SOIL AMENDMENTS FROM URBAN RESIDUALS AND THEIR EFFECT ON CROP PRODUCTIVITY AND NUTRIENT CYCLING

by

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Abstract

Urban residuals have been used in agriculture to decrease disposal costs, recycle nutrients, and prevent or counteract the degradation of soils linked to the intensification of agriculture. Technological advancements continue to produce novel residuals that can be used as soil amendments, with the potential to reduce or eliminate waste. This thesis entails two studies that examine the potential to utilize new urban residuals for food production. The objectives of the first study were to look at the potential benefits and impacts, on crop productivity and nutrient cycling, of using monopotassium phosphate (MKP) fertilizers, made using the co-products of biodiesel production. The treatments in this study include MKP-M, a purified form of MKP, MKP-C, a crude MKP from biodiesel production with glycerin and MKP-C2, similar to MKP-C but with double the glycerin. There were no differences in yields in the field trial. The greenhouse trial showed higher pepper yields using MKP-C and foliar MKP-M, and higher number of fruits with foliar MKP-M and a retail MKP. Soil analyses suggest that glycerin in certain amounts can inhibit nitrification and improve nitrogen (N) uptake. In the second study, a compost like material (HTI Compost) made in 24 hours was tested to better understand the effects unstable and immature compost could have on yield, nutrient cycling and greenhouse gas (GHG) emissions. The treatments were the HTI compost, UBC farm compost (typical municipal compost), a mix of the two composts, HTI compost + bloodmeal, and no amendment. The results show the HTI treatments had similar yields to the UBC farm compost for beets, but lower yields in spinach due to reduced or delayed germination. The HTI treatments delayed soil N availability and resulted in higher GHG emissions. Emissions of carbon dioxide and methane from the HTI treatments were high in the beginning of the season when the compost was decomposing, while nitrous oxide emissions were highest later on as decomposition rates declined. These results show promising benefits for using urban residuals as soil amendments, but the management of these amendments is crucial to avoid any negative impacts on crop productivity or the environment.

Lay summary

This thesis describes two studies that were conducted in order to investigate the potential benefits and impacts of using two novel urban residuals as agricultural amendments on crop productivity and nutrient cycling. In the first study, residuals made from biodiesel co-products were applied as either a soil amendment or directly to crop leaves in a field and greenhouse environment. Crops yields and soil nitrogen availability were assessed. In the second study a compost made in as little as 24 hours in a high-throughput in-vessel composter was applied as a soil amendment at the University of British Columbia farm. The results show that while these new products can be beneficial to the agriculture industry, further research is needed to identify specific management practices to maximize crop production benefits while minimizing impacts to the environment.

Preface

The work presented in this thesis in Chapter 2 is the result of a collaboration between the Sustainable Agricultural Landscapes Lab at the University of British Columbia and Earth Renu Energy Corp. and in Chapter 3 with Recycling Alternative. The general experimental design for both projects was developed by Dr. Sean Smukler and myself, with feedback from Earth Renu Energy Corp. and Recycling Alternative. The fertilizers used in Chapter 2 were provided by Earth Renu Energy Corp. and the composts used in Chapter 3 were provided by Recycling Alternative and the UBC farm.

I was responsible for the field design, all the data collection, most of the laboratory analysis, and the data interpretation. Soil elemental analysis was done by the Ministry of Environment in Chapter 2, and by members of the SAL lab in Chapter 3. I was also responsible for growing and maintaining the crops used in Chapter 2, while the UBC farm was responsible for crop production in Chapter 3.

The SAL lab and Dr. Gabriel Maltais-Landry were responsible for the installation of the Picarro greenhouse gas (GHG) analyzer used in Chapter 3. I was responsible for utilizing the analyzer to collect all GHG data.

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List of abbreviations

ANOVA	Analysis of Variance
$BaCl_2$	Barium Chloride
BCPs	Biodiesel Co-Products
C	Carbon
CO_2	Carbon Dioxide
CH_4	Methane
DAP	Days After Planting
FFA	Free Fatty Acids
HCl	Hydrochloric Acid
HTI	High-throughput in-vessel
KCl	Potassium Chloride
MKP	Monopotassium Phosphate
MKP-C	Crude monopotassium Phosphate
MKP-C2	Crude Monopotassium Phosphate with double the glycerin
MKP-I	Isopropanol washed Monopotassium Phosphate
MKP-M	Methanol washed Monopotassium Phosphate
NaOH	Sodium Hydroxide

NPK	Nitrogen Phosphorus Potassium fertilizer
N	Nitrogen
NH_4^+-N	Ammonium Nitrogen
NO_2^-	Nitrite
NO_3^--N	Nitrate Nitrogen
N_2O	Nitrous oxide
P	Phosphorus
PAN	Plant Available Nitrogen
UBC	University of British Columbia

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1. General introduction

In recent years, environmental and economic factors, which include the impacts of constructing and maintaining landfills, the emissions and cost of transporting waste products, and the emissions and high costs associated with synthetic fertilizer, have created an opportunity to transform urban waste products into residuals that can be used to benefit agricultural production (Hargreaves et al., 2008). Residuals that originate from urban settings are primarily from the food industry or landscaping, which are characterized by organic residues and raw materials (Jayathilakan et al., 2012). Given that organic materials can be decomposed effectively they have the potential to be used in agricultural settings to decrease their disposal costs, recycle the nutrients that are contained in them, and to prevent or counteract the degradation of soils linked to the intensification of agriculture (Giusquiani et al., 1988).

The main urban residual that is extensively used in agricultural settings is composted municipal solid waste (MSW), which consists mainly of kitchen waste and yard trimmings (Hargreaves et al., 2008). MSW is used as a soil conditioner and as a fertilizer, to increase soil organic matter and to meet crop nitrogen requirements (Hargreaves et al., 2008). Much research has been done to look at its effects on the chemical properties of soils, on soil aggregate stability, and soil microbial activity (Giusquiani et al., 1988; Annabi et al., 2007; Ros et al., 2003). And, while there are benefits to using MSW compost as a soil amendment, there are also potential negative impacts such as salt or metal contamination of the soil (Hargreaves et al., 2008).

Other soil amendments, often categorized as industrial bio-waste, include products from fish waste, seaweed, or the meat and poultry industry (Lopez-Mosquera et al., 2011; Jayathilakan et al., 2012). Many of these bio-wastes are either used directly after composting or refined to produce a type fertilizer that can be used in organic agriculture. Co-composting of fish offal with drift-seaweed and pine bark, for example, has been shown to be an effective means of transforming what many consider a waste product into a valuable nutrient resource for agriculture (Lopez-Mosquera et al., 2011).

While there is much research on the utilization of urban residuals as agricultural soil amendments there are still management challenges that need to be addressed to ensure their optimal use. Furthermore, technological advances continue to introduce new or improved residuals. These products have the potential to close the loop between food or fuel production and waste, with potential to reduce or even eliminate waste and increase the sustainability in food production. Before novel residuals are used for agriculture (or any recycling application) they need to be carefully assessed to determine their impact on crop productivity and the environment.

1.1 Fertilizers from biodiesel production

Biodiesel production has become an important industry worldwide, and while this industry has changed how we view our automotive fuel, it has also forced us to consider uses for its potentially valuable co-products or residuals. There are a number of residuals that are produced during biodiesel processing that instead of being seen as waste requiring expensive disposal, are now being investigated for potential utilization value. Biodiesel co-products (BCP), mainly glycerin, free fatty acids, and monopotassium phosphate (MKP) recovered from production can be used as renewable resources. Recovered MKP combined with glycerin or on its own may be an effective fertilizer for crop production (Hopkins et al., 2010; Soerens and Parker, 2012).

The highly soluble properties of MKP make it ideal for providing nutrients to plants as a foliar spray, hydroponics or through fertigation (Boman, 2001; Hopkins et al., 2010). Given that it is not formulated with a nitrogen (N) source using MKP enables agricultural producers to customize nutrient application rates. Nitrogen, P and K needs of the crop can therefore be targeted effectively to optimize marketable yield, which is particularly beneficial in crops like potatoes, a prominent crop in British Columbia. Other studies have demonstrated the use of MKP as a foliar fungicidal spray. The spray has been effective for reducing foliar pathogens including powdery mildew, rust, northern leaf blight and bacterial spot in different crops such as cucumber, tomato, bell pepper, broad-leaf bean, maize, rose, grapevine, apple, nectarine and mango (M. Reuveni, Oppenheim, & Reuveni, 1998; R. Reuveni, Dor, & Reuveni, 1998). This is due to the toxic effect that phosphates have on fungi, while providing access to nutrients that help to increase the plant's natural defense mechanisms (Reuveni and Reuveni, 1998). A number of studies have shown positive yield outcomes when using MKP compared to more typical fertilizers, but not all. There have been observed decreases in corn yields following MKP foliar applications (Liu et al., 2013). Other studies have illustrated the benefits of using glycerin and free fatty acids as soil amendment (Liu et al., 2013; Qian et al., 2011 and Subbarao et al., 2008). Adding these co-products, which have a high concentration of readily available C, to soil, has been shown to immobilize soil N as microbial population utilize the C additions and quickly consume any N in the system. The increased microbial activity after the addition of the amendments can thus decrease the overall amount of N lost to leaching or de-nitrification (Redmile-Gordon et al., 2013). Reducing leaching losses could help protect groundwater resources from nitrate (NO_3^-) contamination which has been shown to impact human and ecosystem health. Reducing de-nitrification could also decrease nitrous oxide emissions, a greenhouse gas with ~300 times the radiative forcing of carbon dioxide (IPCC 2013). A reduction in N losses is also beneficial for the producer as it results in a more efficient use of a costly input. A lot of research has been conducted on MKP fertilizers as well as on glycerin, however little is known on the effects of MKP specifically recovered from biodiesel production mixed with glycerin, the major biodiesel co-product on plant growth. MKP fertilizers can be recovered from biodiesel residuals by adding phosphoric acid to the residuals to create crude MKP fertilizer with glycerin (Johnson and Taconi, 2007). If this crude MKP is further purified with methanol, a pure form of MKP is created, similar to retail MKP fertilizers. This novel way of creating MKP fertilizers needs to be investigated to better understand if and how they can be used for crop production.

1.2 Compost from high-throughput in vessel composters

Major recent advances in in-vessel composting have integrated technology and microbial processes to improve processing times to unprecedented speeds, drastically increasing the potential to divert large quantities of organic materials from landfill and reduce transport costs. Typically, industrial composting facilities operate on a scale of one to three months to produce compost and then let the compost stabilize for another 3-6 months before making it available as a valuable soil amendment (Litterick et al., 2003). A new alternative, high-throughput in-vessel (HTI) composters, could effectively recycle organic materials while reducing transport and storage impacts, as they can convert food waste into a compost like product in as little as 24 hours. These vessels also contain the composting material during the sanitation phase, which prevents the odor and dust typically released during the composting process (Areikin et al., 2012).

Composting is the biological decomposition of organic materials controlled by the type of inputs, time, temperature and moisture. Managing these factors effectively ensures the decomposition of organic materials and reduction of pathogens. Specifications for managing these factors are dependent on the type of composting method used, which include vermicomposting, windrow composting and aerated static pile composting. All composting systems use microorganisms such as bacteria and fungi, decompose materials into smaller particles. Bacteria and fungi utilize the carbon (C) and N contained in the organic inputs as an energy source releasing mainly carbon dioxide into the atmosphere. The most effective composting can be achieved when the C:N ratio of input materials are between 20:1 and 30:1. A typical composting process includes three phases: a mesophilic phase, a thermophilic phase and second mesophilic phase. In the first phase, mesophilic bacteria break down organic matter and increase the temperature of the compost, leading to the thermophilic phase, in which decomposition continues with thermophilic bacteria. As the high source of labile C in the residual material decreases, the microbial activity and temperature decrease, resulting in the second and final mesophilic phase. This phase is also associated with maturation and stability of the final compost product. This process leads to compost, a stable by-product with a C:N ratio between 14:1 and 20:1 that can be used as a soil amendment. A stable and mature compost has undergone thorough decomposition during the composting process and does not lead to N immobilization which typically occurs in soils amended with materials with C:N ratios >25:1 (Hadas et al., 2004).

Rapid HTI composting differs from the typical composting process described above by containing the waste material within a chamber and adding proprietary microorganisms. This chamber has internal rotating arms for the mixing of the waste materials, and moisture and temperature are carefully controlled. The temperature of the chamber is raised to 75 C for one hour to eliminate pathogens (Oklin International, 2015). Within 24 hours the volume of input materials can be reduced by 80% to 90%. These HTI composters are drastically changing the typical environmental factors and microbial populations that are used in composting, which likely affects the stability and maturity of the compost. It is possible that this technology results in a very different type of compost and its impact on crop productivity and nutrient cycling are largely unknown. It is likely that the materials are still highly microbially active and will continue to decompose after being applied to soil, as compost takes a few weeks (depending on the source of organic materials) to fully decompose under the right conditions (Epstein, 1996). In order to ameliorate these short-term negative impacts of using an unstable and immature compost, I have decided to look at the effects of mixing HTI compost with other soil amendments, such as mature compost or bloodmeal, which would provide the necessary nutrients at the beginning of the season while the HTI compost is undergoing decomposition. However, the impact of using HTI compost alone, or mixed with other soil amendments, are still unknown.

To address the research gaps associated with the utilization of BCP and HTI compost I conducted two separate studies that each consisted of a number of experiments. The first study, described in Chapter 2, investigated the effects of using the fertilizer made from BCP on crop productivity and soil nutrient cycling. The second study, described in Chapter 3, investigated the effects of using HTI compost on crop productivity, soil nutrient cycling and greenhouse gas emissions.

My specific objectives for Chapter 2 were to determine: 1. If MKP made from BCP mixed with different levels of glycerin would have the equivalent impact on vegetable yield as a typical retail fertilizers and 2. how these different fertilizer mixes would affect the soil nitrogen cycle particularly the availability of ammonium (NH_4^+) and NO_3^-. To meet these objectives, I carried three different experiments, a germination test, a field trial and a greenhouse trial. In these experiments, three different grades of recovered MKP containing different levels of impurities were tested: a highly purified MKP fertilizer in powder form washed with Methanol (MKP-M) which would be very similar to a commercially available (retail) MKP; an unwashed or crude version containing a glycerin co-product which comes in a semi-liquid form (MKP – C); and a crude MKP with glycerin with twice the amount of glycerin (MKP – C2). The control in these experiments is a commonly used commercially available fertilizer containing N, P and K (retail-NPK). Because MKP does not contain a N source, N in the form of urea was added to the fertilizer applications. And finally, for the greenhouse trial, we also used a retail MKP with an added source of urea as an additional treatment, and applied MKP-M and retail MKP both to the leaves (as a foliar spray) and directly to the soil, to determine the difference between these two application options on crop performance.

My hypotheses for the biodiesel study in chapter 2 were:

H1: The germination rate of lettuce amended with BCPs will not differ from retail fertilizer as BCPs do not contain concentrations of compounds known to be toxic to seedlings.

H2: Yields of potatoes and squash grown in field trial will be higher in the MKP-C2 treatment, as the N inhibitors in the glycerin will prevent nitrogen losses through leaching and will make it available later in the season in the form of nitrate for plant uptake, other BCP treatments will not differ from the retail fertilizers.

H3: There will be no differences in crop quality, determined by the percent of internal and external defects in the marketable harvest, among the different fertilizer types.

H4: Soil ammonium and nitrate content will be higher in the MKP-C2 treatment, as the nitrogen inhibitors in the glycerin will prevent nitrogen losses to the environment.

H5: Yields of potatoes in the greenhouse trial will be higher in the MKP-C2 treatment as the N inhibitors in the glycerin will prevent nitrogen losses through leaching, making it available for plant uptake. And the yields of peppers grown in the greenhouse trial will be higher in the MKP-M foliar and retail-MKP-foliar as nutrients will be more readily available to the crop through the leaves.

