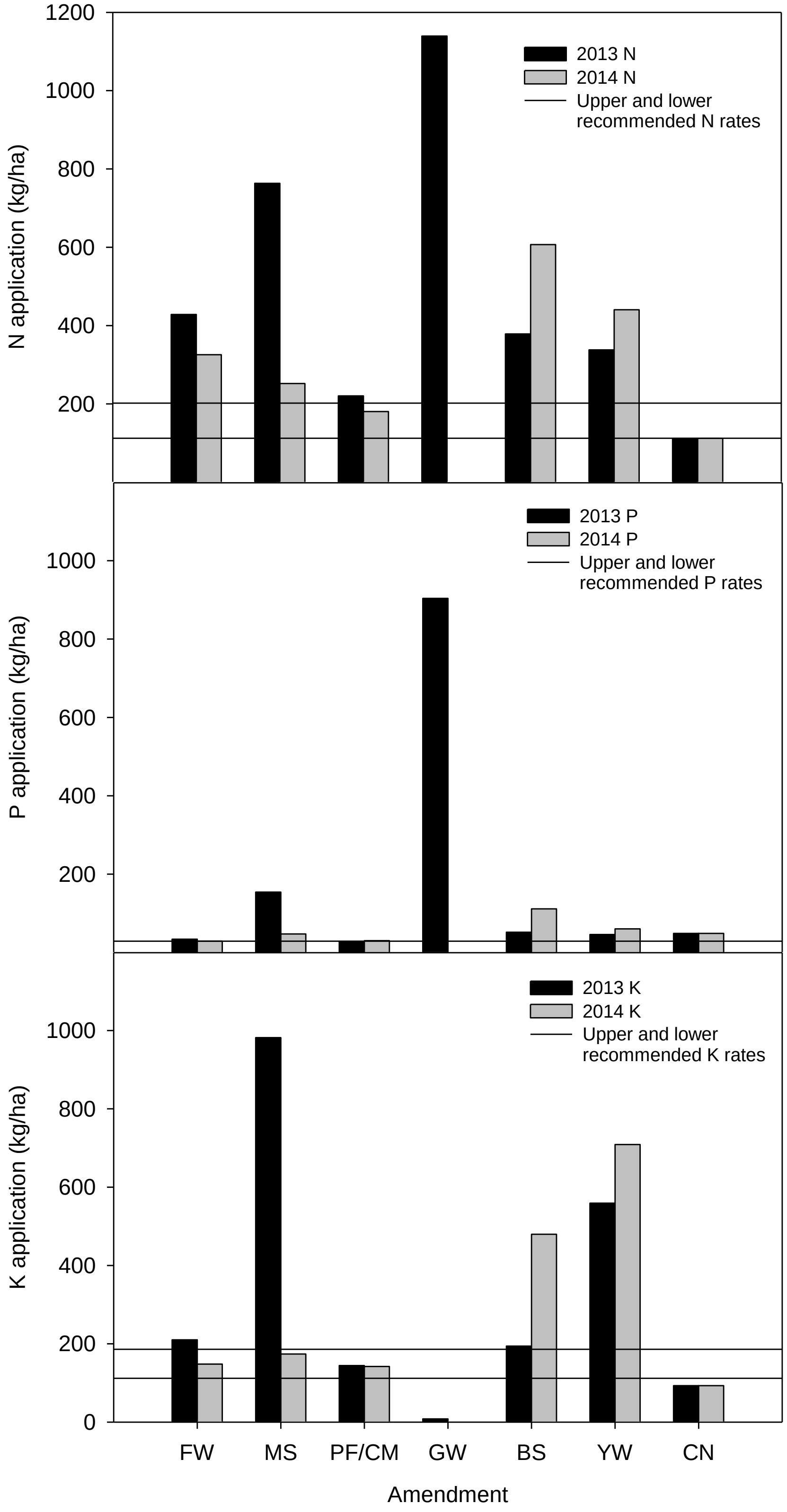


Figure 5. Application rates of N, P and K from 2013 and 2014. Upper and lower recommended agronomic rates for corn, squash and potatoes, are designated (lower limit is 0 if not otherwise indicated). Recommended application rates for P based on optimum soil P levels; recommended K application rates based on below-optimum soil K levels. BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber, YW = yard waste.

Recommended application rates of K are also dependent on existing soil levels. Although excess K does not have the same potential as N and P to cause environmental problems, like eutrophication, excess K will be taken up by plants, beyond what they need, and may depress uptake of Ca and Mg, causing nutritional imbalances in the plant (Brady and Weil, 2008).

Unlike P levels, soil tests indicated that K levels were below optimum in March 2013. For soils with below-optimum K levels, additions of 112 kg K/ha for sweet corn, 139 kg K/ha for winter squash, and 186 kg K/ha for potatoes are recommended (Hazzard and Howell, 2014). All plots received the recommended rate of K for winter squash and sweet corn with the exception of the gelatin waste plots and control plots. Because of the very low K content of the gelatin waste these plots received only 8 kg K/ha in 2013, and none in 2014 (since gelatin waste was not reapplied). Control plots received 93 kg/ha K each year. Potassium application rates in paper fiber/chicken manure (2013 and 2014), dehydrated food waste (2014), and multisource compost (2014) plots also did not meet recommendations for potatoes. Amendments were also sources of Ca and Mg (Table 6).

Table 6. Application rates of Ca and Mn from amendments. BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste.

Amendment	Calcium			Manganese		
	2013	2014	Total	2013	2014	Total
	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
FW	464.6	156.2	620.7	0.0	0.0	0.0
MS	7120.7	1150.1	8270.8	32.1	8.8	40.8
PF	1914.2	1245.8	3160.0	13.4	6.1	19.5
GW	3452.9	0.0	3452.9	0.0	0.0	0.0
BS	438.7	619.1	1057.8	5.5	12.1	17.7
YW	558.8	935.0	1493.8	9.3	33.2	42.5
CN	0.6	0.6	1.1	0.8	0.8	1.7

Soil Quality

Electrical Conductivity

Reduction of crop yield due to soil salinity was unlikely at the EC levels found in this study. Yield losses for sensitive crops begin at EC levels of ~1 mS/cm, corn and potatoes yield losses are likely above 1.7 mS/cm, while squash tolerances are higher (Maas, 1984). The highest EC levels found in this study (0.587 mS/cm) were observed in control potato plots, immediately after amendment in 2014 (Figure 6). As hypothesized, the increase in salinity due to amendment application was temporary, and all soil EC levels had fallen sharply by the next sampling date (two months later). These results suggest that the amendments used in this study, applied at or below the rates used, will not contribute problematic levels of salts to the soil.

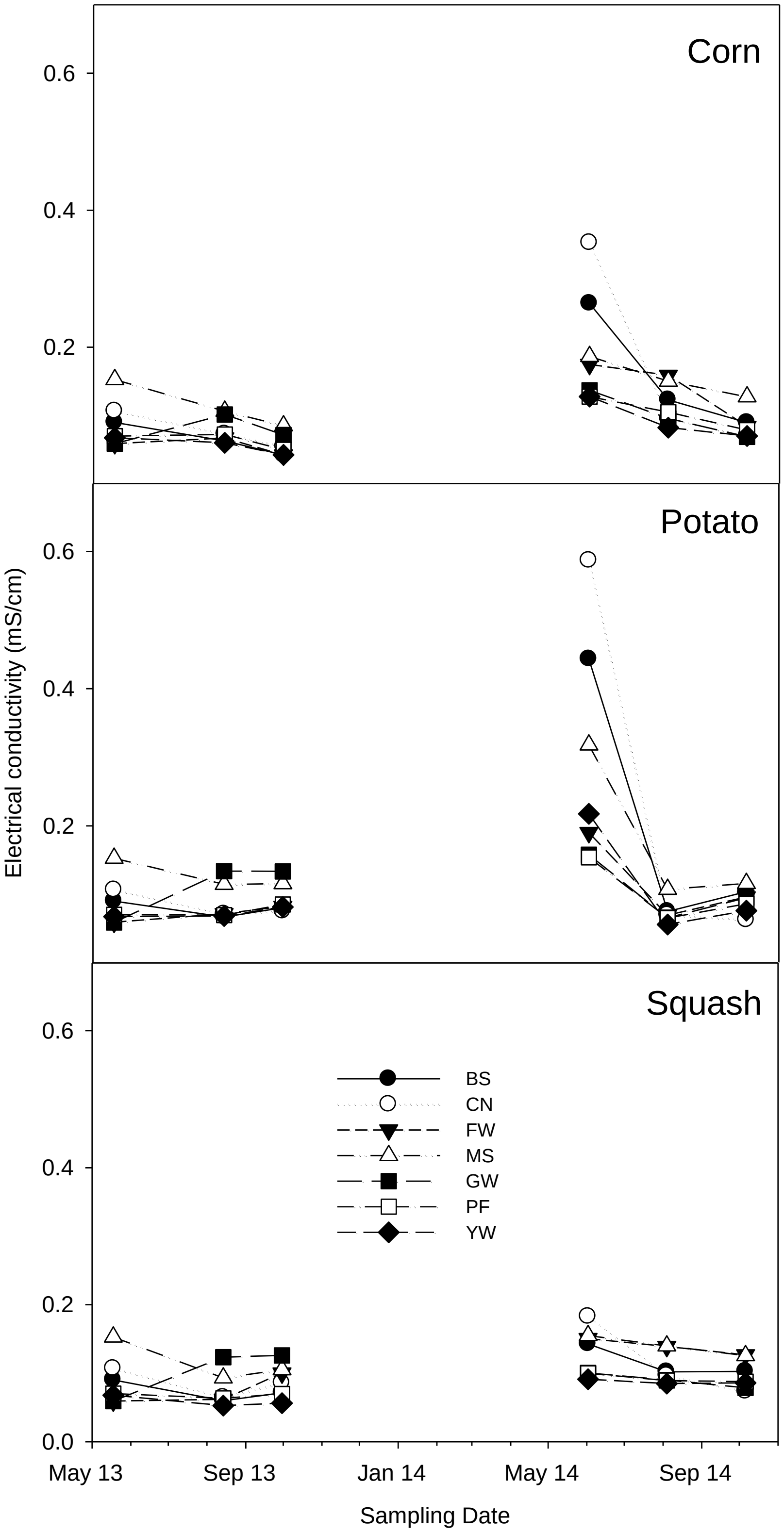


Figure 6. Mean soil electrical conductivity (n=4) for plots in 2013 and 2014. BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 7 for Fisher's LSD results.

Table 7. Fisher's LSD results for soil electrical conductivity in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different ($p<0.05$).

Sample Date	Crop	LSD (mS/cm)	BS	CN	FW	MS	GW	PF	YW
May (5-18-13)	Combined	0.030566	BC	B	D	A	D	CD	CD
August (8-14-13)	Corn	0.026315	B	B	B	A	A	B	B
	Potato	0.019244	C	C	C	B	A	C	C
	Squash	0.026101	C	C	C	B	A	C	C
September (9-30-13)	Corn	0.018771	C	BC	C	A	AB	C	C
	Potato	0.022559	B	B	B	A	A	B	B
	Squash	0.030283	CD	BCD	ABC	AB	A	D	D
June (6/2/14)	Corn	0.10846	AB	A	BC	BC	C	C	C
	Potato	0.083103	B	A	D	C	D	D	D
	Squash	0.060285	ABC	A	ABC	AB	BC	BC	C
August (8/4/14)	Corn	0.044903	AB	B	A	A	B	B	B
	Potato	0.018577	B	BC	BC	A	BC	BC	C
	Squash	0.042663	ABC	BC	AB	A	C	C	C
October (10/6/14)	Corn	0.020054	B	BC	BC	A	C	BC	BC
	Potato	0.022559	A	A	A	A	A	A	A
	Squash	0.02939	AB	B	A	A	B	B	B

pH

I expected that amendments with a high pH, such as BS ('14), MS, PF, and YW, would raise soil pH significantly. However, the only treatment that had a significant effect over the duration of the study was MS, which had the highest soil pH for all months, except May 2013 (Figure 7). The pH for MS treatment was significantly higher than all other treatments in August 2013 potato plots, and all months and crops sampled in 2014. Although this compost had a higher pH (6.7-7.1) than the soil, it did not have the highest pH of the amendments used in the study (Table 2). It did, however, contain a significant amount of seashells, which are made primarily of $CaCO_3$. Calcium carbonate is used to neutralize soil acidity, and therefore could have been responsible for the higher pH in these plots. Crushed oyster shells and clam processing wastes have previously been shown to increase soil pH (Lee et al., 2008; Owen et al., 2008). These results indicate that amendments containing seashells may provide the additional benefit of raising soil pH.

I anticipated that waste amendments, which are high in organic C and/or N, would lower soil pH**,** due to the release of acidity from the decomposition of organic matter and oxidation of ammonia (Bolan and Hedley, 2005). The results did not support this hypothesis for all amendments. The soil pH of plots amended with PF and GW was never significantly lower than the control, and plots amended with FW were only significantly lower in corn plots in September 2013. It appears that acidity released from application of these wastes was similar to the acidity produced by conversion of urea and NH_4 from the control fertilizer. As stated earlier, the pH of plots amended with MS was consistently higher, potentially due to the acid neutralizing effect of shells. However, the pH of plots treated with YW and BS was often significantly lower than the control in 2014. This is not likely due to the pH of the amendments alone, since the 2014 YW treatment had a pH of 6.7 and the 2014 BS treatment had a pH of 7.9, the highest of all the amendments applied. Instead, the low pH was likely related to processes that release acidity such as decomposition of organic matter, or oxidation of N or S. These results indicate that some waste amendments have the potential to significantly lower pH in comparison to a mineral fertilizer.

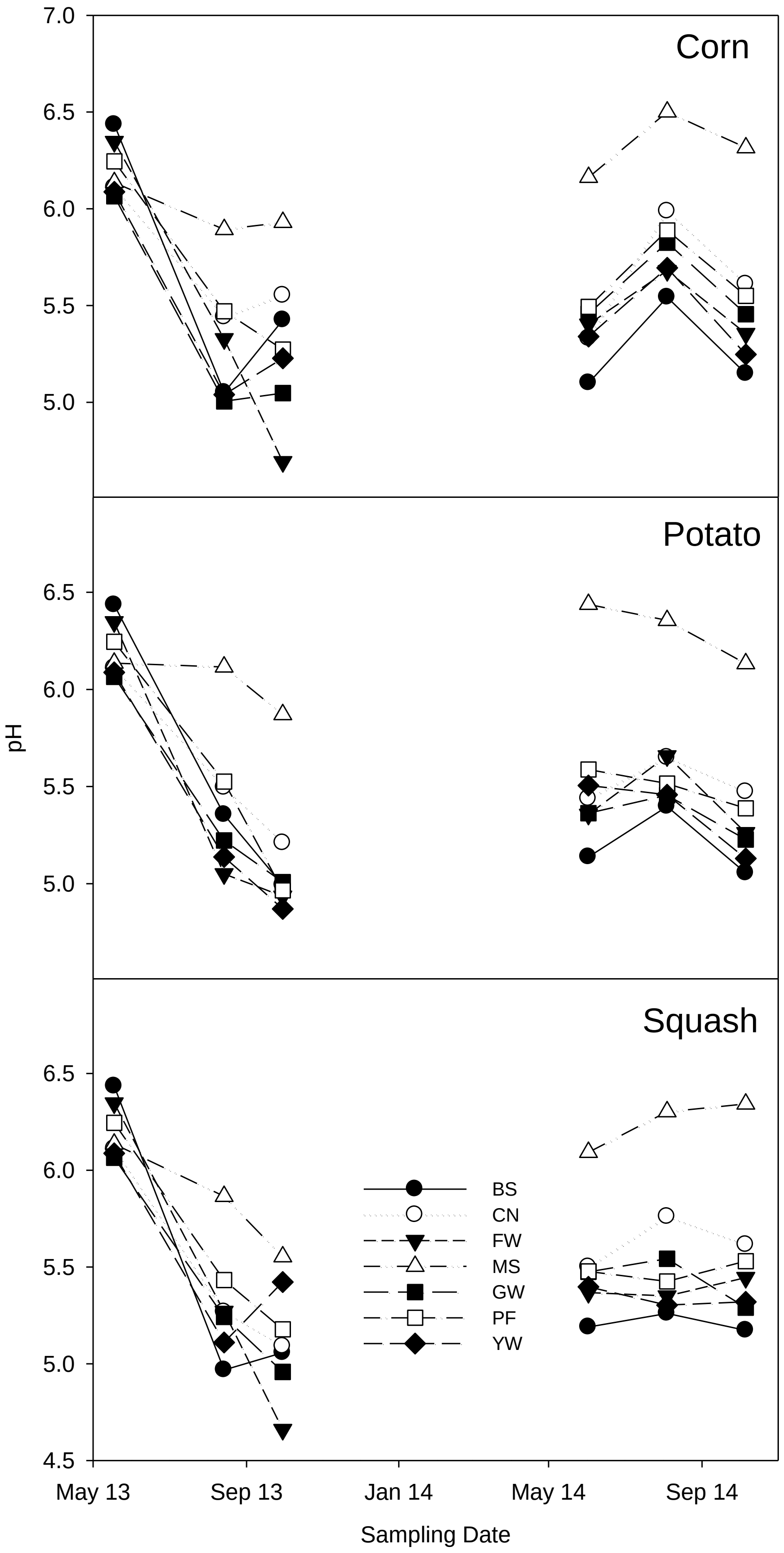


Figure 7. Mean soil pH for plots in 2013 and 2014 (n=4). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 8 for Fisher's LSD results.

Table 8. Fisher's LSD results for soil pH in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different (p<0.05).

Sample Date	Crop	LSD (pH)	BS	CN	FW	MS	GW	PF	YW
May (5-18-13)	Combined	0.1254	A	D	AB	CD	D	BC	D
August (8-14-13)	Corn	0.5336	B	AB	B	A	B	AB	B
	Potato	0.5151	B	B	B	A	B	B	B
	Squash	0.5994	A	A	A	A	A	A	A
September (9-30-13)	Corn	0.672	AB	AB	C	A	BC	ABC	BC
	Potato	0.7062	A	A	A	A	A	A	A
	Squash	0.6336	A	A	A	A	A	A	A
June (6/2/14)	Corn	0.3295	C	BC	BC	A	B	B	BC
	Potato	0.3648	C	BC	BC	A	BC	B	B
	Squash	0.275	C	B	BC	A	B	B	BC
August (8/4/14)	Corn	0.3257	C	B	BC	A	BC	B	BC
	Potato	0.3643	B	B	B	A	B	B	B
	Squash	0.421	C	B	BC	A	BC	BC	C
October (10/6/14)	Corn	0.2972	D	B	BCD	A	BC	B	CD
	Potato	0.3221	D	B	BCD	A	BCD	B	CD
	Squash	0.3583	C	B	BC	A	BC	BC	BC

Bulk Density

Plots which received waste amendments were expected to have lower bulk density, because of the low density of the amendments themselves, and the addition of OM which provides the energy for biological processes involved in aggregation, as well as organic polymers from decomposition that bind soil particles (Brady and Weil, 2008). Most waste amended plots had lower bulk density than the control treatment, although only plots amended with FW were significantly lower. The exception was MS amended plots, which had a higher mean bulk density than the control, although not significantly (Figure 8).

Changes in soil bulk density were likely not due to the incorporation of amendments with lower bulk density alone. While MS raised bulk density, and FW decreased it, compared to the control, FW itself had a higher bulk density than MS (0.65 and 0.54 g/cm^3 respectively) (Table 3). While both FW and MS contained seashells, which are dense (1.7 g/cm^3), MS contained more (15.5 vs. 47.4% of total C from shells) (Manohara et al., 2014). Because the C from shells is less available to soil microorganisms, and MS was already composted, it may have provided less of the products involved in aggregation (C for energy and polymers from decomposition).

