Co-Composting Poultry Manure with Biochar: Effects on Gas Emissions and Plant Growth

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Slow and steady wins the race, unless it’s a speed race;
in that case, faster is generally better.

Brendan

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Contribution of Authors

Brendan Peachey is the principle author of this work, which was supervised by Dr. O. Grant Clark, from the Department of Bioresource Engineering, McGill University, Ste-Anne-de-Bellevue, Quebec, Canada. The experimental work was conducted entirely using departmental facilities, on the Macdonald Campus of McGill University, and on the Macdonald Campus Farm.

Brendan Peachey wrote both manuscripts presented in this dissertation, with assistance editing from Dr. Grant Clark and Dr. Michael Boh. Dr. Timothy Schwinghamer and Dr. Pierre Dutilleul assisted with the statistical analysis and writing of the corresponding methodology. The first manuscript, entitled "Co-composting Poultry Manure with Biochar: Part 1) Effects on Gas Emissions", has been submitted for peer review to the Journal of Environmental Quality, the second, entitled "Co-composting Poultry Manure with Biochar: Part 2) Effects on Plant Growth", has been submitted to the same journal.

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Abstract

Co-composting with biochar is beneficial because biochar provides a habitat for microbes, promotes aeration, and absorbs moisture, nutrients, and dissolved organic matter (Li et al., 2014; Schultz et al., 2013). Biochar compost in soil sequesters carbon and improves soil quality and plant growth (Biederman and Harpole, 2012). Co-composting with biochar has sometimes also been reported to have detrimental effects, perhaps due to variability in the feedstock used for pyrolysis, the process temperature, or postproduction treatment (Beesley et al., 2011, Masiello, 2004).

This research investigated the effects of biochar particle size on the composting process and plant growth. Three sizes of biochar [fine (<1.6 mm), medium (6.4 – 3.2 mm), and coarse (19.2 – 12.8 mm)] were mixed with poultry manure, wheat straw, and softwood shavings, in proportion of 4:6:1:3 (vol.). The control treatment included extra wood shavings in place of biochar. Gas emissions, pH, bulk density, and temperature were compared. Emergence tests were then conducted with spring barley (*Hordeum vulgare*) grown in mixtures of 0, 20, 40, 60, 80, and 100% compost with soil. A growth trial was then conducted using lettuce (*Lactuca sativa* Butterhead).

Biochar influenced gas emissions and physical aspects of the compost, although the effects differed among gases. Coarse biochar reduced the concentrations of CO_2, NO, and NH_3 in the exhaust air. Finer biochar had more pronounced effects on the emission of N_2O and CH_4 and was associated with slightly higher concentrations of SO_2. Biochar particle size affected compost bulk density. All biochar treatments were less dense than the control, compost with medium biochar was less dense than that with fine ($p < 0.005$). Coarse biochar significantly increased peak compost temperatures ($r = -0.31$, $p < 0.0001$) and accelerated the return to ambient temperatures as compared with finer biochar. This suggests that coarse biochar benefits compost microbial activity more than finer biochar (Oviedo-Ocaña et al., 2015). Biochar particle size had variable effects on the exhaust concentrations of CH_4, CO, and SO_2, and compost pH.

The percentage of biochar compost in the soil significantly affected the barley stem length in the emergence trials ($H = 12.04$, $p = 0.0005$). Soil with 40-60% compost supported plants with the longest stems, independent of biochar particle size. Plants grown in 40 and 60% compost with medium biochar had the highest wet weight ($H = 4.19$, $p = 0.04$). The barley dry weight was affected by biochar particle size ($H = 4.41$, $p = 0.04$) and particle size ($H = 10.94$, $p = 0.0009$). Barley in soil with coarse or medium biochar produced the most biomass, while plants in soil with the control

compost produced the least. These results demonstrated that soil with 20 and 40% compost was best suited for plant growth.

Compost had a significant effect on lettuce wet weight in the growth trials ($F = 4.78$, $p = 0.0018$), with the heaviest plants growing in soil with 40% fine biochar compost ($p = 0.016$). Similar trends were observed for lettuce dry biomass, moisture content, and number of leaves.

Studies similar to the one presented here have likewise yielded both positive and negative results. As such, understanding of the nature of the interaction between compost, biochar, and plant growth, remains equivocal. Additional research is required to elucidate the relationships, which can eventually be used for a meta-analysis. This research adds to that growing body of evidence.

Résumé

Le compostage transforme les résidu agricole, en augmentant leurs stabilité chimique, diminuant les effets dangereux et en produisant un amendement riche en éléments nutritifs. Le compost est souvent critiqué parce que ca libère des gazes nocives pour l'environnement et est capable de diminuer la valeur nutritive du substrat (Godbout et al., 2010).

Le co-compostage avec le biochar a le potentiel d'augmenter l'efficacité du processus tout en diminuant les effets secondaires indésirables. Le biochar introduit la microporisité, ce qui sert a un habitat pour les microbes, qui favorise l'aération, qui absorbe l'humidité, les nutriments et les matières organiques dissoute. (Li et al., 2015, Zhang et al., 2014a). Dans la présence du biochar, les nutriments dans le compost sont moins sujets à la volatilisation et le lessivage, ainsi ils restent disponibles aux plantes si le compost est ensuite utilisé comme amendement de sol (Schultz et al., 2013). Quand le mélange de biochar et composte est appliquer au sol, des avantages additionnels émergent, qui comprend la séquestration du carbone, une qualité de sol améliorer et une meilleurs croissance de plantes (Biederman et Harpole, 2012). D'autre part, des chercheurs ont déclaré que le co-compostage avec le biochar résulte aux effets nocives, comme une augmentation d'émissions de gazes, un diminution de croissances de plantes et une accumulation de métaux lourds dans les plantes (Beesley et al., 2011, Karmi et al., 2011, Rogovska et al., 2011). Cette ambivalence entre les effets positifs et négatifs sont du, en partie, a la variabilité physicochimique du biochar, qui résulte des différences en matières premières, de la température de pyrolyse et des traitements de post-production (Masiello, 2004).

Cette étude a été conçu pour examiner les effets de divers tailles de particules de biochar sur le processus de compostage et ultérieurement la croissance des plantes. On a mélanger 3 tailles de particules de biochar [fin (<1.6 mm), moyen (6.4 – 3.2 mm), et gros (19.2-12.88 mm)] avec le fumier de volaille, la paille de blé et des copeaux de bois dans une proportion de 4:6:1:3 (par volume). Le dispositif témoin avait la même proportion sauf pour des copeaux de bois additionnels au lieu du biochar. On a ainsi comparé les émissions gazeuses du compost, le pH, la masse volumique apparente, la température et la respiration pour chaque dispositif. Après le compostage, un test de phytotoxicité a été effectué avec l'orge (*Hodeum vulgare* L.) au but de déterminer l'optimale proportion de compost dans le sol pour la croissance des plantes. La proportion des dispositifs

variait de 20-100, en incréments de 20%. Le dispositif témoin contenant 100% de sol. Un test de croissance de plante, utilisant la laitue (*Lactuca sativa*), a été effectué avec les proportions optimales.

Nous avons émis une hypothèse que due a sa plus grande surface spécifique, le biochar fin réduira les émissions de gazes et augmentera la rétention des nutriments, la rétention d'eau et l'activité microbienne. Nous avons aussi émis une hypothèse que le biochar fin aurait une forte influence sur la croissance de plante. Toutefois, la variabilité dans nos résultats a rendu des conclusions décisives difficile a achevé.

Le biochar a influencé les émissions de gazes et d'autre aspect physiques du compost, durant le compostage de fumier de volaille, mais l'importance de ces effets était radicalement différente pour les différentes espèces de gazes. Nos résultats démontre avec certitude que le biochar de taille grosse diminue les concentrations de CO_2, NO, et NH_3 durant le compostage. Le biochar de taille grosse a moins d'effets que les graines de plus petite tailles sur les émissions de N_2O et CH_4. Les graines fines de biochar mènent à des concentrations d'émission de SO_2 légèrement plus large. La taille de particule de biochar avait aussi un effet significatif ($p < 0.005$) sur la masse volumique apparente; tout les dispositifs de biochar était invariablement moins dense que le témoins sans biochar. Le biochar de taille moyenne et invariablement moins dense que le biochar fin, tandis que l'effet du biochar de taille grosse était ambigu. En outre, la taille de particule avait un effet sur la température de compost (Spearman's r=-0.31, $p < 0.0001$). Le compost avec le biochar de taille grosse et moyenne avait une température maximale plus grande, suivi par une descente plus rapide aux températures ambiantes, que les dispositifs de biochar plus petits. Cela pourrait signifier que, relatif au graines plus petites, le biochar plus gros a un effet positif plus grand sur l'activité microbienne, et ultérieurement sur le taux de dégradation de la matières organique (Ermolaev et al., 2014, Oviedo-Ocana et al., 2015). A l'inverse, l'effets de taille de particule de biochar sur les concentrations d'émissions de CH_4, CO et SO_2, autant que le pH, avait suffisamment de variabilité que poursuivre d'autres enquêtes serait recommandé pour élucidé les facteurs contributifs.

Le compost modifié avec le biochar avait des effets variables sur la croissance des plants d'orge. En générale, la croissance de l'orge n'était pas affectée par la taille de particule du biochar. Le pourcentage de compost biochar dans le sol avait un effet significatif sur la longueur de la tige (H = 12.04, p = 0.0005). Les plantes avec les tiges les plus longues se trouvait dans le sol avec une proportion de compost : sol de 60:40 ou 40:60, indépendamment de la taille de graine de biochar. En outre, la proportion de compost biochar dans le sol avait un effet significatif sur le poids humide de l’orge ($H = 4.19$, $p = 0.04$). Les plantes cultivées dans le dispositif 100% compost avec du biochar fin avaient les plus bas poids humides, et ceux cultivées dans les proportion de compost : sol de 60:40 ou 40:60 avec du biochar de taille moyenne avait les plus hauts poids humides. La taille de particule de biochar et le pourcentage de biochar compost dans le sol avait un effet significatif sur le poids sec de l’orge ($H = 4.41$, $p = 0.04$, et $H = 10.94$, $p = 0.0009$). L’orge cultivée dans du compost avec du biochar gros ou moyen a produit la plus grande biomasse (poids sec), tandis que celle cultivée dans le témoin (compost sans biochar) a produit le moins de biomasse. Les plants cultivées avec 20% de compost avaient les poids secs les plus hauts, tandis que celles cultivées avec 100% de compost avaient le moins. Sur la base de ces résultats, on a déterminé que les proportions de 20:80 et 40:60 de compost et sol étaient les meilleurs adaptée pour la croissance de plantes.

Dans le long terme, le composte utiliser pour tester la croissance de laitue avait un effet significatif sur le poids humide de la laitue ($F_{4.70} = 4.78$, $p = 0.0018$). Par exemple, le poids de la laitue cultivées dans du compost biochar de proportion 20:80 avec des graines fines de biochar était 12.2 a 14.9 g plus lourds que celui de laitue cultivée dans le sol témoin (Scheffé’s-adjusted $p = 00082$, Fig. 5.4). De même, les plantes cultivées dans le compost biochar 40:60 de taille fines étaient 10.0-11.6 g plus lourdes que la laitue cultivée dans le sol témoin ($p = 0.016$). Des tendances similaire on été observé pour la biomasse sec de la laitue et la teneur en eau. La taille de particule de biochar a aussi affecté le nombre de feuilles de laitue. Les plantes cultivées dans un sol avec du compost biochar de taille moyenne a produit 9.5-13 % plus de feuilles que celles cultivées dans le témoin de sol. ($F_{4.71} = 5.28$, $p = 0.0009$). Indépendamment du rapport de mélange, les plantes cultivées dans le sol avec du compost biochar fin on produit 7-8.6% plus de feuilles que celle cultivées dans juste du sol ($p = 0.0052$).

Comme nos résultats, la littérature scientifique sur les effets du co-compostage avec le biochar sur les paramètres physiques du compost, les émissions de gazes et la croissance des plantes dans du sol modifié est peu concluante. Une méta-analyse de la littérature serait utile. Nos résultats contribuent à cette domaine scientifique en pleine croissance.

List of Figures and Tables

Chapter 1 – Introduction

The green revolution of the late 1960s, which has been credited with preventing at least 1 billion people from starving, was facilitated, in part, by advent of industrial production of synthetic nitrogen (N) fertilizers (De Datta et al., 1968). The current global consumption of N fertilizer is about 108 Mt per year (Long and Ort, 2010). This is roughly a 10-fold increase over the last 40 years, from 11.6 Mt in 1961 to 104 Mt in 2006 (FAO, 2009). Canadian farmers used twice as much synthetic N fertilizer in 2010-2011 as they did thirty years earlier (Statscan, 2011). Increased fertilizer use has generally resulted in increased agricultural productivity (Cameron et al., 2013). However, it has been observed that long term use of chemical fertilizers, even at balanced application rates, can result in detrimental effects to soil quality (e.g. Prasad, et al., 1983, Abroal et al., 2000, Verma and Sharma, 2008), which subsequently decreases crop yields (Mulvaney et al., 2009, Cameron et al., 2013, Gilbert et al., 2014). Generally, declining crop yields are countered by increasing fertilizer application, perpetuating this cycle.

In addition to potential detriments to soil quality, the use of synthetic N fertilizers is detrimental to the environment in other ways. More than 60% of chemical fertilizers used in industrial agricultural are synthesized using the Haber-Bosch process (Cherkasov et al., 2015). This process is energy intensive, and leads to the emission of at least 300 Mt of CO_2 annually (Gilbert et al., 2014, Cherkasov et al., 2015). Agricultural N can also be supplied by plant residues, fixation by leguminous plants, and fertilization with animal manure (Pau Vall and Vidal, 1999). The latter is an inextricable component of our society's food requirements, using it as an agricultural N source is pragmatic, as are technologies that make its use more efficient.

Animal manures and synthetic fertilizers both contain nitrogen (N), phosphorous (P), and potassium (K), which are the primary limiting nutrients for plant growth. While animal manures have lower nutrient densities than synthetic fertilizers, not all synthetics contain macronutrients (Varanini et al., 2008). The nutrient content of manures varies based on animal type and their nutrition regimes (Pau Vall and Vidal, 1999). Poultry manure, for example, which is a mixture of excreta, bedding material, waste feed, and feathers, contains appreciable amounts of calcium, sulfur, magnesium, calcium, chlorine, sodium, manganese iron, copper, zinc, molybdenum, and arsenic (Kelleher et al., 2002). All of these nutrients are required for plant growth (Thibodeau, 2006).