H6: There will be no differences in crop quality among the different treatments.

My specific objectives for the HTI study in Chapter 3 were to investigate the impacts of using HTI compost made from food waste as an agricultural soil amendment on: 1. Vegetable seed germination 2. Organic vegetable productivity, nitrogen availability and GHG emission 3. Soil health. To meet these objectives, I set up two experiments, a germination test and a field trial.

In the germination test I compared different rates of the HTI compost on germination rate and biomass in order to determine if there are any negative impacts on seed germination associated with the use of HTI compost.

To assess the effects of HTI compost crop productivity, nitrogen availability and GHG emission I established an experimental field trial at the University of British Columbia's (UBC) Farm. The treatments were: 1. HTI compost only, a mixture of HTI compost and bloodmeal, 3. HTI compost and compost that is typically used by the UBC farm; 4. the typical UBC farm compost alone; and 5. a control with no soil amendment. In each plot, I planted spinach and beets. Baseline soil samples were taken to determine the initial soil properties (bulk density, texture, N, P, K, NH_4^+-N and NO_3^--N levels). During the growing season, I monitored the availability of NH_4^+-N and NO_3^--N in soil samples taken every two weeks. I also tracked decomposition and greenhouse gas (GHG) emissions using a Picarro Cavity Ring Down Spectrometer weekly. At the end of the growing season, end line soil properties were assessed, and the yields of spinach and beet measured. This research project will help determine the potential benefits of a technology that decreases the time it takes to produce compost, with important implications for the storage and transport requirements for compost and food waste.

My hypotheses for the HTI study in Chapter 3 were:

H7: The application of HTI will not result in significant differences in germination rates or biomass compared to standard potting mix.

H8: Spinach and beet yields and quality will be highest in HTI and bloodmeal as the bloodmeal provides an immediate source of available nitrogen, and the HTI compost releases nutrients as it matures ensuring nutrients are available throughout the entire growing season.

H9: Ammonium and nitrate availability will be initially lowest in the treatments that have HTI compost in them (HTI compost, HTI compost + bloodmeal and HTI compost + UBC farm compost) and higher later in the season as N from microbial activity will be released through mineralization.

H10: N_2O emission will be lower in HTI compost treatments than UBC farm compost because the majority of N will utilized by microbial populations during decomposition but increased microbial activity will result in higher CO_2 and CH_4 emissions. Cumulative GHG emissions will be highest in the HTI compost treatments than the UBC farm compost and the control for the same reasons mentioned above.

H11: Total microbial activity will be higher with HTI compost because the nutrients are not stable and are readily available to the microbial communities, increasing their populations.

The outcomes of this research are important for understanding how fertilizers with biodiesel co-products used in an agricultural setting can affect crop productivity and soil nutrient cycling, and how a high-throughput in-vessel compost like product made in 24 hours can also affect crop productivity and nutrient cycling, as well as greenhouse gas emissions.

2. Monopotassium fertilizers with glycerin co-products and their impacts on crop productivity and soil nutrient cycling

2.1 Introduction

Biodiesel production has become an important industry worldwide as an alternative and potentially more sustainable fuel source. In the process of making biodiesel several co-products or residuals are produced. Finding ways to efficiently utilize these co-products could increase the sustainability of the fuel source, and if made marketable, could potentially positively change the economics of production. During the production of biodiesel from recycled oils, a number of co-products can be generated. Large-scale biodiesel facilities usually use potassium hydroxide as the catalyst for biodiesel production (Boyd et al., 2004). A major co-product of the process is potassium phosphates (or sodium phosphate), used in the conversion of oils and alcohol into biodiesel and crude glycerin, which can be used for the production of fertilizers (Boyd et al., 2004). The raw glycerin by-product from biodiesel production contains methyl esters, glycerol, methanol and soaps. The amount and ratio of the other co-products will depend on how the biodiesel waste is processed and how much free fatty acids (FFA) are present in the source oil (Boyd et al., 2004). There have been a number of uses explored for recycling biodiesel co-products (BCP) including use in agricultural production.

A few studies have investigated the impacts of biodiesel co-products, BCPs, in agricultural production, particularly focused on soil processes (Liu et al., 2013; Qian et al., 2011 and Subbarao et al., 2008). Subbarao et al., (2008) found, in a study that compared traditional agricultural practices with applications of small amounts of BCP (glycerin) as a soil amendment, that losses of nitrogen (N) from the soil profile were greatly reduced. Applying BCPs provides a readily available carbon (C) source for soil microbes, enabling their utilization of available N and a rapid increase in their community size. Microbial utilization of N results in N immobilization, thus preventing it from leaching to groundwater (Subbarao et al., 2008). These findings indicate that adding BCPs as a soil amendment could be an effective method to reduce N losses from agricultural soils and prevent nitrate (NO_3^-) pollution of groundwater.

Glycerin has been shown to have benefits for plant growth. A study in Western Australia investigated the effects of directly applying crude glycerol on a wheat field at seeding time (Franco et al., 2000). Results showed that glycerol applications could help correct water repellency of the non-wetting sandy soils by covering the non-wetting coatings on soils particles (hydrophobic particulate organic matter) at a decreased cost compared to alternative methodologies (Franco et al., 2000). Another study looked at the effect of applying glycerol on wheat crops in Saskatchewan at different rates and assessed subsequent wheat growth and soil characteristics (Qian et al., 2011). The results showed that wheat biomass and nitrogen uptake increased at low and medium rates of glycerol (100 and 1,000 kg glycerol ha^{-1} respectively) applications. However, adding glycerol at the highest rate of 10,000 kg glycerol ha^{-1} resulted in decreased yield. This loss in yield was explained as a consequence of N immobilization indicating both the potential benefits and negative consequences of BCPs utilization.

Another BCP, free fatty acids (FFAs), and their methyl esters are also thought to act as inhibitors of nitrification (Subbarao et al., 2008). Studies that tested the biological nitrification inhibiting capabilities of a number of FFAs including linoleic acid (LA), linolenic acid (LN) and methyl linoleneate (LA-ME) showed an inhibitory effect on nitrifying micro-organisms (Subbarao et al., 2008). Inhibiting nitrification can delay the microbial oxidation of NH_4^+ to NO_3^-, a more soluble and leachable form of N, which could reduce denitrification and losses of N to the atmosphere as nitrous oxide (N_2O) a greenhouse gas with the climate forcing potential 300 times that of carbon dioxide (Subbarao et al., 2008).

Recovering monopotassium phosphate (MKP) during the biodiesel production process could also be effectively used in an agricultural setting, as potassium (K) and phosphate (P) based fertilizers are commonly used in fertigation, hydroponics or as foliar fertilizers when a fast response is required. Potassium and P are specifically used by plants for the formation and transportation of sugars, starches and acids, as well as for increasing fruit quality and product shelf life. Phosphorus promotes root growth and early maturity. The purity of the fertilizer makes it easy for both elements to be taken up by the plants to satisfy demands for these macronutrients (Chapagain and Wiesman, 2004). MPK is water soluble, which makes it ideal for fertigation (Hopkins et al., 2010). The lack of N in the initial fertilizer mix enables users to develop a custom application rate to avoid excess or unnecessary N applications. If N is needed, an additional source such as another fertilizer, manure or compost can be added.

There are a number of other reported benefits associated with MKP in addition to its agronomical advantages. MKP does not contain any chloride, sodium or heavy metals, making it relatively safe for use with all kind of plants (Haifa Group, 2014). A low salt index, and lack of ammonia makes it ideal for hydroponic cultures (Haifa Group, 2014). MKP has been investigated for its fungicidal properties, and has been shown to be effective in controlling powdery mildew in many crops including grape, apple, nectarine, and cucurbits such as melon and cucumber (Reuveni et al., 1998). Many of the MKP fertilizers available in the market are sold in a salt form that is water soluble, and it can further be mixed with pesticides for a simultaneous application of both (Haifa Group, 2014).

There is evidence that MKP could be particularly appropriate for potato production (Hopkins et al., 2010). A study conducted in Idaho, USA, between 2004 and 2006 investigated the efficacy of MPK as an in-season fertigation option for potatoes and found that P-fertilizer can result in increased tuber yields and quality when potato petioles show deficiencies in P concentrations (Hopkins et al., 2010). Potatoes have surface feeding roots once the canopy closes, which help facilitate the uptake of fertigated P when it is applied in a water-soluble form (Hopkins et al., 2010).

Almost all commonly used P fertilizers contain ammonia (e.g. Monoammonium phosphate and diammonium phosphate), which can be problematic if the nitrogen status of the potato plant is already high (Hopkins et al., 2010). When the N levels are already high in the plant, adding additional N can be detrimental to crop yields due to their sensitivity to excessive N, which can result in vegetative growth at the expense of tuber growth (the cash crop), and delay skin development (Hopkins et al., 2010). MKP can be applied with a custom application rate of N, therefore meeting the plant's P and K demands without over supplying N.

There is some evidence that MKP, used as a starter fertilizer or a foliar spray, can impact crop yields. MKP-based starter fertilizers are thought to enhance snap bean yield (Hochmuth, 2006). Hochmuth (2006) determined that yield was enhanced by the MKP-based starter fertilizer application, and demonstrated that the direct application of MKP on the seed was safe and did not lead to any damage. Grapefruit trees that received foliar applications of MKP (post bloom) have been shown to produce fruit that were significantly larger than a control treatment (Boman and Hebb, 1998). In another study however, Sawyer and Barker, (2000) found a slight decrease in corn grain yield after foliar application of MKP compared to a control. No visible leaf damage was observed from these applications and the study provided no explanation for the decreased yield (Sawyer and Barker, 2000). So, while there have been a number of studies to document the advantages of using MKP as a fertilizer there is at least one case that has documented potential negative impacts of foliar applications to corn.

While there is substantial evidence that using BCPs, particularly glycerin and MKP for agricultural production, there are also indications that there may be some potential negative impacts. It is unclear how management options impact the optimization of BCPs. It is also unclear if BCPs can be used to improve beneficial outcomes. Using MKP fertilizers that include sizable concentrations of FFAs in the form of glycerin from biodiesel production could increase the efficiency of N fertilizer applications and decrease N losses to the environment while supplying crops with the nutrients they require.

My objectives for this study were to investigate the impacts of using a biodiesel co-product, glycerin and recovered MKP, for crop production. More specifically, I wanted to determine if MKP with different levels of glycerin would have the equivalent impact on crop seed germination and yield as a typical retail fertilizer. I also wanted to determine the impact of glycerin on the nitrogen cycle specifically the availability of NH_4^+ and NO_3^-.

2.2 Materials and methods

2.2.1 Germination test

The first experiment I carried out was a germination test in the Horticulture Greenhouse at UBC, to ensure that the MKP fertilizers made from biodiesel production, purified or with glycerin, do not inhibit crop germination. Four lettuce seeds *(Lactuca satvia)* were planted per pot, to test the MKP fertilizers: highly purified MKP in powder form that was washed from impurities using methanol (MKP-M); a purified MKP also in powder form washed with isopropanol (MKP-I); a crude MKP fertilizer with a glycerin co-product (MKP-C); and a retail NPK as a control. I had four replicates per treatment, and the pots were randomly ordered to account for external factors in the greenhouse. The pots were watered daily by the greenhouse staff. A germination assessment, or the number of germinated seeds per treatment, was done on day 5, day 10 and day 15.

2.2.2 Field trial

Shortly following the germination trial, in June 2015, a field trial was conducted at the Totem Fields Research Station at UBC, a research field within the UBC campus. The climate is a moderate oceanic climate with mild and wet winters and dry summers. The soil type at the research station is a sandy loam from the Bose soil series. The field trial was established to test the response of potato (*Solanum tuberosum L*) and squash (*Cucurbita pepo*) crops to additions of the three different grades of MKP fertilizers (MKP-M, MKP-C, MKP-C2), with an added nitrogen source, urea. MKP-C2 is similar to MKP-C (described above), but contains twice the amount of glycerin. The amounts of fertilizers that were administered to the plants were calculated using recommended N, P and K amounts for potatoes and squash respectively. For both crops, I followed typical production practices for planting, spacing, weed control, irrigation rate and frequency, and other management practices for optimal plant growth. The fertilizer applications were split into two, the first shortly after the germination of the crops, and the second before the flowering of the crops. For the potato crops, the fertilizer was mixed in water and applied to the soil surface. For the squash plants, the fertilizer was sprayed directly on the leaves in order to maximize fertilizer uptake. The fertilizer application rates were determined using the N and K requirements of the crops, as K is the limiting nutrient in MKP fertilizers. Application rates for the squash were 90 kg N ha^{-1}, 74 kg P ha^{-1} and 141 kg K ha^{-1}, and for potatoes, the rates were 225 kg N ha^{-1}, 59 kg P ha^{-1} and 133 kg K ha^{-1}. Treatments were applied in a completely randomized block design to account for the differences in soil properties across the field, with four replicates each. Within each plot, four squash plants, and three potato plants were planted.

2.2.2.1 Crop productivity

For both squash and potato plants, the yield was measured at the end of the growing season, ~90 days after planting. The yield was obtained for the marketable crop, as well as the above ground biomass (AGB), which is the non-marketable plant material (i.e. stems and leaves). Squash fruits were collected by hand, and potatoes were dug from the ground with a pitch fork. The AGB was cut as close to the ground as possible. The marketable crop yield was divided into size classes: small, medium and large for the squash crop and different diameter size classes from potatoes: over 7.5 cm, under 7.5 cm, under 6 cm, under 4 cm and under 2.5 cm. Marketable yield was then analyzed for external and internal defects (all potato tubers were analyzed, and four squash fruits from different size classes were randomly selected for quality assessment). The quality of the crop is reported in percentage of the sample showing defects. Marketable yield and AGB were weighed fresh and the AGB was oven dried at 60 C for 48 hours and re-weighed.

2.2.2.2 Soil nutrient cycling

Soil samples from the 0-15 cm and 15-30 cm depths were taken using an Oakfield soil probe (1.9 cm in. dia.) at the beginning of the experiment to determine a baseline for nutrients and soil physical properties. Soil samples were collected every two weeks after the first fertilizer application, from the 0-15 cm depth. From each plot, 3 cores were taken and composited. Soil samples were immediately taken back to the laboratory and extracted for both available NH_4^+ and NO_3^-. A 5-g field-moist subsample was extracted with 25 mL of 2 *M* potassium chloride (KCl) and shaken for 30 min before centrifuging (5000 rpm for 5 minutes) and filtering (Fisherbrand Q2 filters). The extracted samples were frozen until they were analyzed to determine the NH_4^+ (Weatherburn 1967) and NO_3^- (Doane and Horwarth 2003) concentrations by colorimetry. Soil samples were also sent to the Ministry of Environment laboratory to determine extractable P and K using the Mehlich III method, and total C and N using an elemental analyzer.

2.2.3 Greenhouse trial

The greenhouse trial was designed to replicate the potato production from the field experiment in a controlled environment but also to assess the use of the different grades of MKP fertilizers for use in typical greenhouse production of bell peppers (*Capsicum annuum*). For the greenhouse trial, the potatoes received five different treatments, the three MKP fertilizers used in the field trial (MKP-M, MKP-C, MKP-C2), a retail MKP fertilizer from the brand Haifa (retail-MKP) and a typical retail NPK fertilizer. The peppers received the same treatments as the potatoes, with two added treatments: MKP-M and the retail MKP applied as foliar fertilizer sprays. Pots for each crop were placed in a completely randomized design with five replicates. The crops were fertilized weekly for 8 weeks. The fertilizers were mixed with water and either applied directly to the soil for the potatoes at a rate of 225 kg N ha^{-1}, 135 kg P ha^{-1} and 160 kg K ha^{-1}, or applied to the leaves using a spray bottle for the peppers at a rate of 200 kg N ha^{-1}, 60 kg P ha^{-1} and 350 kg K ha^{-1}.