With the exception of MS, results indicate that the waste amendments tested have the potential to lower bulk density, especially FW. Low bulk density is desirable because it allows plant roots to more easily penetrate the soil and increases pore space which allow movement of gases and water (Brady and Weil 2008).

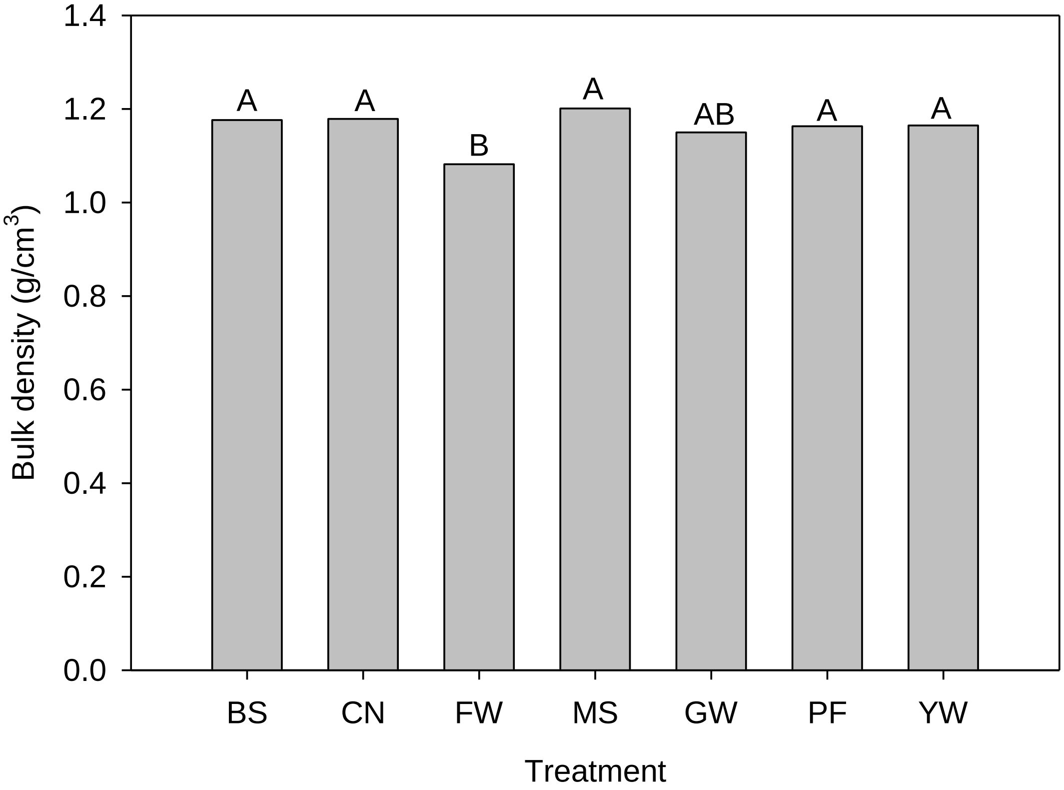


Figure 8. Mean soil bulk density for corn plots in 2014 (n=4). Samples were taken in the spring (4/10/14) after the 2013 growing season. Treatments with the same letter were not significantly different (LSD = 0.0686 g/cm^3). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste.

Organic Matter

Despite large additions of organic matter to plots amended with waste materials, and no addition of OM to control plots, there was no significant variation in soil OM between treatments for any of the crops or months tested for both 2013 and 2014 (Data not shown). This could be due, in part, to a systematic variation in OM in the field where the experiment was located. The pattern of variation became evident when values of OM from the May 2013 soil samples (post-amendment) were plotted against their location in the field, measured as a distance from the west end of the field (Figure 9). There was a strong positive correlation between OM content (%) and field position: as distance from the west edge of the field increased, the OM content of the soil increased by almost two percentage points over 60 m. This variation was large enough to obscure the increase in OM of <1 percentage point that could be expected from even the highest amendment rates in this study (22,000 kg/ha OM addition in PF plots over 2 years).

To compensate for the preexisting gradient of OM in the experimental plots, I used four data points from plots that had not received any OM additions (two outside plots and the two control plots) to estimate the slope of the existing OM gradient. This value was used to calculate the background level of OM for each plot, based on distance from the west edge of the field, which was subtracted from all my results to eliminate the pre-existing variation. This left a value which represented the change in soil OM during the study, due to the application of treatments (Figure 10).

There were no significant differences in the change in OM between treatments in 2013. Some of these values were negative, likely because the slope estimate was based on values from spring 2014, and all plots had increased in OM since the beginning of the 2013 growing season. In 2014 there were significant differences in the change in OM in the August corn, and October corn and squash plots. In those months and crops the YW and BS plots had the highest increase in OM. The MS, GW and FW plots had the lowest changes in OM in most instances, although not significantly lower than the control plots.

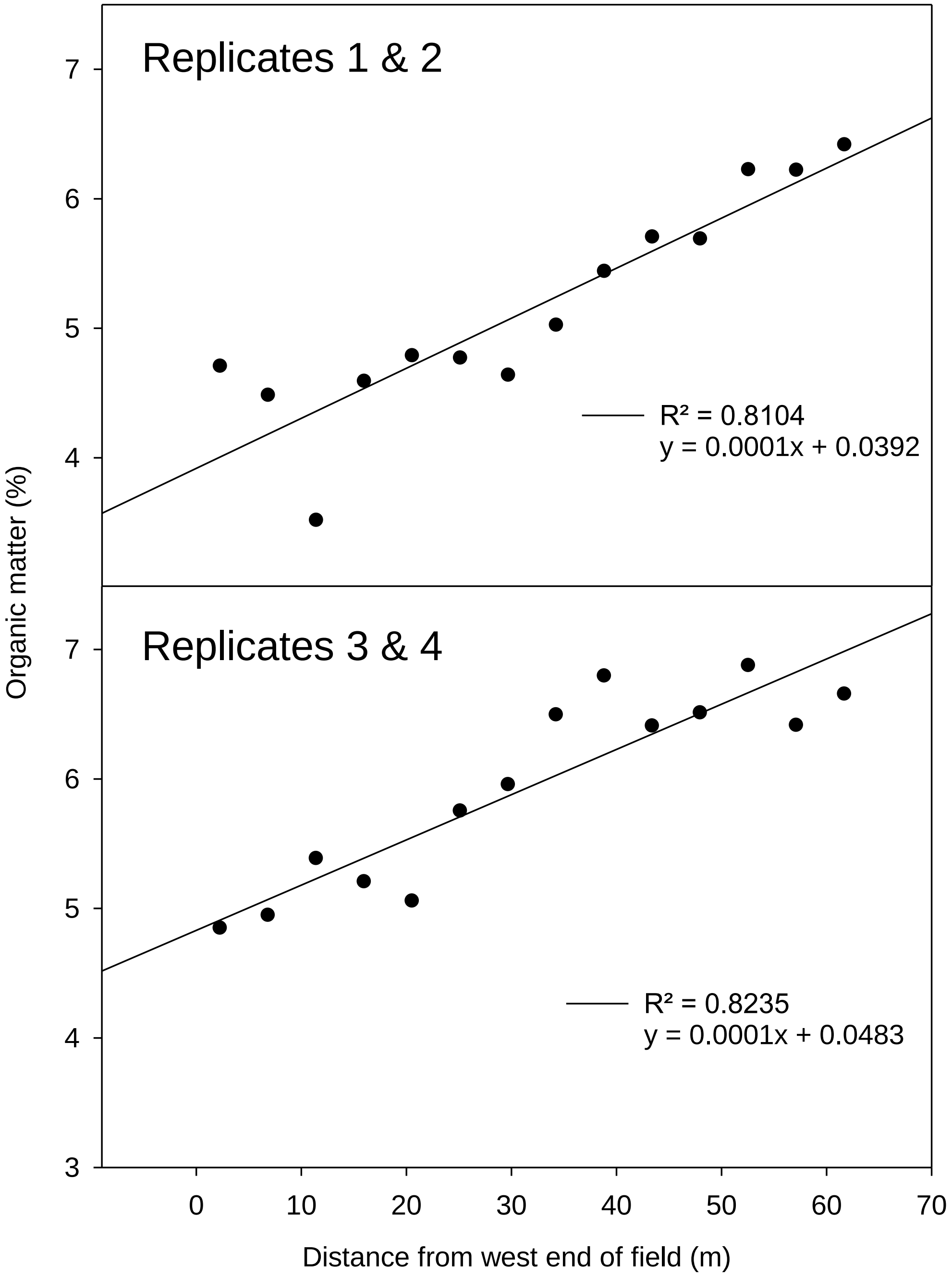


Figure 9. Correlation between soil organic matter and distance from the west end of the field for samples taken in May 2013, after amendment application. Replicates 1&2 and 3&4 ran parallel to each other from approximately west to east (Figure 1). The line indicates a positive correlation between OM and distance.

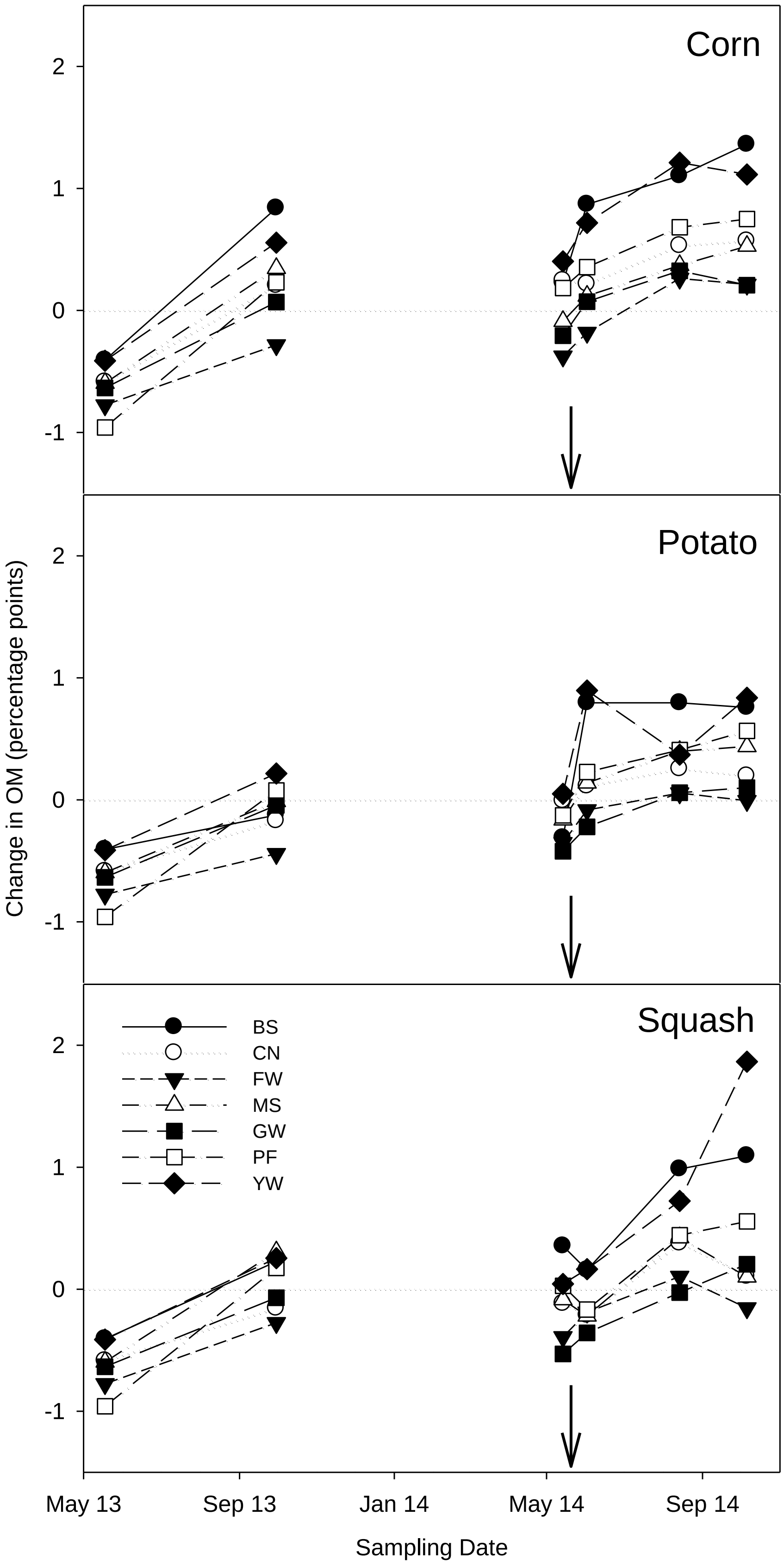


Figure 10. Mean change in organic matter (n=4) for plots in 2013 and 2014. Arrow indicates date of amendment application (5/20/14). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 9 for Fisher's LSD results.

Table 9. Fisher's LSD results for soil organic matter content in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different ($p<0.05$).

Sample Date	Crop	LSD (percentage points)	BS	CN	FW	MS	GW	PF	YW
May (5/18/13)	Combined	0.81	A	A	A	A	A	A	A
September (9/30/13)	Corn	0.81	A	A	A	A	A	A	A
	Potato	0.8	A	A	A	A	A	A	A
	Squash	0.96	A	A	A	A	A	A	A
May (5-14-14)	Corn	0.79	A	A	A	A	A	A	A
	Potato	0.78	A	A	A	A	A	A	A
	Squash	0.92	A	A	A	A	A	A	A
June (6-2-14)	Corn	0.8	A	A	A	A	A	A	A
	Potato	0.79	A	A	A	A	A	A	A
	Squash	0.82	A	A	A	A	A	A	A
August (8-4-14)	Corn	0.69	A	AB	B	B	B	AB	A
	Potato	0.78	A	A	A	A	A	A	A
	Squash	0.92	A	A	A	A	A	A	A
October (10-6-14)	Corn	0.75	A	BC	C	BC	C	ABC	AB
	Potato	0.75	A	A	A	A	A	A	A
	Squash	1.18	AB	BC	C	BC	BC	BC	A

I hypothesized that addition of waste amendments would increase soil OM relative to the control plots; however, by the end of the study, the only plots with statistically significant increases in soil OM from the control were the corn plots amended with BS and the squash plots amended with YW. Although not statistically different, the change in OM for MS and FW plots was lower than the control for both corn and squash plots in October. Higher soil OM levels in control plots, despite receiving no addition of OM, could be explained by higher biomass production in these plots. Lower OM levels in waste amended plots could be the result of increased mineralization of existing soil OM due to increases in microbial biomass from the addition of large amounts of organic matter. While this phenomenon, known as the priming effect, has been reported following the addition of fresh organic matter to soil, its mechanisms are poorly understood (Fontaine et al., 2003). This could explain the low OM levels at the end of the study in some GW and FW plots.

The statistically significant effect of BS and YW on soil OM may be due to the type of organic compounds they contained. Both BS and the YW were composted, a process which leaves behind the organic compounds most resistant to breakdown (Bernal et al., 1998b; De Neve et al., 2003). Higher concentrations of resistant organic compounds could explain why BS and YW had a significant effect on OM levels while other non-composted wastes (PF, GW, and FW) did not. Although MS was also composted, almost 50% of its C was from an inorganic source, and therefore less likely to contribute to soil OM, as discussed previously.

Despite the short duration of this study, it appears that the addition of some of these amendments may have been enough to offset losses of OM due to cultivation (Lal, 2004). Furthermore, use of composted amendments, such as YW, may increase soil OM levels in comparison to a mineral fertilizer, which could increase carbon sequestration and benefits to soil quality associated with organic matter, such as increased nutrient and moisture retention, and lower bulk density.

Moisture

Soil gravimetric water content did not vary significantly by treatment for any months or crops sampled in either 2013 or 2014 (Figure 11). Based on the soil type (silt loam) and an average OM content of 6%, the wilting point for soil at the experiment site is approximately 14.3% and field capacity is 33.0% (gravimetric water content) (Saxton and Rawls, 2006). The only soil samples with moisture content below 14.3% were taken on 8/29/14, after most crop growth had ceased. No samples were at field capacity (33.0%), the point at which water has ceased draining from macro pores, usually 1-3 days after irrigation or rain, likely because samples were not taken soon after any rain or irrigation events.

These results do not support my hypothesis that the addition of waste amendments would increase soil moisture retention due to increased organic matter. However, because OM is the driving force behind moisture retention, and there was no significant variation in OM, one would not expect a variation in moisture either. The lack of significant variation between treatments which received waste amendments and the control is possibly due to the underlying gradient in soil OM (Figure 9), which resulted in a large variation between replicates and obscured treatment effects. Although there was no evidence of a benefit in terms of moisture retention from applying waste amendments, there was also no negative effect.

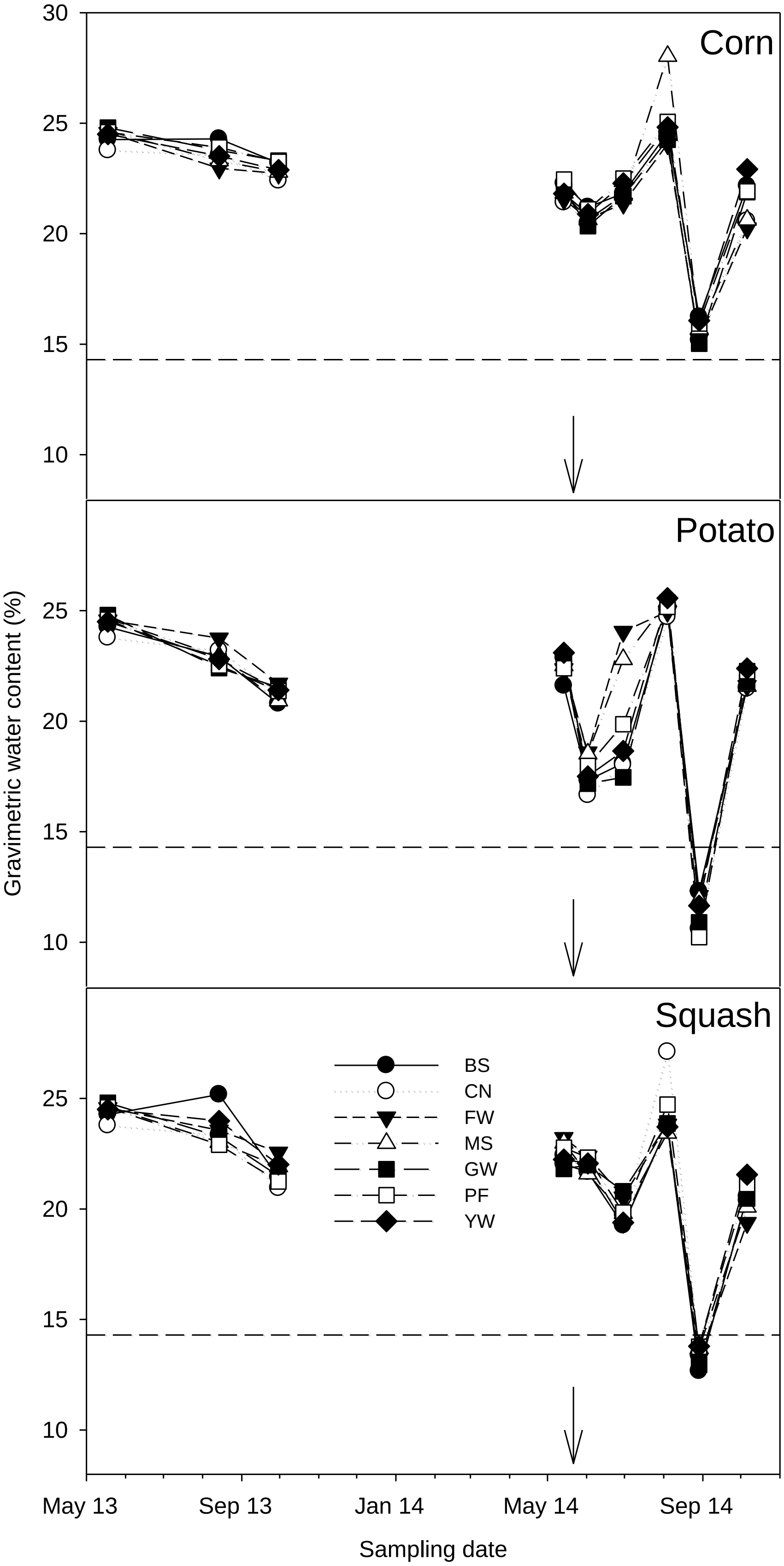


Figure 11. Mean gravimetric water content (n=4) for plots in 2013 and 2013. Line indicates estimated permanent wilting point (14.3%). Field capacity (33.0%) not indicated. Arrow indicates date of amendment application (5/20/14). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 10 for Fisher's LSD results.