Animal manures make excellent fertilizer, and conveniently are often produced en-mass in areas that also grow crops. The Canadian poultry industry yielded roughly 700 million birds in 2012 (Statscan, 2012). For comparison, the American industry is roughly 13 times larger (equating to nearly 10 billion birds, US-EPA 2014). This corresponds with the annual production of roughly 4.2 Mt of poultry manure in Canada, and 58 Mt in the United States [based on the 55 kg waste/year/bird, and an average 32-day life span of meat birds (Leinonen et al., 2012).

While manures are nutrient rich and abundant, they're also malodourous, and can emit ozone depleting, or bio-hazardous volatiles, such as carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and ammonia (NH_3; Lehmam and Rondon, 2006). Manure contains pathogenic microorganisms that can pose health risks to humans, and other animals, when exposure occurs (Sobsey et al., 2006, Thorne et al., 2007). Such risks are minimized by proper storage and treatment prior to field application. In Canada, in 2003 (the most recent year such information was available), 48% of farms apply raw manures to their fields, 14% employ pre-application processing, such as aeration, application of stabilizing additives, filtering, drying, and other methods, the remaining 38% pre-treat their manures by composting (StatsCan, 2004).

Composting

Composting is the exothermic oxidation of solid organic materials by bacteria, actinomyces, and fungi (Nahm, 2003, TMECC 0100). It results in compost, as well carbon dioxide, water vapour, and heat (Ouatmane et al., 2000, Xi et al., 2005). Relative to the starting material, compost is chemically stabile, hygienic, free of plant seeds, with a diminished pathogen load, and decreased potential for production of biohazardous, phytotoxic, or otherwise detrimental substances (Tiquia and Tam, 1998, Haug, 1993). Relative to raw manure, composted manure is safer to manipulate, store, transport, and apply to fields, and has fewer environmental ramifications (Hansen et al., 1993).

However, composting releases a considerable portion of its input material to the environment, in the form of volatiles such as NH_3, CH_4, CO_2, CO, and sulfur dioxide (SO_2; Nahm, 2003), as well as through leaching of soluble compounds (Cambardella et al., 2003). Compost microbes reduce organic nitrates to elemental N, via a series of intermediate compounds (Hua et al., 2009, Kirchmann and Witter, 1989). Intermediates include gaseous NH_3, which volatilizes into the atmosphere (Bernal et al., 1998), and ionized ammonium (NH_4^+), which is highly water-soluble, and is readily transformed into nitrate (NO_3^-; Moreno et al., 2010). The majority of nitrogenous compounds that are emitted during composting are in a gaseous form, yet liquid bound N can also constitute significant losses (Martins and Dewes, 1992). The amount of N that is lost during composting of poultry manure varies widely depending on composting conditions; research on the matter generally states that losses are in the range of 35-65%, within 10-25 days of the start of composting (Schefferle, 1965, Kirchmann and Witter, 1989, Hansen et al., 1989, Tiquia and Tam, 2000, Hua et al., 2009 Steiner et al., 2010, Wang et al., 2013), yet others have reported loses as high as 88% (Ogunwande et al., 2008).

The loss of N from compost is environmentally detrimental, and constitutes a decrease in the commercial and agronomic value of the product (Kithome et al., 1999). Methods of reducing such loses are pragmatic, and have been widely investigated. Some success has been achieved by modifying composts' carbon-to-nitrogen ratios, bulk densities, turning frequencies, and aeration rates (Ogunwande et al., 2008, Jiang et al., 2011). However, such parameters can be difficult or costly to manipulate on a large scale (Wang et al., 2013). Other, low-tech, methods of nutrient capture are potentially more practical.

Biochar

The application of biochar to compost has been shown, in several instances, to be a promising compost additive (Hua et al., 2009, Li et al., 2014). Biochars are high carbon biological residues, which result from the slow thermochemical decomposition of organic materials, in the absence of oxygen (Scott and Piskorz, 1984, Chan et al., 2007). The product is a highly recalcitrant heterogeneous matrix of condensed aromatic and heterocyclic carbon, interspersed with fragmented graphene sheets, and other carbonized structures, as well as inorganic elements, sorbed volatiles, water, and ash (Brewer et al., 2009, Keiluweit et al., 2010, Lehmann et al., 2009). Biochars have excellent cation exchange capacities, and are highly sorbent of organic and inorganic elements, in both liquid and gas phases (Lehmann, 2007). Biochar structure and composition is highly variable, as a function of its feedstock characteristics, pyrolysis conditions, and post-production treatments (Yamulki and Jarvis, 1999, Masiello, 2004).

Biochar has potential to be highly active in compost, yet its physical variability, in combination with variability in the compost itself, confounds the ways in which interactions manifest. Both physical and chemical interactions occur. Chemical reactions between compost and biochar include: electrostatic interactions; H bonding; ionic bonding; p-interactions between aromatic moieties (Joseph et al., 2010); as well as various other chemical reaction mechanisms (Petit et al., 2009, Seredych et al., 2009, Seredych et al., 2010). Physical reaction mechanisms include dissolution of soluble compounds into the biochar's pore moisture, and trapping of gaseous compounds in the biochar's pore space, or between graphine sheets (Spokas et al., 2012). Of these mechanisms, physical adsorption likely has the greatest influence on compost N dynamics (Hua et al., 2009).

Biochar's gas adsorption capacity in compost is variable, reportedly ranging from <1mg NH_3 per gram of non-oxidized biochar, to >60 mg NH_3 per gram of dry oxidized biochar (Seredych and Bandosz, 2007), or an average of 6 mg ammonia per gram generally (Taghizadeh-Toosi et al., 2011). Co-composting poultry manure compost with biochar can reportedly reduce NH_3 gas emissions by 64%, relative to no-biochar compost, and total N-losses can reportedly be reduced by up to 52% (Steiner et al., 2010).

Biochar affects several other aspects of the composting process, including: increasing its cation exchange capacity (Spokas et al., 2012, Steiner et al., 2010, Hua et al. 2009); buffering its pH (Dias et al., 2010); stabilizing its moisture content (Prost et al., 2012); and increasing the surface and nano-porosity of the compost matrix, thus improving its aeration properties (Glaser et al., 2009, Lehmann et al., 2009). Further, biochar has been shown to enhance compost-microorganisms' proliferation and community structure (Pietikeainen et al., 2000, Yoshizawa et al., 2005, Yoshizawa et al., 2007). Biochar matrices sorbe nutrients upon which microbes can feed, while simultaneously providing a structure upon which they can grow, and find refuge from predators such as collembola, nematodes, and protozoa (Atkinson et al., 2010). Enhancing compost's microorganism activity has thermodynamic ramifications, which include increasing peak temperatures, decreasing time to reach the thermophilic stage, and increasing its duration (Li et al., 2014, Malinska et al., 2014). As a result, co-composting with biochar can result in increased rates of organic matter degradation (Sanchez-Garcia et al., 2015). Both microbial communities and organic matter degradation affect compost gas emission, as well as compost quality in general (Lehmam and Rondon, 2006).

While composting results in the degradation of organic matter, biochar is thought to be sufficiently recalcitrant to resist thermal and microbial-degradation (Brodie et al., 2000, Leconte et al., 2011). Thus, the presence of biochar should not alter compost's bio-available C/N ratio (Steiner et al., 2010). However, the veracity of this remains equivocal; while several authors claim that biochar is unaffected by composting, others have demonstrated otherwise (Sheridan et al., 2002, Dias et al., 2010). For example, Dias et al. (2010) demonstrated that as much as 70% of the biochar that they added to poultry manure was humified during composting. If degradation of biochar occurs during composting, its abundant C may become bioavailable. That results in a relative decrease in the amount of bioavailable N, leading to more complete microbial immobilization of N. As a result, NH_3 volatilization would decrease (Lehmann and Rondon, 2005). Higher C/N ratios in compost have also been implicated with reducing microbial biomass (Eiland et al., 2012). Conversely, if biochar does not degrade in compost, it retains useful function in subsequent field application. Biochar degradation in compost is an important, yet not-fully understood, phenomenon. In all likelihood, degradation does occur, at rates that vary as a function of the biochar type and composting conditions.

Plant growth

Charred materials as agricultural soil amendments have been utilized for thousands of years, yet understanding of the agronomic potential of the association is still developing (Ogawa and Okimori, 2010). Biochar affects soils, microbes, and plant roots individually; thoroughly characterizing the dynamics is complex (Joseph et al., 2010). Both positive and negative agronomic effects have been observed (e.g. Atkinson et al., 2010, Lehmann et al., 2011, Major et al., 2010, Novak et al., 2009). Regardless, field application of biochar has been identified as a means of long-term sequestration of C in soil (Lehmann, 2007, Tenenbaum, 2009); this strategy has been recognized by the IPCC as a means of mitigating the effects of GHG emissions (Follett, 2001).

Biochar has been shown to be beneficial for several metrics of soil quality, which directly affect plant growth (Steiner et al., 2007). However, alone biochar does not contain appreciable amounts of plant nutrients (Steiner et al., 2008). Adding untreated biochar to soils that have low initial nutrient value can even restrict plant growth, through competition via nutrient retention (Beesley et al., 2011). Benefits to growth may only occur when nutrients are supplemented using a separate source (Asai et al., 2009, Van Zwieten et al., 2010). Composting has been shown to be a practically ideal means of doing so (Schmidt, 2011).

Composting inoculates biochar with essential plant nutrients, while providing previously mentioned benefits for the composting process, and subsequently to the soil structure. As previously mentioned, composting imparts plant micronutrients and beneficial microorganisms in biochar, which are absent in synthetic fertilizers (Steinbeiss et al., 2009, McHenry, 2008). Compared to synthetics, composted biochar also tends to release its nutrients slowly, decreasing the propensity for nutrient leaching, and providing more persistent plant sustenance (Lehmann et al., 2003). As a result, biochar compost needs not be applied as frequently as synthetics or untreated manures. This nullifies the tendencies of heavy metal accumulation associated with repeated application of manures, and soil quality degradation associated with repeated application of synthetics (Lehmann and Joseph, 2009, Gilbert et al., 2014).

Reports regarding biochar compost as a soil amendment are not invariably positive (e.g. Novak and Busscher, 2011, Spokas et al., 2012). Negative effects include instances of decreased plant growth in biochar compost amended soils (Kishimoto and Sugiura, 1985, Mikan and Abrams, 1995). These may result from the previously mentioned potential for biochar to compete with plants for soil nutrients. Biochar "assimilates" metal ions on its surface, this has the effect of reducing nutrient leaching, yet at the same time may reduce their bioavailability (Beesley et al., 2011). Further, some researchers have implicated biochar soil amendment with heavy metal accumulation in plants (Karami et al., 2011).

Composting with biochar is a promising agricultural development. The associated increases the efficiency of a practical treatment for an abundant waste product, and results in an improved soil amendment. However, the use of this "magic bullet" treatment should be approached cautiously, with scientific rigors, to thoroughly elucidate the confounding variables and ramifications, be them positive or negative.

Conclusion

Compost as an agricultural fertilizer has an efficient energy balance: it inputs an abundant agricultural waste product, increases its chemical stability and eliminates its biohazards, and returns an effective soil amendment. Yet, composting is also subject to losses, which decreases its efficiency; N losses are both harmful to the environment, and decrease the nutrient value of the compost product.

Biochar has great potential to increase composting efficiency. It benefits the compost's microbial community, decreases detrimental emissions, and yields compost that is higher in nutrients. If the compost is subsequently used as a soil amendment additional benefits emerge, including potential increases in soil quality and plant growth, as well as C sequestration (Ogawa and Okimori, 2010, Schmidt, 2011); such interactions are well represented in the scientific literature.

However, not all of the reported effects are positive. As such, understanding of the nature of the interaction between compost, biochar, and plant growth, remains equivocal. The variables confounding the matter are complex, and include variability in biochar properties, which are a function of its parent material, pyrolysis temperature, and postproduction treatments (Masek et al., 2011). Additional research is required to elucidate the effects of these variables, so that the association can be optimized, and the effects accurately quantified. This study is intended to address the effects of one such variable, biochar particle size, on several aspects of the composting process, including its gas emissions, and subsequent performance as a soil amendment.

Chapter 2 – Literature review

General Overview

Much research has been devoted to optimizing the composting process. Proposed methods include: alteration of physical compost parameters, such a pile orientation, and turning frequency (Yanez et al., 2009, Lim et al., 2010), microorganism inoculation (Dach, 2010, Doublet et al., 2011); the addition of natural and mineral adsorbents (Zorpas and Loizidou, 2008, Dach et al., 2009); and the addition of various bulking agents, including biochar. For example, Dias et al. (2010) investigated the effects of three bulking agents (biochar, coffee husks, and sawdust, each in a proportion of 50% by weight) on poultry manure composting. They concluded that biochar was well suited as a compost additive, but did not perform as well as sawdust as a means of reducing N loss. This difference was attributed to relatively increased microbial activity and higher pH values in the biochar compost mixture, which favoured NH_3 volatilization, rather than adsorption by the biochar. Similarly, Wei et al. (2014) compared the effects of co-composting poultry manure and tomato stalks with either biochar, peat, or zeolite. They found that the co-composting with biochar resulted in shorter time to reach the thermophilic phase, longer thermophilic phase, and higher peak temperature, compared to the other treatments and the control. Also, they reported that biochar compost had relatively highest C/N ratio and volatile fatty acid concentration, as well as had the greatest influence on the bacterial community composition.

The potential of co-composting with biochar has been increasingly scrutinized. Results are variable, but biochar has been reported to do the following: decreases bulk density, resulting in better aeration (Jindo et al., 2012b, Kuzyakov et al., 2009); decrease emission of nuisance gasses (Jindo et al., 2012b; Hua et al., 2009; Steiner et al., 2010); increase nutrient and moisture retention (Glaser, 2007, Glaser et al., 2009); and increase compost pH (Chen et al., 2010). All of these qualities have been correlated with microbial abundance, diversity, and respiration rates (Jindo et al., 2012a, Yoshizawa et al., 2005, Steiner et al., 2011). Stronger microbial communities increase compost peak temperatures, decrease time to peak temperature, prolong the thermophilic composting stage (Li et al., 2014, Wei et al., 2014, Malinska et al., 2014), which ultimately increases organic matter degradation rates (Dias et al., 2010, Li et al., 2014).

Type and Amount of Biochar in Compost

Physical properties of biochar, such as bulk density, CEC, particle size, pH, and porosity, vary as a function of its feedstock material, pyrolysis temperature and duration, and postproduction treatments (Masek et al., 2011). Such properties influence how biochar affects compost. At least two studies have attempted to quantify these effects. Li et al. (2014) investigated the effect of co-composting pig manure with 2.5% biochar (mass) made at different pyrolysis temperatures. They demonstrated that biochar prepared at 500°C was best suited for composting, while biochar prepared at over 700°C resulted in compost with an unfavorably high pH, higher NH_3 emissions, and a lower seed germination index. Zhang et al. (2014b) analyzed biochars made from hardwood, bamboo, and rice husks, to determine their relative influence on composting rate. They reported that the wood-derived biochar had better hydrophobic, gas sorption, and aromatic properties, compared to the others, which resulted in increased composting rate. The authors concluded that of the biochar that they tested, the one made of wood was best suited as a compost additive.