2.2.3.1 Crop productivity

Marketable crop yield was measured for each treatment, as well as the above ground biomass 148 days after planting. The marketable portion of the crop was classed in size classes for potatoes as described above in the field trial; and for peppers: small, medium and large. Four peppers and potatoes of each size classes per treatment were selected to assess external and internal damage of the crop. For the peppers, the fourth pepper was selected from the most dominant size class in the harvest in order to select a representative sample for crop quality determination.

2.2.4 Statistical analysis

Analysis of variance (ANOVA) was used to detect crop productivity differences among fertilizer treatments using block as a fixed effect. If any differences were found, Tukey's range test was then used to determine where the differences occur among treatments. Quality assessment, or internal and external damage count, was assessed using the Chisquare test. And finally, for the PAN results, I used a repeated measures ANOVA using block as a random effect. In cases where there were interactions between the treatments and the sampling dates (time) an ANOVA was run for each date and if significant, a Tukey's range was used. Data was tested for normality using the Shapiro-Wilk test, and when the assumptions for the test were not met, the data was log-transformed. Function plots and qqnorm were used to test mixed models for normality. All statistical analyses were done using R (R Core Team 2016).

2.3 Results

2.3.1 Germination test

The lettuce seed germination trial showed a high rate of germination for all fertilizer treatments (Figure 2.1). By day 5 all treatments had an average germination of >75%, by day 10 >85% and by day 15 > 87% (data not shown). There were no significant differences among the four fertilizer treatments ($P < 0.05$).

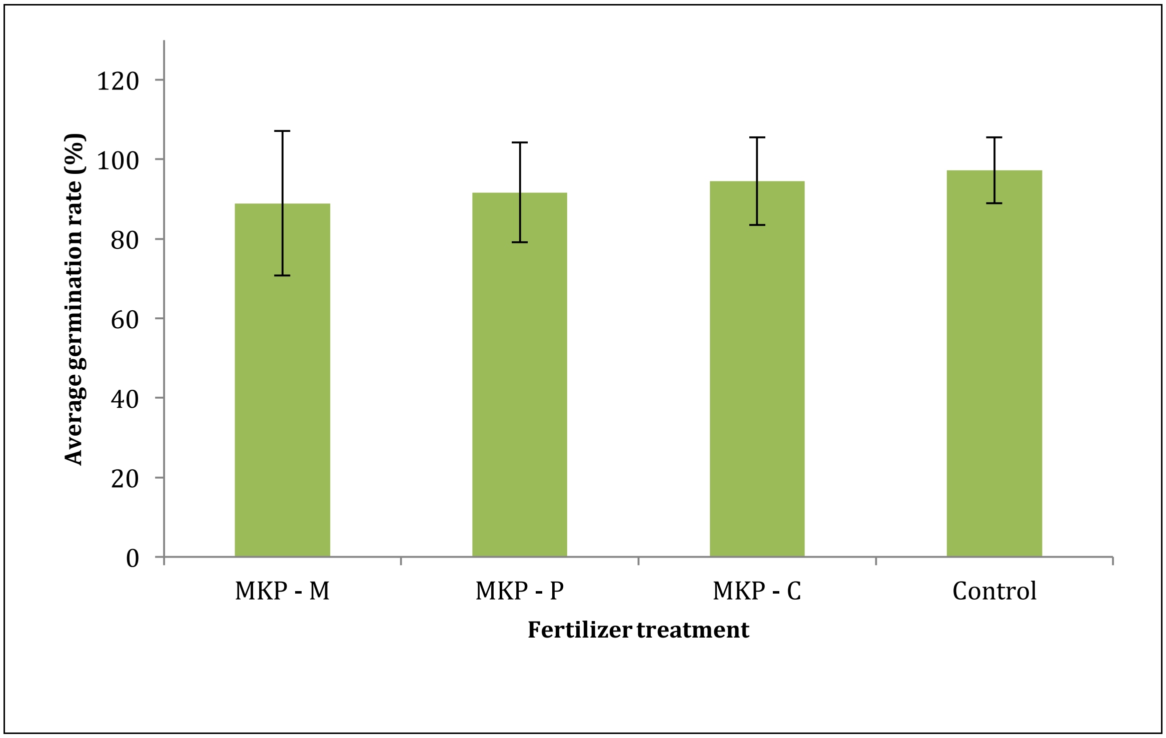

Figure 2.1. Average germination rate on day 15 of the germination trial for three types of monopotassium phosphate (MKP) fertilizer: methanol-washed (MKP-M); Isopropanol-washed MKP (MKP – P); MKP with glycerin (MKP – C); and no fertilizer (Control). Error bars represent standard error. No significant differences were found (P > 0.05).

2.3.2 Field trial

2.3.2.1 Crop productivity

In the field trial, the average yield of potatoes was highly variable both in terms of the total yield and distribution across the size classes (Table 2.1). There were however, no significant differences in ABG or marketable yields among the treatments (P > 0.05). The number of potatoes was consistent across the treatments and again there were no significant differences (P > 0.05).

Observations of the quality of the potatoes was also consistent across the treatments and low for both internal and external defects (<13% of the sample) and there no significant difference found (P > 0.05).

Table 2.1. Average (± standard error) potato yield by size class in kg ha^{-1}, fruit number and potato quality in percent by fertilizer treatment: crude MKP with glycerin (MKP-C); crude MKP with double the amount of glycerin (MKP-C2); high grade MKP washed with methanol (MKP-M); and a commercial NPK fertilizer (retail-NPK). No significant differences were found (P > 0.05).

	Average yield (kg ha^{-1}) by size class (cm)						Average fruit #	Quality (% with defects)	
Treatment	7.5 +	7.5	6	4	2.5	Total yield		External	Internal
MKP-C	2699	5111	3804	244	69	11,925 ± 1,785	12 ± 1.1	0.0	1.3
MKP-C2	1729	4987	2137	207	38	9,097± 941	10 ± 1.4	1.3	1.9
MKP-M	723	5009	4598	186	9	10,523 ± 2,708	10 ± 2.1	0.3	0.3
retail-NPK	3822	7009	3003	135	55	14,024 ± 2,453	9 ± 2.4	3.1	7.0

The results for the squash harvest were similar to potatoes (Table 2.2). There were no significant differences across the treatments for yields or quality (P > 0.05).

Table 2.2. Average (± standard error) squash yield by size class in kg ha^{-1}, average fruit number and squash quality in percent by fertilizer treatment: crude MKP with glycerin (MKP-C); crude MKP with double the amount of glycerin (MKP-C2); high grade MKP washed with methanol (MKP-M); and a commercial NPK fertilizer (retail-NPK). No significant differences were found (P > 0.05).

		Average yield (kg ha-1) by size class				Quality (% with defects)	
Treatment	Small	Medium	Large	Total yield	Average fruit #	External	Internal
MKP-C	2466	3075	13374	18,914 ± 8148	6.0 ± 2.3	0.0	0.0
MKP-C2	5748	9551	16964	32,304 ± 12338	9.5 ± 0.5	0.0	0.0
MKP-M	6477	5510	15847	27,834 ± 8570	9.3 ± 3.0	0.0	0.6
retail-NPK	4454	3849	10460	18,763 ± 6481	6.5 ± 2.7	0.0	0.6

2.3.2.3 Soil properties

Soil concentrations of K, P, total N and total C for both the potato and squash trial were not significantly different for any treatments at either depth (P > 0.05) (Appendix Tables, A.X.1 and A.X.2).

2.3.2.5 Plant available nitrogen

Plant available nitrogen (PAN) in the form NH_4^+-N and NO_3^--N varied substantially in the potato field over the growing season (Figure 2.2). Soil NH_4^+-N content started at 0 mg NH_4^+-N kg^{-1} soil and increased until hitting a peak at 65 days after planting (DAP) before decreasing to its initial values after crop harvest for all treatments (Figure 6.1a). NO_3^--N however decreased until 30 DAP, then increased after the fertilizing events also reaching its peak at 65 DAP and decreasing slightly after harvest (Figure 6.1b). Although time was significant ($P < 0.05$), no significant differences were found for either NH_4^+-N and NO_3^--N by treatment ($P > 0.05$).

Similar to the PAN results for potatoes, NH_4^+-N content in the squash field was close to zero at the beginning of the season, increased until 65 DAP and decreasing after harvest. NO_3^--N decreased from 8 mg kg^{-1} to almost zero and increased after the fertilizing events. It continued to increase after harvest (Figure 2.2). At 32, 48, and 65 DAP, the MKP-C treatment had significantly higher soil NH_4^+-N content than all the other treatments (MKP-C2, MKP-M and NPK) ($P < 0.05$). There were however no significant differences for NO_3^--N content among the fertilizer treatments ($P > 0.05$) (Figure 2.2b).

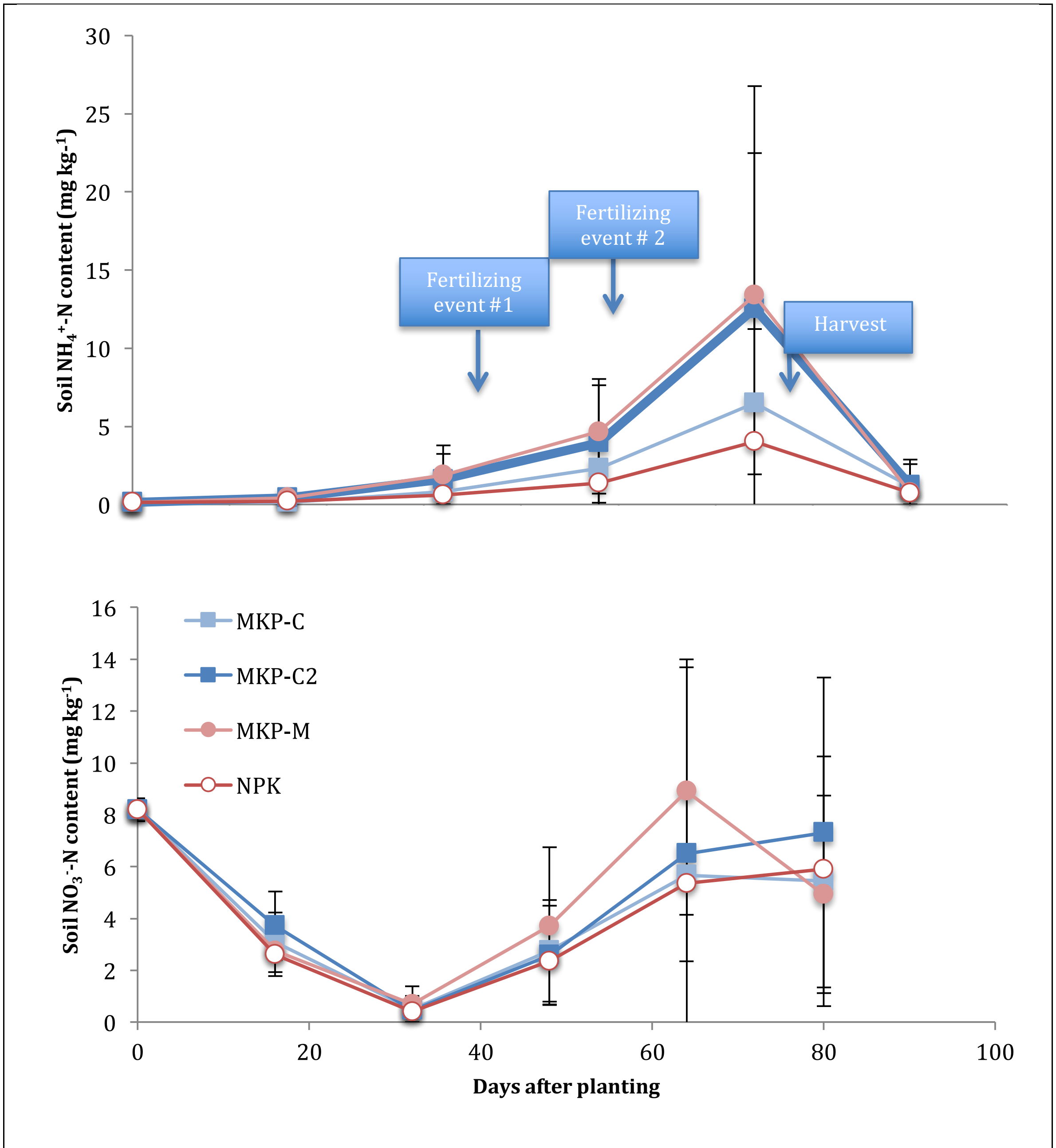

Figure 2.2. a. Soil ammonium (NH_4^+-N) content (mg kg^{-1}) and **b.** soil nitrate (NO_3^--N) content (mg kg^{-1}) throughout the season in the potato field for the different fertilizer treatments: crude MKP with glycerin (MKP-C); crude MKP with double the amount of glycerin (MKP-C2); high grade MKP washed with methanol (MKP-M); and a commercial NPK fertilizer (retail-NPK). Error bars represent the standard error. No significant differences among treatments were found ($P < 0.05$).

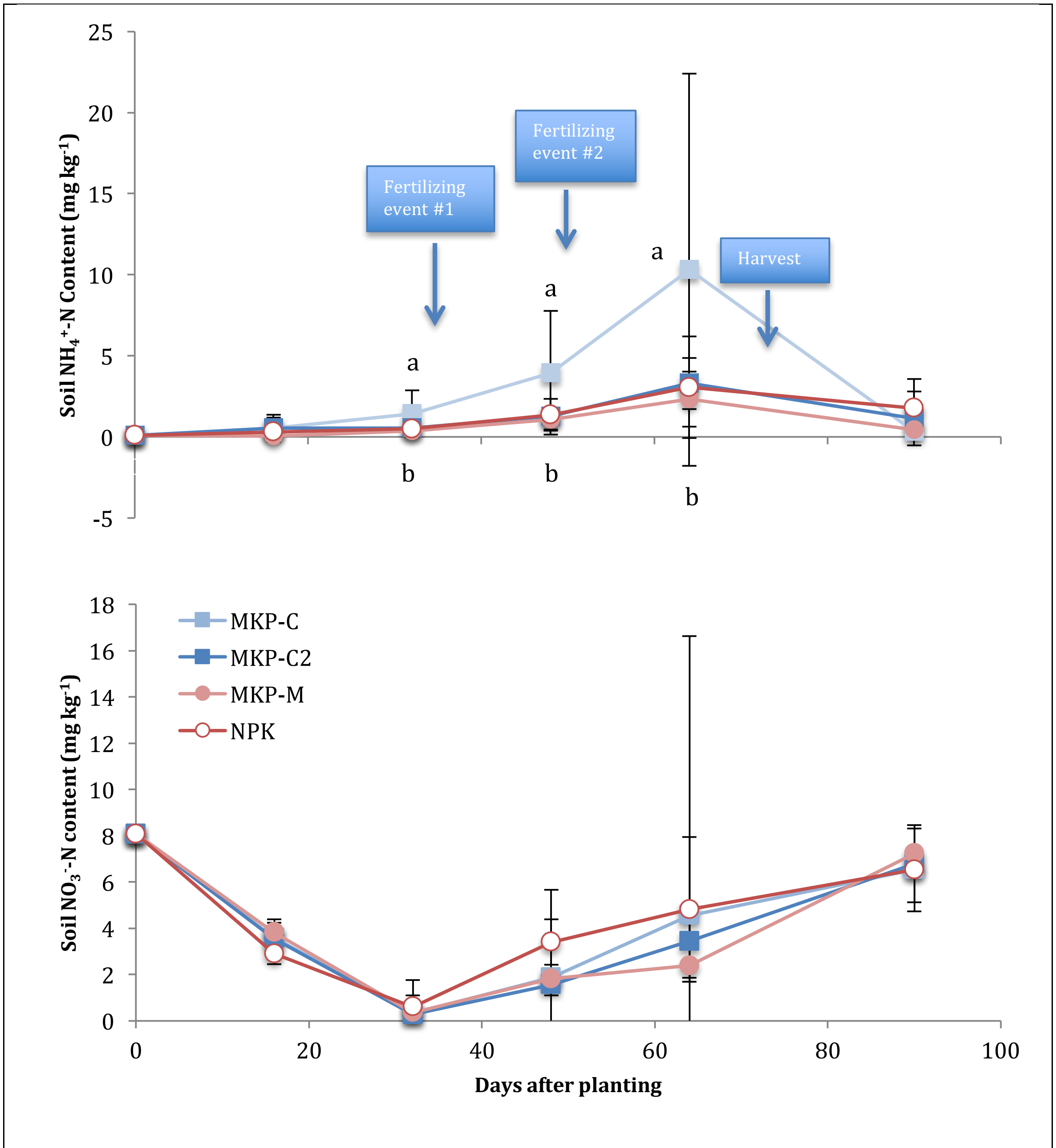

Figure 2.3. a. Soil ammonium (NH_4^+-N) content (mg kg^{-1}) and **b.** soil nitrate (NO_3^--N) content (mg kg^{-1}) throughout the season in the squash field for the different fertilizer treatments: crude MKP with glycerin (MKP-C); crude MKP with double the amount of glycerin (MKP-C2); high grade MKP washed with methanol (MKP-M); and a commercial NPK fertilizer (retail-NPK). Error bars represent the standard error. Letters indicate significant differences ($P < 0.05$).