Table 10. Fisher's LSD results for soil gravimetric water content in 2013 and 2014. Within the same row and month, treatments with the same letter are not significantly different ($p<0.05$).

Sample Date	May (5-18-13)	August (8-14-13)			September (9-30-13)		
Crop	combined	Corn	Potato	Squash	Corn	Potato	Squash
LSD (%)	1.36	1.13	1.68	2.54	1.95	1.66	2.6
BS	A	A	A	A	A	A	A
CN	A	A	A	A	A	A	A
FW	A	A	A	A	A	A	A
MS	A	A	A	A	A	A	A
GW	A	A	A	A	A	A	A
PF	A	A	A	A	A	A	A
YW	A	A	A	A	A	A	A

Sample Date	May (5/14/14)			June (6/2/14)			July (6/30/14)		
Crop	Corn	Potato	Squash	Corn	Potato	Squash	Corn	Potato	Squash
LSD (%)	1.12	1.32	1.94	1.28	1.98	1.8	1.84	6.44	4.11
BS	A	A	A	A	A	A	A	A	A
CN	A	A	A	A	A	A	A	A	A
FW	A	A	A	A	A	A	A	A	A
MS	A	A	A	A	A	A	A	A	A
GW	A	A	A	A	A	A	A	A	A
PF	A	A	A	A	A	A	A	A	A
YW	A	A	A	A	A	A	A	A	A

Sample Date	August (8/4/14)			September (8/29/14)			October (10/6/14)		
Crop	Corn	Potato	Squash	Corn	Potato	Squash	Corn	Potato	Squash
LSD (%)	4.53	1.02	4.89	4.21	4.3	2.42	2.71	0.82	2.75
BS	A	A	A	A	A	A	A	A	A
CN	A	A	A	A	A	A	A	A	A
FW	A	A	A	A	A	A	A	A	A
MS	A	A	A	A	A	A	A	A	A
GW	A	A	A	A	A	A	A	A	A
PF	A	A	A	A	A	A	A	A	A
YW	A	A	A	A	A	A	A	A	A

Heavy Metals

Soil samples from corn plots taken on 5/18/13 and 6/2/14 were tested for Mo, Pb, Se, As, Hg, Zn, Cu, Ni, Cr and Cd. Levels of Cd, Ni, and Mo were below detection limit for both years. There no were statistical differences between treatments for any of the metals in either year (Figure 12).

I expected that amendments high in heavy metals would raise soil levels, although the increase might be below the level of detection. None of the amendments exceeded the ceiling concentrations for heavy metals established by the U.S. EPA (1994) for land application of biosolids, although 2014 YW exceeded the more restrictive guidelines for As (Appendix 1). The lack of a statistical difference in soil heavy metal levels indicates that short-term application of these wastes will not significantly raise levels in comparison to a mineral fertilizer. Studies of short-term application of composted sewage sludge and paper-mill sludge did not find any significant increase in soil heavy metals (Casado-Vela et al., 2007; Douglas et al., 2003)

Because heavy metals are retained in the soil by binding to OM or by reacting with carbonates, oxides of iron and manganese or sulfides, long term-application of wastes could still lead to accumulation in the soil. Mantovi et al. (2005) found that 12 years of biosolids application significantly increased Zn and Cu in the soil while Schroder et al. (2008) reported significant increases in Cd, Cu, Pb, Mo and Zn after 13 years of application of biosolids. Although long-term application may increase soil heavy metal levels, they may not reach a problematic level. A model of application of the wastes used in this study found that it would take more than 24 years of yearly application for soil heavy metal levels to exceed federal limits (Bercaw et al., 2014).

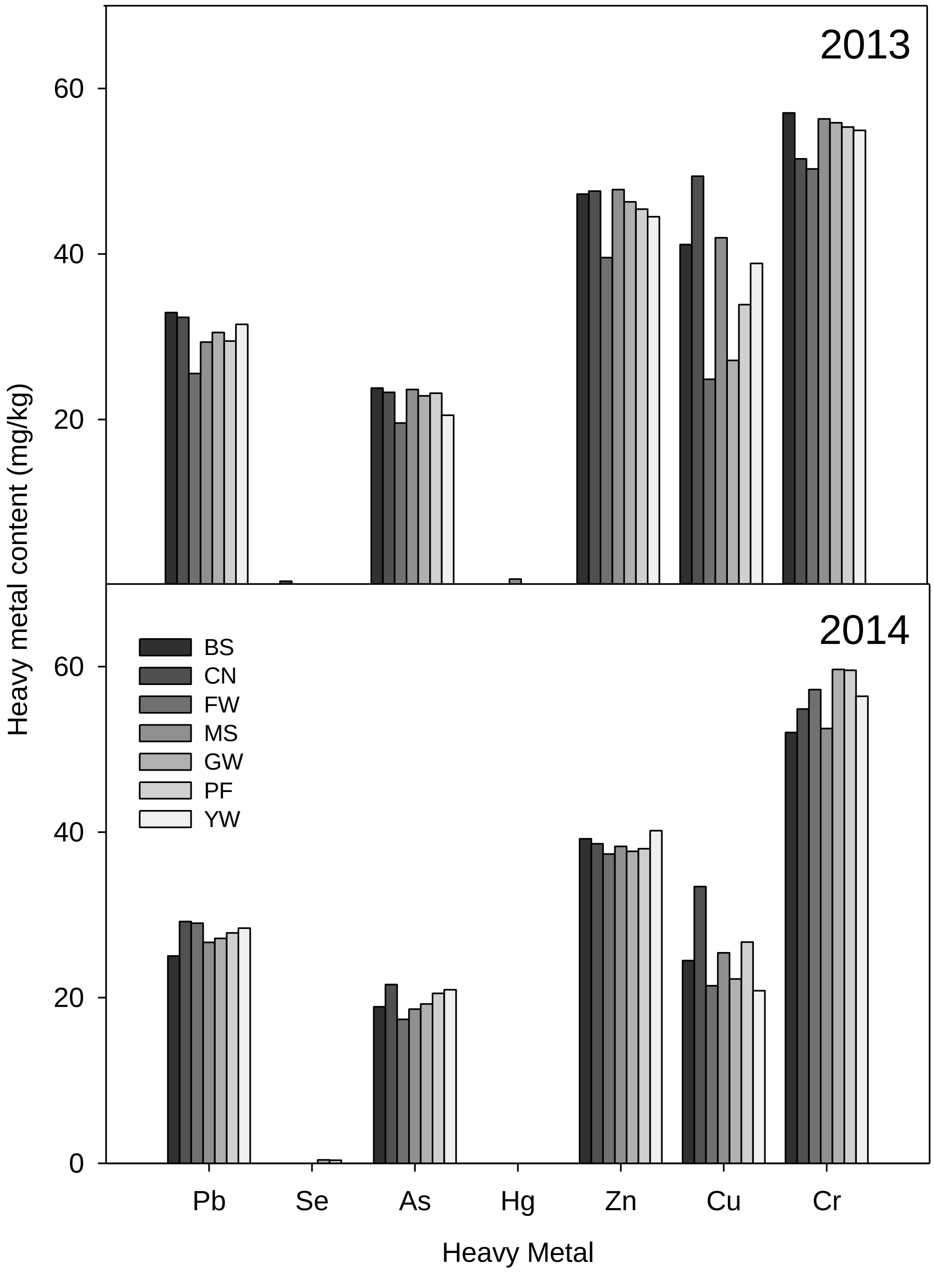


Figure 12. Mean soil heavy metal concentrations for corn plots in 2013 and 2014 (n=4). Levels of Cd, Ni and Mo were below detection limit. There were no significant differences between any treatments. BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 11 for Fisher's LSD results.

Table 11. Fisher's LSD results for soil heavy metal concentrations for corn plots in 2013 and 2014. Within the same row and month, treatments with the same letter are not significantly different ($p<0.05$). LSD of 0 indicates all samples were below detection level.

Sample Date	May (5/18/13)									
Element	Mo	Pb	Se	As	Hg	Zn	Cu	Ni	Cr	Cd
LSD (mg/kg)	0	7.9289	0.5039	10.171	0.8022	15.186	40.281	0	13.652	0
BS		A	A	A	A	A	A		A	
CN		A	A	A	A	A	A		A	
FW		A	A	A	A	A	A		A	
MS		A	A	A	A	A	A		A	
GW		A	A	A	A	A	A		A	
PF		A	A	A	A	A	A		A	
YW		A	A	A	A	A	A		A	

Sample Date	June (6/2/14)									
Element	Mo	Pb	Se	As	Hg	Zn	Cu	Ni	Cr	Cd
LSD (mg/kg)	0	7.605	0.6203	9.0451	0	7.693	28.764	0	13.949	0
BS		A	A	A		A	A		A	
CN		A	A	A		A	A		A	
FW		A	A	A		A	A		A	
MS		A	A	A		A	A		A	
GW		A	A	A		A	A		A	
PF		A	A	A		A	A		A	
YW		A	A	A		A	A		A	

Soil Fertility

Inorganic Nitrogen

The application of amendments with a C:N ratio > 25:1 was expected to cause early season immobilization of N as soil microbes decomposed the excess C. The PF amendment was the only treatment with a C:N ratio above this threshold, even after blending with chicken manure. Despite receiving less total N than all other treatments (except the control) in 2013, and having the highest C:N ratio (66:1), the PF plots did not have the lowest inorganic N (NO_3 and NH_4) levels for any months or crops in 2013 (Figure 13). YW plots often had lower inorganic N levels, despite receiving more total N in the form of a waste with a lower C:N ratio, although differences were not significant.

In 2014 PF was, once again, the only amendment with a C:N ratio above the threshold likely to cause N immobilization (51:1), and PF plots received the lowest amount of total N (with the exception of the control). Although PF plots had the lowest soil inorganic N levels for all crops at the June and July sampling dates, for August, September and October sampling dates YW plots were generally the lowest. These results suggest that C:N ratio alone is not a reliable indicator of N availability from waste amendments.

I expected that soil inorganic N levels, later in the season (after July 1st) would be higher in waste amended plots than control plots. Inorganic N from mineral fertilizers is subject to plant uptake or loss by leaching or volatilization soon after application, therefore side-dressing with additional N later in the season in recommended (Hazard and Howell, 2007). Because the organic N in wastes is expected to mineralize slowly throughout the season as organic matter decompose, side-dressing later in the season may be unnecessary. However, results did not show that all waste amendments were better sources of late season inorganic N than the control. In 2013, only plots amended with GW consistently had inorganic N levels that were significantly higher than control plots. However, plots amended with GW received a much higher rate of total N (1,140 kg N/ha) compared to control plots which received mineral fertilizer (112 kg N/ha). Although plots amended with MS and FW also received large applications of total N (763 and 428 kg N/ha respectively), they did not consistently have late season inorganic N levels significantly higher than the control. In 2014, only plots amended with FW consistently had late season inorganic N significantly higher than the control. In both 2013 and 2014, plots amended with PF, YW and BS never had significantly higher inorganic N than the control plots, despite receiving more total N (Figure 5).

Although most waste amended plots did not have significantly higher late-season inorganic N levels compared to the control, side-dressing would have been unlikely to improve yields for most treatments. In New England, yield responses are unlikely above a threshold of 20-25 µg NO_3/g soil for corn and 25-30 µg NO_3/g soil for butternut squash and other long season vegetables (Hazard and Howell, 2007). In 2013 total soil inorganic N levels (NH_4 and NO_3) for all plots were below this level on June 24th, however, by August 14th they were all above 25 µg inorganic N/g soil. In 2014 samples taken on June 30th were consistently above this level for all crops except plots amended with PF and YW.

Despite receiving more total N, YW was a poorer source of inorganic N than the control. Additionally, plots amended with YW had the lowest inorganic N levels more often than PF did, despite having a much lower C:N ratio (13:1 for YW vs. 51 to 66:1 for PF). While C:N ratio has often been relied on as an indicator of potential N availability, studies have found that N mineralization is also related to factors not represented by this ratio such as the type of carbon containing compounds, alkyl-C content, water-soluble fraction, and uric acid content of a material (Cabrera et al., 2005). Although pH and salinity can effect N mineralization, YW did not have an exceptionally high or low pH (6.5-6.7), or high salinity (1.8-4.0 mS/cm). While, YW had slightly higher heavy metal levels, particularly Pb and As, compared to the other wastes in this study, heavy metals have been shown to both increase and decrease N mineralization (Cabrera et al., 2005) (Appendix 1).

Table 12. Fisher's LSD results for soil inorganic N levels in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different ($p<0.05$).

Sample Date	Crop	LSD (µg N/g dry soil)	BS	CN	FW	MS	GW	PF	YW
May (5-18-13)	Combined	7.0287	A	AB	C	AB	B	C	C
June (6-24-13)	Corn	4.6013	C	C	AB	BC	A	C	C
	Potato	2.3464	B	B	B	B	A	B	B
	Squash	5.6712	C	C	B	C	A	C	C
August (8-14-13)	Corn	574.71	B	B	B	B	A	B	B
	Potato	286.15	B	B	B	B	A	B	B
	Squash	958.54	A	A	A	A	A	A	A
September (9-30-13)	Corn	2.5052	B	B	B	A	A	B	B
	Potato	5.0865	BC	C	BC	B	A	BC	BC
	Squash	5.5988	BC	C	B	BC	A	C	C
May (5-14-14)	Corn	1.9743	C	BC	BC	A	AB	BC	BC
	Potato	1.7676	B	AB	AB	A	B	AB	B
	Squash	2.3165	A	A	A	A	A	A	A
June (6/2/14)	Corn	24.13	B	A	C	BC	C	C	C
	Potato	20.426	B	A	D	C	CD	D	CD
	Squash	7.2751	A	A	BC	B	CD	D	CD
July (6/30/14)	Corn	15.378	AB	A	A	C	BC	D	CD
	Potato	40.019	AB	A	AB	BC	C	C	C
	Squash	59.608	A	A	A	A	A	A	A
August (8/4/14)	Corn	11.616	B	B	A	B	B	B	B
	Potato	2.0739	BC	ABC	A	AB	BC	BC	C
	Squash	12.072	A	A	A	A	A	A	A
September (8/29/14)	Corn	8.5581	B	B	A	B	B	B	B
	Potato	4.3875	B	B	A	B	B	B	B
	Squash	3.5038	AB	BC	A	AB	BC	BC	C
October (10/6/14)	Corn	2.7551	B	B	A	A	B	B	B
	Potato	4.9315	A	A	A	A	A	A	A
	Squash	5.9046	B	B	A	B	B	B	B

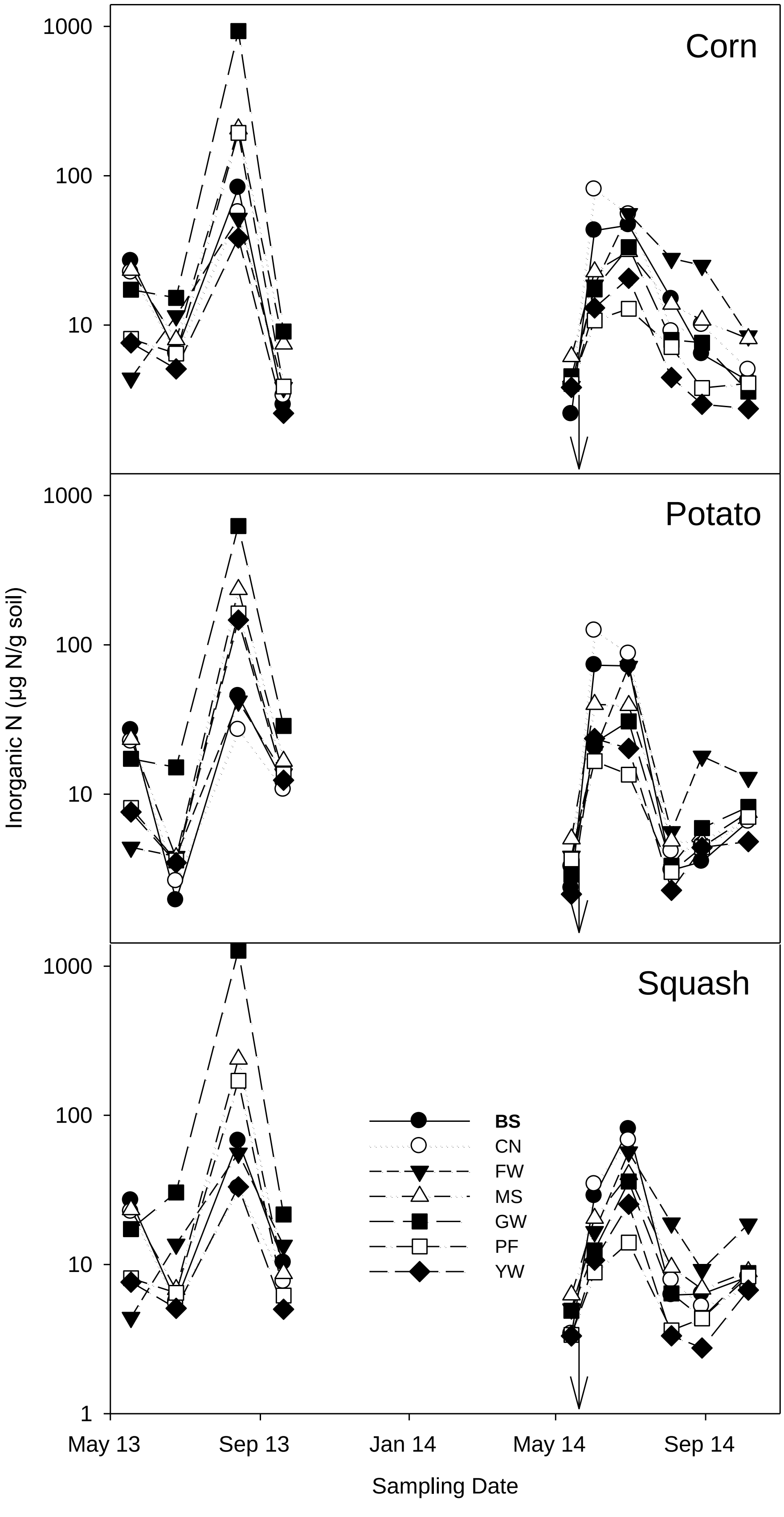


Figure 13. Mean inorganic N levels (n=4) for plots in 2013 and 2014 ($\log_{10}$ scale). Arrow indicates date of amendment application (5/20/14). BS = biosolids/ yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 12 for Fisher's LSD results.

Potentially Mineralizable Nitrogen

Potentially mineralizable nitrogen (PMN) is a measure of the organic N that is mineralized to inorganic forms during a 7-day incubation and takes into account immobilization caused by excess C. Although PMN and inorganic N levels are based on soil samples taken on the same date, PMN values represent the inorganic N that could become available in the seven days following sampling (under ideal conditions), and do not include the inorganic N present at the time of sampling.

I predicted that PMN would be higher in waste amended plots, which received organic N, than control plots, which did not. In 2013, control plots did not have the lowest PMN for any months or crops sampled, and only plots amended with GW had significantly higher PMN than control plots. In 2014, there was often no significant variation in PMN between any treatments. However, when there were significant variations, some or all of the waste amendments had significantly higher PMN than the control plots. These results indicate that waste amendments can increase PMN in comparison to a mineral fertilizer control, although not reliably.