Another variable that affects the influence of biochar in compost is the relative amount of biochar being used. For this dissertation studies using thirty-eight different biochar-to-compost ratios were reviewed, with an average mass concentration of 9.6% (±7.4% standard deviation). Zhang et al. (2014b) investigated co-composting sewage sludge and straw with 3 proportions of hardwood biochar. They reported that a ratio of 12-18% (mass) resulted in the highest compost microbial activity and degradation rate. Chen et al. (2010) added 3% and 9% (vol.) biochar to pig manure compost, and reported that the 9% treatment retained 23% more N than the 3% treatment. Further, the 9% treatment had relatively less heavy metal mobility. Khan et al. (2016) composted poultry manure and sawdust with three types of biochar, each at mass concentrations of 5% and 10%, and found that different proportions had no consistent effect on composting.

Biochar Compost Nitrogen Dynamics

Compost requires an appropriate C:N ratio to metabolize the available organic matter (Hua et al., 2009). The process reduces the N content of the parent material, which manifests as nitrogenous gases, predominantly in the form of NH_3, and to a lesser extent NO_2 (Lehmam and Rondon, 2006). The proportion of initial N that is lost during composting of poultry manure is variable. For instance, Wang et al. (2013) reported that as much as 65% is lost, Tiquia and Tam (2000) reported 59%, and Ogunwande et al. (2008) reported 71-88%.

Nitrogen volatilization lowers the agronomic value of the compost, so methods to reduce such losses have been the subject of a considerable amount of investigation. For example, Hua et al. (2009) co-composted sewage sludge with 9% biochar (vol.) and found that total N loss was reduced by 64.1% relative to the control. They attributed this reduction to thermophilic bio-oxidation of biochar during composting, which increased the amount of carboxylic acid groups on the biochar surface, which resulted in the sorption of NH_3. Khan et al. (2016) also reported that composting increased the surface oxidation of biochar. They composted poultry manure and sawdust with biochar of various origins at different concentrations. They found that compost with biochar retained more N, but also C, sulfur, and boron, as compared to the control.

While adsorption of NH_3 by biochar is a key mechanism for reducing compost volatiles, secondary factors, such as the compost's pH and C:N ratio, also have considerable effects. A review of such mechanisms was presented by Lehmam and Rondon (2006). They suggest that composting with biochar lowers the initial concentration of N, thus permitting microbial immobilization of a relatively greater proportion of the available N, decreasing volatilization. However, there was little mention of the recalcitrant nature of C in biochar.

Other research suggests that biochar increases the pH of compost and thereby changes the N dynamics. For example, Steiner et al. (2010) investigated co-composting poultry manure with 20% (vol.) biochar made from pine chips, and found that the compost pH increased. Emissions of NH_3 were thereby decreased by 64%, and total N losses were decreased by 52%, relative to the controls. Similarly, Chen et al. (2010) added 3% and 9% biochar (vol.) to pig manure compost and observed increases in pH leading to a 65% reduction in total N losses.

Composting with biochar does not always decrease gas emissions. Wang et al. (2013) found that composting pig manure with 3% (mass) biochar increased its pH relative to controls, but did not cause a reduction in N gas emissions. Dias et al. (2010) found that the high pH of poultry manure compost inhibits biochar from adsorbing ammonia. Sanchez-Garcia et al. (2015) composted poultry manure and barley straw with 3% biochar (mass) and found that biochar did not have an effect on the emission of gasses (CO_2, CO, CH_4, N_2O, and H_2S), nor on the overall loss of N. To the contrary, the study demonstrated that the presence of biochar increased NH_3 formation during thermophilic composting and accelerated nitrification during the maturation phase.

Microbe Community Dynamics

Composting involves complex mineralization and nitrification processes whereby microorganisms convert organic compounds into various N-containing volatiles, H_2O, and CO_2, and release heat (Haug, 1993). Increased microbial activity in compost can affect the type and amount of volatile gases that are released, as well as accelerate heating, increase peak temperatures, and prolong thermophilic composting (Li et al., 2014, Wei et al., 2014, Sonoki et al., 2012, Lehmam and Rondon, 2006). Compost microbial activity is influenced by pH, nutrient availability, oxygen concentration, and porosity (Anderson et al., 2011, Chen et al., 2010). Biochar in compost is generally beneficial for microbiota because it influences those properties, while retaining dissolved nutrients, and serves as a matrix for microbial growth that offers refuge from predators (Lehmam and Rondon, 2006, Jindo et al., 2012b, Wardle et al., 2008).

Wei et al. (2014) and Sanchez-Garcia et al. (2015) reported that composting poultry manure, tomato stalks, and barley straw with 3% (vol.) biochar increased microbial activity. Jindo et al. (2012a and 2012b) co-composted homogenized mixtures of poultry manure, rice husks, and apple pomace, and poultry manure and cow manure, with 10% (mass) and 2% (vol.) hardwood biochar, respectively. In both cases they observed that biochar increased the microbial activity and fungal diversity. In a separate study, Wang et al. (2013) showed that co-composting pig manure with 3% (mass) biochar reduced the abundance of NO_2^--producing bacteria, and increase the abundance of N_2O-consuming bacteria, relative to the controls. As such, pig manure that was co-composted with biochar had lower concentrations of NO_2^-—N gas, and decreased total N_2O emissions, especially during the maturation phase, relative to non-biochar controls.

Carbon dioxide is a product of aerobic respiration, so its production is indicative of microbial activity in compost (Sonoki et al., 2012). Steiner et al. (2011) co-composting poultry manure with variable percentages of soft wood biochar. They reported that of CO_2 production and, by inference, aerobic microbial activity and organic matter degradation, were positively correlated with the amount of biochar that was added. Similarly, Steiner et al. (2010) and Malinska et al. (2014) each co-composted sewage sludge with biochar, and each reported increased composting temperatures and rates of organic matter decomposition, relative to their controls. Steiner et al. (2010) reached this conclusion by inference from CO_2 production and compost temperature, while Malinska et al. (2014) measured organic matter content directly. Li et al. (2014) found pig manure co-composted with 2.5% (mass) biochar had 14-29% more degradation of organic matter and a prolonged thermophilic phase, relative to their controls.

Conversely, Jindo et al. (2012a) co-composted a mixture of poultry manure and organic wastes (rice husks and apple pomace) with 2% (vol.) biochar, and found relatively lower microbial biomass in the biochar compost (yet the total content of certain enzymes produced by microbes was higher).

Physical Dynamics

Bulking agents that improve airflow during composting increase the degradation of organic matter (Kuzyakov et al., 2009). Sanchez-Garcia et al. (2015) reported that 3% (mass) biochar in poultry manure compost prevented the formation of large clumps and enhanced airflow. Prost et al. (2013) composted a homogenized mixture of farmyard manures and straw, in which they put mesh bags containing 50.0 g of crushed and sieved biochar (50 bags in a 1 m^3 composter). They found that the moisture content of the biochar increased by 50-100% during composting (they demonstrated this using the specific moisture content of compost and biochar in combination with the biochar's specific surface area, micropore surface area, and micropore space). Theoretically, moisture absorption by biochar particles results fewer anaerobic pockets in the surrounding compost substrate (Yoshizawa et al., 2005, Jindo et al., 2012a). Other authors, such as Steiner et al. (2010) and Li et al. (2014), have similarly demonstrated that biochar influences compost moisture dynamics.

Organic Nutrient Dynamics

Nutrient dynamics during composting influences microbiological activity, off gassing, leachate composition, and the fertilizer value of the resulting compost (Lehmam and Rondon, 2006). However, the effect of biochar on nutrient dynamics is not well reported in the literature. Notably, Khan et al. (2016) reported that the thermophilic oxidation of biochar during composting poultry litter increased compost's cation exchange capacity and the sorption of N, C, B, and S, as compared to control treatments. Sanchez-Garcia et al. (2015) found that 3% biochar (mass) composted with poultry manure and barley straw increased the rate of nitrification. Wei et al. (2014) found that when poultry manure was composted with 3% (mass) biochar, it had a higher volatile fatty acid concentration than control treatments. Jindo et al. (2012a) co-composted a mixture of poultry manure, rice husks, and apple pomace, with 2% (vol.) biochar, and observed that the biochar treatments had 30% less water soluble C, and 10% more C captured by humic substances, relative to the controls. They attributed this effect to enhanced compost degradation rate and sorption of organic compounds into the biochar.

Plant Growth using Biochar Compost

Biochar alone contains few plant nutrients (Lehmann and Joseph, 2009). However, Schmidt (2011) wrote that composting inoculates biochar with microbes, nutrients, and other organic compounds, improving it as a soil amendment. Fischer and Glaser (2012) reported that composting oxidizes the surface of biochar, enhancing its capacity to absorb minerals, nutrients, and dissolved organic matter. Composted biochar in soil can improve plant growth more than the same amounts of compost and biochar added separately (Schmidt, 2011).

Much research has been devoted to the effects of biochar on soil quality and plant growth (e.g. Schultz and Glaser, 2012, Fischer and Glaser, 2012, Liu et al., 2012). Jeffery et al. (2011) and Biederman and Harpole (2012) each conducted meta-analyses of literature about the effects of biochar on plant growth and nutrient cycling. They found that the application of biochar to soil generally resulted in increased aboveground productivity, crop yields, soil microbial biomass, rhizobia nodulation, and soil P, K, and total N and C, relative to controls. However, they also found that there was no correlation between the amount of biochar that added, and the magnitude of the crop yield increases. Moreover, the effects were confounded by the variety of soil and biochar types among studies that they included, so the authors were unable to draw any definite conclusions about the association of biochar, soil, and plant growth.

The effects of biochar compost on plant growth are generally presented as addenda to other research findings. For example, Li et al. (2014) studied the effects co-composted pig manure with 2.5% (mass) biochar, and included ryegrass germination as one experiment among many. They found that biochar compost benefited ryegrass germination, relative to their controls. Similarly, Schultz et al. (2013) studied various aspects of composting with, and found that soil containing 0 – 50% biochar compost enhanced the growth of oat plants in proportion to the amount of biochar. Agegnehu et al. (2015) found that plant growth increased in proportion to the amount of biochar compost mixed with the soil, which they attributed to biochar increasing the soil's capacity to adsorb moisture and plant available nutrients. Lashari et al. (2013) found that wheat straw composted with 33% biochar (vol.), when applied to fields at 12 t ha^{-1}, mitigated the effect of soil salinity on wheat growth, resulting in a 38% increase in yield relative to the non-biochar controls. Finally, Steiner et al. (2008) investigated the effect of biochar compost, biochar alone, compost alone, and a control on N retention in sorghum grown on Amazonian soil. They demonstrated that soils treated with biochar compost had significantly lower N leaching rates, and greater plant productivity, compared to other treatments. Of the few studies published about the effects of biochar compost on plant growth only one reported neutral results: Schmidt et al. (2014) found that growth and nutrient uptake of grape vines in a vineyard was not affected by the addition of biochar compost, compost alone, or biochar alone.

Chapter 3 - Materials and Methods

General Overview

This investigation was designed to elucidate the influence of biochar particle size during co-composting with poultry manure. The analysis is divided into two phases: during the preliminary composting phase we quantified *in situ* gas emissions, as well as other metrics of compost quality; during the secondary phase we examined the effects of mature compost on plant growth. Phase two is divided into two parts: first we conducted a phytotoxicity test to determine what ratio of compost to soil was best suited for plant growth and, second, the resulting concentration was used to test the compost's influence on lettuce production.

Experimental and Apparatus Design

An in-vessel composting experiment was carried out in the Large Animal Research Unit on the Macdonald Campus of McGill University, Ste-Anne-de-Bellevue, Quebec, Canada (latitude 45°24'20.68" N, longitude 73°56'30.56" W). Each of the 12 compost vessels was made from a 205 L cylindrical polyethylene barrel (Item #8001, Jos Le Bel Inc., Montreal, QC, Fig. 3.1). The lids were sealed to the top of the barrels with metal locking rings, and the sides insulated with foil bubble insulation (Reflectix Bubble Pack, Reflectix Inc., Markleville, IN). The vessels were elevated 100 mm off of the floor by wooden frames. Barrels were passively aerated through a plenums formed by expanded metal platforms (3.2 mm diameter wire, 19 mm openings), supported 150 mm from the bottom of each vessel, by metal legs. The expanded metal platforms were further covered with plastic window screen (0.18 mm diameter wire, 0.88 mm openings) to prevent fine particles from falling into the plenum. A 100 mm hole was cut in the side of each vessel as an air inlet to the plenum. Another hole of equal size was cut in the middle of the lid as an exhaust port, and connected to a 0.90 m-long vertical section of 100 mm diameter galvanized ventilation duct. The inlet hole and the top of the exhaust ducts were covered with plastic window screen to prevent the movement of insects in and out of the vessels. A 5 mm-diameter hole was drilled 300 mm from the top of each exhaust duct to allow the measurement of air velocity, and covered with duct tape when not in use. A similar hole was drilled through the lid halfway from the center to allow the insertion of a gas sample line. Another hole was drilled in the side of each barrel, 300 mm below the lid, to allow the insertion of a thermocouple probe, and at the bottom of each vessel, 40 mm from the outer edge, to allow drainage of any leachate into a plastic dish.