2.3.3 Greenhouse trial

In the greenhouse trial, potato yields were significantly different among fertilizer treatments ($p<0.0001$) (Table 2.3). Potatoes yields varied by over 60% from 207 grams per pot for retail-MKP to 75 g per pot for MKP-M. Yields for retail NPK were 147% higher than MKP -M but were not significantly different from MKP-C or MKP-C2. There were also significant differences in the number of potato tubers among the different treatments ($P < 0.05$). Retail-MKP had four times more fruits than the lowest treatment, MKP-M. There were no significant differences found for internal and external damage among the treatments ($P > 0.05$).

Table 2.3. Average (± standard error) potato yield by size (g pot^{-1}), average fruit number and potato quality in percent by fertilizer treatment in the greenhouse: crude MKP with glycerin (MKP-C); crude MKP with double the amount of glycerin (MKP-C2); high grade MKP washed with methanol (MKP-M), commercial NPK fertilizer (retail-NPK) and commercial MKP fertilizer (retail-MKP). Five pots were measured per treatment. Significant differences ($P < 0.05$) are indicated by different letters.

Treatment	Average yield (g pot^{-1})	Average tubers (# plot^{-1})	Quality (% with defects)	
			External	Internal
MKP-C	198.9 ± 21.7 **ab**	6.2 ± 1.4 **ab**	0.0	0.0
MKP-C2	106.7 ± 5.4 **abc**	3.6 ± 1.6 **ab**	1.3	0.0
MKP-M	83.6 ± 10.7 **c**	2.4 ± 0.7 **b**	0.0	0.0
Retail-MKP	207.6 ± 16.2 **a**	8.6 ± 0.9 **a**	0.0	1.3
Retail-NPK	142.7 ± 17.2 **b**	4.6 ± 0.5 **ab**	1.3	0.0

In the greenhouse trial, the yield of peppers varied by 85% between MKP-C2, the lowest yielding treatment, and the MKP-M-foliar treatment (Table 2.4). MKP-M-foliar and MKP-C had significantly higher yield ($P < 0.05$) than MKP-C2 and retail-NPK but did not differ from the other treatments. The number of fruits per pot for peppers varied from 1 pepper only on average for Retail-NPK to 6 peppers per pot for MPK-M-foliar. MKP-M-foliar, retail-MKP-foliar, and retail-MKP had the highest number of fruits and were significantly ($P < 0.05$) greater than retail-NPK. There were no significant differences among the other fertilizer treatments ($P > 0.05$). MKP-M-foliar was the only fertilizer treatment with no internal or external damage; all other treatments had both some type of internal and external damage. While some fertilizer treatments had external and/ or internal damage, and others did not, no significant differences were found among the treatments ($P > 0.05$).

Table 2.4. Average (± standard error) pepper yield by size (g pot^{-1}), average fruit number and potato quality in percent by fertilizer treatment in the greenhouse: crude MKP with glycerin (MKP-C); crude MKP with double the amount of glycerin (MKP-C2); high grade MKP washed with methanol (MKP-M); and a commercial NPK fertilizer (retail-NPK), commercial MKP (Retail-MKP) and commercial MKP and MKP-M sprayed foliarly (retail-MKP-foliar; MKP-M-foliar). Five pots were measured per treatment. Significant differences ($P < 0.05$) are indicated by different letters.

Treatment	Average yield (g)	Average fruit (#)	Quality (% with defects)	
			External	Internal
MKP-C	163.1 ± 13.9 **a**	5.2 ± 0.8 **ab**	0.0	1.3
MKP-C2	31.9 ± 18.7 **b**	2.0 ± 1.1 **ab**	2.5	1.3
MKP-M-foliar	199.2 ± 27.0 **a**	6.4 ± 1.0 **a**	0.0	0.0
MKP-M	105.7 ± 9.8 **ab**	4.2 ± 0.7 **ab**	0.0	2.5
Retail MKP-foliar	126.6 ± 10.7 **ab**	5.4 ± 1.2 **a**	2.5	2.5
Retail-MKP	131.3 ± 11.2 **ab**	5.2 ± 0.9 **a**	0.0	1.3
Retail-NPK	78.3 ± 12.9 **b**	1.2 ± 0.7 **b**	2.5	2.5

2.4 Discussion

2.4.1 Germination test

The results from the germination test indicated that there are no concerns with the MKP fertilizers or the glycerin for germination. All the treatments had a germination rate of above 90% and there were no significant differences among the germination rates for the different treatments. These results were consistent with Soerens and Parker (2012) who also looked at the effects of glycerin on germination and found no impacts.

2.4.2 Field trial

Overall, there were no significant differences among the fertilizer treatments applied to the crops in the field trial. Crop yields, number of tubers or fruits and the crop quality were similar regardless of fertilizer type. While the variability was high for some of the results these were likely due to differences in soil properties that were not measured across the field. However, I did see a trend in performance showing that the mean yield and number of tubers/fruits was the highest for the retail NPK fertilizer and the MKP–M fertilizer and the lowest consistently being MKP–C2. This trend was also consistent with the visual observations of the field trial, with the retail NPK and MKP –M having the largest and healthiest looking plants, and the MKP–C2 and MKP-C having the smallest plants, with smaller or fewer fruits and some damage to the plants. While on one hand these results are promising, suggesting that BCP fertilizers are as effective as retail NPK we had expected that they would outperform the retail NPK. When Hopkins et al. (2010), carried out a similar experiment, comparing yield and quality of potatoes using a retail potassium nitrate (KNO_3) fertilizer and MKP fertilizer, they found significantly higher yield for the potato crops fertilized with MKP (Hopkins et al., 2010). They suggested this was due to the low P concentration in the soil and MKP providing potato crops with P mid-season, boosting tuber production. The quality was also higher for the same reasons (Hopkins et al., 2010). The baseline concentrations of P in the potato field in my study were above

200 mg kg^{-1} of soil for all treatments, indicating that the potatoes were not likely deficient in P (Penn State Extension, 2002). There would therefore be no benefit to adding additional P which could partly explain the lack of significant differences in yield among the different treatments.

For the PAN results, given that two of the fertilizer treatments (MKP-C and MKP-C2) contain glycerin, a nitrification inhibitor, I expected to see higher NH_4^+-N levels over the season in these treatments and lower NO_3^--N contents. Glycerin is thought to be a promising soil amendment to reduce N loss and promote its use efficiency (Liu et al., 2013). Nitrification inhibitors, such as glycerin, work by temporarily stopping nitrifying bacteria from turning NH_4^+ to nitrite (NO_2^-) (from several weeks to several months) (Liu et al., 2013). They deactivate the ammonia monooxygenase enzyme responsible for the oxidation of NH_4^+ to NO_2^-. Nitrogen in the soil is therefore kept in the form of NH_4^+-N for longer, which increases nitrogen uptake opportunities for plants (Kim et al., 2012). Liu et al., (2013) also found differences in treatments when they conducted a study where glycerin, a reported nitrification inhibitor, was added to the soil. The results from their experiment show that the application of glycerin significantly increased the NH_4^+-N content of the soil which could contribute to increasing the N uptake of the plant and ultimately, crop yields (Liu et al., 2013). Although I observed increased N availability in the squash trial I did not see this result in differences in yields. Surprisingly, this pattern of increased NH_4^+-N was only observed for the MKP-C treatment in the squash trial, and not the treatment MKP-C2 which had double the concentration of glycerin or in the potato trial. In a review of N inhibitors Liu et al 2013, found that that very low application rates often had similar or better inhibition effects. While no explanation was given as to why very low rates performed as well and in some cases, better, this is consistent with my findings.

The sampling protocol I used might help explain why PAN differed for the squash and not the potatoes. For the potato crop, the fertilizer was applied at the base of each plant, while soil samples were taken at a minimum distance of 30 centimeters of the plant to avoid causing any damage to the roots given the sampling intensity. It is possible that soil samples were taken outside of the area most influenced by the BCPs. For the squash crop however, the zone of influence was likely much wider given that when the fertilizer was sprayed on the leaves and dripped to the ground at the edge of the canopy.

2.4.3 Greenhouse trial

The results from the greenhouse trial showed clear differences among the fertilizer treatments in terms of crop yield and fruit number for both potatoes and peppers. For potatoes, there were interesting differences in yields. While the retail-MKP fertilizer resulted in higher yields than retail-NPK, the MKP-M surprisingly did not. There were however clear yield benefits from the addition of glycerin (MKP-C). Again, this could be due to the nitrifying effect of the glycerin in the MKP-C, which is what I had expected to see. The results for the MKP-C2 were consistent with those of the field trial in that it did not perform better than the lower dose of glycerin. For the peppers, a similar trend was observed where the yields of the MKP–C treatment were significantly higher than the NPK fertilizer but the MKP-C2 was not. For the number of fruits, significant differences can be seen in both potatoes and peppers. Interestingly the foliar applications of MKP resulted in higher yields and a greater number of peppers. In this case, we could assume that applying the MKP–M and Retail-MKP to the leaves increased the uptake of P and K by the plants, which was shown to increase the number of peppers produced (Boman and Hebb, 1998). The uptake of K by the plants post-bloom induces fruit production. Similar results were reported in an experiment using grapefruit that showed there was a higher proportion and bigger fruits when MKP was applied to the leaves post-bloom as opposed to a soil application or a retail NPK fertilizer, which was also applied to the soil (Boman and Hebb, 1998).

The yields of the MKP-C2 treatment were low because of the mortality of three out of the five plants. Mortality was observed only in the MKP-C2 treatment suggesting the additional glycerin contributed to the losses. Soerens, 2012, when looking at adding glycerin as a soil amendment determined that adding more than 1% glycerin of the total volume of the growing medium was detrimental to plant growth, which is likely due to the hygroscopic properties of glycerin. The glycerin could have absorbed the water and made it unavailable to the plants (Soerens, 2012). In my study, I added over 20% of the total volume of MKP-C2 which corroborates with this threshold and explains the sudden wilting of three pepper plants in the MKP-C2 treatment.

2.5 Conclusion

In the germination trial, no differences were seen among the BCP fertilizer treatments and the control, indicating MKP fertilizers or added glycerin do not inhibit germination. The results of the field trial indicate that BCP fertilizers perform no differently than retail fertilizers in terms of crop yields, numbers and quality. The BCP fertilizers did however impact the availability of soil NH_4^+-N. In the squash trial, MKP treatments with added glycerin consistently had higher concentrations of NH_4^+-N. This is probably due to the immobilization of N by an increase in microbial communities facilitated by the addition of C in the glycerin. After the glycerin is consumed, N is once again available for plant uptake. For the greenhouse trial, both potatoes and peppers showed differences in yield and number of tubers. In the controlled environment of the greenhouse I observed clear differences in the performance of the BCP fertilizers. The MKP-C fertilizer performed as well as retail MKP fertilizer and better than retail NPK. Doubling the glycerin (i.e. MKP-C2) however, has a negative impact on pepper productivity, resulting in a high rate of mortality. The treatments that were most beneficial for greenhouse growth are MKP fertilizers with urea applied directly to the leaves, likely due to the direct uptake of the nutrients by the plants. And finally, there were no differences in crop quality among the different treatments. The results of this series of experiments indicate BCP fertilizers could be sold as a substitute for current retail fertilizers and may even have some additional benefits if used appropriately.

3. The effects of high-throughput in-vessel compost on soil properties and crop productivity

3.1 Introduction

Food waste disposal has become an important problem worldwide. For example, in the United States of America, over 97% of food waste is buried in landfills (Levis et al., 2010). Efforts to divert food waste from landfills have led to the development of alternative technologies that promise to be more sustainable (Kim et al., 2008). Composting, which is defined as the biological decomposition and stabilization of organic waste under specific temperature, is the most popular option for food waste disposal given its low environmental impact (Kim et al., 2008). It is also attractive as it generates a product from food wastes that can be used to grow food, closing the loop between food production and food waste. Over the last few decades, in-vessel composting has known major advancements and has grown in popularity and is now used in many large scale municipal composting operations (Areikin et al., 2012). The in-vessel composting process occurs within a chamber where environmental factors are controlled, and contains a biofilter to prevent odor and dust from escaping the chamber. The advantages associated with in-vessel composting are: less space required for the composting process, higher processing efficiency, and control of the odor and dust typically associated with composting (Areikin et al., 2012; Kim et al., 2008).

While in-vessel composting has many advantages, a number of studies have evaluated how the impacts of using in-vessel compost differs from more typical compost (e.g. static pile, turned windrow). Iyengar and Bhave (2006), report that in-vessel composting creates a product of higher quality than typical composting; characterized by higher concentrations of humus that is known to help enhance soil physical properties and provide basic plant nutrients. Kim et al., (2008), also report that the in-vessel compost is well suited for agricultural use, based on compost maturity, electrical conductivity, and heavy metals concentrations. Large scale, in-vessel compost has been used for agricultural production for many years and has clearly demonstrated that it can produce a nutrient rich, pathogen free source of organic inputs to maintain soil functioning effectively (Langarica-Fuentes et al., 2014). Within the last few years, there have been substantial advances in this type of technology that has reduced the size of the machinery and the speed in which a batch is processed, thus enabling high throughput of organic materials. While large scale in-vessel composting has been studied extensively, there is little to no information on the effects of using high-throughput compost made in vessels that are using new technologies that allow the production of a compost-like product in as little as 24 hours.

High throughput in-vessel (HTI) compost differs from other compost operations primarily in terms of the time food waste is processed. The makers of HTI machines are promising a usable by-product from food waste within 24 hours, and the reduction of the input materials by 80% to 90%. This processing rate is far faster than other composting types, for example in-vessel composting, only reduces the materials by as much as 65% to 70% over 30 days (Iyengar and Bhave, 2006). These changes are likely to affect the stability and maturity of the compost, two important factors that affect crop productivity and nutrient cycling.