Because PMN is calculated by subtracting the NH_4 present at the beginning of incubation from the amount present at the end, PMN values can be negative if more inorganic N was immobilized by soil microbes than was mineralized. The largest negative values were seen in June 2014 samples taken after amendment application in plots amended with BS and the control fertilizer (Figure 14).This would be expected for control plots, because no organic N was added and recent tillage likely accelerated decomposition by breaking down plant residue in the soil and increasing microbial access to oxygen, causing soil microbes to immobilize some of the inorganic N present. Negative PMN values in plots amended with BS could be due to the maturity of the compost. Bernal et al. (1998a) found that a mixture of raw sewage sludge and cotton waste caused the most immobilization when added to soil, once the materials had reached the end of the active phase of composting they caused less immobilization (2 days), and mature compost did not cause any immobilization. However, this does not explain why plots amended with FW, which is not fully composted, had the highest PMN in corn and potato plots from the same month.

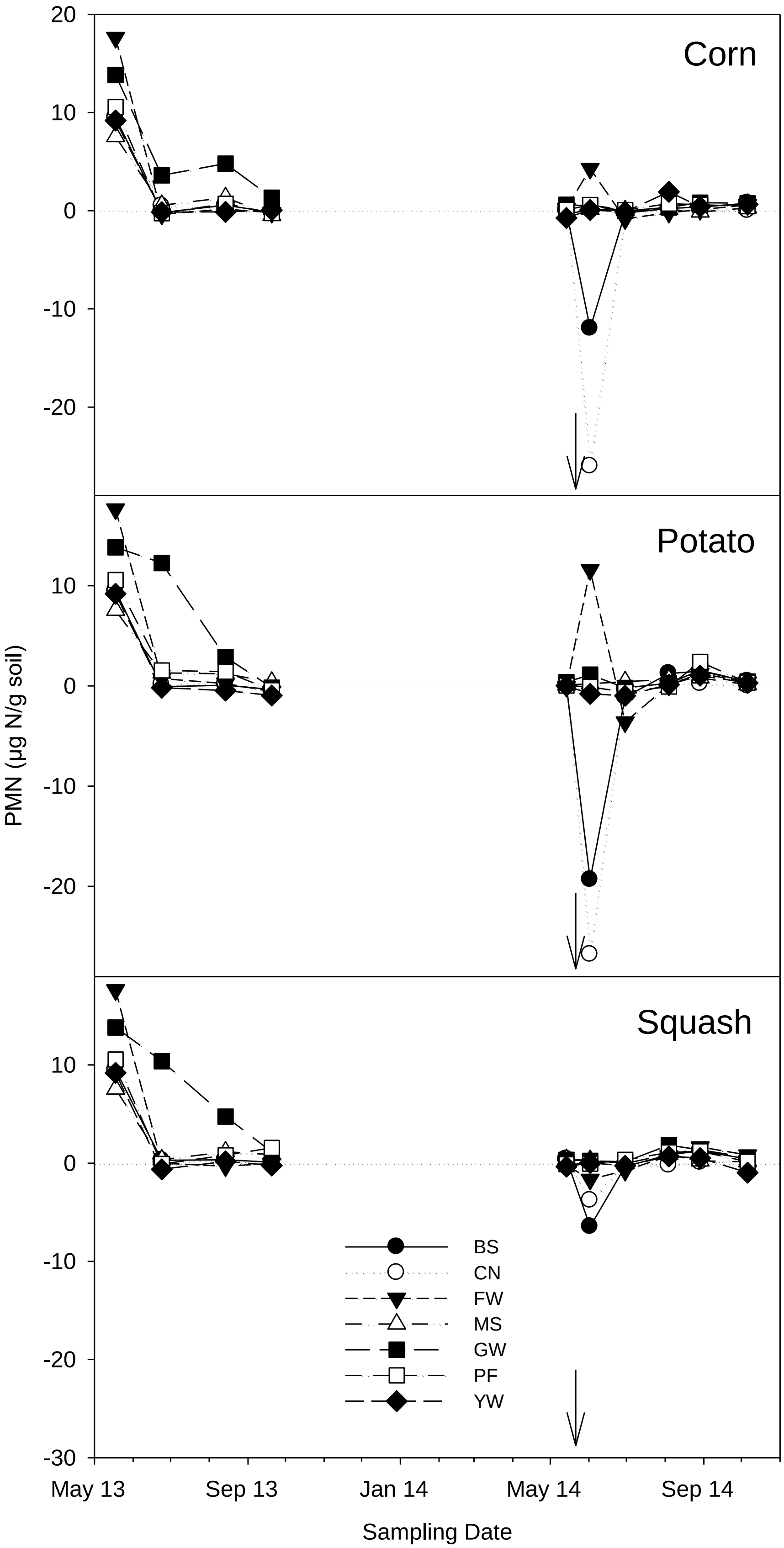


Figure 14. Mean potentially mineralizable N levels (n=4) for plots in 2013 and 2014. Arrow indicates date of amendment application (5/20/14). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 13 for Fisher's LSD results.

Table 13. Fisher's LSD results for soil potentially mineralizable N levels in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different ($p<0.05$).

Sample Date	Crop	LSD (µg N/g dry soil)	BS	CN	FW	MS	GW	PF	YW
May (5-18-13)	Combined	7.2509	A	A	A	A	A	A	A
June (6-24-13)	Corn	0.9985	B	B	B	B	A	B	B
	Potato	5.6645	B	B	B	B	A	B	B
	Squash	6.0021	B	B	B	B	A	B	B
August (8-14-13)	Corn	1.9513	B	B	B	B	A	B	B
	Potato	1.2707	CD	BCD	BCD	BC	A	B	D
	Squash	3.4303	A	A	A	A	A	A	A
September (9-30-13)	Corn	1.108	A	A	A	A	A	A	A
	Potato	1.1878	A	A	A	A	A	A	A
	Squash	1.8369	A	A	A	A	A	A	A
May (5-14-14)	Corn	0.8356	A	A	A	A	A	A	A
	Potato	0.4963	A	A	A	A	A	A	A
	Squash	1.0046	A	A	A	A	A	A	A
June (6/2/14)	Corn	13.537	B	C	A	AB	AB	AB	AB
	Potato	10.738	C	C	A	B	AB	B	B
	Squash	3.3059	C	BC	AB	A	A	A	A
July (6/30/14)	Corn	1.1274	A	A	A	A	A	A	A
	Potato	2.6442	A	A	A	A	A	A	A
	Squash	0.9087	A	A	A	A	A	A	A
August (8/4/14)	Corn	1.9261	A	A	A	A	A	A	A
	Potato	0.5995	A	BC	BC	B	BC	C	BC
	Squash	1.185	A	A	A	A	A	A	A
September (8/29/14)	Corn	0.9415	A	A	A	A	A	A	A
	Potato	0.9445	AB	C	B	BC	AB	A	BC
	Squash	1.0137	AB	D	A	CD	AB	ABC	BCD
October (10/6/14)	Corn	0.5	A	B	A	AB	A	AB	A
	Potato	0.5704	A	A	A	A	A	A	A
	Squash	1.443	A	A	A	A	A	A	A

Crop Quality

Emergence and Early Growth

I hypothesized that emergence and early growth could be enhanced or inhibited by amendment effects on soil moisture, OM, bulk density and N availability. Plots amended with PF had significantly lower emergence of potatoes than the control in 2014, as well as significantly shorter plants in both 2013 and 2014 (Figures 16, 17 and 18). The negative influence of PF on emergence and early growth of potatoes may be associated with its high C:N ratio (51:1). However, this effect was not seen in corn and squash which were planted later. Plots amended with YW and PF had significantly shorter potato plants than the control in both 2013 and 2014, and plots amended with FW and GW also had significantly shorter potato plants in 2014.

No waste amendments had significantly higher emergence than the control, and only GW corn plots had significantly taller plants than the control (2013) (Figures 15, 16, 17 and 18). The significantly taller corn plants in plots amended with GW could be due to the large addition (1,140 kg/ha) of N in those plots. The lack of significant improvement in emergence or early growth in waste-amended plots, in combination with a lack of statistical difference in soil OM or moisture, does not support the hypothesis that improved soil conditions from waste amendments would improve germination and early growth. Furthermore, lower emergence in PF potato plots indicates that PF may have an inhibitory effect on early growth of potatoes. While Levy and Taylor (2003) reported inhibition of seedlings grown in municipal solid waste compost, but not paper pulp mill solids, Roe et al. (1997) found that seedling emergence was delayed when grown in composts made from biosolids and yard trimmings compared to a sandy soil. Emergence was also delayed and early seedling growth was inhibited when grown in the same compost with the addition of mixed waste paper.

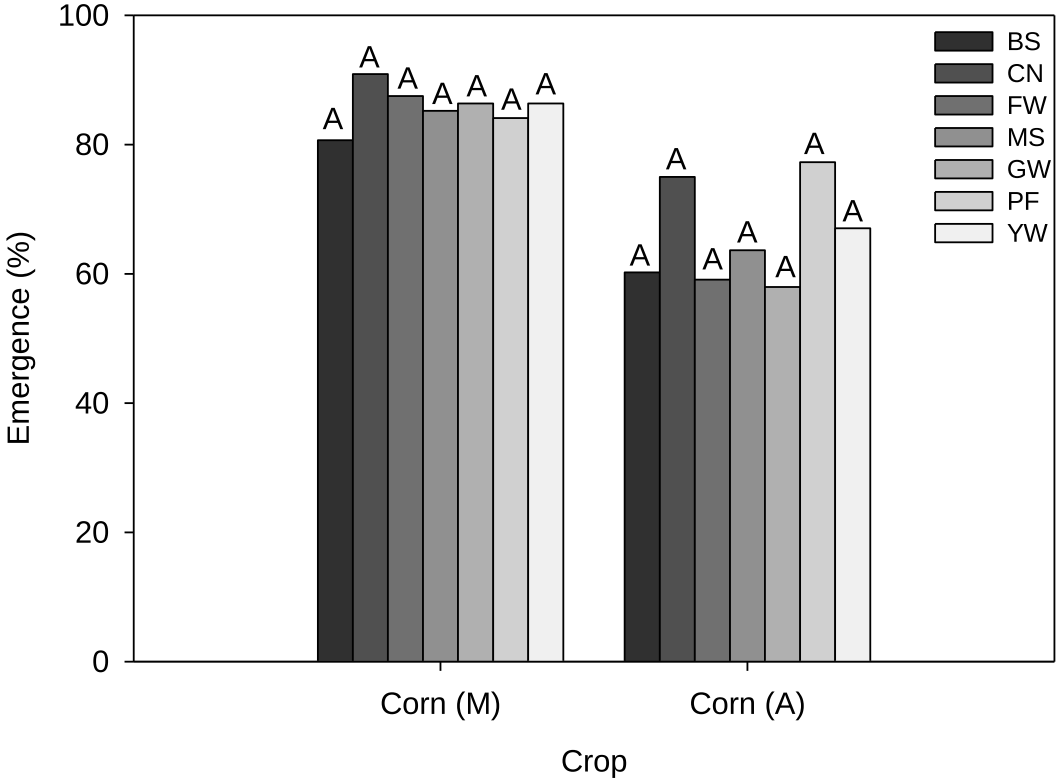


Figure 15. Mean corn emergence (n=4) for plots in 2014. Emergence was not measured for 2013. Treatments with the same letter were not significantly different. Cultivars were analyzed separately (Montauk LSD = 9.14%, Applause LSD = 17.58%). Cultivars: M = Montauk, A = Applause. BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste.

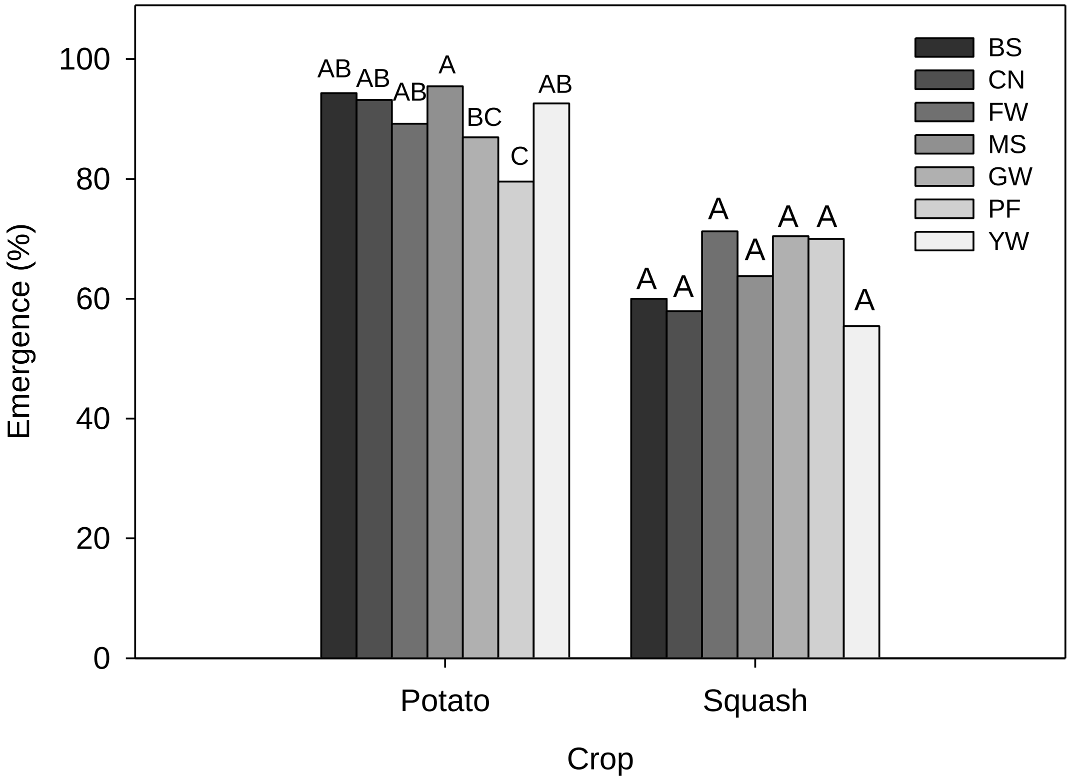


Figure 16. Mean potato and squash emergence (n=4) for plots in 2014. Emergence was not measured for 2013. Treatments with the same letter were not significantly different. Crops were analyzed separately (Potato LSD = 7.62%, Squash LSD = 20.68%). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste.

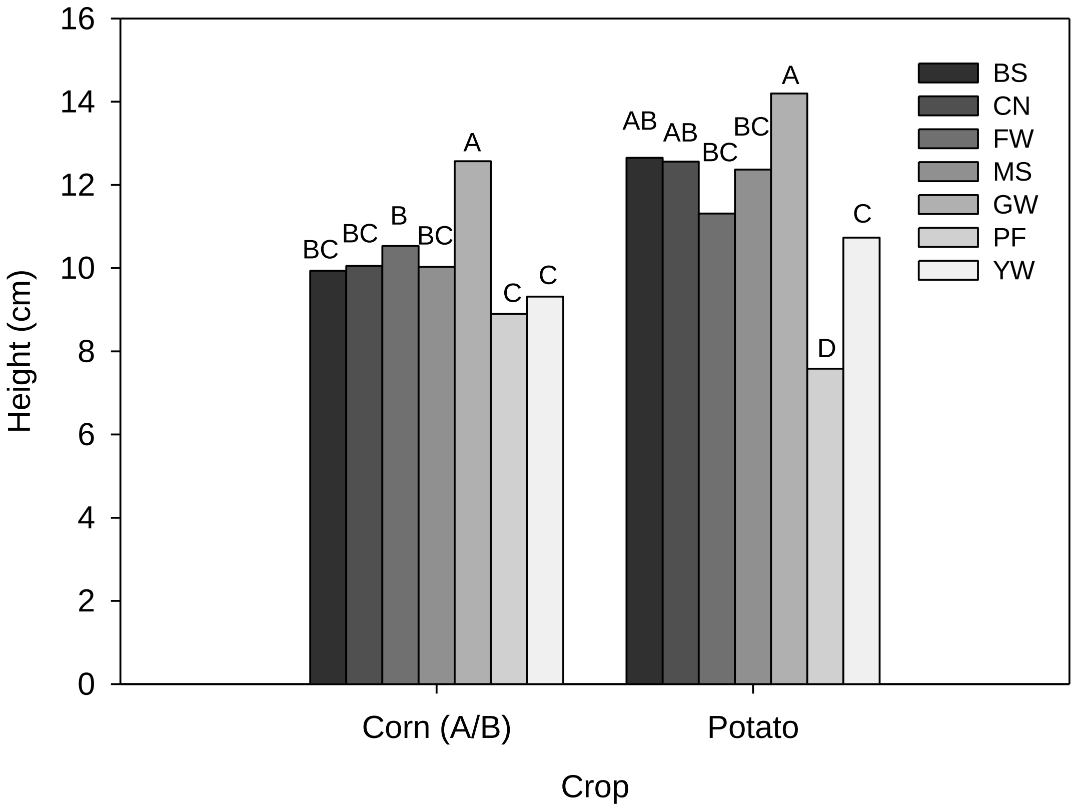


Figure 17. Mean plant early growth (height) (n=4) for plots in 2013. Treatments with the same letter were not significantly different. Crops were analyzed separately (Corn LSD = 1.1956 cm, Potato LSD = 1.7076 cm). Corn cultivars: A = Applause, B = Brocade. BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste.

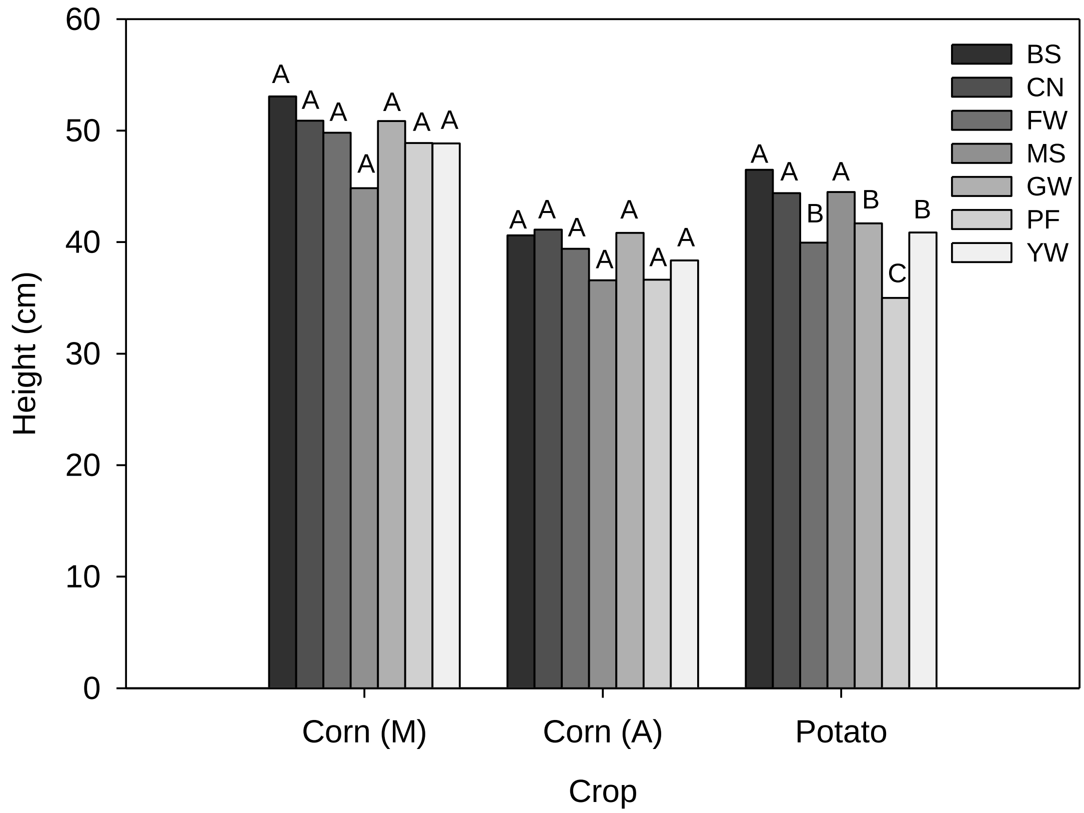


Figure 18. Mean plant early growth (height) (n=4) for plots in 2014. Treatments with the same letter were not significantly different. Crops and cultivars were analyzed separately (Montauk LSD = 8.8024 cm, Applause LSD = 7.3576 cm, Potato LSD = 2.5684). Corn cultivars: M = Montauk, A = Applause. BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste.