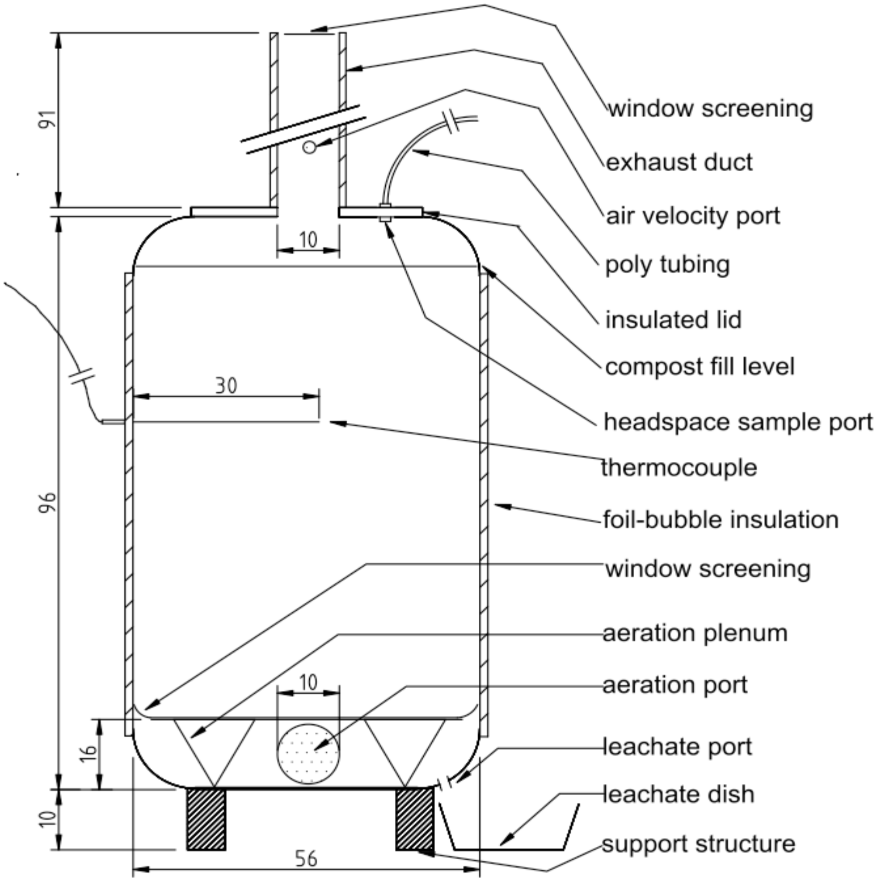

Figure 3.1 Schematic diagram of a compost vessel. Number values in cm. Exhaust duct and tubing truncated.

Untreated biochar of three particle sizes [Fine (<1.6 mm), Medium (6.4 – 3.2 mm), Coarse (19.2 – 12.8 mm); Fig. 3.2], made from sugar maple (*Acer saccharum*), was obtained from Basques Hardwood Charcoal, Rimouski, QC. In addition to poultry manure and biochar, pine wood shavings (*Pinus* spp.), wheat straw (*Triticum aestivum*), and water were used to prepare the compost mixture. The initial carbon-to-nitrogen (C:N) ratio at the start of the experiment was set at 35:1 and moisture content of compost was 60%. The initial volumes of material used for compost are shown in Table 3.1. Four compost mixtures, based on the three biochar particle sizes and a control without biochar, were used to fill the compost vessels. Additional pine wood shavings were added to the control treatment to adjust the initial C:N ratio to 35:1. Each experimental treatment was replicated four times. The vessels were randomly placed in a grid pattern and were not moved during the experiment. Composting began on 21 August 2013, and lasted 32 days, after which time the compost temperatures approached ambient. Ambient temperatures ranged between 21 and 32°C.

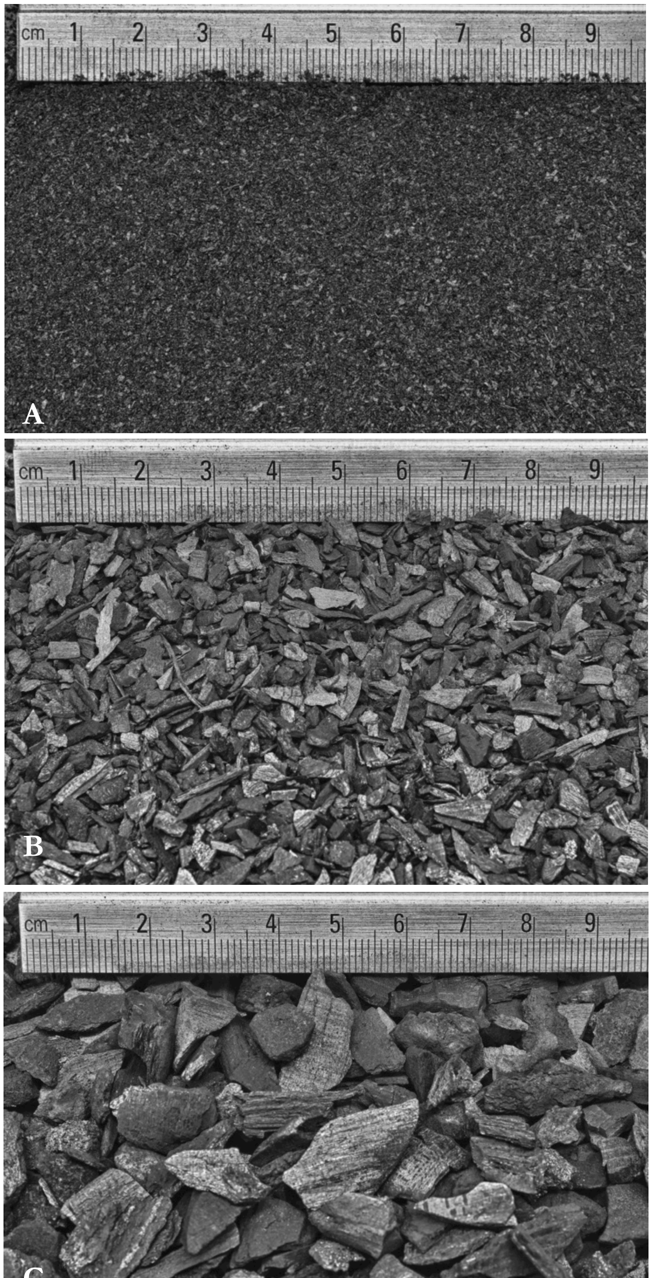

Figure 3.2 Biochar particle sizes. A: Fine (<1.6 mm), B: Medium (6.4 - 3.2 mm), C: Coarse (19.2 – 12.8 mm). Ruler (cm) shown for scale.

Table 3.1 Initial mixture ratio and characteristics of compost material.

	Biochar treatments (% v.)	Control treatments (% v.)	Moisture (% w.w.)	Organic matter (% d.w.)	C:N	pH
Compost	-	-	65	-	30:1	-
Poultry manure	31	31	74.93 ± 1.27	73.20 ± 1.92	Nd	8.49 ± 0.06
Softwood chips	15	35	32.2	Nd	Nd	Nd
Wheat straw	9	9	Nd	87.38 ± 1.78	Nd	Nd
Biochar	20	0	Nd	Nd	Nd	Nd
Water	25	25	-	-	-	Nd

Values are means ± standard error, Nd = not determined, v. = volume, w.w. = wet weight, d.w. = dry weight. Values to the right of the vertical line are mixture ratios, and left of the vertical line are compost physical characteristics

Phase One – Composting and Gas Emissions

Gas emissions were sampled using a custom-built multi-stream sampling system (Avensys Solutions, Montreal, QC) and analyzed with a Fourier Transform Infrared (FT-IR) gas analyzer (CX4000, Gasmet Technologies, Helsinki, Finland) which detects gaseous compounds by their absorbance of infrared radiation. The gas analyzer had a Peltier-cooled BaF_2 mercury cadmium telluride (MCT) detector with a 900–4200 cm^{-1} wavelength range and a 1.07 L multi-pass sample cell maintained at 180°C. A 5 L min^{-1} sample flow rate was maintained through the cell. The multi-stream sampler was controlled using Matlab (v.R2012a, The MathWorks, Natick, MA) and National Instruments drivers (NI-DAQmx, National Instruments Corporation, Austin, TX). The gas analyzer was controlled and the data preprocessed using the manufacturer's proprietary software (Calcmet v.11, Gasmet Technologies). Library spectra were included for CH_4, NH_3, N_2O, NO, NO_2 CO, CO_2, and SO_2 gases. The FT-IR background spectrum was manually recalibrated daily according to manufacturer's specifications. Gas samples were drawn from the headspace of each reactor through 3.2 mm-diameter polypropylene tubing, wrapped with insulating foam tape (no. FV15H, Thermwell Products, Mahwah, NJ). The sample gas passed through in-line filters (9 μm mesh size, 25 mm diameter, in-line Delrin plastic filter holders, Pall Canada, Montreal, QC), and custom-built water traps. Filters and water traps were checked daily and replaced or emptied as required. Exhaust gas was sampled sequentially from each vessel for 3 min every 36 min, for the duration of the experiment.

A K-type thermocouple (Omega Environmental, Laval, QC) was inserted into the compost to a horizontal depth of 300 mm, through the aforementioned hole in the side of each vessel for temperature measurements. Temperature was recorded using a data logger (Model 34970A, Agilent Technologies, Santa Clara, CA) at 10 min intervals for the duration of the experiment.

Bulk density was measured four times during the experiment, on days 1, 10, 20, and 30. A 20 L bucket was filled with compost and dropped onto the ground from a height of 300 mm. Additional compost was then added to level off the bucket and the net mass was measured and recorded with a precision of 0.2 kg. The total mass of each compost vessel was also recorded at the beginning and end of the experiment. Exhaust gas velocity was measured daily by inserting a hot-wire anemometer (VelociCalc™ model 9545, TSI, Shoreview, MN) into the aforementioned hole in the side of the exhaust duct and recorded to the nearest 0.1 m/s.

Composite compost samples were taken from the middle of each barrel on the first day of composting, and subsequently at 10-day intervals. Samples were transported to a lab on Macdonald Campus for analysis. Analytical protocols used were based on the American Composting Council guidelines (TMECC, 2003). A bench-top meter (SympHony SB70P, VWR International, Radnor, PA) was used to measure pH. Ammonium and nitrates were measured by homogenizing dry samples using a blender, followed by KCl extraction. Compost maturity was analyzed by measuring the specific oxygen uptake rate (TMECC 05.08). Samples were incubated in an oxygen rich environment for 2 h at 37°C, after which time the sample vessels were sealed and the oxygen concentration was tracked for 2 h using galvanic cell oxygen sensors and data loggers (Model SO-200, Apogee Instruments, Logan, UT; Fig. 3.3). The percent oxygen concentration was calculated in accordance with the manufacturer's protocol and the subsequent depletion rates were calculated. The rate of change of O_2 depletion was used as a proxy of heterotrophic microbial activity, which is indicative of their relative stages of stability (Iannotti et al., 1994). The resulting oxygen depletion curves had inexplicably positive slopes (possibly due to air leakage), and were therefore excluded from analysis.

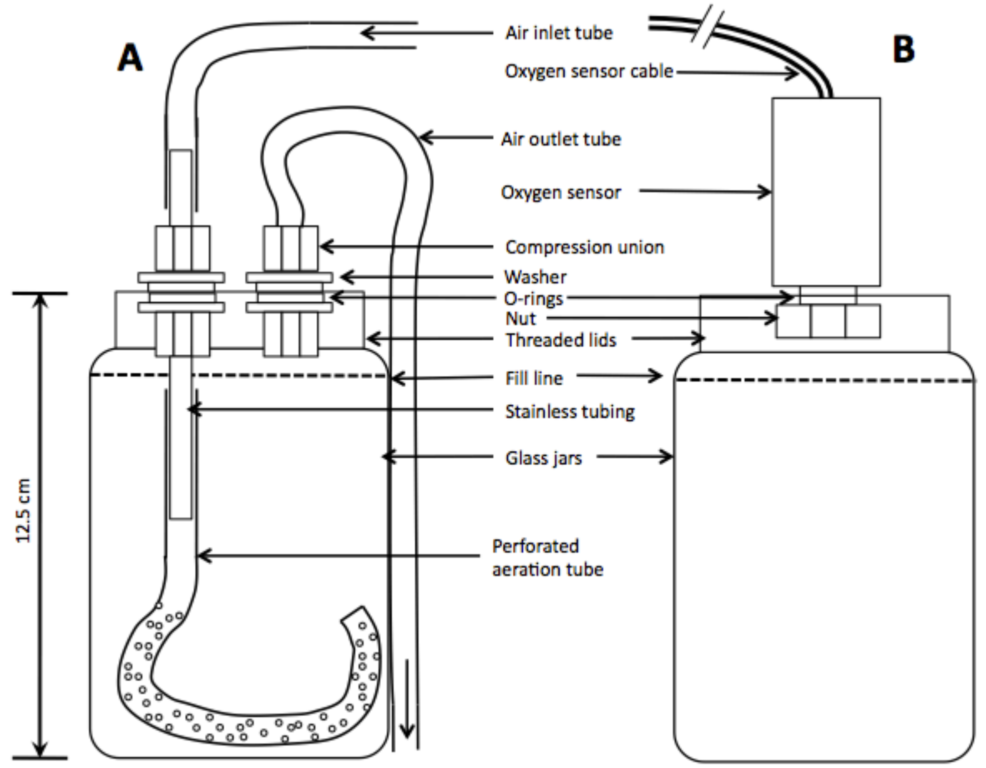

Figure 3.3 Specific oxygen uptake rate (respiration) flask assembly: (A) with aeration assembly attached and (B) with oxygen sensing assembly attached.

Phase two - Plant Growth

The preliminary stage of this research involved adding 3 different particle sizes of biochar to poultry manure and then monitoring the composting process. Following the thermophilic stage of composting, the product was left to cure for roughly 2 months. At that point, stage two of the research was initiated: examining the effect of poultry manure co-composted with various sized biochar on plant growth. The investigation was divided into two parts: first, a phytotoxicity test was preformed to determine which biochar compost-to-soil ratio would best support plant growth, second, a longer-term test was conducted regarding the biochar compost's effect on lettuce production.

Phytotoxicity Determination – Spring barley (*Hordeum vulgare)*

Phytotoxicity tests were conducted on compost derived from each of the four compost treatments described above. Barley seeds (*Hordeum vulgare L.,* CDC McGwire) were sown in different mixtures of potting soil and compost to assess the optimal (non-phytotoxic) proportions of compost for seed germination and growth.

To begin, seeds were soaked for five min in 0.2% sodium hypochlorite solution, rinsed 20 times with tap water, then four times with distilled water to disinfect them. Disinfected seeds were soaked in distilled water at 4˚C for 12 h to stimulate germination. They were then drained and spread evenly on trays lined with moist paper towel and covered in perforated tinfoil. After 30 h, 90% of the seeds had germinated.

Each of the four compost types derived from the previous experiment were mixed in five proportions (by volume) with potting soil (G10 Agrimix, Fafard, Saint-Bonaventure, QC), in addition to a soil-only negative control, to achieve a 4 x 5 factorial experimental design. The soil to compost treatment ratios were as follows: 20:80; 40:60; 60:40, 80:20, and 100% compost. Pre-germinated single seedlings were sown in a 74-well tray, each well measuring 15 x 15 x 40 mm. Each treatment was replicated 60 times with individual plants making a total of 1260 plants in 21 germination trays. Germination trays were placed in a greenhouse with a 14 h photoperiod and 25˚C ambient temperature, and randomly repositioned every second day to reduce any boundary effects. Plants were manually irrigated daily. The growth phase lasted 12 days.