It is likely that the materials made in HTI composters in only 24 hours are still highly microbially active and will continue to decompose after being applied to soil (Benito et al., 2003). When unstable or immature compost is applied as a soil amendment, it can lead to anaerobic conditions for micro-organisms due to the decomposition of organic materials, which can lead to nitrogen immobilization and high greenhouse gas emissions (Benito et al., 2003) N immobilization increases with the increase in microbial communities (which increases with the addition of undecomposed organic matter) due to the assimilation of the inorganic N contained in the soil (Aoyama and Nozawa, 1993). Under anaerobic conditions, we are likely to see an increase in CH_4, a greenhouse gas 34 times more powerful than CO_2. Anaerobic conditions also lead to microbial communities inefficiently utilizing N, which can result in increased N_2O emissions, a greenhouse gas 298 times more powerful than CO_2. For these reasons, I want to determine if by mixing this immature material with either a readily available N source (e.g. fertilizer or bloodmeal) or an already mature compost, the immobilization impacts could be minimized. Another issue associated with unstable and immature composts is phytotoxicity due to organic acids produced in the early stages of composting (He et al, 1995).

The overarching objective of this study is to better understand the potential for utilizing HTI compost, an unstable and immature compost, in the production or organic vegetables. More specifically, I wanted to assess: 1. The impact of various rates of HTI compost on seed germination 2. How HTI alone or mixed with mature compost or bloodmeal, an organically certified N rich fertilizer, affects crop productivity, soil N availability and GHG emissions.

3.2 Materials and methods

3.2.1 Germination trial

The first experiment carried out was a germination trial in the Horticulture Greenhouse at UBC, to ensure that the HTI compost does not inhibit seed germination. Four lettuce seeds (*Lactuca satvia*) were planted per pot, to test the HTI at different application rates: The application rate set for meeting crop N demands for the field trials, 29 Mg ha^{-1} (1x), half the field application rate (0.5x), twice the application rate (2x), ten times the field application rate (10x), twenty times the application rate (20x), and no amendment as the control (0x). There were four replicates per treatment, and the pots were randomly ordered to account for any variation within the greenhouse environment. The pots were watered daily by the greenhouse staff as they would typically for plant germination. A germination assessment, or the number of germinated seeds per treatment, was done on day 15, and the biomass of the seedlings was measured.

3.2.2 Field trial

3.2.2.1 Crop productivity

Shortly following the germination trial, in July 2016, a field trial was conducted at the UBC Farm. The UBC Farm, run by the Center for Sustainable Food Systems, is 24-ha research and production farm located on the UBC campus in Vancouver, British Columbia. The climate is a moderate oceanic climate with mild and wet winters and dry summers. The soil type at the farm is a sandy loam from the Bose soil series.

The field trial was established to test the response of beets (Beta vulgaris) and spinach (*Spinacia oleracea*) crops to different compost treatments: HTI compost, HTI compost and bloodmeal, HTI compost and UBC Farm compost, UBC Farm compost and no compost. The amounts of compost and bloodmeal that were applied to the plots were calculated using an average of the recommended rates of N at 150 kg ha^{-1} (Appendix Table A.X.4). For both crops, management followed UBC Farm's typical production practices for planting, spacing, weed control, irrigation rate and frequency, and other management practices for optimal plant growth. Compost treatments were applied a week before planting to plots that were three beds (70 cm of bed and 30 cm of path) wide and 5 m long. Treatments were applied in a completely randomized block design to account for the differences in soil properties across the field, with four replicates each (20 plots total).

For both the spinach and beet crops, yield was measured when it was considered marketable. For the spinach, only the marketable aboveground biomass (AGB) was harvested. For the beets, the yield was obtainable for the marketable root of the crop. Yields were taken within a randomly selected 2-m length of the bed, buffering greenhouse gas collars and edges of the plots.

3.2.2.2 Soil analysis

Soil samples at 0-15 cm depths were taken using an Oakfield soil probe (1.9 cm in. dia.) at the beginning of the experiment, to determine a baseline for nutrients and soil physical properties. To determine extractable P and K, a Fourier Transform Infrared (FTIR) spectrometer was used. Total C and N were measured by combustion on a Vario EL Cube Elemental Analyzer (Elementar, Langenselbold, Germany). From each plot, four cores were taken and composited. Soil samples were then collected every two weeks after the first treatments application, again at the 0-15 cm depth. Soil samples were taken back to the laboratory and extracted for the plant available nitrogen (PAN) content in the form of ammonium (NH_4^+-N) and nitrate (NO_3^--N). A 5-g field-moist subsample was extracted with 25 mL with 2 *M* potassium chloride (KCl), shaken for 30 min before centrifuging (5000 rpm for 5 minutes) and filtering (Fisherbrand Q2 filters). The extracted samples were frozen until they were analyzed to determine the

NH_4^+-N (Weatherburn 1967) and NO_3^--N (Doane and Horwarth 2003) concentrations by colorimetry.

3.2.2.3 Greenhouse gases measurements

Soil GHG measurement were taken every ten days throughout the growing season using a Picarro G208 cavity ring down spectrometer (Picarro Inc., Santa Clara, CA, USA). Simultaneous measurements of N_2O, CO_2 and CH_4 were made using a non-steady state chamber system (Christiansen et al., 2015). An opaque chamber lid with a fan was used to cap 15-cm long PVC collars with a 20-cm inner diameter pounded into the soil at the beginning of the season leaving 5-10 cm above the surface. Gas accumulation in the headspace was measured during a 5-min enclosure. Air was re-circulated at a rate of 2 L min^{-1} using a vacuum pump during measurements. After each sample, the system was flushed with outside air (10 L min^{-1} for 2 min) to reduce gas concentrations to background levels. Greenhouse gas fluxes were computed with MATLAB v. R2014a (MathWorks Inc. 2014), using the following formula:

$$F = (\rho * S * V) / (A)$$

where F is the flux (μmol m^{-2} s^{-1}), ρ is the molar density (mole m^{-3}) of dry air (i.e., corrected for the average mixing ratio of water measured during measurements), S is the slope of GHG accumulation within the headspace (μmol mol^{-1} s^{-1}), V is the headspace volume (m^{-3}), and A is the headspace area (m^{-2}). The slope of gas accumulation was measured by linear regression, and slopes were utilized without further modification if the coefficient of determination (R^2) was greater than 0.75. Slopes with $R^2 < 0.75$ were visually examined and converted to zero (if no quantifiable gas accumulation in the headspace) or removed (when measurement issues were observed).

Cumulative GHG fluxes were computed using linear interpolation between measurements (Gana et al., 2016), using the following formula:

$$F(t) = F(t_1) + (t - t_1) * (F(t_2) - F(t_1))/(t_2 - t_1)$$

where $F(t_1)$ and $F(t_2)$ are fluxes at time t_1 and t_2, and $t_1 < t < t_2$.

3.2.2.4 Soil incubations

Soil samples were collected at a depth of 0-15 cm from each plot at the end of the growing season to determine if there were any differences in microbial communities among the different soil amendments using methods modified from (Franzluebbers, 1999). From each plot 3 cores were taken and composited. The soil samples were air dried, ground using a rolling pin and passed through a 2-mm sieve. 80 grams of soil was then re-wetted, and incubated in 1 L mason jars with 10 mL of distilled water and 10 mL of sodium hydroxide (NaOH) for a 3-day period, as described by Franzluebbers (2016). Two vials containing only NaOH and distilled water were incubated to determine the ambient concentration of CO_2. The NaOH was then collected and mixed with 3.5 mL of 1.5 M barium chloride ($BaCl_2$) and two drops of phenolphthalein color indicator, and titrations were performed using hydrochloric acid (HCl). The amount of HCl used in the titrations was then converted to the evolved amount of CO_2 from the soil sample using the following equation (Franzluebbers, 1999).

$$\text{Flush of } CO_2 \text{ (mg } CO_2 - C \cdot kg^{-1} \text{ soil)} = (V_{[blank]} - V_{[\text{sample}]}) \cdot C_{HCl} \cdot k/m$$

where:

$V_{[blank]}$ = total volume of HCl used in titration of blank (mL)

$V_{[sample]}$ = total volume of HCl used in titration of sample (mL)

C_{HCl} = concentration (normality) of acid (mol/L)

k = 6000, a conversion factor involving molar mass of carbon, mol ratio between *HCl* and CO_2 and unit conversion from L to mL and g to kg

m = soil mass (g)

3.2.3 Statistical analysis

Germination, yield, soil properties and soil incubation results were compared for significant differences among treatments using analysis of variance (ANOVA). If any differences were found, Tukey's range test was used to determine where differences occur among treatments. For soil PAN and GHG measurements, a linear mixed effect model was used, using treatment, time and treatment x time interaction as fixed effects with block as a random effect. If an interaction between treatment and time was found, an ANOVA was used to look at the differences among the treatments for each sampling date. Data was tested for normality using the Shapiro-Wilk test, and when the assumptions for the test were not met, the data was log-transformed. Function plots and qqnorm were used to test mixed models for normality. Statistics were done R Studio Version 0.99.491 (R Core Team 2016).

3.3 Results

3.3.1 Germination test

Differences in germination and biomass were found during this trial, with high concentrations of HTI compost resulting in lower germination rates and lower biomass. The lettuce seed germination trial showed no significant differences in germination rate among the 0x, 0.5x, and 2x application rates with all three treatments having a germination rate of above 80%. The 0x treatment had a significantly higher germination rate than 1x, 10x, and 20x, which were not significantly different. The 20x, which has a significantly lower germination rate than all the other treatments, with a germination rate of around 10% (Figure 3.1.a).

The lettuce seedling biomass resulted in a somewhat different pattern. Again, there were no significant differences in average biomass among treatments with low application rates of HTI, 0x, 0.5x, 1x, and 2x, with values ranging from 0.87 g for 0x to 0.55g for 0.5x. The biomass of 10x was four times lower than the highest biomass and 20x was even lower, 100 times lower than the highest biomass, at only 0.15 g and 0.008 g respectively (Figure 3.1.b).

3.3.2 Crop productivity

Crop productivity results showed that UBC farm compost had a higher yield than HTI compost and HTI compost + bloodmeal for spinach, but no significant differences in yield were found for the beets. UBC Farm Compost spinach yields were twice as high as either the HTI compost or HTI compost + bloodmeal (Figure 3.2.a). There were however, no significant different among the other treatments. The biomass of marketable beet yields ranged from an average of 17,000 kg ha^{-1} in the HTI + UBC farm treatment to 20,000 kg ha^{-1} in the HTI compost and UBC farm compost treatments (Figure 3.2.b) but there were no significant differences ($P > 0.05$).

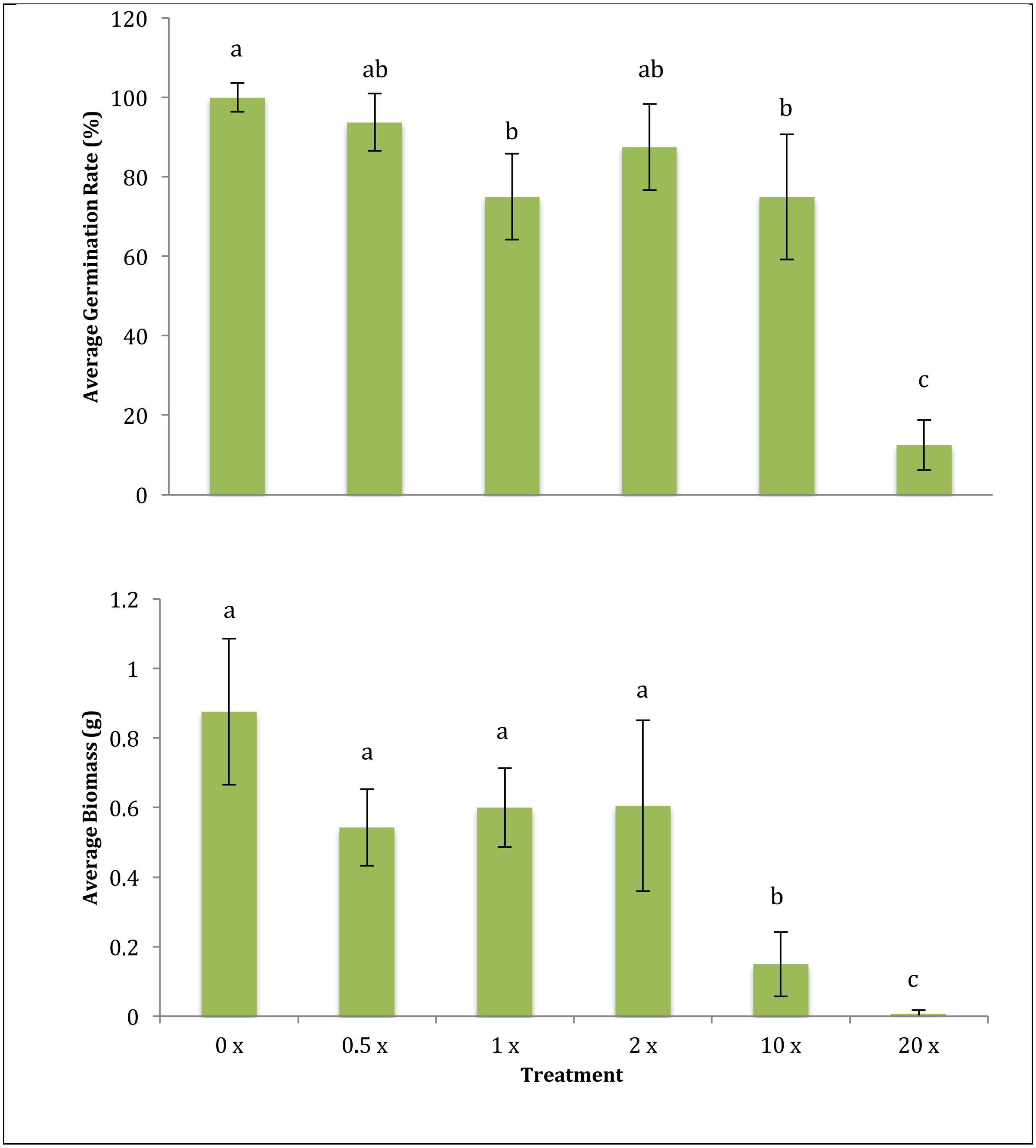

Figure 3.1. a. Average germination rate (%) and **b.** average biomass (g) on day 15 of the germination trial for six application rates of high throughput in-vessel (HTI) compost: 0x – no HTI compost, 0.5x – half the field application rate, 1x - field application rate, 2x – double the field application rate, 10x – ten times the field application rate, and 20x – twenty times the field application rate. Error bars represent standard error. Different letters represent significant differences ($P < 0.05$).