Tissue Nutrients

Nitrogen. Tissue N levels did not, as hypothesized, reflect N application rates. Despite the largest N application in 2013 (1,140 kg N/ha), corn tissue from plots amended with GW had the lowest N levels, although not significantly lower than the control (Figure 19). Although squash tissue (2013) from plots amended with GW had the highest N concentrations, they were not significantly different than the control. While N application rates also varied in 2014, levels of N in corn tissue did not. Potato tissue samples from control plots had significantly higher N than tissue from plots amended with GW, BS, PF and YW. The same was true for squash tissue samples from plots amended with YW and PF, despite higher total N application rates than the control for all waste amended plots except GW, which was not amended in 2014. No amendment yielded tissue samples that were consistently higher in N than the control across all crops and years sampled, despite higher N application rates. All tissue N levels were considered adequate, which indicates all amendments provided sufficient N (Maynard and Hochmuth, 2007).

Table 14. Fisher's LSD results for tissue N concentrations in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different ($p<0.05$).

Year	Crop	LSD (mg/kg)	BS	CN	FW	MS	GW	PF	YW
2013	Corn (Applause)	2240	ABC	CD	ABC	A	D	AB	BCD
	Squash	10417	B	AB	A	AB	A	B	B
2014	Corn (Applause)	2703	A	A	A	A	A	A	A
	Potato	3495	BC	A	A	AB	BC	CD	D
	Squash	9843	A	AB	AB	AB	BC	D	CD

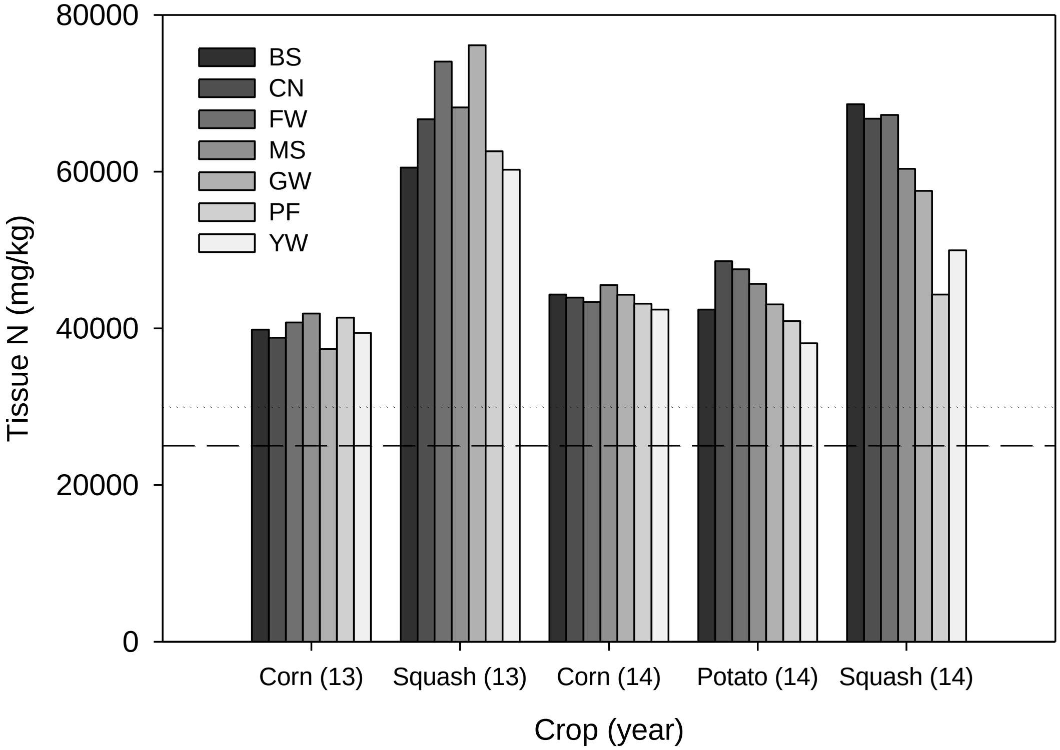


Figure 19. Mean tissue N concentrations (n=4) for corn and squash plots in 2013 and corn, squash and potato plots 2014. Dotted line indicates adequate squash and potato tissue N, dash line indicates adequate corn tissue N (Maynard and Hochmuth, 2007). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 14 for Fisher's LSD results.

Phosphorus. As was the case with N, tissue P did not reflect P application rates. Despite cumulative P application rates that varied from 59 to 904 kg/ha, tissue P levels only varied significantly in 2014 for potatoes (Figure 20). Potato tissue samples from plots amended with PF had the highest P, despite receiving the lowest total application of P over the two years of the study. In addition to the lack of significant variation, all tissue P levels were considered adequate for crop growth, which suggests that P applications, in combination with existing soil P levels, were sufficient to meet crop needs (Maynard and Hochmuth, 2007).

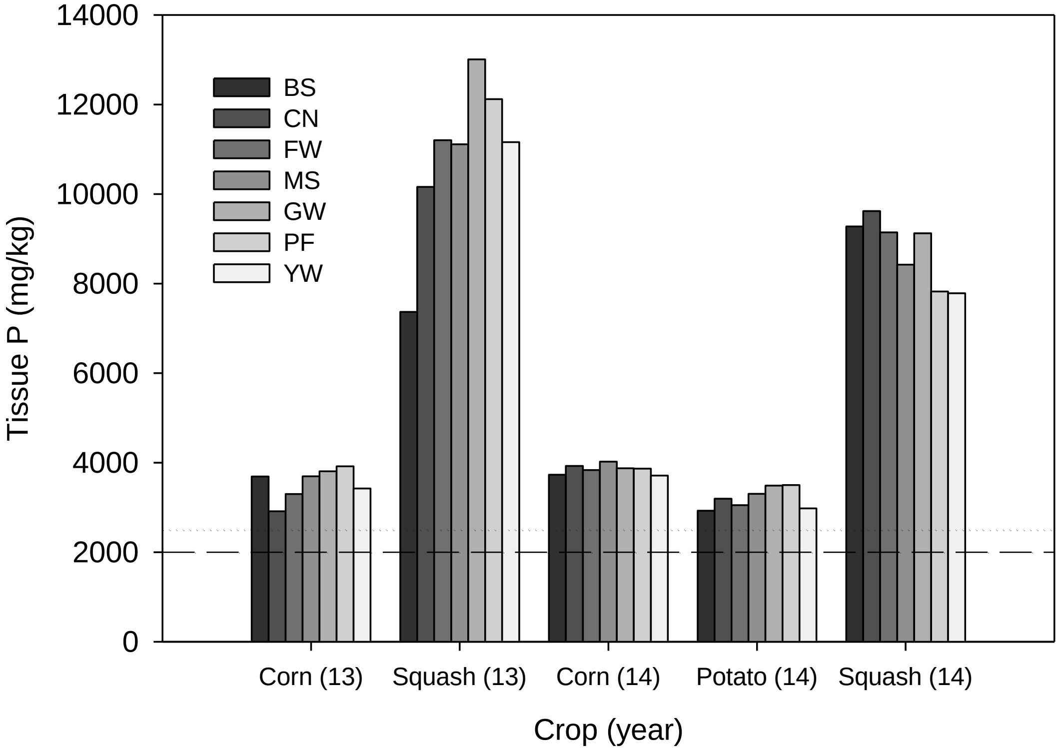


Figure 20. Mean tissue P concentrations (n=4) for corn and squash plots in 2013 and corn, potato and squash plots in 2014. Dotted line indicates adequate squash tissue P, dash line indicates adequate corn and potato tissue P (Maynard and Hochmuch, 2007). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 15 for Fisher's LSD results.

Table 15. Fisher's LSD results for tissue P concentrations in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different ($p<0.05$).

Year	Crop	LSD (mg/kg)	BS	CN	FW	MS	GW	PF	YW
2013	Corn (Applause)	972	A	A	A	A	A	A	A
	Squash	3332	A	A	A	A	A	A	A
2014	Corn (Applause)	225	A	A	A	A	A	A	A
	Potato	387	B	AB	B	AB	A	A	B
	Squash	1729	A	A	A	A	A	A	A

Potassium. Like N and P, tissue K concentrations did not reflect application rates. Despite control plots receiving the lowest K application rates (after only GW), no amendments yielded tissue samples with significantly higher K (Figure 21). Plots amended with GW, which received almost no K (<8 kg/ha cumulative), had significantly lower tissue K than the control for all three crops in 2014. However, there were no significant differences in 2013. Tissue K levels were deficient for corn from GW and control treatments 2013, and all treatments in 2014 (Maynard and Hochmuth, 2007). No squash tissue samples were considered deficient although 2014 potato samples from GW treatments were.

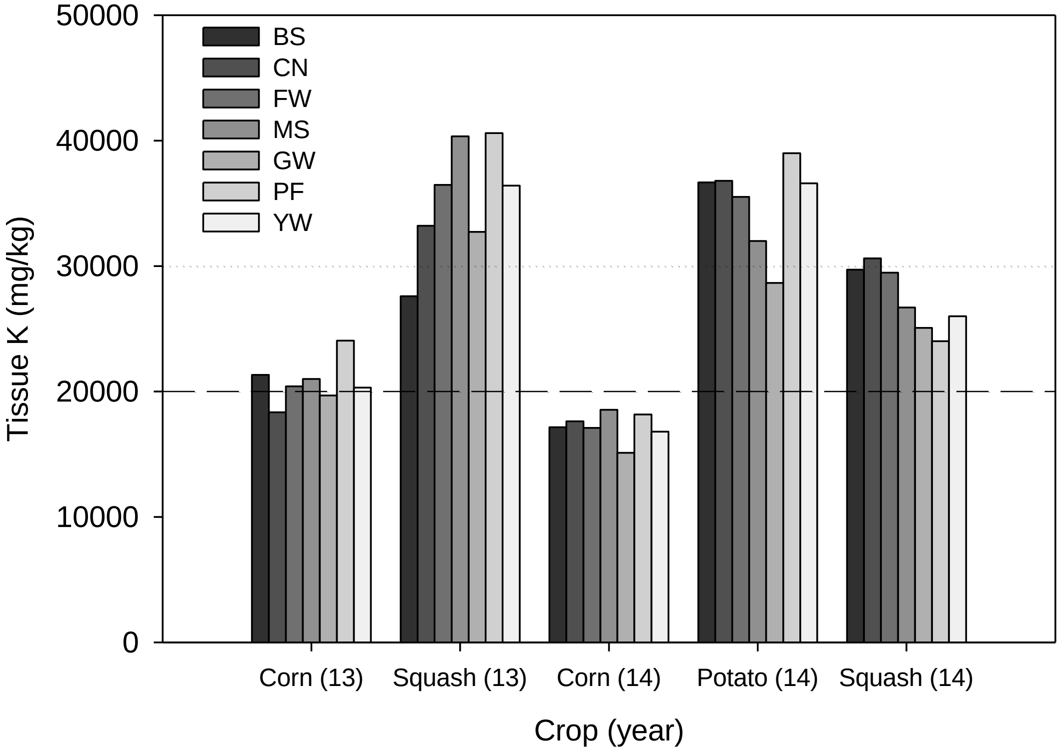


Figure 21. Mean tissue K concentrations (n=4) for corn and squash plots in 2013 and corn, potato and squash plots in 2014. Dotted line indicates adequate potato tissue K, dash line indicates adequate corn and squash tissue K (Maynard and Hochmuth, 2007). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 16 for Fisher's LSD results.

Table 16. Fisher's LSD results for tissue K concentrations in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different ($p<0.05$).

Year	Crop	LSD (mg/kg)	BS	CN	FW	MS	GW	PF	YW
2013	Corn (Applause)	6826	A	A	A	A	A	A	A
	Squash	10555	A	A	A	A	A	A	A
2014	Corn (Applause)	1845	A	A	A	A	B	A	AB
	Potato	4487	A	A	AB	BC	C	A	A
	Squash	3702	AB	A	ABC	BCD	D	CD	D

Calcium. Because Ca is important to plants not only for its physiological roles, but also because it protects cells against toxic elements, and can be lost by leaching, erosion and crop removal, a waste amendment that provided Ca would be beneficial (Brady and Weil, 2008). Although cumulative Ca application rates ranged from 0 to 8,270 kg/ha, tissue Ca concentrations only varied significantly for corn (Table 6 and Figure 22). Despite receiving higher applications of Ca in both 2013 and 2014, corn tissue from plots amended with MS had significantly lower Ca concentrations than tissue from plots amended with GW. Although control plots had the lowest concentration of Ca in corn tissue in 2013, plots amended with PF had lower levels in 2014, despite receiving more Ca (1245 kg/ha). While waste amendments contained more Ca than the mineral fertilizer, and tissue samples from waste amended plots generally had higher concentrations, tissue Ca levels did not always reflect the rates at which Ca was applied. Tissue Ca levels were adequate or higher for all treatments (Maynard and Hochmuth, 2007).

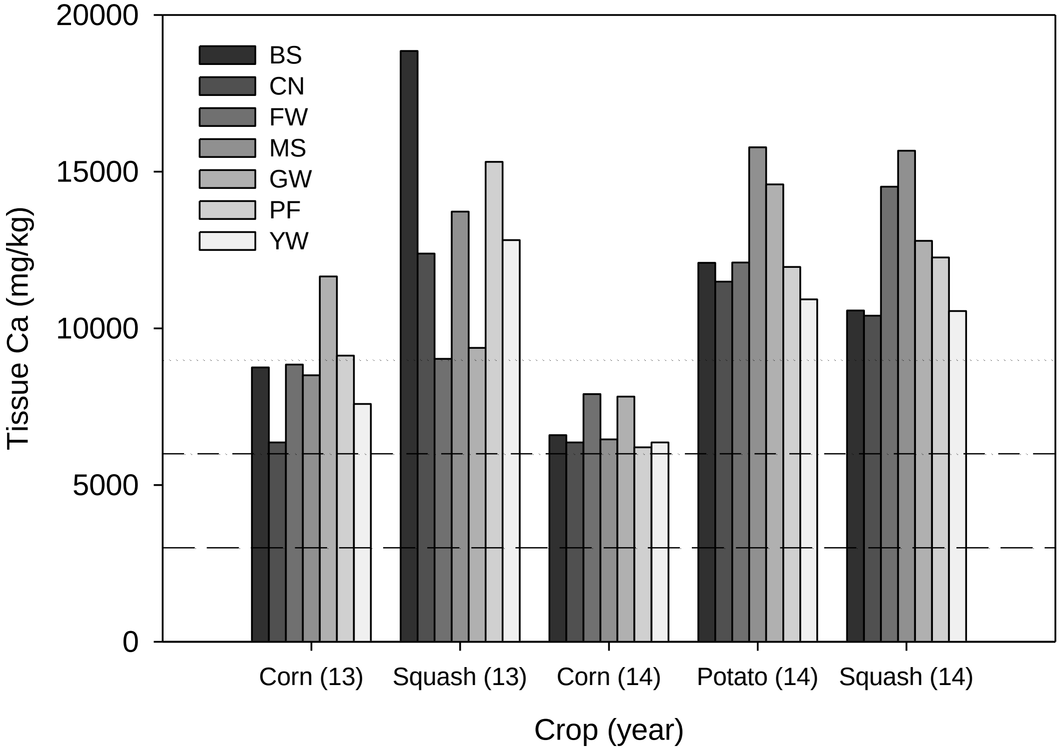


Figure 22. Mean tissue Ca concentrations (n=4) for corn and squash plots in 2013 and corn, potato and squash plots in 2014. Dotted line indicates adequate squash tissue Ca, dash-dot line indicates adequate potato tissue Ca, and dash line indicates adequate corn tissue Ca (Maynard and Hochmuth, 2007). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 17 for Fisher's LSD results.

Table 17. Fisher's LSD results for tissue Ca concentrations in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different (p<0.05).

Year	Crop	LSD (mg/kg)	BS	CN	FW	MS	GW	PF	YW
2013	Corn (Applause)	2253	B	C	B	BC	A	B	BC
	Squash	6962	A	A	A	A	A	A	A
2014	Corn (Applause)	845	B	B	A	B	A	B	B
	Potato	3776	A	A	A	A	A	A	A
	Squash	6365	A	A	A	A	A	A	A

Manganese. Manganese is essential for N transformation and assimilation in both plants and the microorganisms that symbiotically fix N (Brady and Weil, 2008). While plots amended with MS, PF, BS and YW received Mn, plots amended with FW and GW did not, and control plots received only minimal Mn (<1 kg/ha/yr) (Table 6). Tissue Mn rates did not, however, reflect these application rates. Plots amended with MS had lower tissue concentrations of Mn than GW and FW plots for all three crops in 2014, despite receiving more Mn (Figure 23). Plots amended with FW had significantly higher corn and potato tissue Mn than the control in 2014, despite no application of Mn. Tissue samples from all treatments were deficient for Mn for some or all of the crops or years tested (Maynard and Hochmuth, 2007). The availability of Mn in the soil solution can be effected not only by application rates, but also by soil pH, as Mn becomes less available at high pH (Hochmuth et al., 2012). This could explain the low concentrations of Mn from plots amended with MS, despite high application rates, as these plots generally had the highest pH.

Table 18. Fisher's LSD results for tissue Mn concentrations in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different ($p<0.05$).

Year	Crop	LSD (mg/kg)	BS	CN	FW	MS	GW	PF	YW
2013	Corn (Applause)	18.654	A	A	A	A	A	A	A
	Squash	17.458	A	A	A	A	A	A	A
2014	Corn (Applause)	16.952	A	B	A	B	B	B	B
	Potato	5.2717	A	D	AB	D	CD	BCD	BC
	Squash	7.3966	A	BC	B	D	BC	BC	A

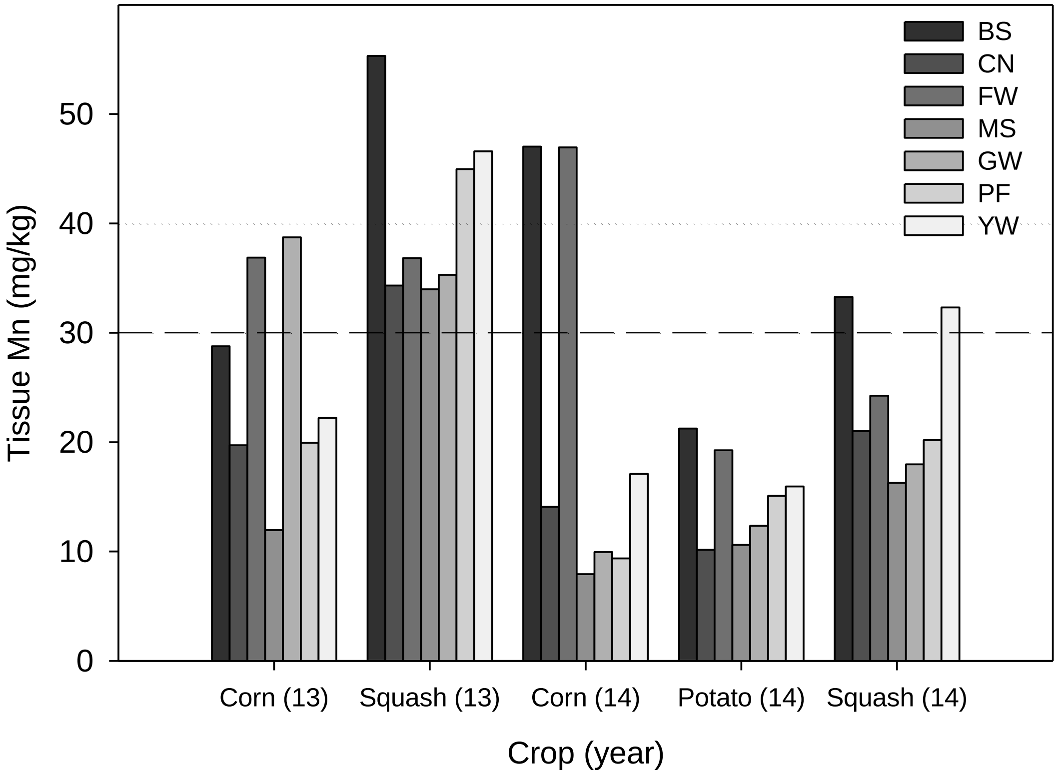


Figure 23. Mean tissue Mn concentrations (n=4) for corn and squash plots in 2013 and corn, potato and squash plots in 2014. Dotted line indicates adequate squash tissue Mn and dash line indicates adequate corn and potato tissue Mn (Maynard and Hochmuth, 2007). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 18 for Fisher's LSD results.