Following the growth phase, each plant was assigned a numerical score for appearance as follows: 1 (no growth); 2 (dead plant); 3 (highly discoloured and/or wilted); 4 (healthy plant with at least one imperfect leaf); and 5 (perfect plant). Whole plants were harvested and total length and above-ground biomass (wet weight) were measured. To obtain dry weights of above ground biomass, plants were wrapped in foil, oven-dried at 105˚C for 24 h, and then re-weighed.

Production Viability – Butterhead lettuce *(Lactuca sativa)*

Based on the results of the phytotoxicity test, it was determined that the best combinations of compost-potted soil mixture were 20:80 and 40:60% by weight. A control treatment composed exclusively of the standard greenhouse soil (G10 Agrimix, Fafard, Saint-Bonaventure, QC) was used as the third treatment. For each treatment, 2 encapsulated lettuce seeds (*Lactuca sativa*) were sown in a 6 L pot, placed in a greenhouse with the same conditions as mentioned earlier, and monitored for germination. Treatments were replicated 4 times each. If both of the seeds in a pot germinated, then one plant was removed. A balanced fertilizer (20:20:20) was applied 4 and 21 days after sowing. Adequate water was supplied to the plants by means of drip irrigation. Plants were allowed to grow for 43 days before harvesting in accordance with the seed supplier's recommendations. Above- and below-ground wet and dry weights, and stem and root lengths were measured for each plant, and a numerical score was assigned based on visual assessment (as above, for barley).

Statistical Analyses

Composting/Gas Phase

Statistical analysis for all experiments was performed using SAS 9.4 software (SAS Institute Inc., Cary, NC). Generalized linear mixed models (SAS PROC GLIMMIX) were used to relate the exhaust gas velocities and the mean daily compost temperatures in each barrel. The model fit to the emission data for each gas was as follows:

$$Y_i = c_i + u_{ij}$$

Where the temporal covariance matrix of σu_{ij} was structured based on (SAS default) standard variance components (type = vc), ci indicates the compost, and i indicates the barrel.

The biochar particle size was coded as a fixed factor in the model, and barrel position was coded as a random factor. The velocities were multiplied by the molecular weight and concentration of each component gas of interest to estimate its mass flux. The gas flux was then integrated over time to estimate the mass of the nutrient (N or C) being volatilized.

The best-fitting distribution for lab data, chosen from the exponential family of distributions, was determined based on the Bayesian information criteria (Schwarz, 1978). Differences between treatments were determined using Bonferroni-adjusted limits at the 95% confidence level.

For gas emission and bulk density data, locally-weighted scatter-plot smoothing charts were generated using PROC SGPLOT with the LOESS statement to estimate local regression (SAS Institute Inc., Cary, NC; Fig. 4.6). Locally-weighted scatterplot smoothing charts are nonparametric procedures for hypothesis testing. They are not based on any assumptions about the probability distributions of the variables being tested (Sheskin, 2004).

Plant Growth Phase

For analysis of barley phytotoxicity and lettuce growth data, models were fit using SAS PROC GLIMMIX as above. The data was found to have Gaussian (normal) distribution for fresh weight measurements and inverse Gaussian for stem length measurements.

The ideal compost mix level was selected as the one with the consistently greatest LS-mean, with 95% confidence limits, for plant weight and stem length, averaged across each experimental treatment. The fresh weight of lettuce was determined to have Gaussian (Normal) distribution. Sheffés's single-step adjustment for multiple comparisons was applied.

Connecting statement #1

This research has a clear division between the preliminary composting and gas monitoring phase, and the secondary plant growth phase. The primary phase includes the composting of poultry manure with three particle sized of biochar, and subsequently measurement of gas emissions, pH, bulk density, temperature, and respiration.

The following chapter describes the methodology and results of the composting phase. The chapter has been submitted for review in the Journal of Environmental Quality. Table and Figures have been renumbered to be consistent with the rest of the dissertation. The references for this chapter are presented at the end of the dissertation.

Chapter 4 – Co-composting Poultry Manure with Biochar: Part 1) Effects on Gas Emissions

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Abstract

Co-composting with biochar appears to influence the emission of nuisance gasses from compost, but the understanding of the mechanisms behind this influence is not well understood. Investigations on the matter have yielded ambiguous results, due in part to variability in biochar from different manufacturing conditions and post-production treatments. This study investigated the effect of co-composting three different particle sizes of biochar [fine (<1.6 mm), medium (6.4 – 3.2 mm), and coarse (19.2 – 12.8 mm)] with poultry manure, wheat straw, and softwood shavings, in the proportions of 4:6:1:3, (20% biochar, by vol. including water). Gas emissions were measured using Fourier transform infrared spectroscopy (FT-IR). Our results demonstrate that gas emissions from compost with larger sized biochar had lower concentration of CO, CO_2, NO, and NH_3, relative to smaller biochar. Biochar particle size also had significant effect (non-parametric test; $p < 0.05$) on compost bulk density, and temperature (Spearman's $r = -0.31$, $p < 0.0001$). Compost that included either of the two larger sized biochars experienced greater peak temperatures, followed by a more rapid return to ambient temperatures than the smaller sized biochar treatments. Conversely, the effect of biochar particle size on the emission concentrations of CH_4, and SO_2 gases, as well as compost pH was sufficiently variable that further investigation is recommended to elucidate the contributing factors. This information is relevant for poultry producers who are considering which bulking agents are best suited for compost.

Introduction

Composting is the managed, thermophilic, aerobic, microbial degradation of organic material, which produces a stabilized soil amendment that is largely free of viable pathogens and plant seeds. Water vapor and carbon dioxide are released during composting as a result of the aerobic metabolism and warm temperatures. Nitrogen (N) is also readily volatilized during the process, which reduces the fertilizer value of the resulting compost (Nahm, 2003). N gases include ammonia (NH_3), nitric oxide (NO), nitrous oxide (N_2O). Other nuisance compost gases include carbon monoxide (CO), methane (CH_4), and sulfur dioxide (SO_2). All of these gases can negatively impact the environment and the health of compost workers.

The emission of nuisance gases can be somewhat controlled by modifying the carbon to nitrogen (C:N) ratio, bulk density (BD), turning frequency, and aeration rate (Ogunwande et al., 2008, Jiang et al. 2011). However, these parameters can be difficult or costly to manipulate on an agricultural or industrial scale (Wang et al., 2013). As such, other methods of reducing compost gas emissions have been proposed, including co-composting with biochar.

Biochar is a carbonaceous material produced by the slow pyrolysis of biomass (Chan et al., 2007). Researchers have demonstrated positive effects of co-composting with biochar. For example, Hua et al. (2009) observed that composting with biochar decreased odour emissions from sewage sludge compost, possibly due to increased cation exchange capacity and porosity within the composting matrix. Dias et al. (2010) observed that mixing 50% (mass) biochar with poultry manure before composting resulted in an increase in the rate of humification of degradable organic material. Yoshizawa et al. (2005, 2007) showed that biochar in compost accelerated microbial growth and changed the microbial community structure. Several researchers reported that biochar adsorbed and retained NH_3 (e.g. Dias et al., 2010; Steiner et al., 2010).

On the other hand, some researches have demonstrated neutral or negative effects of co-composting with biochar. Sanchez-Garcia et al. (2015) added 3% biochar (by mass) to poultry manure and barley straw compost and found that biochar did not affect the emission of gasses (CO_2, CO, CH_4, N_2O, and H_2S), nor did it decrease the overall loss of N. The study demonstrated that the presence of biochar increased the formation of NH_3 during composting, and enhanced the rate of N mineralization (ammonification and nitrification rates were calculated using gas generation and mineralization rates) during the compost maturation phase. Similarly, Wang et al. (2013) found that co-composting pig manure with 3% biochar (by mass) did not reduce N gas emissions. The different results may be due in part to the variability of the physical and chemical properties of biochar, which strongly depend on the type of biomass and operating conditions used for its production (Prost et al., 2012). This study is intended to investigate the effect of biochar properties, specifically its particle size, on aspects of the composting process, including gas emissions.

Materials and Methods

In this study we investigated the influence of biochar particle size on gas emissions during composting. We composted poultry manure, which is a nitrogen-rich substrate, together with one of three sizes of biochar, and continuously quantified gas emissions using a Fourier transform infrared (FT-IR) gas analyzer.

An in-vessel composting experiment was carried out in the Large Animal Research Unit on the Macdonald Campus of McGill University, Ste-Anne-de-Bellevue, Quebec, Canada (latitude 45°24’20.68” N, longitude 73°56’30.56” W). Each of the 12 compost vessels was made from a 205-L cylindrical polyethylene barrel (Item #8001, Jos Le Bel Inc., Montreal, QC, Fig. 1). The barrels’ lids were sealed with metal locking rings, and the sides insulated with foil bubble insulation (Reflectix Bubble Pack, Reflectix Inc., Markleville, IN). Vessels were elevated 100 mm off of the floor using wooden frames. Passive aeration was facilitated using plenums made from expanded metal (3.2 mm diameter wire, 19 mm openings), 150 mm from the vessels’ bottoms. The plenums were covered with plastic window screen (0.18 mm diameter wire, 0.88 mm openings) to prevent fine particles from falling through. A 100 mm hole was cut in the side of each vessel as an air inlet to the plenum. Another hole of equal size was cut in the middle of the lids, as an exhaust port, and connected to 0.90 m-long vertical sections of 100 mm diameter galvanized ventilation duct. The inlet holes and the top of the exhaust ducts were covered with plastic window screen to prevent the movement of insects in and out of the vessel. A 5 mm diameter hole was drilled 300 mm from the top of each exhaust duct to allow the measurement of air velocity, and covered with duct tape when not in use. Three similar holes were drilled in each vessel: one through the lid halfway from the center to allow the insertion of a gas sample line, another in the side, 300 mm below the lid, to allow the insertion of a thermocouple probe, and finally one in the bottom, 40 mm from the outer edge, to allow drainage of any leachate into a plastic dish.

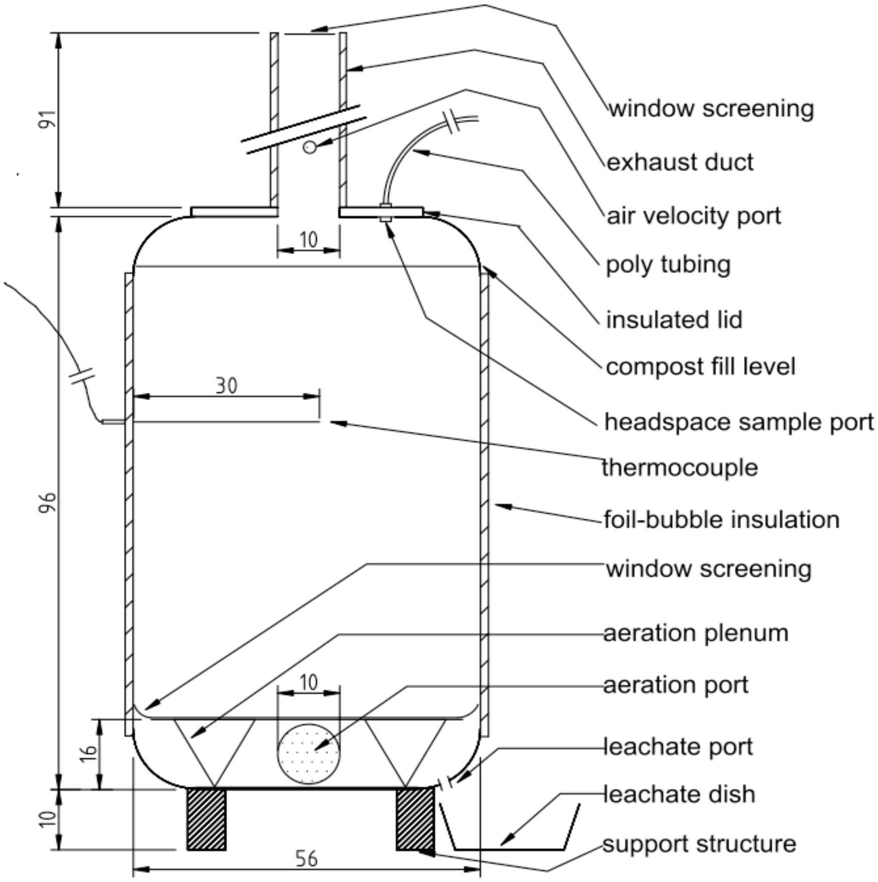

Figure 4.1. Schematic diagram of a compost vessel. Number values in cm. Exhaust duct and tubing truncated.

Untreated biochar of three particle sizes [fine (<1.6 mm), medium (6.4 – 3.2 mm), and coarse (19.2 – 12.8 mm); Fig. 2], made from sugar maple (*Acer saccharum*), was obtained from Basques Hardwood Charcoal, Rimouski, QC. In addition to poultry manure and biochar, pine wood shavings (*Pinus* spp.), wheat straw (*Triticum aestivum*), and water, were used in the proportion of 4:6:1:3 (20% biochar, vol. including water). The initial carbon-to-nitrogen (C:N) ratio was set at 35:1, and the moisture content was 60%. The initial volumes of materials used for the compost mixture are shown in Table 1. Four distinct mixtures were made, with the three biochar particle sizes, and a non-biochar control. Additional pine wood shavings were added to the control treatment, to compensate for its lack of biochar. Each experimental treatment was replicated four times. The vessels were randomly placed in a grid pattern and were not moved during the experiment. Composting began on 21 August 2013, and lasted 32 days, until compost temperatures approached ambient. During that time ambient temperatures ranged between 21 and 32°C.