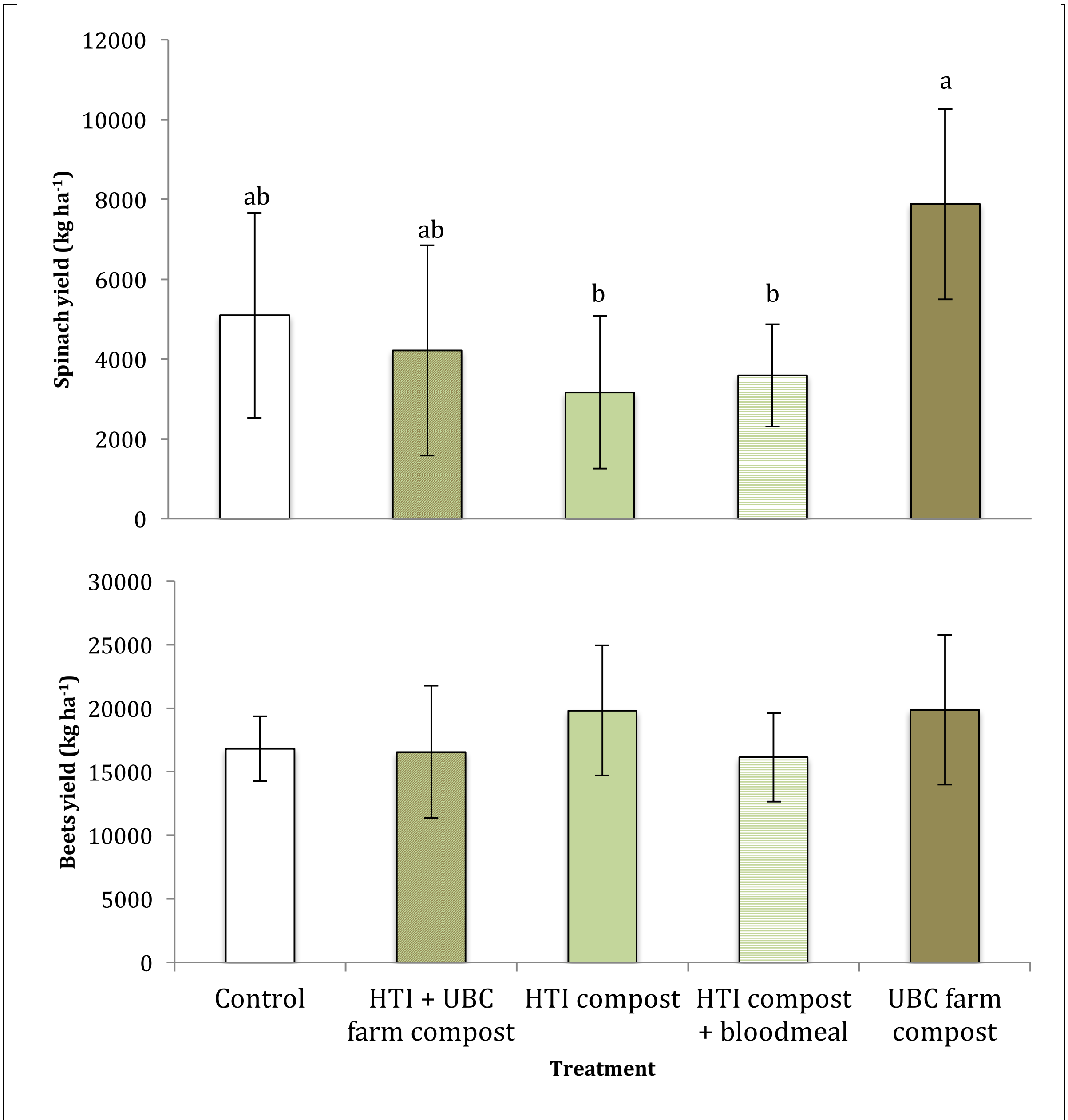

Figure 3.2. a. Average spinach and **b.** beet yield (kg ha^{-1}) by treatment: Control represents no soil amendment, HTI + UBC Farm compost is a mixture of the current UBC Farm management practice with the high throughput in-vessel (HTI) compost, HTI compost is the high throughput in-vessel compost alone, HTI compost + bloodmeal is a mixture of HTI compost and bloodmeal, and UBC Farm compost is the farm's current management practice only. Error bars represent standard error. Different letters represent significant differences ($P < 0.05$).

3.3.3 Soil analyses

Endline samples showed no significant differences among the treatments in average soil %N, %C or C:N ratios ($P < 0.05$) (Table 3.1). These results show that the different amendments to the soil did not alter any of its basic physical properties or nutrient contents.

Table 3.1. Average (± standard error) endline soil properties for nitrogen (%N), carbon (%C) and C:N ratio per treatment: Control consists of no soil amendment, HTI + UBC farm compost is a mixture of the current UBC farm management practice with the high throughput in-vessel (HTI) compost, HTI compost is the high throughput in-vessel compost alone, HTI compost + bloodmeal is a mixture of HTI compost and bloodmeal, and UBC Farm compost is the farm's current management practice only. No significant differences were found ($P > 0.05$).

Treatment	% C	% N	C:N ratio
Control	6.40 ± 0.46	0.39 ± 0.03	16.5
HTI + UBC farm compost	7.50 ± 0.62	0.48 ± 0.04	15.7
HTI compost	7.20 ± 1.31	0.50 ± 0.10	14.8
HTI compost + bloodmeal	6.51 ± 1.10	0.42 ± 0.06	15.6
UBC farm compost	7.33 ± 1.60	0.48 ± 0.07	15.3

3.3.4 Plant available nitrogen

Plant available nitrogen in terms of both soil NH_4^+-N and NO_3^--N was highly variable over the season. Although there were significant effects for date and treatment for both NH_4^+-N and NO_3^--N, their response varied by sampling date as the interaction was significant (Table 3.2). Through most of the season there were significant differences among treatments but the response pattern varied by sampling event. Soil NH_4^+-N concentrations were in general almost twice those found for NO_3^--N.

Soil NH_4^+-N content increased after compost application and peaked by sampling event 4 on August 17th, before decreasing to its initial values (Figure 3.3a). At the first sampling event after treatment application (Sampling event 2, on July 21st), there were no significant differences in soil NH_4^+-N content among the treatments.

At sampling event 3 on August 3rd, HTI compost had a significantly higher soil NH_4^+-N content than the other treatments. At sampling event 4 on August 17th, HTI compost, HTI compost + bloodmeal and UBC farm compost had between 4 to 5 times the soil NH_4^+-N content of the other two treatments. By sampling event 5 and 6, only the HTI compost treatment was significantly higher in soil NH_4^+-N content than the other treatments, with around three times more soil NH_4^+-N content than the other treatments.

The overall trend for soil NO_3^--N content over the growing season showed that soil NO_3^--N increased for UBC farm compost and the control shortly after compost application, while it increased for HTI compost later on in the season (one week later). Soil NO_3^--N content for HTI compost + UBC farm and HTI compost + bloodmeal did not increase as much as the other treatments. After sampling event 4 on August 17th, soil NO_3^--N content decreased for all treatments except for HTI compost, which was significantly higher than all the other treatments (Figure 3.4b). At the second sampling event on July 21st, after treatment application, there are no significant differences among the treatments. At sampling event 3 on August 3rd, the UBC farm compost had a significantly higher soil NO_3^--N content than the other treatments. For sampling events 4, 5 and 6, the only significant difference was for HTI compost, which consistently had a significantly higher soil NO_3^--N content than the other treatments until the end of the growing season.

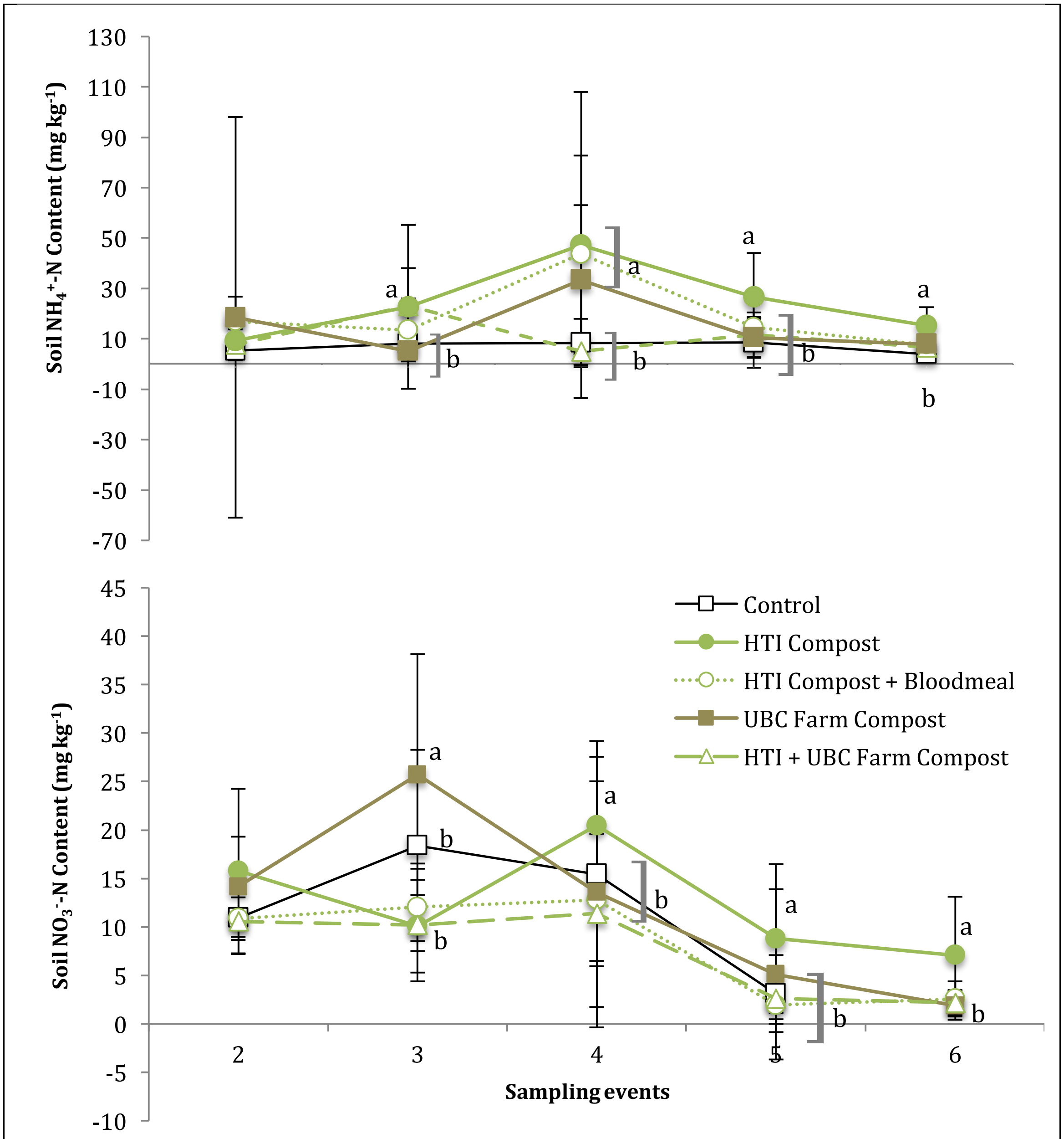

Figure 3.3. a. Soil ammonium (NH_4^+-N) content and b. soil nitrate (NO_3^--N) content in mg kg^{-1}. Control is no soil amendment, HTI + UBC Farm compost is a mixture of the current UBC Farm management practice with the high throughput in-vessel (HTI) compost, HTI compost is the high throughput in-vessel compost alone, HTI compost + bloodmeal is a mixture of HTI compost and bloodmeal, and UBC Farm compost is the farm's current management practice only. Error bars represent standard error and different letters represent significant differences ($P < 0.05$).

Table 3.2. F and P value for nitrate ($NO3^{-}$-N) and ammonium (NH_4^+-N) soil content by treatment, by date and by the interaction of treatment and date.

	NO_3^--N		NH_4^+-N	
	F	P	F	P
Treatment	4.01	0.02	3.69	0.03
Date	0.30	0.00	4.65	0.05
Treatment*Date	7.03	0.02	9.73	0.02

3.3.5 Greenhouse gases emissions

3.3.5.1 Seasonal emissions

Fluxes of all three GHGs varied over the course of the season and there was a significant interaction between treatment and date (Table 3.3). Fluxes of N_2O increased for HTI compost, HTI compost + bloodmeal and HTI compost + UBC farm compost in the middle of the season for a couple of weeks before decreasing to initial values. Alternatively, the UBC farm compost and control treatments had low and stable emissions (Figure 3.4a). The fluxes of CO_2 and CH_4 were highest at the beginning of the season for treatments containing HTI compost, peaking at the second and third sampling date respectively before decreasing and leveling out (Figure 3.4b and c). UBC farm compost and the control treatments had stable CO_2 and CH_4 fluxes over the season.

For the first five sampling events, there were no significant differences in N_2O fluxes among the different treatments (Figure 3.4a). On August 12th, all the treatments containing HTI compost; HTI compost, UBC farm + HTI compost and HTI compost + bloodmeal had a significantly higher N_2O flux than the other two treatments. On August 19th, HTI compost had a significantly higher N_2O flux than all the other treatments with a N_2O flux of over 10 mg m^2 day^{-1}, which is twice as much as the next highest treatment; HTI + UBC farm compost, and HTI compost + bloodmeal also had higher N_2O fluxes than the other two treatments. On August 26th, HTI compost had a higher N_2O flux than all the other treatments. For the rest of the sampling events, there were no significant differences in fluxes among the treatments, but on September 23rd, HTI compost once again was significantly higher than all the other treatments.

At the first sampling event, on July 8th, there were no significant differences in CO_2 flux among the treatments (Figure 3.4b). On July 15th, the CO_2 flux of the HTI compost treatment was 16 times higher than the lowest treatments (UBC farm and control) and over 3 times more CO_2 flux than HTI compost + bloodmeal and HTI + UBC farm compost. On July 22nd and 29th, the HTI compost treatment had a significantly higher CO_2 flux, but there were no differences among the other treatments. For the rest of season, there were no significant differences in CO_2 flux among the treatments.

On July 8th, there are no significant differences in CH_4 fluxes among the treatments (Figure 3.4c). On July 15th and 22nd, the CH_4 flux was significantly higher for the HTI compost treatment than the other treatments, and the HTI + UBC farm compost and HTI compost + bloodmeal were significantly higher than the control and the UBC farm compost treatments. HTI compost had a daily flux 5 times higher than HTI compost + bloodmeal and HTI + UBC farm compost, while the UBC farm compost and the control had negative CH_4 fluxes. On July 29th, HTI compost was significantly higher than the control and the UBC farm compost, with no differences among the other treatments. And finally, for the rest of the growing season, there were no significant differences in CH_4 flux among the treatments.

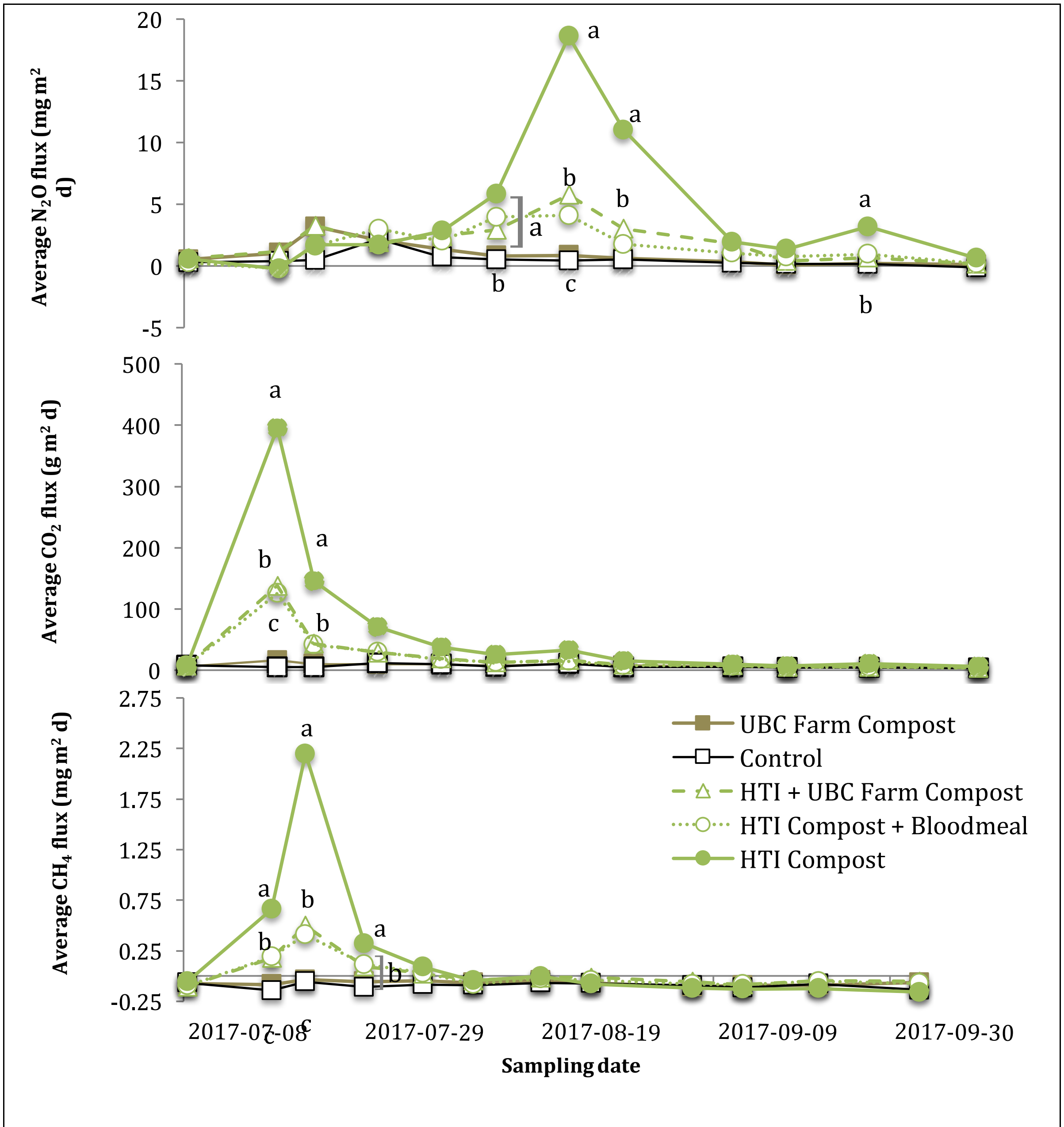

Figure 3.4. **a.** Average N_2O flux in mg m^2 day^{-1} **b.** average CO_2 flux in g m^2 day^{-1} and **c.** average CH_4 flux in mg m^2 day^{-1}. Control is no soil amendment, HTI + UBC Farm compost is a mixture of the current UBC Farm management practice with the high throughput in-vessel (HTI) compost, HTI compost is the high throughput in-vessel compost alone, HTI compost + bloodmeal is a mixture of HTI compost and bloodmeal, and UBC Farm compost is the farm's current management practice only. Different letters represent significant differences ($P < 0.05$).