Other Nutrients

Although application rates of Mg and Mo are not known, there was significant variation in tissue levels of both (Figure 24 and 25). However, all tissue concentrations of Mg and Mo were sufficient, therefore application rates, in combination with existing levels, were adequate (Maynard and Hochmuth, 2007). Tissue B concentrations were deficient for corn (2013 and 2014) and potatoes (2014) for all treatments (Figure 26) (Maynard and Hochmuth, 2007). While corn yields may have been negatively affected by B deficiency, there was no significant variation in corn tissue levels, so all treatments were likely effected similarly. Although there was significant variation in potato tissue B levels, no treatment was significantly different than the control. All squash tissue B levels were adequate.

There was no significant variation in tissue Al, Cu, Fe, Na, Pb, or Zn levels for any year or crop tested. Tissue levels of Cu and Fe were sufficient for all crops and years tested (Appendix 3). Potato tissue samples for 2014 were, however, Zn deficient for all treatments.

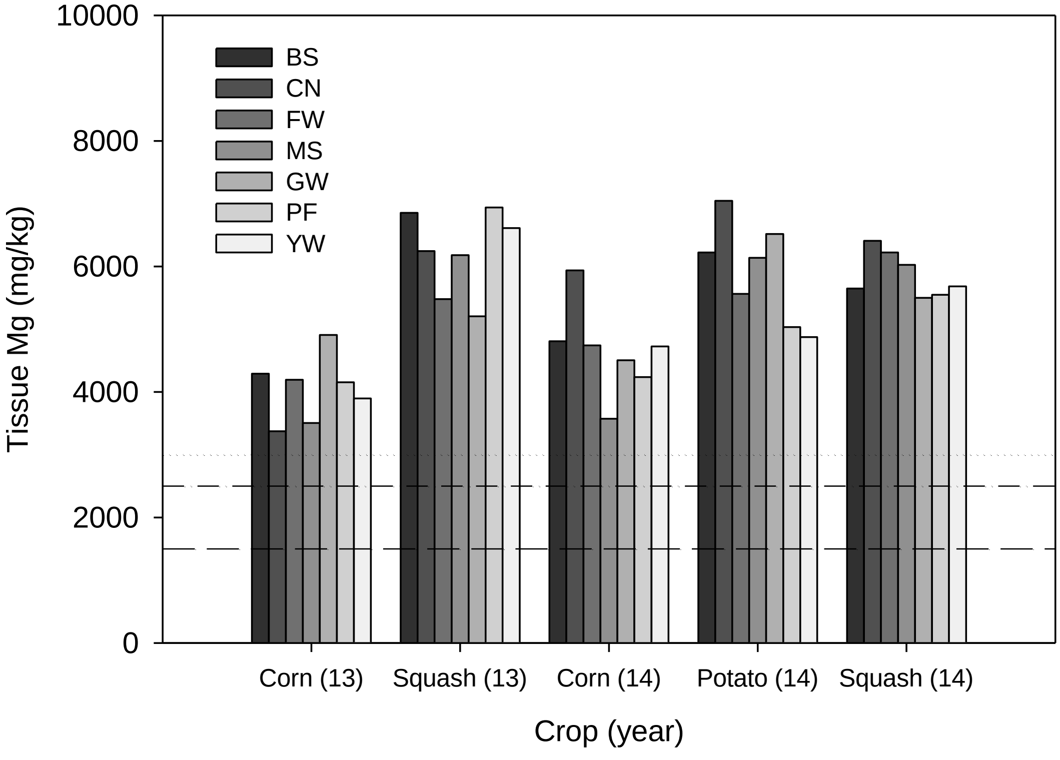


Figure 24. Mean tissue Mg concentrations (n=4) for corn and squash plots in 2013 and corn, potato and squash plots in 2014. Dotted line indicates adequate squash tissue Mg, dash-dot line indicates adequate potato tissue Mg and dash line indicates adequate corn tissue Mg (Maynard and Hochmuth, 2007). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 19 for Fisher's LSD results.

Table 19. Fisher's LSD results for tissue Mg concentrations in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different (p<0.05).

Year	Crop	LSD (mg/kg)	BS	CN	FW	MS	GW	PF	YW
2013	Corn (Applause)	1054	A	A	A	A	A	A	A
	Squash	2048	A	A	A	A	A	A	A
2014	Corn (Applause)	686	B	A	B	C	B	BC	B
	Potato	1682	A	A	A	A	A	A	A
	Squash	1253	A	A	A	A	A	A	A

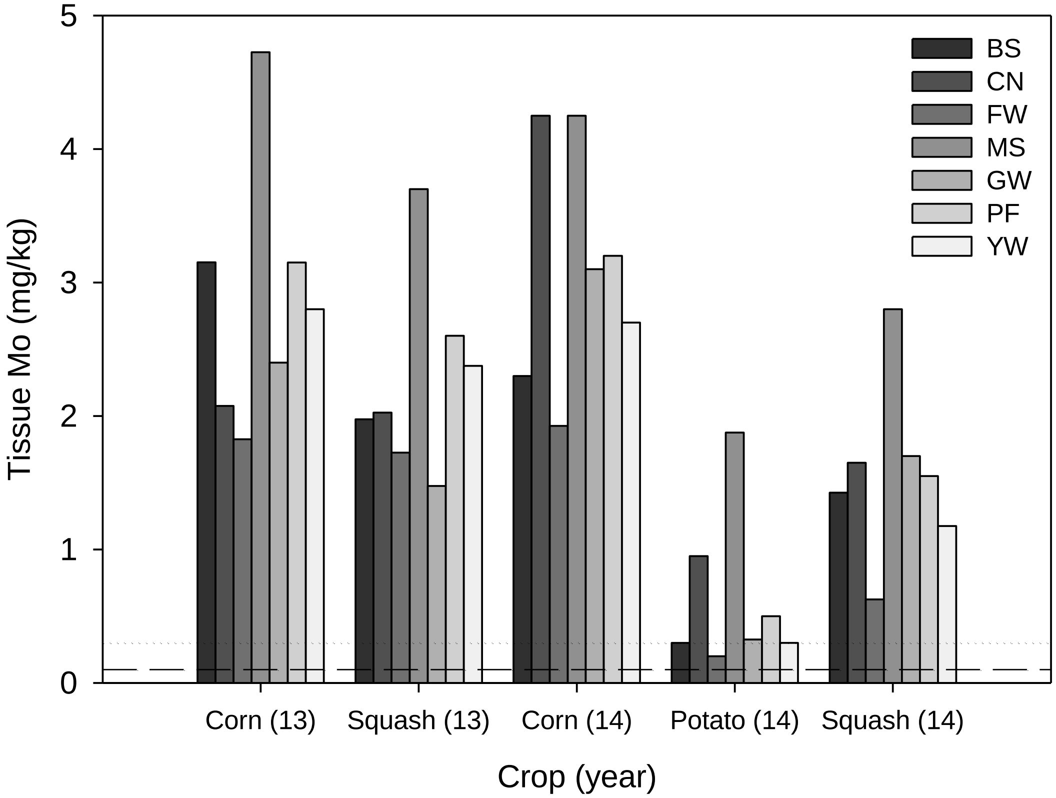


Figure 25. Mean tissue Mo concentrations (n=4) for corn and squash plots in 2013 and corn, potato and squash plots in 2014. Dotted line indicates adequate squash tissue Mo and dash line indicates adequate corn and potato tissue Mo (Maynard and Hochmuth, 2007). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 20 for Fisher's LSD results.

Table 20. Fisher's LSD results for tissue Mo concentrations in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different ($p<0.05$).

Year	Crop	LSD (mg/kg)	BS	CN	FW	MS	GW	PF	YW
2013	Corn (Applause)	1.7364	AB	B	B	A	B	AB	B
	Squash	1.0709	BC	BC	BC	A	C	B	BC
2014	Corn (Applause)	0.6962	CD	A	D	A	B	B	BC
	Potato	0.3464	C	B	C	A	C	C	C
	Squash	0.6672	B	B	C	A	B	B	BC

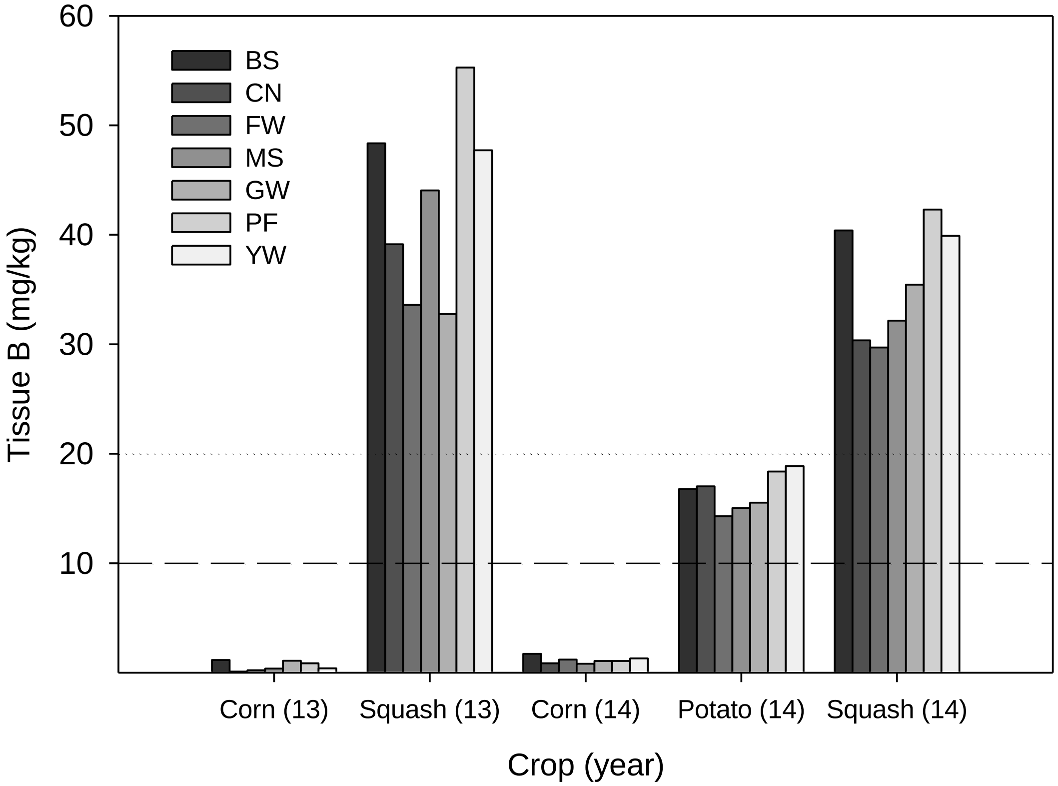


Figure 26. Mean tissue B concentrations (n=4) for corn and squash plots in 2013 and corn, potato and squash plots in 2014. Dotted line indicates adequate squash and potato tissue B and dash line indicates adequate corn tissue B (Maynard and Hochmuth, 2007). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 21 for Fisher's LSD results.

Table 21. Fisher's LSD results for tissue B concentrations in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different (p<0.05).

Year	Crop	LSD (mg/kg)	BS	CN	FW	MS	GW	PF	YW
2013	Corn (Applause)	1.2639	A	A	A	A	A	A	A
	Squash	16.668	A	A	A	A	A	A	A
2014	Corn (Applause)	1.8892	A	A	A	A	A	A	A
	Potato	3.111	ABC	ABC	C	C	BC	AB	A
	Squash	6.4493	AB	C	C	C	BC	A	AB

Tissue Heavy Metal Levels

Levels of heavy metals were determined for Montauk corn ears, including husk and cob, harvested in 2014. Levels of Cd, Ni, Pb, As and Hg were below detection. There were no statistical differences between treatments for any of the metals tested (Figure 27). I hypothesized that increases in soil heavy metal levels would not be reflected in tissue heavy metal levels because of low metal bioavailability. Although there were no statistical differences in tissue heavy metal levels, there were also no statistical differences in soil levels. These results suggest that short-term use of these waste amendments, at similar rates, will not lead to significantly higher levels of heavy metals in corn ears when compared to mineral fertilizer grown corn.

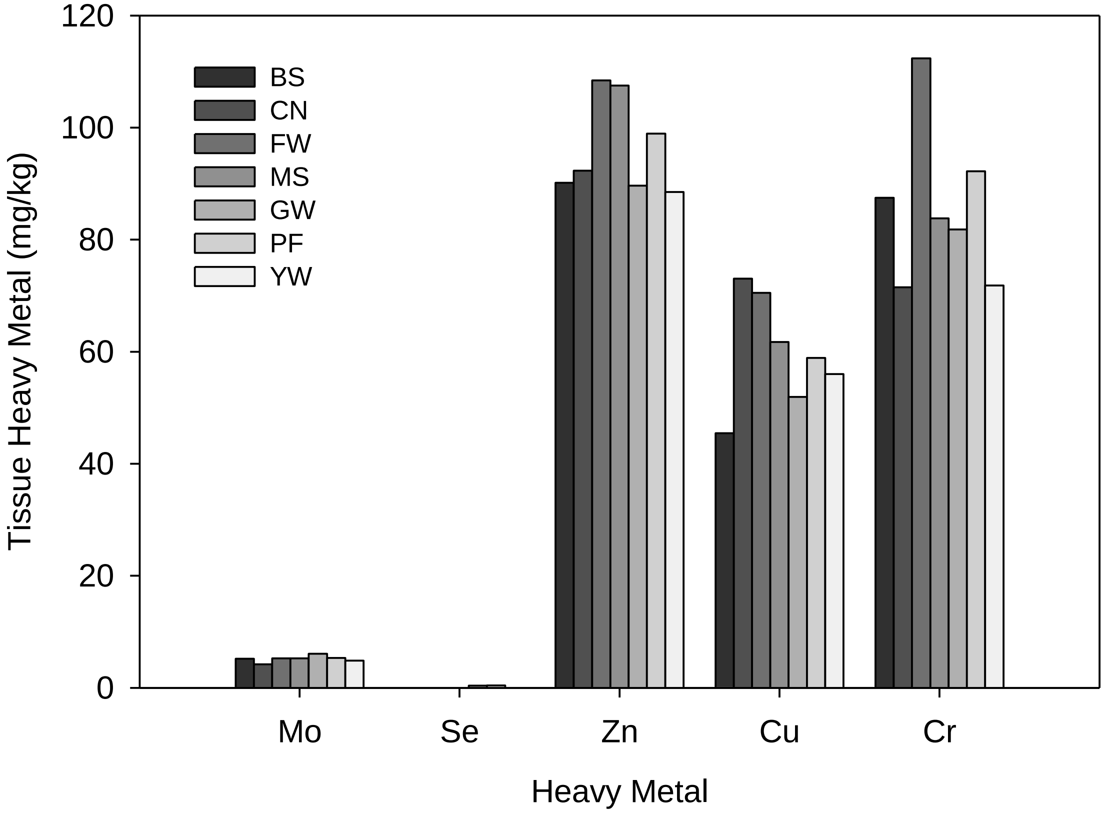


Figure 27. Mean Applause corn ear tissue heavy metal concentrations (n=4) for 2014. Levels of Cd, Ni, Pb, As, and Ag were below detection. There were no significant differences between treatments for any heavy metal. BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 22 for Fisher's LSD results.

Table 22. Fisher's LSD results for corn cob (Applause) tissue heavy metal contents in 2014. Within the same row, treatments with the same letter are not significantly different ($p<0.05$). Tissue levels of Pb, As, Hg, Ni, Co, Sn and Ag were below detection.

Element	Mo	Se	Zn	Cu	Cr
LSD (mg/kg)	3.1926	0.6487	19.211	37.946	33.955
BS	A	A	A	A	A
CN	A	A	A	A	A
FW	A	A	A	A	A
MS	A	A	A	A	A
GW	A	A	A	A	A
PF	A	A	A	A	A
YW	A	A	A	A	A

Yield

Although I hypothesized that waste amended plots would achieve yields comparable to control plots, some did not.

Corn. For corn, the only amendment that consistently underperformed the control was MS. Despite receiving rates of N, P and K that were higher or equal to the control, plots amended with MS yielded significantly fewer ears per plant (2014 Montauk), less weight per plant (2014 Applause and Montauk), and less weight per ear (2014 Applause) than the control (Figures 28).

Based on tissue test results there is no specific nutrient deficiency that explains poor corn yields from plots amended with MS. Tissue levels of macro and micro nutrients were either sufficient for Applause corn (N, P, Ca, Mg, Mo, Cu, Fe, Zn) or deficient for all treatments (B). The exceptions were K (all but GW and control treatments sufficient in 2013) and Mn (only FW and GW sufficient in 2013 and BS and FW in 2014). Deficiencies of K are unlikely to explain poorer yield in MS amended corn plots because there was no statistical difference in corn tissue K levels in 2013 and MS treatments had the highest tissue K levels in 2014. Although there were also no statistical differences in corn tissue Mn levels in 2013, in 2014 MS plots had the lowest levels, although they were not significantly lower than the control. It should be noted that tissue tests were only performed on Applause samples, Montauk or Brocade plants was not sampled.

Squash. In 2014 plots amended with YW, PF, and MS yielded significantly less butternut squash (by weight) than the control, and the plots amended with YW and PF had significantly smaller squash than the control in both years (Figure 29 and 30). Compared to the control, plots amended with YW, PF, and MS received equivalent or higher rates of N, P, and K; the exception was PF which received ~30 kg P/ha, which was less than the control (49 kg P/ha) but more than the recommended rate for butternut squash of 20 kg P/ha (Hazzard and Howell, 2014).

While some squash tissue samples were deficient in Mn, this may not explain the significant difference in yield between the control and plots amended with YW, PF, and MS. This is because, in 2014, YW treatments had significantly higher tissue Mn than control plots and although PF and MS had lower levels, they were not significantly different.

Squash were considered unmarketable based on disease, insect, and/or animal damage and the fraction of total harvest culled was calculated (Figure 31). While there were no statistical differences in the fraction culled by weight in either year, a significantly higher number of squash were culled in 2013 from plots amended with GW compared to all other treatments.