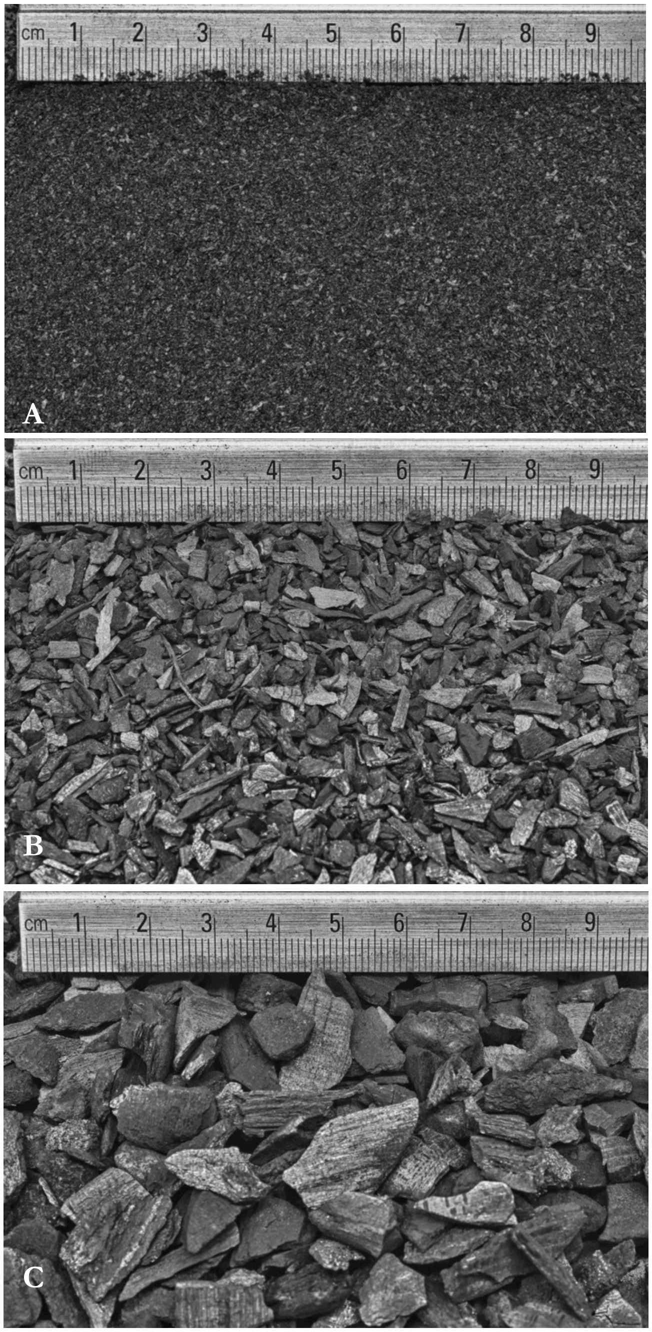

Figure 4.2 Biochar particle sizes. A: Fine (<1.6 mm), B: Medium (6.4 - 3.2 mm), C: Coarse (19.2 – 12.8 mm). Ruler (cm) shown for scale.

Table 4.1. Combined initial mixture ratios and characteristics of compost material.

	Biochar treatments (% v.)	Control treatments (% v.)	Moisture (% w.w.)	Organic matter (% d.w.)	C:N	pH
Compost	-	-	65	-	30:1	-
Poultry manure	31	31	74.93 ± 1.27	73.20 ± 1.92	Nd	8.49 ± 0.06
Softwood chips	15	35	32.2	Nd	Nd	Nd
Wheat straw	9	9	Nd	87.38 ± 1.78	Nd	Nd
Biochar	20	0	Nd	Nd	Nd	Nd
Water	25	25	-	-	-	Nd

Values are means ± standard error, Nd = not determined, v. = volume, w.w. = wet weight, d.w. = dry weight. Values to the right of the vertical line are mixture ratios, and left of the vertical line are physical characteristics

Gas emissions were sampled using a custom-built multi-stream sampling system (Avensys Solutions, Montreal, QC) and analyzed with a Fourier Transform Infrared (FT-IR) gas analyzer (CX4000, Gasmet Technologies, Helsinki, Finland). The gas analyzer had a Peltier-cooled BaF_2 MCT detector with a 900–4200 cm^{-1} wavelength range, a 1.07 L multi-pass sample cell maintained at 180°C, and a 5 L min^{-1} sample flow rate. The multi-stream sampler was controlled using Matlab (v. R2012a, The MathWorks, Natick, MA) and National Instruments drivers (NI-DAQmx, National Instruments Corporation, Austin, TX). The gas analyzer was controlled, and the data pre-processed, using the manufacturer's proprietary software (Calcmet v.11, Gasmet Technologies). Library spectra were included for CH_4, NH_3, N_2O, NO, NO_2 CO, CO_2, and SO_2 gases. The FT-IR background spectrum was manually recalibrated daily according to manufacturer's specifications. Gas samples were drawn from the headspace of each vessel through 3.2 mm inner-diameter polypropylene tubing, wrapped with insulating foam tape (no. FV15H, Thermwell Products, Mahwah, NJ). The sampled gas passed through in-line filters (9 μm mesh size, 25 mm diameter, Delrin plastic filter holders, Pall Canada, Montreal, QC), and custom-built water traps. Filters and water traps were checked daily and replaced or emptied as required. Exhaust gas was sampled sequentially from each vessel for 3 min every 36 min, for the duration of the experiment.

A K-type thermocouple (Omega Environmental, Laval, QC) was inserted into the compost to a horizontal depth of 300 mm, through the aforementioned hole in the side of each vessel for temperature measurements. Temperature was recorded using a data logger (Model 34970A, Agilent Technologies, Santa Clara, CA) at 10 min intervals, for the duration of the experiment.

Bulk density was measured on days 1, 10, 20, and 30. For this, a 20-L bucket was filled with compost at 1/3 intervals, and compacted by dropping onto the ground from a height of 300 mm. The bucket was leveled using additional compost, and the mass was measured with a precision of 0.2 kg. Exhaust gas velocities were measured daily by inserting a hot-wire anemometer (VelociCalc™ model 9545, TSI, Shoreview, MN) into the aforementioned hole in the side of the exhaust duct and recorded to the nearest 0.1 m s^{-1}.

Composite compost samples were taken from the middle of each barrel on the first day of composting, and at subsequent 10-day intervals. Samples were transported to a lab on Macdonald Campus for analysis. Analytical protocols used were based on the American Composting Council guidelines (TMECC, 2003). A bench top meter (SympHony SB70P, VWR International, Radnor, PA) was used to measure pH.

Statistical Analysis

For all experiments, statistical analysis for all experiments was performed using SAS 9.4 software (SAS Institute Inc., Cary, NC). Generalized linear mixed models (SAS PROC GLIMMIX) were used to relate the exhaust gas velocities and the mean daily compost temperatures in each barrel. After transformation with the lognormal distribution for nitrous oxide, and transformation with the inverse Gaussian distribution for all the other gases, the model fitted to the emission data for a given gas was as follows:

$$Y_{ij} = m + c_i + u_{ij}$$

Where the variance-covariance matrix for the experimental barrels (nested within the compost treatment factor) over days was structured using the default Variance Components type, and c_i represents the compost effect in the equation, where m is the overall population mean, and u_{ij}, the error term for barrel j with compost i.

The biochar particle size was coded as a fixed factor in the model, and barrel position was coded as a random factor. The velocities were multiplied by the molecular weight and concentration of each component gas of interest to estimate its mass flux. The gas flux was then integrated over time to estimate the mass of the nutrient (N or C) being volatilized.

The best-fitting distribution for lab data, chosen from the exponential family of distributions, was determined based on the Bayesian information criteria (Schwarz, 1978).

Differences between treatments were determined using Bonferroni-adjusted limits at the 95% confidence level.

For gas emission and bulk density data, locally-weighted scatter-plot smoothing charts were generated using PROC SGPLOT with the LOESS statement to estimate local regression (SAS Institute Inc., Cary, NC; Fig. 6). Locally-weighted scatterplot smoothing charts are nonparametric procedures for hypothesis testing. They are not based on any assumptions about the probability distributions of the variables being tested (Sheskin, 2004).

There were three semi-continuous periods of gas measurement during the experiment. Means measurements were calculated per barrel per period of semi-continuous measurement and compared by classical ANOVA.

Results and Discussion

pH Determination

The initial pH of the control treatment was more than 1 pH unit higher than that of the biochar compost treatments (Fig. 3). This is contrary to other reports where the addition of biochar to compost increases its pH (Steiner et al., 2010, Dias et al., 2010). It is unclear how the addition of softwood chips affected the pH of the control treatment, since the pH of the softwood chips we used was not measured. Differences in pH between biochar treatments were too minor to resolve. Compost pH increased by at least 0.2 pH units in all treatments after 30 days of composting. Increasing pH values are likely due to ammonification (Khan et al., 2014). There is less potential of a pH increase due to ammonification in compost with biochar because biochar adsorbs charged ions such as NH_4^+ (Malinska et al., 2014).

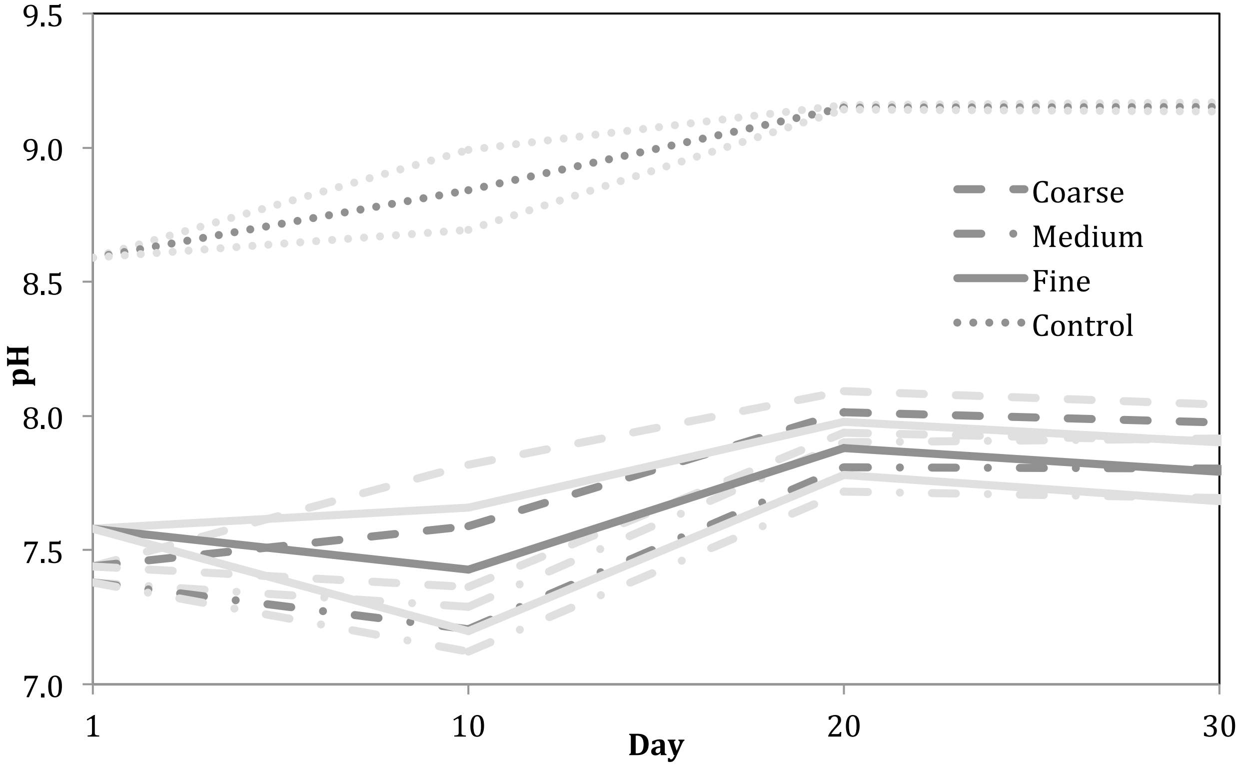

Figure 4.3. Mean pH of compost (n=4). Light lines above and below represent standard errors. Treatment types are Control (no biochar), Fine (<1.6 mm), Medium (3.2 – 6.4 mm) and Coarse (12.8 – 19.2 mm) biochar particle size.

Compost Bulk Density

Bulk density was lower in all the biochar treatments compared to the controls (non-parametric test, $p < 0.05$; Fig. 4). Of the biochar treatments, there was a significant difference between the medium size, which had the lowest density, and the small size, which had the highest. While the density of all the composts increased as the experiment progressed, the density of the coarse size treatment increased at a greater rate than the other treatments. Coarse biochar compost started with the lowest density, yet by the end of the experiment had the highest density. Decreased bulk density is beneficial for compost as it enables better movement of air through the compost matrix, which rusults in more complete and highter rate of organic matter degradation (Steiner et al., 2010, Alam et al., 2013, Oviedo-Ocaña et al., 2015).

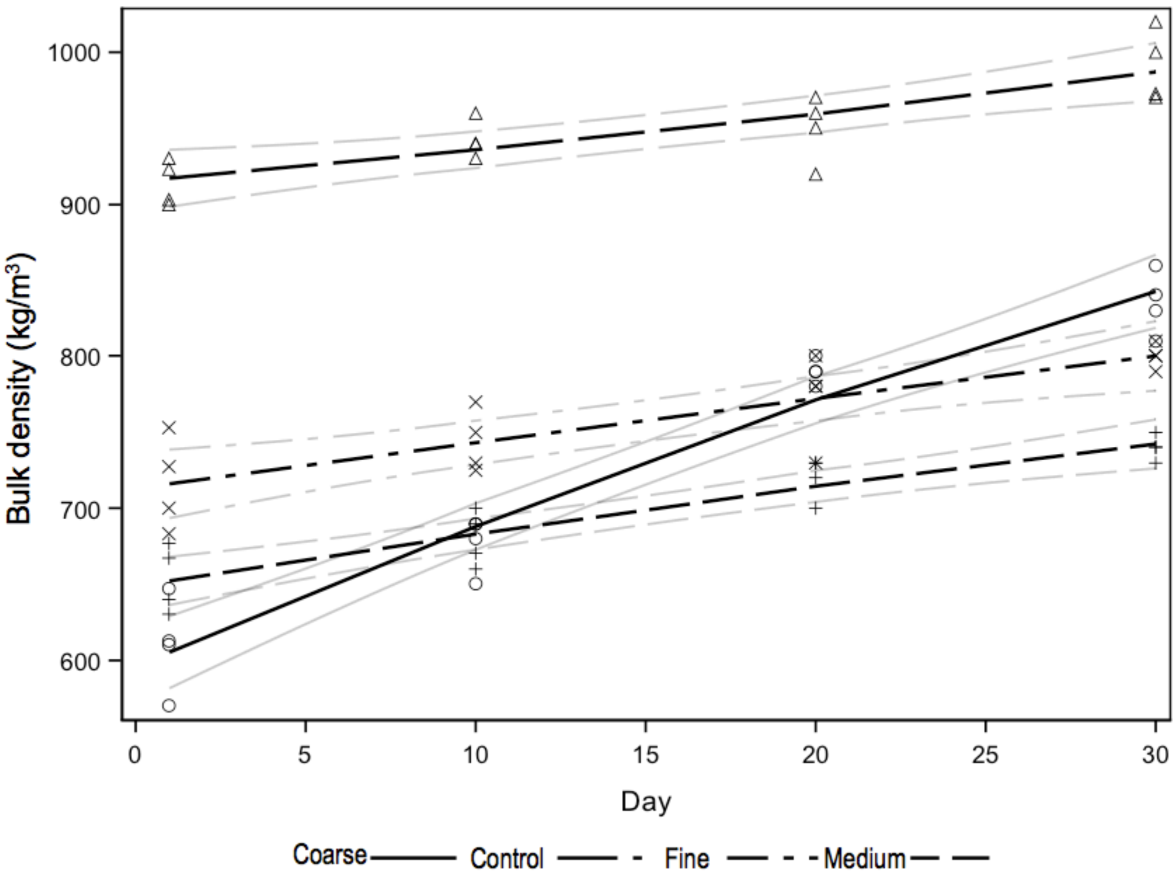

Figure 4.4. Nonparametric regression of compost bulk density. Values are means (n=8). Light grey lines represent 95% confidence intervals. Control (no biochar added), Fine (<1.6 mm), Medium (3.2 – 6.4 mm) and Coarse (12.8 – 19.2 mm) biochar particle size.