Table 3.3. F and P value for CO_2, N_2O and CH_4 fluxes by treatment, by date and by the interaction of treatment and date.

	CO_2		N_2O		CH_4	
	F	P	F	P	F	P
Treatment	19.64	< 0.01	1.30	0.27	0.08	0.99
Date	138.85	< 0.01	0.18	0.68	0.94	0.33
Treatment*Date	5.02	< 0.01	3.66	0.01	3.75	< 0.05

3.3.5.2 Cumulative greenhouse gases

The results for cumulative GHGs were highest for HTI compost for all three gases, N_2O, CO_2, and CH_4 (Figure 3.5). Cumulative N_2O flux for HTI compost was significantly higher than all the other treatments, with over twice the flux of the second highest treatment, HTI + UBC farm compost ($P < 0.05$); the other treatments did not differ significantly (Figure 3.5a). The same pattern was observed for the cumulative CO_2 flux where the HTI compost treatment had again over double the flux than the rest of the treatments (Figure 3.5b). HTI compost treatments also had a significantly higher CH_4 fluxes than the control and the UBC farm compost treatments. All three treatments containing HTI compost have positive cumulative CH_4 fluxes over the growing season, while the control and the UBC farm treatments resulted in CH_4 consumption (Figure 3.5c).

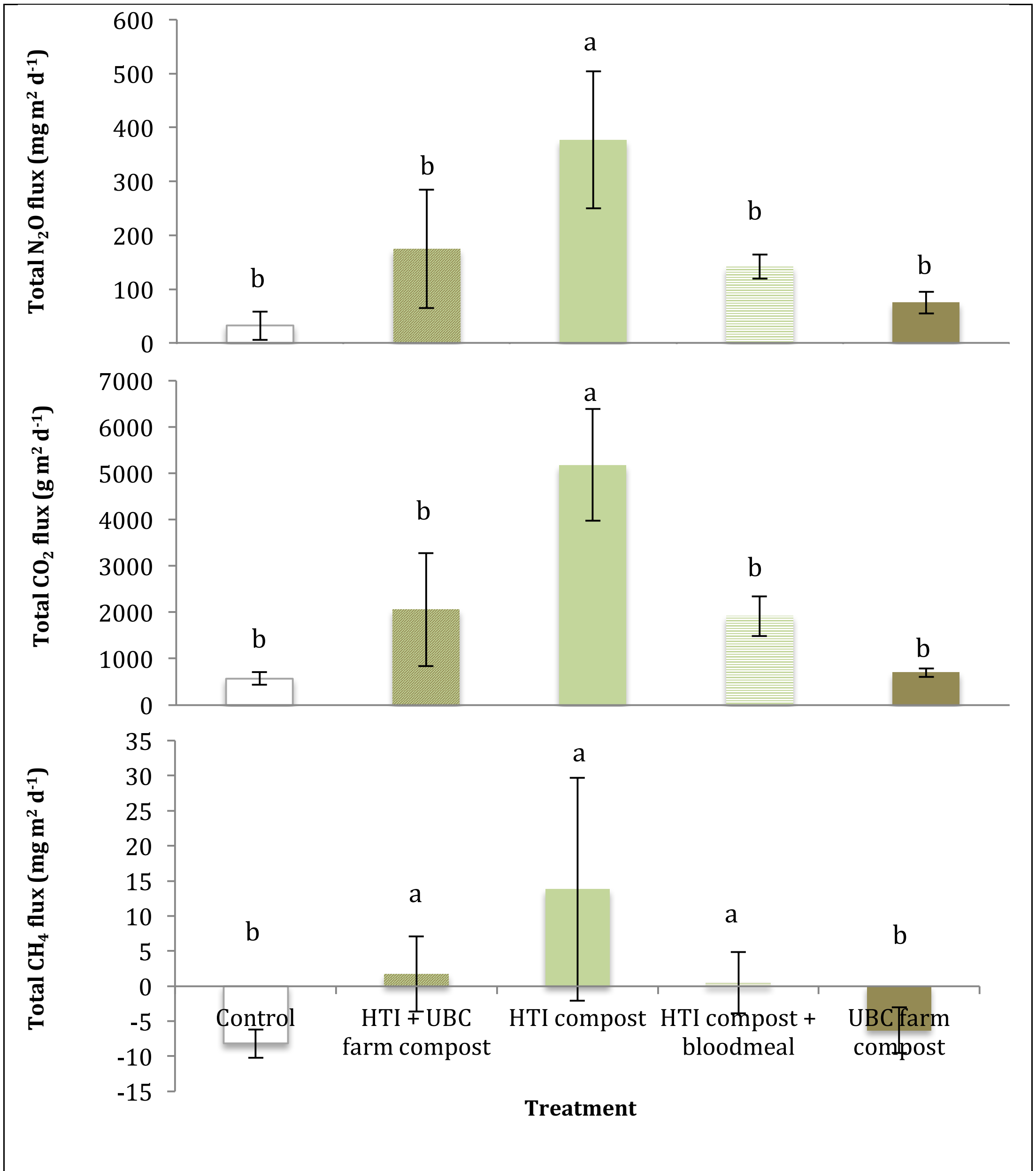

Figure 3.5. **a.** Cumulative N_2O flux in mg m^2 day^{-1}, **b.** cumulative CO2 flux in g m^2 day^{-1} over and **c.** cumulative CH_4 flux in mg m^2 day^{-1} over the entire season. Control is no soil amendment, HTI + UBC Farm compost is a mixture of the current UBC Farm management practice with the high throughput in-vessel (HTI) compost, HTI compost is the high throughput in-vessel compost alone, HTI compost + bloodmeal is a mixture of HTI compost and bloodmeal, and UBC Farm compost is the farm's current management practice only. Error bars represent standard error and different letters represent significant differences ($P < 0.05$).

3.3.6 Soil incubations

The results of the soil incubations, or the CO_2 flush after rewetting soil samples that were obtained at the end of the growing season, were generally higher for the treatments containing compost than the control. The CO_2 flush of HTI compost treatment was 34% higher than the control ($P < 0.05$). There were no significant differences among the other treatments.

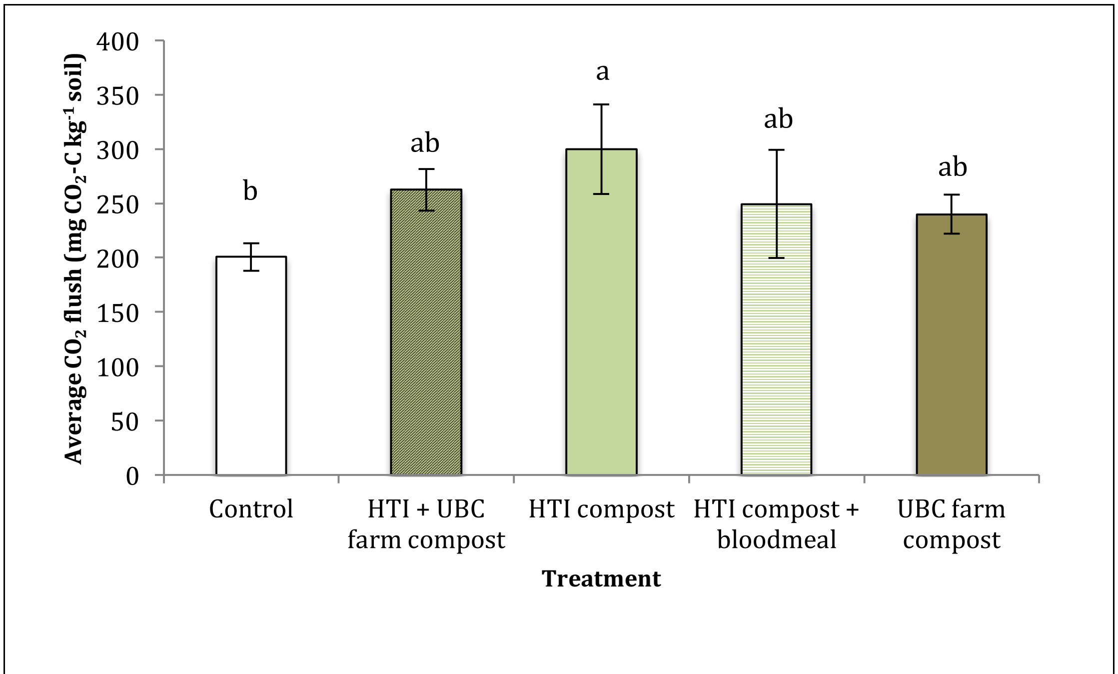

Figure 3.6. Average CO_2 flush in mg CO_2-C kg^{-1} soil among the different treatments at the end of the growing season. Control is no soil amendment, HTI + UBC Farm compost is a mixture of the current UBC Farm management practice with the high throughput in-vessel (HTI) compost, HTI compost is the high throughput in-vessel compost alone, HTI compost + bloodmeal is a mixture of HTI compost and bloodmeal, and UBC Farm compost is the farm's current management practice only. Error bars represent standard error and different letters represent significant differences ($P < 0.05$).

3.4 Discussion

3.4.1 Germination test

In this study, the use of HTI compost clearly had an effect on germination both in the greenhouse and in the field. While germination rates were not affected greatly by the addition of HTI compost to the growing medium until twenty times the field application rate was added, the biomass of the seedlings was affected by the addition of the compost at only 1x, which is the application rate at 29 Mg ha^{-1}. There are several reasons why HTI compost could have impacted germination and early establishment. Germination can be affected by salinity, which can inhibit seed growth by decreasing water uptake. Salt-sensitive plants can be affected at conductivities below 4 $mS.cm^{-1}$ (Marchiol et al., 1999). The conductivity of the HTI compost was 4.8 $mS.cm^{-1}$ and sodium was 25.7%, while optimum ranges are below 4 mS.cm-1 and <1% respectively (Appendix Table A.X.3). The high salt content could explain the differences in biomass among the different treatments, as lettuce is particularly sensitive to salinity during the early seedling stages (Shannon & Grieve, 1998).

The HTI compost used was immature and unstable as indicated by the GHG emissions, and may have had higher organic acids, although this was not measured. Immature compost is thought to have an effect on seed germination due to potential of phytotoxicty from organic acids released during the composting process (Ozores-Hampton et al., 1999; He et al, 1995).

3.4.2 Crop productivity

My results showed the spinach yields of the UBC farm compost, the current management practice used by the UBC farm, was over twice as much as the HTI compost and the HTI compost + bloodmeal, but did not differ from the control and the HTI + UBC farm compost. Alternatively, there were no differences among the treatments for beets. The difference in spinach yield is most probably due to the delayed or even lack of germination that was observed in the spinach seedlings in the treatments with HTI compost. Chanyasak et al., (1983) in a study examining the effects of compost maturity on Komatsuna growth (a Japanese mustard spinach), concluded that the immature compost had an inhibitory effect on the growth of the of the crop during early stages of development due to the presence of low fatty acids (propionic acid and n-butyric acid). Delayed germination was also observed for beets, but the longer growing period to maturity enabled the crop to eventually catch up resulting in no differences in yield.

3.4.3 Soil nitrogen content

For soil NH_4^+-N content, across most of the sampling dates throughout the season, HTI compost was higher than the other treatments, except on sampling event 4 on August 17th where HTI compost, HTI compost + bloodmeal and UBC farm compost were significantly higher than the other two treatments. This is probably due to higher N mineralization. The nature of the compost, immature and unstable, means a probable increase in soil microbial communities and a lack of readily available nitrogen, which led to the immobilization of NH_4^+-N (Brady and Weil, 2010). For soil NO_3^--N content, HTI compost had a significantly higher NO_3^--N content than all the other treatments throughout the growing season, except at the third sampling event on August 3rd where UBC farm compost had a significantly higher NO_3^--N content than all the other treatments. We can clearly see that UBC farm NO_3^--N content peaks earlier in the season and HTI compost treatments peak later in the season. Again, this is probably due to the nature of the HTI compost. UBC farm compost is already mature and stable and releases N earlier in the season while N in HTI composts is immobilized by microbial activity before being mineralized when microbial activity decreases throughout the season (Brady and Weil, 2010).

3.4.4 Greenhouse gases emissions

All GHG emissions were highest for the treatments that had HTI compost: HTI compost, HTI compost + bloodmeal and HTI compost + UBC farm compost. CO_2 and CH_4 emissions for the treatments with HTI compost were highest at the beginning of the season, right after compost application, and N_2O emissions were highest mid-season, which coincides with the PAN data. Given that composting is the microbial transformation of organic materials, emissions of CO_2 and CH_4 are clear indicators of continued microbial consumption of C (Epstein, 1996). The emissions observed for the HTI compost follows the same pattern as those observed in the generation of compost in typical industrial facilities. First, biogenic CO_2 is emitted from the decomposition of the composted waste, followed by N_2O emissions when the readily available carbon has been consumed (Boldrin et al., 2009). In the literature, observations of CH_4 emissions from composting vary. Some studies have found that there are no CH_4 emissions during composting (Jackel et al., 2005), while others found that CH_4 is emitted even in well-aerated processes (Clemens and Cuhls, 2003). Interestingly, the stable UBC compost and control resulted in the consumption of CH_4 while the HTI containing compost resulted in fluxes. Overall the GHG results confirm the immaturity and instability of the HTI compost.

Although the GHGs where higher in HTI containing treatments this does not necessarily mean that the use of these materials has a greater climate forcing impact, or carbon footprint, than other typical composts (e.g. the UBC farm compost). When the carbon footprint of a compost is evaluated over its life cycle there are impacts that can be assessed generally as direct or indirect emissions. Direct emissions are those from the composting process at the composting site, and are linked to the degradation or decomposition of the composted material. Indirect emissions, are those produced by a compost after it has left the composting facility, including transport and post application soil emissions (Boldrin et al., 2009). This study quantified emissions from the soil, and without a full life cycle assessment, no conclusions can be made regarding the relative global warming potential of HTI compost.