Potato. No amendment produced significantly lower potato yield than the control in either year (Figure 32). The quality of potato yield was determined by separating them into three categories: "A” (marketable), "B" (potentially usable for secondary market like processing) and "C" (culls). Potatoes were placed in the "B" or cull category because of mechanical damage, disease or insect damage (including wire worm, the larvae of click beetles, Coleoptera Elateridae). While plots amended with PF produced a lower total weight of potatoes than the control in both years, although not significantly, the potatoes harvested were of significantly better quality than the control in 2014, e.g. a higher proportion of firsts and fewer seconds (Figure 33). This was in spite of an overall drop in quality in 2014, when all treatments yielded a lower proportion of firsts and high proportion of seconds compared to 2013, due to increased incidence of disease and pests. This indicates that the PF amendment may have contributed to lower disease and/or pest pressure. Suppression of *Rhizoctonia solani* and snap bean root rot (*Pythium* spp. and *Aphanomyces euteiches*) have been reported after amendment with composted and raw paper fiber (Croteau and Zibilske, 1998; Rotenberg et al., 2007). Although amendment with composted paper fiber reduced symptoms of bacterial speck (*Pseudomonas syringae* pv. *tomato*) in tomatoes and thale cress (*Arabidopsis thaliana*), non-composted paper fiber did not (Vallad et al., 2003).

Although experimental plots were small, which can effect estimates of yield per hectare, most treatments in this study met or exceeded local average yields for winter squash, potatoes and sweet corn. The average sweet corn yield for Rhode Island in 2014 was 7,400 kg/ha (USDA, 2015a). While yields in this study varied by year, cultivar and treatment, ranging from 8, 300 to 23,700 kg/ha, they all exceeded the state average. The average yield in Rhode Island for potatoes was 27,600 kg/ha and treatment yields ranged from 22,600 to 40,200 kg/ha (USDA, 2015a). An average yield of winter squash in New England is 11,200 kg/ha while a good yield is between 22,400 and 67,300 kg/ha and yields for this study ranged from 24,100 kg/ha to 34,200 kg/ha (Clifton, 2006; Hazzard and Howell, 2014).

Together, these results show that YW, PF and MS were not able to match the yields of the mineral fertilizer control for squash or corn (MS only), although for potatoes all treatments yielded as well as the control. While some treatments resulted in deficient levels of nutrients in tissue samples, there was no clear connection between deficiencies and reduced yields. Additionally, PF may have potential to improve the quality of potato crop yields.

Table 23. Fisher's LSD results for corn yield, measured as weight of ear per plant, number of ears per plant and weight per ear in 2013 and 2014. Within the same row, treatments with the same letter are not significantly different ($p<0.05$).

Year	Cultivar	LSD	BS	CN	FW	MS	GW	PF	YW
Weight/Plant (kg)									
2013	Applause	0.0718	A	A	A	A	A	A	A
	Brocade	0.057	A	A	A	A	A	A	A
2014	Applause	0.0424	A	A	AB	D	ABC	CD	BCD
	Montauk	0.105	A	BC	AB	D	CD	CD	CD
Ears/Plant (#)									
2013	Applause	0.2199	A	A	A	A	A	A	A
	Brocade	0.2591	A	A	A	A	A	A	A
2014	Applause	0.1352	A	A	A	A	A	A	A
	Montauk	0.2193	A	B	A	C	BC	BC	BC
Weight/Ear (kg)									
2013	Applause	0.0192	B	AB	B	B	A	B	B
	Brocade	0.0177	A	A	A	A	A	A	A
2014	Applause	0.0186	A	ABC	AB	D	ABC	CD	BC
	Montauk	0.0448	A	A	A	A	A	A	A

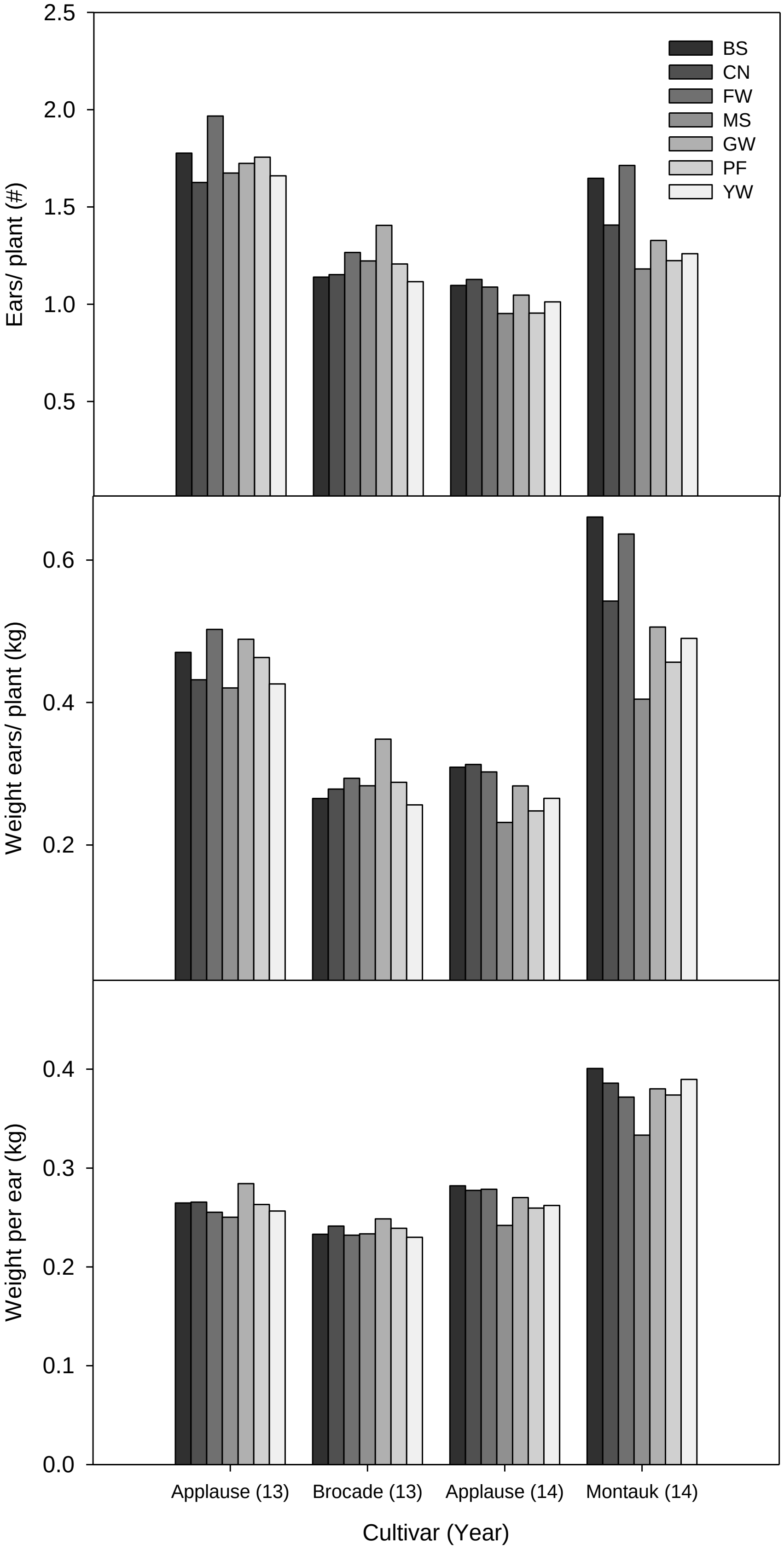


Figure 28. Mean corn yield, measured as weight of ear/ plant, number ears/ plant and weight/ ear, for plots in 2013 and 2014 (n=4). Corn yield was calculated on a per plant basis because of inconsistent stand establishment. BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste. See Table 23 for Fisher's LSD results.

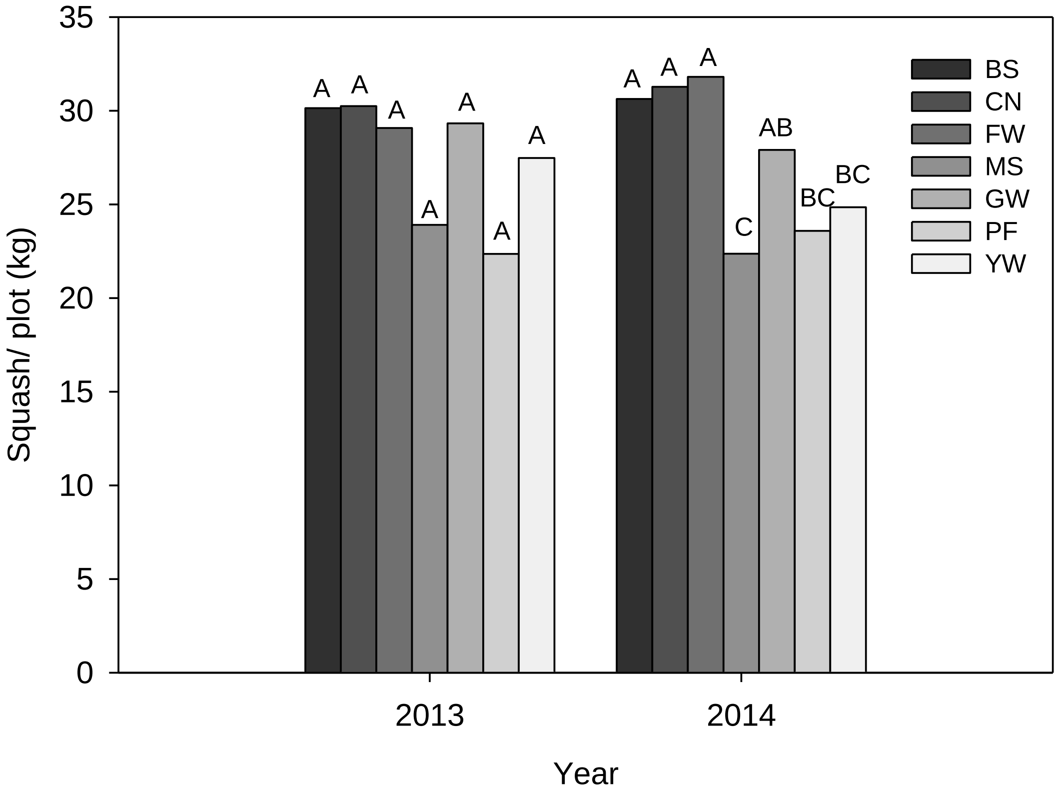


Figure 29. Mean squash yield, measured as weight of fruit harvested per plot, for 2013 and 2014 (n=4). Treatments with the same letter were not significantly different. Each year was analyzed separately (2013 LSD = 6.7773 kg, 2014 LSD = 5.0584 kg). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste.

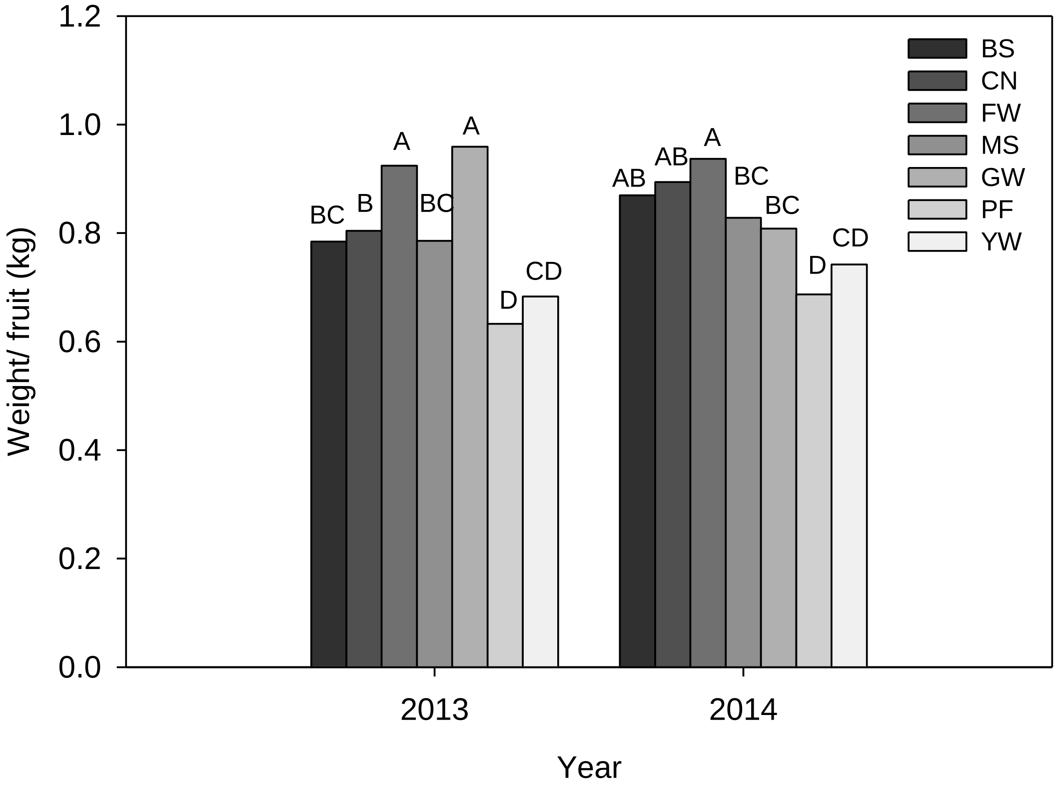


Figure 30. Mean squash quality, measured as average weight per fruit, for plots in 2013 and 2014 (n=4). Treatments with the same letter were not significantly different. Each year was analyzed separately (2013 LSD = 0.1139 kg, 2014 LSD = 0.1047 kg). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste.

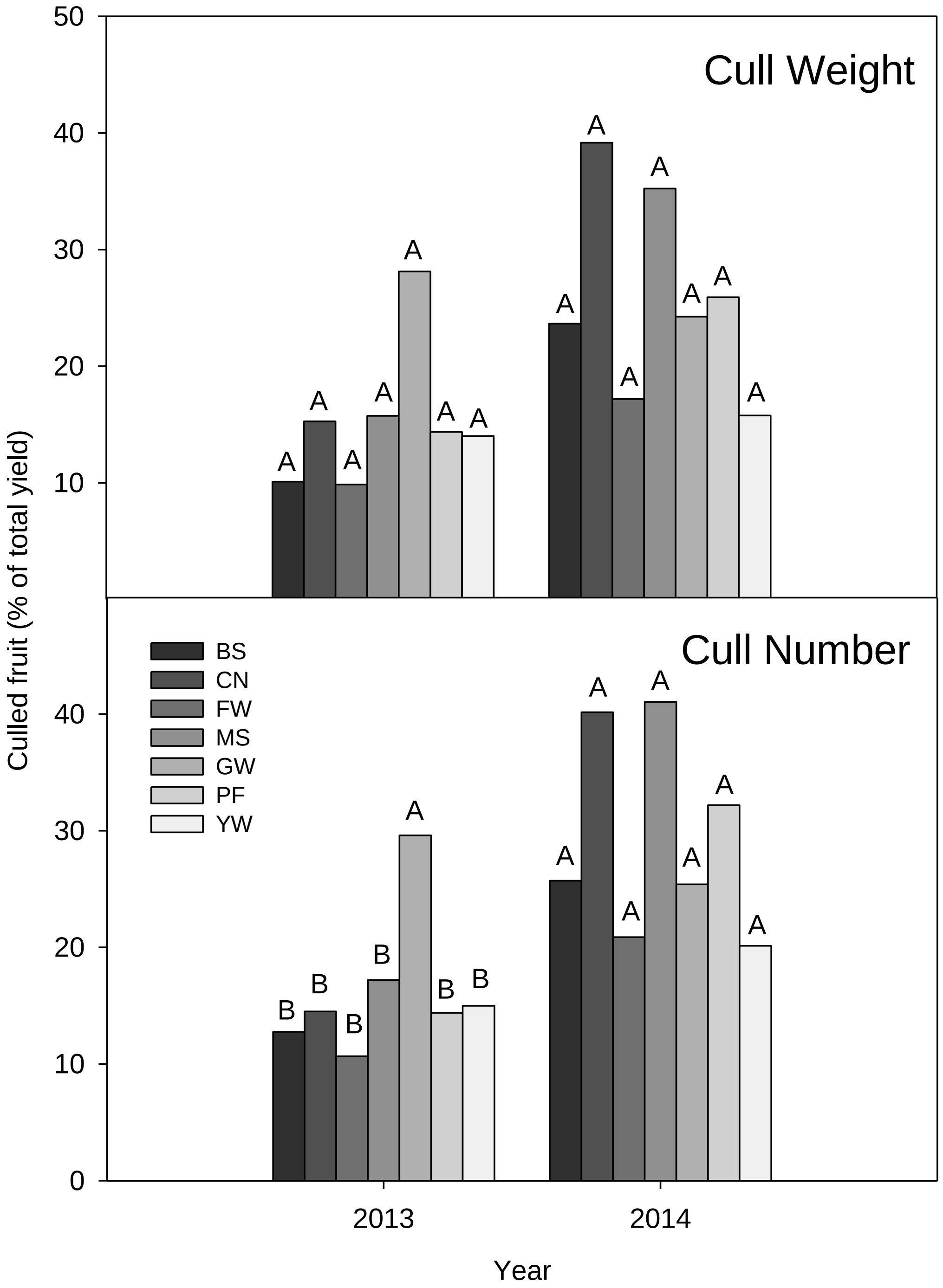


Figure 31. Mean squash quality, measured as the fraction of total harvest that was culled, by weight and number, for 2013 and 2014 (n=4). Treatments with the same letter were not significantly different. Each year was analyzed separately (2013 Cull Wt. LSD = 11.37 %, 2014 Cull Wt. LSD = 27.446 %, 2013 Cull # LSD = 10.6 %, 2014 Cull # LSD = 28.021 %). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste.

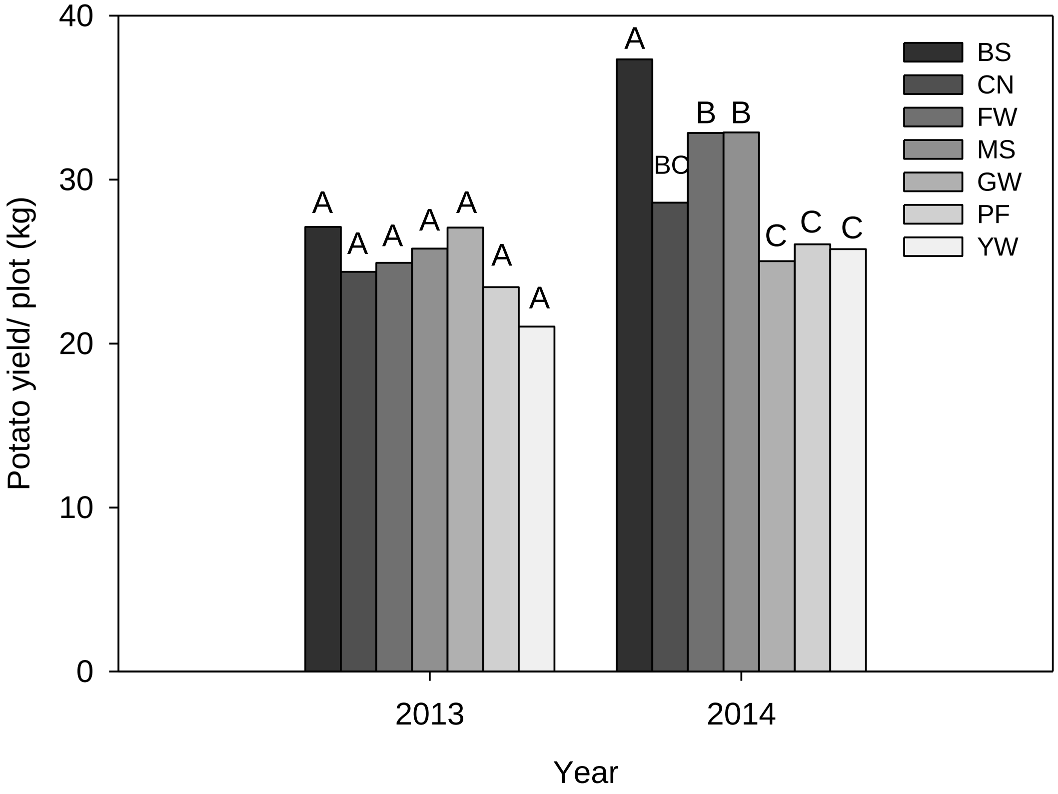


Figure 32. Mean potato yield per plot, by weight, for 2013 and 2014 (n=4). Treatments with the same letter were not significantly different. Each year was analyzed separately (2013 LSD = 3.9792 kg, 2014 LSD = 4.3512 kg). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste.