Compost Temperature

Biochar particle size was negatively correlated with temperature; i.e. finer biochar particles were associated with higher compost temperatures (Spearman's $r = -0.31$, $p < 0.005$; Fig. 5). All four treatments reached thermophilic conditions (> 45°C) within 5 days. The temperature in coarse and medium biochar treatments decreased to ambient levels (<30 °C) by day 30, yet temperatures remained above 30°C in the control and fine biochar treatments until the end of the experiment. The two finer biochar treatments had lower peak temperatures, and sustained higher temperatures, relative to the other treatments (Fig. 5). Such trends can be taken as a proximate indicator of more persistance availability of biodegradable organic matter, thus slower degradation rates, in compost (Kuter et al., 1985, Adhikari et al., 2013, Oviedo-Ocaña et al., 2015). By inference, prolonged high temperatures in our smaller grain sized treatments, in combination with their effect on compost bulk density, suggests that these treatments have decreased rates of organic matter degradation, possibly due to less favourable conditions for aerobic micro organisms, relative to larger sized treatments, although degradation rates and microbial activity was not measured directly.

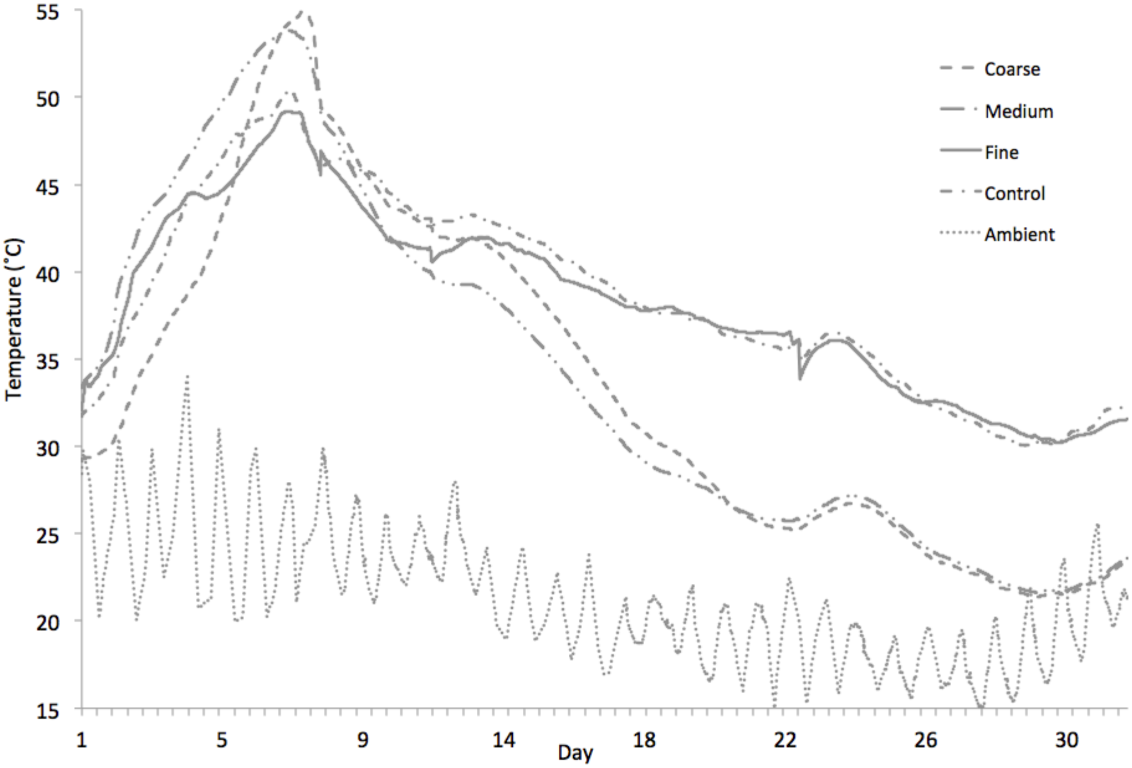

Figure 4.5. Mean daily compost temperatures as affected by biochar particle size (n=144). The three biochar particle sizes are Coarse (12.8 – 19.2 mm), Medium (3.2 – 6.4 mm), and Fine (< 1.6 mm). Standard error omitted for clarity. Measurements were taken continuously for the 31-day composting process, at a frequency of 10 minutes.

Exhaust Gas Composition

Methane emission concentrations from each of the treatments had no statistical differences for the first 20 days of composting (Fig. 6a). Following the second mixing event the coarse and fine treatments emitted a higher concentration of CH_4 than the medium sized and control treatments (non-parametric test, $p < 0.05$). Mean CH_4 emissions were lowest in compost that included medium sized biochar (Table 2). CH_4 in compost generated by anaerobic mathanogenic organisms, especially during the early stages of composting when the activity of oxygen consuming microrganisms is highest (Sánchez et al., 2015). It follows that if biochar improves compost aeration, it should also limit the activity of anaerobic methanogens, thus reducing methane production in compost (Sonoki et al., 2013). It has been demonstrated that co-composting cattle manure and municipal solid waste with biochar favours aerobic microbial conditions that result in the reduction of CH_4 emission (Sonoki et al., 2011, Sonoki et al., 2013, Vandecasteele et al., 2013). Conversly Sánchez-Garcia et al. (2015) co-composted poultry manure with biochar and measured no significant reduction in CH_4 emissions. There was no apparent relationship between compost bulk density and methane emissions in our experiement. More detailed microbial community profiling would be required to elucidate the drivers for our trends in methanogenesis.

Table 4.2 Concentration of exhaust gases in compost treatments

	Fine	Medium	Coarse	Control
CH_4	3.0 ≤807.4 (±855.6) ≤4623.1	1.0 ≤378.8 (±775.0) ≤4896.2	7.9 ≤541.4(±668.8) ≤2546.1	53.8 ≤780.8 (±737.4) ≤1714.0
N_2O	0 ≤97.0 (±0.2) ≤6.57	0 ≤50.9 (±0.2) ≤4.92	0 ≤38.7 (±0.2) ≤11.7	0 ≤86.6 (±0.2) ≤16.7
NH_3	4.9 ≤129.5 (±34.9) ≤747.2	1.5 ≤101.7 (±24.0) ≤988.8	1.3 ≤53.6 (±9.2) ≤902.3	2.1 ≤90.6 (±20.0) ≤437.6
NO	0.5 ≤10.9 (±1.6) ≤36.8	0.1 ≤9.6 (±1.3) ≤43.9	0.1 ≤5.7 (±0.6) ≤45.4	0 ≤5.1 (±0.6) ≤19.5
$CO_2^\dagger$	1.00 ≤5.5 (±3.0) ≤13.69	0.45 ≤4.4 (±2.9) ≤12.95	0.32 ≤3.5 (±2.9) ≤12.13	0.69 ≤4.1 (±2.6) ≤12.26
CO	0 ≤5.0 (±0.6) ≤36.6	0 ≤3.1 (±0.3) ≤14.6	0 ≤4.6 (±0.5) ≤6.53	0 ≤8.0 (±1.2) ≤7.09
SO_2	1.72 ≤377.9 (±67.4) ≤6.57	1.67 ≤559.7 (±120.3) ≤4.92	1.91 ≤430.2 (±81.5) ≤6.53	1.73 ≤220.6 (±29.5) ≤7.09
NO_2	0 ≤5.7 (±0.7) ≤ 24.7	0 ≤4.5 (±0.5) ≤18.6	0 ≤3.8 (±0.4) ≤ 11.7	0 ≤2.7 (±0.2) ≤16.7
$H_2O^\dagger$	1.72 ≤X (±X) ≤6.57	1.67 ≤X (±X) ≤4.92	1.91 ≤X (±X) ≤6.53	1.73 ≤X (±X) ≤7.09

Emission concentration values are presented as follows: minimum ≤ mean (± standard deviation) ≤ peak value. $^\dagger CO_2$ and H_2O concentration was measured in % vol., all others were measured in µL/L. Values are least-square means and standard errors of 600 measurements, with 4 replicates, taken uniformly over 30 days (n=2400). Control (no biochar added), Fine (<1.6 mm), Medium (3.2 – 6.4 mm), and Coarse (12.8 – 19.2 mm) biochar particle size.

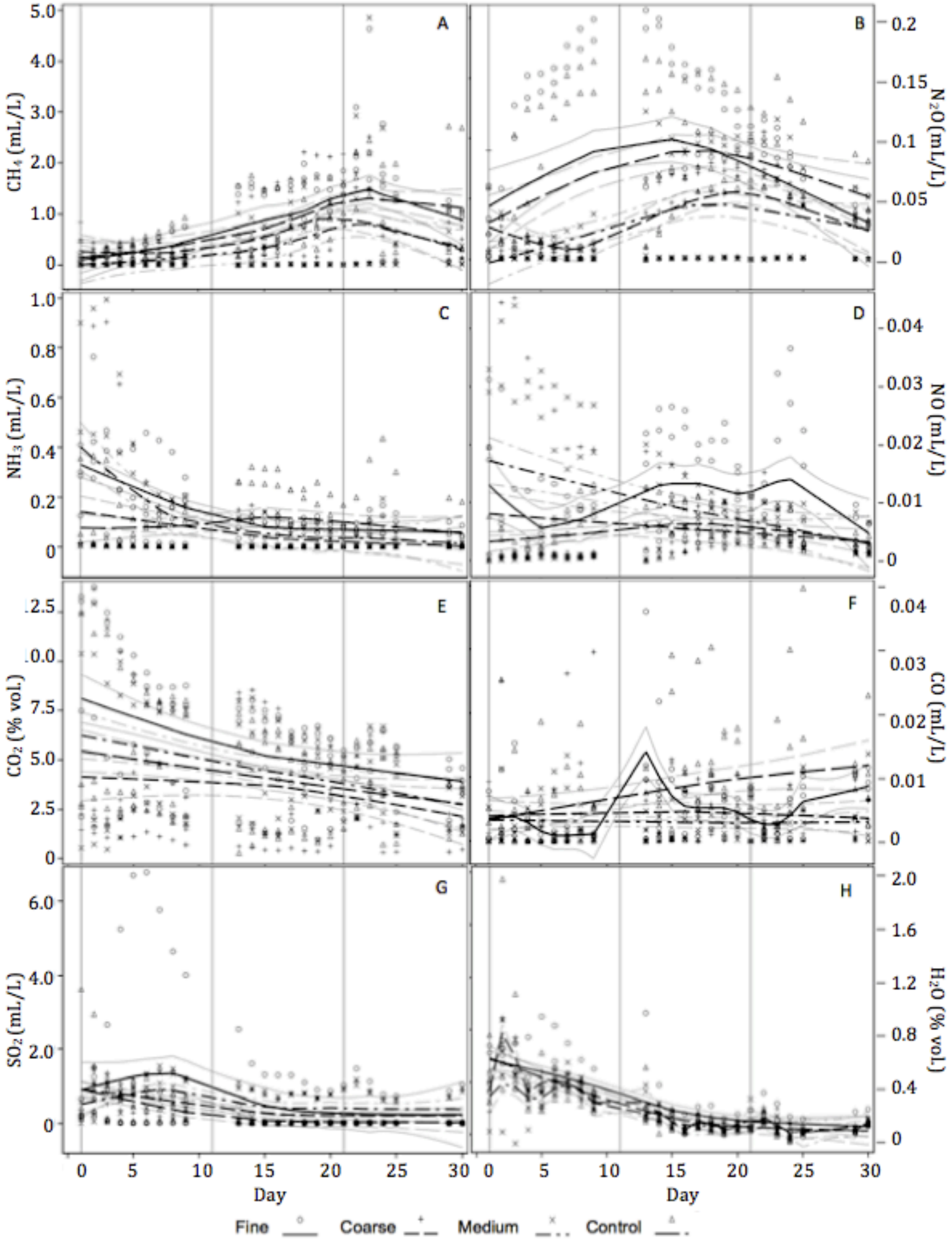

Figure 4.6. Nonparametric regression of compost gas emission concentration over time as affected by biochar particle size. Light grey lines represent the 95% confidence limits. Vertical lines represent compost-mixing events. Letters A, B, C, D, E, F, G, and H represent methane, nitrous oxide, ammonia, nitrogen monoxide, carbon dioxide, carbon monoxide, sulfur dioxide and water vapor emissions, respectively.

There was a tendency towards increasing N_2O concentration in the compost exhaust air as the experiment progressed (Fig. 6b). The concentration of N_2O emitted from fine and coarse biochar treatments was higher than from the control and medium treatments during the first 20 days of composting. At the end of the experiment, the N_2O concentration was significantly higher from the control and fine biochar treatments than from the medium and coarse treatments (Table 2). Reduced emission of N_2O in medium and coarse biochar treatments may be attribuited to the biochar's bulking effect, which enhances aeration, inhibiting denitrification, and thus increases N retention (Case et al., 2012, Jia et al., 2015). Variations in N_2O emissions have been attributed in earlier studies to factors such as compost temperature, compost maturity, pH, and microbial development (Jiang et al., 2011, Angnes et al., 2013, Andersen et al., 2010). According to Szanto et al. (2007), up to 10% of the initial N can be lost in the form of N_2O during 100 days of composting. Due to the complexity of factors that influence N_2O flux in during composting, further investigation would be required to identify the variables influencing N_2O emission in the present study (Clough et al., 2013).

The concentration of NH_3 was higher in the exhaust of the control and fine biochar composts, compared to medium and coarse treatments (Table 2). All concentrations declined until day 5, after which emissions from all treatments had no statistical differences (non-parametric test, $p < 0.05$; Fig. 6c). Net NH_3 concentration in the coarse biochar compost emissions was lower than in all the other treatments (Table 2). Other studies have associated high NH_3 emissions at the beginning of composting with high temperatures and pH > 6 (Angnes et al., 2013). However, the pH for all of our treatments was greater than 7, even in those with relatively low NH_3 emissions. It is possible the coarser biochar's lesser surface area, compared to fine particle size, may result in the coarse biochar taking longer to become saturated with moisture and dissolved gas, permitting sustained adsorption of NH_4^+ (Taghizader-Toosi et al., 2012, Jia et al., 2015). Further investigation would be required to validate this speculation.