3.4.5 Soil incubations

The results from the soil incubations indicate that the CO_2 flush, and therefore microbial activity after rewetting, was higher for the HTI compost than the control at the end of the production season, with no differences among the other treatments. It was expected, that all of the treatments receiving additional organic inputs from the compost would have resulted in increasing microbial activity (Saison et al., 2006). It was surprising then, that the HTI compost had the highest CO_2 flush and the other treatment did not differ from the control. This may be indicative of the overall high concentration of organic matter in the soils at the UBC farm (~11%). Soil microorganisms have been commonly used as indicators of soil health, with an increase in soil microbial activity equating to increased soil health as they are important to the processes and functions of a healthy soil (Doran and Zeiss, 2000). This CO_2 flush method has been proposed as a cost-effective proxy for assessing microbial populations and thus soil health, but has its limitations. While we know that HTI has resulted in a larger population of microorganism we do not have data on the type or diversity, which may be important if not more critical factors in differentiating the impacts of these treatments on soil health (Franzluebbers, 1999).

3.5 Conclusion

Results of this study indicate that HTI compost has the potential to be a useful soil amendment but needs to be used carefully. Seed germination was negatively affected when high amounts of HTI compost was used suggesting that there are likely compounds in the materials that are toxic at high concentrations. Yield was also affected by HTI compost for spinach, a crop with a short growing season. This was most likely caused by the delayed germination and patchy establishment resulting in low biomass at harvest which was only 35 days after planting. Yields for beets however, where unaffected by HTI compost at harvest at around 70 days after planting. The results for PAN for HTI compost and other treatments with HTI compost were as excepted, with immobilization of N in the form of NH_4^+-N after compost application, but higher N availability later in the season. The same was observed with greenhouse gases results, with high emissions for CO_2 and CH_4 at the beginning of the season due to the ongoing decomposition of this immature compost. N_2O was however the highest mid-season for the HTI compost treatments, which coincides with the release of NO_3^--N after decomposition is complete and microbial activity from decomposition declines. And finally, the incubations showed that at the end of the season, HTI compost has the highest microbial activity potential.

4. General conclusion

4.1 Research findings

In this thesis, I have evaluated some of the impacts of recycling two types of urban residuals for use in agricultural production. In Chapter 2, I examined the effects of combinations of biodiesel co-products (BCPs), specifically monopotassium phosphate fertilizers (MKP) mixed with different rates of glycerin, a nitrification inhibitor, on lettuce seed germination, potato and squash productivity and on nitrogen cycling in the field. And on potato and pepper productivity in a greenhouse setting. In Chapter 3, I examined the effects of high throughput in-vessel (HTI) compost at different rates on seed germination, and HTI compost alone and in various combinations with a typical municipal compost and bloodmeal on crop productivity, soil nitrogen (N) cycling, greenhouse gas emissions (GHG) and microbial activity.

4.1.1 Fertilizers from biodiesel co-products

As expected (H1) there were no differences in germination rate among the different BCP fertilizer treatments and the control. In the field, there were no significant differences in yield, tuber/fruit number or quality of the crops for both potatoes and squash among the different fertilizer treatments indicating BCP based fertilizers perform equally as well as typical retail fertilizers but additional glycerin did not increase yields as hypothesized (H2 and H3). There were also no significant differences in soil ammonium (NH_4^+-N) and nitrate (NO_3^--N) content among the fertilizer treatments for the potato crop. However, significant differences in NH_4^+-N were found for the squash crop. At the sampling events following fertilizing, the MKP-C (crude MKP mixed with glycerin) treatment had a significantly higher soil NH_4^+-N content than the other treatments confirming my hypothesis (H4) that glycerin would act as a N inhibitor but surprisingly the higher rate of glycerin MKP-C2 did not show the same pattern. For soil NO_3^--N content, while a pattern was observed, no significant differences were found.

In a controlled environment, the greenhouse, significant differences in yield were observed for both potato and pepper crops. For the potato crop, the highest yields were obtained using retail-MKP, which had a significantly higher yield than a retail-NPK fertilizer, but did not differ from MKP-C or MKP-C2. These results show that the MKP-M fertilizer, which should have been similar to a retail-MKP, did not perform as well. The addition of glycerin had a positive on impact yield with the MKP-C treatment. The greenhouse peppers also had significant differences in yield, as hypothesized (H5), MKP-M foliar performed better than retail-NPK. Interestingly, MKP-C had much higher yields than MKP-C2 which resulted 60% mortality of the sample. These results indicate that there is limit as to how much glycerin can be added within a certain volume before there are negative consequences for crop productivity. And finally, as expected (H6), there were no differences in crop quality among the different treatments.

4.1.2 High-throughput in-vessel compost

Surprisingly, germination was affected by the HTI compost at application rates higher than 10 times the application rate of 29 Mg ha^{-1} used for the field experiment set to meet crop N demands (H7). This suggests that there is a rate of the HTI compost at which germination is negatively affected, potentially due to high salt content or increased organic acids. Again, as opposed to my hypothesis (H8), the yield of spinach was highest for the UBC farm compost, which was significantly higher than HTI compost and HTI compost + bloodmeal. Lower yields in the treatments with HTI compost were likely due to delayed or reduced germination of the spinach. While this delay was observed in the beet crop, the effect was not significant by the end of the longer growing season.

As expected (H9), plant available nitrogen (PAN) was impacted by treatments with HTI compost. Ammonium was significantly higher than all other treatments early and late in the production season. While NO_3^--N in the HTI compost was much lower than all the other treatments early in the season and then higher towards the end of the season. These results indicate that while N was immobilized by microbial activity when the HTI compost was first applied to the field, it was mineralized later on in the season. Using HTI compost could be therefore be problematic if N availability is not timed with N uptake. Interestingly, adding bloodmeal to HTI did not increase early season PAN, and adding mature compost actually reduced PAN.

As I hypothesized (H10), the HTI compost had the highest cumulative GHG emissions due to its unstable and immature nature, which results in an increase in microbial activity after its application. However, I hypothesized that N_2O emissions would be lower in the treatments with HTI compost thinking the majority of the N would be utilized by microbial populations during decomposition. In fact I found the opposite result, N_2O emissions were the highest for HTI compost. Initially, during the beginning of the growing season, N_2O emissions were similar to the other treatments, but in the middle of the growing season I observed a large increase in emissions corresponding with the release of NO_3^--N. As hypothesized, CO_2 and CH_4 emissions were highest for HTI compost and the other treatments containing HTI compost after application.

And finally, at the end of the season, I did find as expected (H11), that the CO_2 flush was significantly higher than the other treatments for the HTI compost treatment, indicting higher potential microbial activity by the end of the growing season.

4.2 Strengths and contributions to the field of study

The two studies I present in this thesis contribute to the body of literature that looks at the effects of novel soil amendments made from urban residuals on crop productivity, soil N cycling, GHG and microbial activity. While there is an extensive body of literature that has examined some of the impacts of using urban residuals as soil amendments, I have added to this work in a number ways by investigating the impacts of two new, unstudied, sets of materials made from urban residuals:1. novel mixtures of BCPs including recovered MKP and glycerin; and 2. Mixtures of HTI compost.

My research provides a glimpse at the overall efficacy of two novel products and how they can affect crop productivity depending on the rate of application or mixtures. The results of these two studies will help provide guidance to develop management practices for these novel products that can help maximize their benefits for agricultural production while minimizing their negative impacts on the environment. My findings provide some insight on the environmental impacts in terms of potential losses of N in chapter 2 and 3, and GHG emissions in chapter 3. My results show the timing of PAN, which is extremely important for understanding the potential impacts on crop N uptake and unused N that can be lost to contaminate water resources. My study was the first, in my knowledge, to investigate GHG emissions from HTI compost applied on-farm.

4.3 Limitations and directions for future research

In chapter 2, one of the limitations of my analysis was my method for assessing the impacts of BCP fertilizers on PAN. It is probable that my method of soil sampling did not actually capture the impacts of the fertilizer applications, particularly for the potato field. For the potato crop, the fertilizer was applied directly to the soil at the base of each plant whereas my soil samples for PAN were taken at least 30 centimeters away from the stems to avoid causing any damage to the roots. It is therefore probable that I did not capture the bulk of the impact. Alternatively, for the squash, fertilizer was applied foliarly, which resulted in a substantial portion of the application dripping from the edge of the leaf canopy onto the soil. My soil sampling method was well within this drip line. This could explain the differences in PAN results, with no differences seen for the potato, but some seen for the squash. In hindsight, it would have been better apply the fertilizer to a wider area to ensure sampling captured any glycerin effect on PAN.

It would have also been beneficial to investigate changes in microbial communities in study 1 in order to better understand the effects that glycerin has on microbial activity, which could corroborate and help explain the PAN results. It would have also helped to look at the effects of different rates of glycerin on nutrient cycling and microbial activity through laboratory incubations, where the environment is controlled. It would have also been interesting to track loses of N either as leaching or emissions. Future research should incorporate these loss pathways to provide more insights on how glycerin affects soil nutrient cycling and microbial activity.

Limitations for chapter 3 include the fact that soil microbial community through laboratory incubations was only done at the end of the growing season due to the limited soil sampled that was available for incubations. Over 80 grams of soil are needed for one incubation, which was not accounted for as I sampled throughout the season. I therefore only had enough soil to do incubations at the end of the growing season.

Further research on microbial activity, either through incubation or through other methods (e.g. phospholipid fatty acid analysis), would help explain the results obtained for soil N cycling and GHG emissions. It would also be important to look at the effects of using HTI compost on weed control, as the effect of HTI compost on germination could be used to give crops a growth advantage by delaying or suppressing weed germination. It would be critical to track how organic acids and salinity could be impacting the soil over the long-term.

4.4 Implications and recommendations

The research conducted in the studies in chapter 2 and 3 provide some basis for recommendations for agricultural application rates and management practices for BCP fertilizers and HTI compost. For growers, it is important to note that using MKP fertilizers with no added glycerin is beneficial to crop yield, especially when applied as a foliar fertilizer, most probably due to the direct uptake of the nutrients by the plants, which could also minimize leaching potential if applied judiciously. Foliar application of MKP also seems to be a good option for greenhouse production. HTI compost clearly impacted PAN and it is important that users of the material recognize that there is likely a longer duration of PAN supply from HTI than from typical mature compost. This research also highlights the potential negative impacts that glycerin and immature compost can have on crop growth. While glycerin has the potential of being beneficial to plant growth, it is important to note that large quantities of glycerin were shown to kill plants in the greenhouse. From the results in study 2, I would recommend that HTI compost should be used at either very low application rates or on crops that are salt tolerant or have longer production times to maturity, to avoid any negative impacts on germination.

Overall, this study helps us better understand how these novel products that would otherwise be considered waste products can be successfully applied to an agricultural setting and be used by farmers and growers without any negative impacts on crop productivity and the environment.

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Appendix

Figure A.1. Germination trial for study 1.

Figure A.2. Fertilizing potato crop using MKP fertilizers with added glycerin in study 1.

Figure A.3. Photograph of the field trial with squash crops and potato crops in study 1.

Figure A.4. Photograph of the field trial with squash crops and potato crops in study 1.

Figure A.5. Quality assessment of potato crop from the field trial in study 1.

Figure A.6. Fertilizer treatments for the greenhouse trial in study 1, including soil and foliar application fertilizers.

Figure A.7. Greenhouse set-up with potato and pepper crop in the UBC horticulture greenhouse for study 1.

Figure A.8. Quality assessment of pepper crop from the greenhouse trial in study 1.

Figure A.9. Germination trial at day 15 for study 2.

Figure A.10. Biomass measuring on day 15 of the germination trial for study 2.

Figure A.11. Field tilling after treatment application for study 2.

Figure A.12. Field after greenhouse gas chambers installation for study 2.

Figure A.13. Spinach and beet crops for study 2.

Figure A.14. Spinach harvest for study 2.

Figure A.15. Spinach harvest for study 2.

Figure A.16. Yield measurements for beet crop in study 2.

Figure A.17. Example of an endline soil measurement using a soil probe for study 2.

Table A.1. Potato field endline soil average (± standard error) concentrations of potassium (K), phosphorus (P), carbon (C) and nitrogen (N) by fertilizer treatment: crude MKP with glycerin (MKP-C); crude MKP with double the amount of glycerin (MKP-C2); high grade MKP washed with methanol (MKP-M); and a commercial NPK fertilizer (retail-NPK). No significant differences were found (P > 0.05).

Treatment	Depth	K (mg kg^{-1})	P (mg kg^{-1})	Total N (%)	Total C (%)
Control	0-15	246.0 ± 109.1	394.4 ± 105.4	0.2 ± 0.0	4.2 ± 0.1
	15-30	224.0 ± 98.1	335.1 ± 61.1	0.2 ± 0.0	3.9 ± 0.1
MKP-C	0-15	184.8 ± 125.2	292.7 ± 103.9	0.2 ± 0.0	4.1 ± 0.1
	15-30	223.5 ± 131.6	337.1 ± 89.9	0.2 ± 0.0	4.0 ± 0.4
MKP-C2	0-15	241.8 ± 104.4	309.5 ± 71.6	0.2 ± 0.0	4.1 ± 0.2
	15-30	220.3 ± 129.4	336.6 ± 56.1	0.2 ± 0.0	3.9 ± 0.2
MKP-M	0-15	220.5 ± 212.5	316.4 ± 152.3	0.2 ± 0.0	4.0 ± 0.2
	15-30	252.0 ± 72.5	360.6 ± 66.7	0.2 ± 0.0	3.9 ± 0.1

Table A.2. Squash field endline average (± standard error) soil concentrations of potassium (K), phosphorus (P), carbon (C) and nitrogen (N) by fertilizer treatment: crude MKP with glycerin (MKP-C); crude MKP with double the amount of glycerin (MKP-C2); high grade MKP washed with methanol (MKP-M); and a commercial NPK fertilizer (retail-NPK). No significant differences were found (P < 0.05).

Treatment	Depth	K (mg kg^{-1})	P (mg kg^{-1})	Total N (%)	Total C (%)
Control	0-15	234.5 ± 185.5	232.1 ± 142.9	0.2 ± 0.0	3.8 ± 0.2
	15-30	227.3 ± 124.8	273.0 ± 83.9	0.2 ± 0.0	3.7 ± 0.1
MKP-C	0-15	207.5 ± 102.1	225.5 ± 103.4	0.2 ± 0.0	3.8 ± 0.2
	15-30	347.0 ± 161.1	334.7 ± 82.8	0.2 ± 0.0	3.7 ± 0.2
MKP-C2	0-15	196.5 ± 114.1	208.0 ± 81.7	0.2 ± 0.0	3.8 ± 0.2
	15-30	244.8 ± 116.3	287.6 ± 104.2	0.2 ± 0.0	3.9 ± 0.2
MKP-M	0-15	258.0 ± 128.6	258.2 ± 87.4	0.2 ± 0.0	3.7 ± 0.1
	15-30	417.0 ± 132.2	378.4 ± 80.0	0.2 ± 0.0	3.9 ± 0.1

Table A.3. Quality indicators for HTI compost compared to quality indicators for an optimum compost.

Quality indicators	Optimum	HTI compost
Total inert materials	0%	0%
Heavy metals	Not exceeding accepted limits	
C:N ratio	6.5-7	4.9
Moisture content (%)	50-60	44.1
Soluble salts (mS/cm)	< 2	5.1
Sodium (%)	< 1	13.5
Mg/K	7:1	0.33:1
Ca/Mg	5:1	1.5:5
Total N(%)	0.7-2.5	1.95
Nitrate N (ppm)	100-199	202

Table A.4. Wet compost application rates in Mg ha^{-1} for the different treatments.

Treatment	Compost Rate (Mg ha^{-1} wet weight)
HTI compost	29
HTI compost + bloodmeal	15
HTI compost + UBC Farm compost	30
UBC Farm compost	31
Control	0