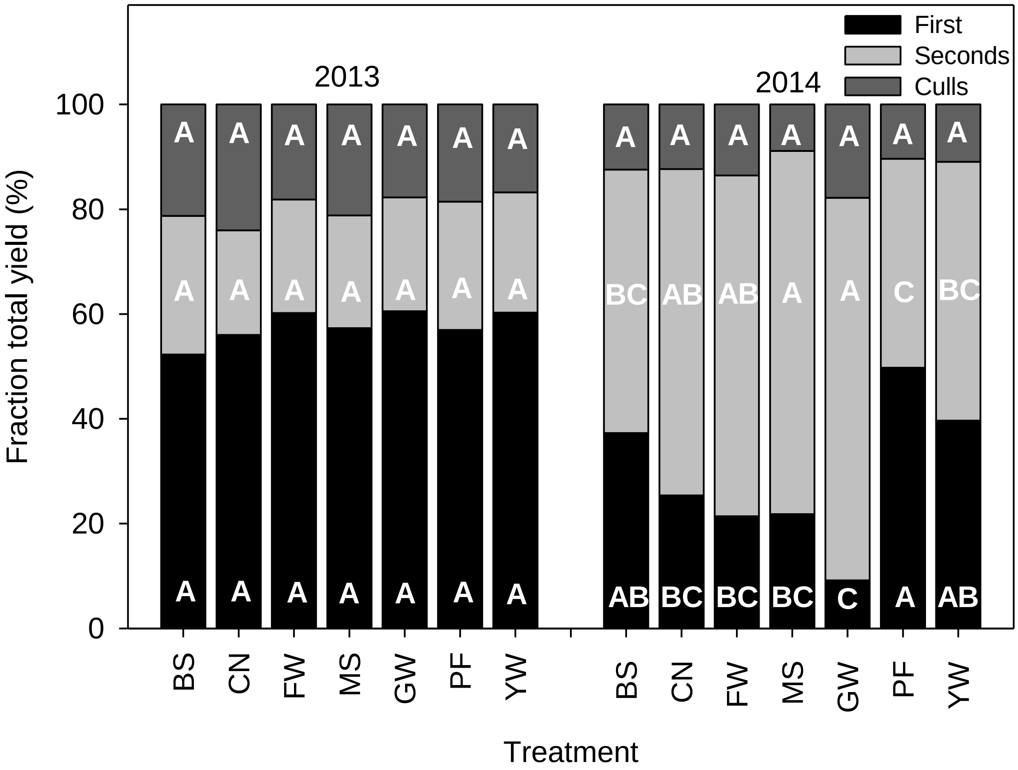


Figure 33. Mean potato quality, measured as the percent of total harvest that were firsts, seconds and culls, by weight, for plots in 2013 and 2014 (n=4). Treatments with the same letter were not significantly different. Each year and category was analyzed separately (LSDs for 2013: Firsts = 13.853%, Seconds = 12.86%, Culls = 10.497%, LSDs for 2014: Firsts = 22.25%, Seconds = 18.361%, Culls = 8.2573%). BS = biosolids/yard waste co-compost, CN = mineral fertilizer control, FW = dehydrated food waste, MS = multisource compost, GW = gelatin waste, PF = paper fiber/chicken manure, YW = yard waste.

CHAPTER 4

CONCLUSIONS

Waste amendments may be effective sources of plant nutrients, and their use as fertilizers for vegetable production could provide both a productive means of disposal and a potential source of carbon to build soil organic matter and improve soil quality.

Amendment qualities. While the amendments used in this study had consistent electrical conductivity from year to year, and were all lower than the control fertilizer, their pH was more variable. Unlike mineral fertilizers, waste amendments contain a large proportion of OM, although this proportion varied from amendment to amendment, as did the fraction of OM that was C. Both FW and MS contained seashells, which affected estimates of the fraction of OM present as C. Furthermore, because the C from seashells would not be as available to soil microorganisms as organic C, affecting C:N ratios, this alters expected N availability.

Waste amendments also varied in texture, density and moisture content, which affect their decomposition in the soil, and can present practical issues, such as transportation problems and the need for specialized spreading equipment. While none of the wastes contained heavy metal concentrations that exceeded the U.S. EPA's (1994) ceiling levels for land application of biosolids, the As content of YW (2014) exceeded more restrictive limits for exceptional quality biosolids.

The nutrient densities of waste amendments also differed. While most contained moderate to low N, GW contained more N than the commercial chicken manure product that was used in this study. All wastes had a C:N ratio below 25:1, the threshold above which N immobilization is likely, except the paper fiber, even after blending with a higher N product (chicken manure). Unlike mineral fertilizers, most N in the waste amendments was organic (>95%). Amendments were not significant sources of P, except GW, which contained almost equal parts N and P. This could lead to the over application of P if GW were applied to meet crop N needs. Finally, wastes contained varying amounts of K but were all low in comparison to the mineral fertilizer used.

Soil quality. The soil EC did not exceed 1 mS/cm, the level that may affect sensitive crops, regardless of treatment. Multisource compost was the only amendment to significantly increase pH compared to the control, likely due to the $CaCO_3$ from seashells. In contrast, at the rates used in this study, BS and YW have the potential to lower pH in comparison to a mineral fertilizer. Multisource compost increased bulk density in comparison to the control, although not significantly, whereas FW significantly decreased bulk density. Yard waste and BS were the only amendments to significantly increase OM compared to the control, although the effect was not consistent across crops. Waste amendments did not affect soil moisture or heavy metal levels.

Soil fertility. Waste amendments were expected to be better sources of late season inorganic N, due the slow mineralization of organic N, but this was not the case for most amendments. Application of waste amendments also did not reliably increase potentially mineralizable N in comparison to the control. Although PF was the only amendment with a C:N ratio above 25:1, the threshold above which N immobilization is likely, inorganic N levels in plots amended with PF were not always significantly lower than the control, or the lowest among waste-amended plots, indicating amendment C:N ratio is not a reliable predictor of N availability.

Crop quality. Plots amended with PF had significantly lower emergence of potatoes (2014) and significantly shorter plants (2013 and 2014), indicating inhibition of early growth of potatoes, although not squash or corn. While concentrations of nutrients (N, P, K, Ca, and Mn) in plant tissue samples varied among treatments, they did not always do so in response to application rates. Corn cob tissue samples were tested for heavy metal concentrations in 2014 and no statistical differences were observed among treatments, indicating short-term application of waste amendments would not significantly increase corn ear heavy metal levels in comparison to a mineral fertilizer.

Although some waste amendments produced yields comparable to a mineral fertilizer, others underperformed. Plots amended with MS produced significantly fewer corn ears per plant (2014 Montauk), less weight per plant (2014 Applause and Montauk), and less weight per ear (2014 Applause), compared to the control, despite receiving higher or equivalent rates of N, P, and K. In 2013, YW, PF, and MS yielded significantly less squash (by weight) than the control, and squash from YW and PF were significantly smaller (2013 and 2014), despite receiving higher rates of N, P, and K. All waste amendments produced potato yields comparable to the control, and 2014 PF potatoes were of significantly better quality than the control, indicating a potential reduction in insect and/or disease damage.

All the waste amendments showed promise as effective replacements for mineral fertilizers for at least one crop. While some treatments resulted in deficient levels of nutrients in tissue samples, there was no clear connection between deficiencies and reduced yields. Application of waste amendments did not have negative effects on soil quality. While most amendments did not appear to increase soil OM or improve quality in the short duration of this study, longer term applications of waste amendments may have more significant effects. Lastly, some waste amendments provided unique benefits such as increasing pH (MS) or improving potato quality (PF).

APPENDIX 1

Appendix 1. Amendment element contents for 2013 and 2014 (n=2-3). Below level of detection indicated as 0. Cd, Hg, Ni, U, Hg, W, Ni, Co, Ba, Cs, Te, Sb, Sn, Cd, Ag, and Pd all below level of detection. U.S. EPA limits are the levels of acceptable heavy metals for exceptional quality biosolids (U.S. EPA, 1994).

Amendment	Mo	Mo Std. Dev.	Pb	Pb Std. Dev.	Se	Se Std. Dev.	As	As Std. Dev.	Zn	Zn Std Dev.	Cu	Cu Std. Dev.	Cr	Cr Std. Dev.
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	Mg/kg
BS 13	0.0	0.0	100.4	0.2	0.0	0.0	11.2	1.0	525.4	17.9	207.5	9.8	25.3	22.0
BS 14	0.0	0.0	126.4	1.2	1.8	3.2	23.8	1.7	665.8	14.7	308.0	10.2	57.0	5.1
CM 14	2.7	4.6	0.0	0.0	0.0	0.0	0.0	0.0	1534.2	52.2	1055.5	31.4	105.7	6.3
FW 13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	44.9	5.6	0.0	0.0	0.0	0.0
FW 14	3.1	5.4	0.0	0.0	0.0	0.0	0.0	0.0	89.2	5.7	44.3	3.7	112.2	7.1
MS 13	0.0	0.0	21.1	4.2	1.7	2.9	7.3	6.6	129.3	13.8	10.2	17.6	42.5	7.5
MS 14	0.0	0.0	30.4	4.1	0.0	0.0	3.8	6.6	157.8	8.1	57.3	8.1	46.1	4.1
CN 14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1148.0	22.0	1151.0	64.4	0.0	0.0
GW 13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	58.1	3.6	0.0	0.0	0.0	0.0
PF 13	0.0	0.0	23.0	1.9	0.0	0.0	0.0	0.0	274.1	18.6	54.2	1.5	14.3	20.2
PF 14	0.0	0.0	19.2	2.8	0.0	0.0	0.0	0.0	213.0	10.5	140.5	22.8	119.4	6.0
PF/CM 13	0.3	0.6	20.1	1.7	0.0	0.0	0.0	0.0	431.6	22.8	179.4	5.2	25.7	18.4
PF/CM 14	0.3	0.6	16.8	2.5	0.0	0.0	0.0	0.0	378.2	15.7	254.9	23.9	117.7	6.0
YW 13	0.0	0.0	145.1	9.1	0.0	0.0	13.1	11.6	249.5	14.5	42.5	4.8	47.5	10.5
YW 14	0.0	0.0	243.7	10.3	2.1	3.6	44.0	5.8	606.6	12.1	208.5	10.5	107.5	1.2
EPA Limit:	-		300		36		41		2800		1500		1200	

Amendment	Zr	Zr Std. Dev.	Sr	Sr Std. Dev.	Rb	Rb Std. Dev.	Th	Th Std. Dev.	Fe	Fe Std. Dev.	Mn	Mn Std. Dev.
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
BS 13	160.5	13.0	107.6	2.3	27.8	1.5	8.2	1.9	9649.6	201.7	489.6	17.9
BS 14	209.2	2.0	126.5	2.5	46.9	1.8	13.9	1.3	16743.0	163.6	636.6	59.4
CM 14	14.8	1.8	58.3	3.2	22.3	0.5	0.0	0.0	4349.1	123.6	1511.3	65.7
CN 14	0.0	0.0	0.0	0.0	107.6	3.6	0.0	0.0	1933.1	48.6	1502.0	103.3
FW 13	0.0	0.0	63.1	6.6	8.7	1.3	0.0	0.0	95.1	34.9	0.0	0.0
FW 14	0.0	0.0	29.3	1.2	7.1	0.9	0.0	0.0	419.8	38.3	0.0	0.0
GW 13	0.0	0.0	39.1	0.9	0.0	0.0	0.0	0.0	276.7	31.2	0.0	0.0
MS 13	883.8	13.7	332.1	9.4	56.2	1.2	19.6	1.1	10384.7	297.5	390.4	25.0
MS 14	595.0	8.9	295.3	2.6	60.9	0.4	15.8	2.5	17489.3	38.2	557.6	33.2
PF 13	53.3	2.6	185.1	6.1	19.2	0.8	0.0	0.0	3133.5	239.3	1048.0	130.7
PF 14	25.7	0.3	37.9	3.3	5.6	4.9	0.0	0.0	4895.0	65.5	240.5	52.9
PF/CM 13	48.5	2.5	169.2	5.7	19.6	0.8	0.0	0.0	3285.5	224.8	1105.9	122.6
PF/CM 14	24.4	0.5	40.5	3.3	7.7	4.4	0.0	0.0	4826.8	72.8	399.4	54.5
YW 13	332.7	25.9	99.5	2.5	62.7	2.4	6.9	6.1	11705.2	206.4	455.8	52.8
YW 14	221.6	4.6	108.7	1.1	62.6	0.8	12.3	2.2	27264.0	122.5	1137.7	63.8

Amendment	V	V Std. Dev.	Ti	Ti Std. Dev.	Sc	Sc Std. Dev.	Ca	Ca Std. Dev.	S	S Std. Dev.
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
BS 13	32.1	27.8	2122.0	40.5	52.9	3.1	38751.2	561.0	7375.2	588.5
BS 14	38.9	34.1	2699.3	6.1	40.2	8.8	32525.8	47.5	6445.9	488.2
CM 14	20.8	18.3	425.9	4.3	32.4	9.7	22937.4	287.9	11945.6	308.6
CN 14	0.0	0.0	19.4	33.6	0.0	0.0	985.2	93.1	899.1	828.7
FW 13	0.0	0.0	0.0	0.0	78.3	2.7	39665.4	837.6	3479.8	101.7
FW 14	0.0	0.0	0.0	0.0	31.9	7.3	16239.2	109.3	2904.2	128.6
GW 13	0.0	0.0	0.0	0.0	181.7	22.6	149102.6	874.0	2044.6	80.9
MS 13	0.0	0.0	2061.1	71.7	18.9	32.8	86653.9	1532.0	5381.1	766.4
MS 14	0.0	0.0	3103.9	25.4	0.0	0.0	73154.7	243.7	5495.7	685.5
PF 13	0.0	0.0	2642.3	67.4	96.3	9.0	177282.9	2217.4	1665.9	61.4
PF 14	31.0	27.0	1997.4	34.9	75.7	16.2	90401.6	356.8	2098.2	396.5
PF/CM 13	2.6	2.3	2365.2	59.5	88.3	9.1	157989.7	1976.3	2950.9	92.3
PF/CM 14	29.8	25.9	1801.0	31.1	70.3	15.4	81968.5	348.2	3329.1	385.5
YW 13	15.6	27.1	1909.6	46.5	0.0	0.0	27420.9	814.3	2095.4	249.9
YW 14	36.0	31.4	1931.3	39.0	42.5	4.0	32019.5	48.8	2941.6	440.4

APPENDIX 2

Appendix 2. Mean crop tissue sample concentrations of Al, Cu, Fe, Na, and Zn for 2013 and 2014 (n=4).

Nutrient	Aluminum (mg/kg)					Copper (mg/kg)				
Crop	Corn	Corn	Potato	Squash	Squash	Corn	Corn	Potato	Squash	Squash
Year	2013	2014	2014	2013	2014	2013	2014	2014	2013	2014
BS	52.7	62.3	101.6	98.5	157.4	16.0	9.4	12.0	14.6	15.3
BS std dev	7.7	7.5	46.0	30.7	108.3	1.6	1.0	2.0	5.9	1.2
CN	44.8	83.9	57.6	149.6	440.6	12.3	9.9	13.1	17.6	16.0
CN std dev	14.6	17.4	62.5	90.2	246.2	2.8	0.8	3.3	2.0	1.0
FW	56.4	97.5	34.5	48.6	410.7	14.8	10.7	15.6	20.6	19.0
FW std dev	18.8	22.6	21.1	6.7	390.9	1.0	0.9	2.3	3.1	5.6
MS	58.1	145.1	136.1	107.3	749.8	15.7	10.2	18.9	21.1	17.7
MS std dev	10.7	98.9	152.4	90.3	493.5	3.8	0.7	4.5	3.2	4.2
GW	69.7	95.7	85.6	99.9	265.4	17.4	10.1	15.3	18.8	14.4
GW std dev	17.7	21.3	67.7	151.9	207.1	4.6	0.8	1.7	1.8	1.3
PF	63.6	99.5	184.1	189.5	947.8	17.2	9.3	14.9	21.1	14.0
PF std dev	19.7	28.5	184.6	134.6	313.3	3.8	0.9	3.8	5.6	1.0
YW	54.9	106.4	159.6	172.9	811.9	15.0	10.9	13.2	20.8	13.1
YW std dev	5.7	46.7	70.1	69.2	872.3	1.9	3.0	5.6	4.2	1.2
Adequate tissue level*	-	-	-	-	-	4.0	4.0	5.0	5.0	5.0

*Lower limit of adequate tissue nutrient (Maynard and Hochmuth, 2007).

Nutrient	Iron (mg/kg)					Sodium (mg/kg)				
Crop	Corn	Corn	Potato	Squash	Squash	Corn	Corn	Potato	Squash	Squash
Year	2013	2014	2014	2013	2014	2013	2014	2014	2013	2014
BS	118.6	146.4	147.6	122.9	188.4	66.1	336.5	382.4	62.2	258.3
BS std dev	11.1	10.4	34.4	41.7	74.7	9.1	51.1	108.3	18.0	32.1
CN	91.7	164.1	120.7	164.9	348.4	64.0	350.7	306.3	64.2	362.1
CN std dev	18.4	20.8	44.8	48.7	135.5	22.5	46.4	108.8	23.1	106.2
FW	112.7	171.6	102.8	124.2	334.2	68.3	297.8	343.1	42.7	428.7
FW std dev	17.6	20.8	12.1	14.2	206.1	18.1	34.1	77.0	11.8	120.5
MS	124.8	194.6	165.9	159.6	482.5	78.1	386.5	392.5	51.9	366.3
MS std dev	12.3	54.4	97.8	26.3	245.9	23.3	61.1	145.1	15.1	59.9
GW	121.9	170.5	131.6	137.1	231.5	83.4	310.8	301.3	50.4	272.0
GW std dev	25.0	11.2	42.0	62.3	97.4	40.5	95.6	94.6	10.5	73.7
PF	128.6	166.6	205.8	206.6	582.8	88.8	371.8	330.2	61.3	333.3
PF std dev	21.9	15.2	119.7	78.4	176.7	47.2	148.7	30.1	26.4	64.0
YW	113.3	175.7	178.4	187.2	530.4	69.5	400.5	375.9	59.4	387.1
YW std dev	8.9	31.2	51.4	30.2	487.9	16.0	110.3	78.6	10.2	161.5
Adequate tissue level*	30.0	30.0	40.0	40.0	40.0	-	-	-	-	-

*Lower limit of adequate tissue nutrient (Maynard and Hochmuth, 2007).

Nutrient	Zinc (mg/kg)				
Crop	Corn	Corn	Potato	Squash	Squash
Year	2013	2014	2014	2013	2014
BS	37.1	28.2	15.5	92.2	86.6
BS std dev	15.5	13.0	2.2	26.7	4.5
CN	19.6	32.7	21.9	102.9	77.6
CN std dev	5.1	24.4	13.1	8.3	10.3
FW	28.8	23.3	19.1	113.9	96.5
FW std dev	8.4	3.9	3.5	18.0	45.1
MS	44.6	22.6	19.7	132.3	77.0
MS std dev	23.3	14.6	7.2	28.6	20.1
GW	57.5	20.8	15.8	96.5	87.1
GW std dev	54.5	10.7	3.0	12.2	16.8
PF	31.9	25.8	24.2	122.4	108.6
PF std dev	12.1	13.1	3.0	17.9	79.9
YW	45.4	32.7	28.9	111.8	82.8
YW std dev	8.0	28.3	15.5	27.2	25.4
Adequate tissue level*	20.0	20.0	30.0	20.0	20.0

*Lower limit of adequate tissue nutrient (Maynard and Hochmuth, 2007).

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