Throughout the thermophilic composting phase, NO emissions were higher in the control treatment compared to all of the biochar treatments (non-parametric test, $p < 0.05$, Fig. 6d). This difference diminished for 12 days, until NO concentrations were not statistically different between any of the treatments and the control. The mean concentration of NO in the exhaust gases from the different treatments compared to one another as follows: control < coarse < medium < fine biochar (Table 2). Notably, NO emissions from the fine treatment started low and increased for the duration of the experiment, where as emissions from the other treatments started relatively high and decreased. The effects of biochar on NO emissions from compost have not been widely reported in the scientific literature.

The percent volume of CO_2 in the exhaust gas from our compost declined over time (Fig. 6e). Fine biochar compost was associated with the highest CO_2 concentrations throughout the experiment, while coarse biochar was associated with the lowest (non-parametric test, $p < 0.05$). However, the effect of biochar treatment on total CO_2 emission was not significant (Table 2). The effect of co-composting with biochar on the emission of CO_2 is lacking in the scientific literature, except in terms of mitigation of other compost gases expressed as CO_2 equivalents (Sonoki et al., 2011).

The concentration of CO emitted from the coarse biochar treatments increased steadily, and remained higher than the other treatments throughout the experiment (Fig. 6f), according to the non parametric test at the $p < 0.05$ level. The exception to this was the fine biochar treatments, from which the mean CO concentration spiked after the first mixing event (day 10), while emissions from the other treatments did not. The spike is assumed to have been caused a relatively greater increase in aerobic microbial activity in the compost with the relatively highest bulk density. Helebrand and Kalk (2001) found a positive correlation between CO emission and bulk density during composting of dung and green waste. The biochar particle size had an effect on CO emissions during the third period of semi-continuous measurement, based on the means of measurements per barrel per time period, and at the 5% level of significance ($F_{3,12} = 4.82$, p = 0.02). Based on the Dunnett-adjusted limits at 95% confidence: the coarse biochar compost would emit 12.6 to 1.7 μL less CO μL^{-1} than controls ($p = 0.0109$), while medium biochar compost would emit 11.5 to 0.5 μL less CO L^{-1} ($p = 0.0121$), and the fine biochar compost would emit 10.5 less to 0.4 more μL CO L^{-1} than controls ($p = 0.0722$). The concentration of CO emitted throughout our experiment was nearly 2 times higher in the control treatment compared to coarse biochar compost, and 1.5 times higher compared to the than fine biochar compost (Table 2). The lowest emission of CO was observed in the medium biochar compost. These results are not consistent with Helebrand and Kalk (2001), and suggest that oxygen availability alone cannot explain the increase in CO emission from poultry manure compost. Phillip et al. (2011) found a positive correlation between CO emission and the incubation temperature of gas samples collected from municipal solid waste compost. They attributed this to a physico-chemical source of CO generation. Again, we have insufficient data to corroborate such claims; a more detailed study would be required for clarification.

There was a small, statistically significant, positive correlation between the biochar size and the concentration of SO_2 in the compost exhaust (Spearman's $r = 0.02$, $p = 0.02$). The concentration of SO_2 emitted from the fine biochar treatments was higher during the first 10 days of the experiment, relative to the other treatments (non-parametric test, $p < 0.05$; Fig. 6g). Mean SO_2 emission concentrations were slightly lower from the control treatments than the biochar treatments (Table 2), yet temporal differences were not obvious using the nonparametric test. It is plausible that the high concentration of SO_2 in the biochar-treated compost is related to sulfur (S) content of the biochar, as demonstrated by Cheah et al. (2014). They found that biochar contains significant amounts of S, of which the total amount and speciation depends on the biochar feedstock and pyrolysis temperature. Again, more specific investigation would be required to corroborate such speculation.

Our results demonstrate that larger sized biochar may influence gas emissions from poultry manure compost to a greater extent than smaller sizes. We have demonstrated with some certainty that large sized biochar reduces gas emission concentration of CO, CO_2, NO, and NH_3 during composting of poultry manure. Conversely, large grain size biochar had less of an effect during composting than smaller grain sizes on the emission of N_2O and CH_4 gases. Smaller gain sized biochar resulted in slightly higher concentrations of SO_2 in compost emissions, yet the effect of biochar on SO_2 emissions was generally ambiguous. Our results indicate that all sizes of biochar act as a suitable bulking agent, though coarser seems to be better than finer in this regard. Compost that included either of the two larger sized biochars experienced greater peak temperatures, followed by a more rapid return to ambient temperatures, compared to the smaller sized biochar treatments. This can be taken as a proximate indicator that larger sized biochar has a greater effect on compost microbial activity, and subsequently on the rate of organic matter degradation, relative to smaller. Additional research is necessary elucidate such speculation.

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Connecting Statement #2

The preliminary stage of this research involved adding three different particle sizes of biochar to poultry manure, followed by monitoring various aspects of the subsequent composting process. Following 32 days of composting, the product was left to cure for roughly 2 months. At that point, stage two of the research was initiated: examining the effect of poultry manure co-composted with biochar on plant growth metrics.

The objective of the plant growth trials was to determine if there are any horticultural benefits to amending soils with various sized biochar treated compost, relative to non-biochar treated compost, and a soil control. The research was divided into two parts: first, a phytotoxicity test was preformed to roughly determine the compost to soil mix ratio that will best support plant growth. Second, using the determined mix ratio, a longer term, horticulture-relevant production trial using lettuce was conducted.

The following is a presentation of the methodology and results of the plant growth phase. The chapter has been submitted for review in the Journal of Environmental Quality. Table and figure numbers have been altered from how they appeared in the original manuscript to be consistent with the rest of the dissertation. The references for this text are presented at the end of the dissertation.

Chapter 5 – Co-composting Poultry Manure with Biochar: Part 2) Effects on Plant Growth

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Abstract

Composting has been cited as being an ideal means of inoculating biochar with nutrients and microbes that subsequently impart benefits to soil. Composted biochar in soil has been shown to enhance plant growth, relative to the same amount of compost and biochar if added separately. However, biochar in soil has potential disadvantages, such as nutrient competition, which is detrimental to plant growth. Research on the matter often gives mixed results, in part because of physical variability in biochar, which significantly influences its performance in compost and soil. Research is needed to elucidate the influence of such variations on the dynamics of plant growth. This investigation was intended to address such variation. Experiments were divided into two parts: first, we assessed the optimal concentrations of biochar compost in soil for the germination of spring barley (*Hordeum vulgare* L); second, we conducted a longer-term growth test using butterhead lettuce *(Lactuca sativa)*. Results indicated that a ratio of biochar compost to soil of 20:80 and 40:60 (4-8% biochar content, by vol.) was optimal for barley growth. Biochar particle size had no effect. The two optimal concentrations, and the non-biochar compost controls, all positively affected the growth of the lettuce. Again, particle size had no statistically significant effect. These results affirm that compost, when used in appropriate quantities, is a beneficial soil amendment. There was no evidence, however, to show that the specific kind of biochar effected plant growth.

Introduction

Charred organic materials have been utilized as soil amendments for thousands of years, yet understanding of their agronomic potential is still developing (Ogawa and Okimori, 2010). Biochar has been shown to benefit soil quality in several ways, including its capacity to retain moisture and mineralizable nutrients, decrease leaching rates, and increase microbial diversity and abundance (Schultz et al., 2013, Agegnehu et al., 2015). However, biochar alone contains very few plant nutrients (Lehmann and Joseph, 2009). Adding untreated biochar to soils with low initial nutrient value can restrict plant growth through competitive nutrient retention (Beesley et al., 2011). Positive effects on plant growth may only be seen following infusion of biochar with nutrients from a separate source (Asai et al., 2009).

Composting has been proposed by Schmidt (2011) as a practical means of activating biochar for use as a soil amendment. Many researchers claim that biochar is beneficial in the composting process, which simultaneously inoculates the biochar with microbes and nutrients that are beneficial for plants (Sanchez-Garcia et al., 2015). It is reported that composting oxidizes the biochar's surface, thereby increasing its physicochemical reactivity and enhancing its capacity to absorb minerals, nutrients, and dissolved organic matter (Fischer and Glaser, 2012).

Several researchers have reported positive agronomic effects of adding biochar compost to soils (Schultz and Glaser, 2012, Fischer and Glaser, 2012). Unlike synthetic fertilizers, biochar compost imparts physical benefits to the soil and contains plant micronutrients (Steinbeiss et al., 2009). Further, biochar compost tends to release its nutrients more slowly than synthetics, providing more persistent plant sustenance, while decreasing the propensity for nutrient leaching (Lehmann et al., 2003).

However, other investigators have reported that amending soil with biochar compost has negligible or even negative effects on plant growth (Schmidt et al., 2014). Biochar adsorbs ions, thus decreasing nutrient leaching, yet it may also reduce nutrient bioavailability (Beesley et al., 2011). Further, Karami et al. (2011) have shown that biochar in soil increases the accumulation of heavy metals and other phytotoxic substances in plants. Persistent compounds such as polyaromatic hydrocarbons and phenols are generated during biochar production and are known to effect plant growth (Hilber et al., 2012).

The use of biochar should not be considered a panacea. Differences in biochar production, such as the parent material, pyrolysis temperature, and postproduction processing, have significant influence on its nano-structure, and therefore on its effects when used in compost or growth media. Although the potential benefits of biochar on plant growth have been reported to increase proportionately with the amount used, too much biochar is liable to be phytotoxic (Agegnehu et al., 2015). Optimal concentrations likely vary based the specific qualities of the biochar compost and soil, and the plant type. For instance, Li et al. (2014) observed that pig manure co-composted with 2.5% biochar was beneficial for the germination of ryegrass. However, for spring barley, biochar has been shown to either inhibit, or had no significant effect on, germination (Bargmann et al., 2013). Agegnehu et al. (2015) investigated the effects of growing oats in compost containing 0 – 50% biochar, and concluded that growth parameters were enhanced proportionately to the percentage of biochar compost used. Contrarily, Schmidt et al. (2014) found that soil amendment with biochar compost had limited influences on the growth of peanut plants.

This research was intended to address the influence of biochar particle size in compost and its concentration in soil on the growth of plants. The experiment was the second in a two-part study, the first experiment being the addition of biochar of different particle sizes to poultry manure, and the subsequent composting of the mixture. The resulting compost was then used for this experiment, which was itself divided into two stages: assessment of the optimal concentration of biochar compost in soil for growth of spring barley (*Hordeum vulgare* L), and a growth trial using butterhead lettuce *(Lactuca sativa).*

Materials and Methods

The primary phase of this investigation involved composting poultry manure with 20% biochar of 3 separate particle sizes [fine (<1.6 mm), medium (6.4 – 3.2 mm), and coarse (19.2 – 12.8 mm)], along with pine wood shavings (*Pinus* spp.), wheat straw (*Triticum aestivum*), and water, in the proportion of 4:6:1:3 (by volume). The biochar was made from sugar maple wood (*Acer saccharum*), and was produced by Basques Hardwood Charcoal (Rimouski, QC, Can). The control treatment was made using the same volumetric ratios, but with additional wood shavings in place of the biochar. Each treatment was replicated 4 times. The experiment was terminated after 32 days, when the compost temperature approached ambient. The product was left to cure for roughly 2 months, prior to the start of this study.

Phytotoxicity Determination – Spring Barley (*Hordeum vulgare)*

Barley seeds (*Hordeum vulgare L.,* CDC McGwire) were sown in different mixtures of potting soil and compost to assess the optimal (non-phytotoxic) proportions of compost for germination and growth. Compost treatments were mixed using each of the four compost treatments described above.

To begin germination, seeds were soaked for five min in 0.2% sodium hypochlorite solution, then thoroughly rinsed. Disinfected seeds were then soaked in distilled water at 4˚C for 12 h to stimulate germination, after which they were drained and spread evenly on trays lined with moist paper towel, and covered in perforated tinfoil. After 30 h, 90% of the seeds had germinated. Each of the four compost types were mixed in five proportions (by volume) with potting soil (G10 Agrimix, Fafard, Saint-Bonaventure, QC) as follows: 20:80, 40:60, 60:40, 80:20 and 100% compost. The negative control treatment was soil only. The experimental design was 4 x 5 factorial compost-type : potting-soil treatments. Germinated seedlings were sown individually in a 74-well tray, each well measuring 15 x 15 x 40 mm^3. Each treatment was replicated 60 times, for a total of 1260 plants in 21 trays. Trays were placed in a greenhouse with a 14 h photoperiod, and 25˚C ambient temperature, and were randomly repositioned every second day to reduce any boundary effects. Plants were manually irrigated daily.

After 12 days of growth, plants were assigned a numerical score based on their appearance, as follows: 1 (no growth), 2 (dead plant), 3 (highly discoloured and/or wilted), 4 (healthy plant with at least one imperfect leaf), and 5 (perfect plant). Whole plants were harvested and measured for their total length and above-ground (wet-weight) biomass. Plants were wrapped in foil, oven-dried at 105˚C for 24 h, and then re-weighed.

Production – Butterhead Lettuce *(Lactuca sativa)*

Based on the results of the phytotoxicity test, it was determined that the best biochar compost to soil ratios were 20:80 and 40:60. In addition, a control treatment was made using greenhouse soil (G10 Agrimix, Fafard, Saint-Bonaventure, QC). For each of the treatments, 2 encapsulated lettuce seeds (*Lactuca sativa*) were sown in a 6-L pot, with 4 replicates each. If both seeds in a pot germinated, one plant was removed. Plants were grown in a greenhouse with the same ambient conditions as used for the barley study. Water was supplied by drip irrigation. A balanced fertilizer (20:20:20) was applied 4 and 21 days after sowing. Plants grew for 43 days before harvesting, in accordance with the seed supplier's recommendation. Above ground wet and dry weights, stem length, and number of leaves, was measured for each plant, which were also assigned a numerical score based on visual assessment (as above, for barley).

Statistical Analysis

Statistical analysis was performed using SAS 9.4 software (SAS Institute Inc., Cary, NC, USA). For analysis of both barley phytotoxicity and lettuce growth data, models were fit using the SAS PROC GLIMMIX procedure. The data was found to follow a Gaussian (normal) distribution for fresh weight measurements, and an inverse Gaussian (mean = μ, variance = $\phi\mu^3$) distribution for stem length measurements indicated positive skew but a lognormal distribution was inappropriate. Sheffés's single-step adjustment for multiple comparisons was applied (Scheffé, 1999). For the non-parametric approach, inferences were made based on Dunn's test for ranked variables (Dunn, 1964). The ideal compost mixture was selected as the one with the greatest LS-means, with 95% confidence limits, for plant weight and stem length, averaged across each experimental treatment.

Results and Discussion

Phytotoxicity of Biochar

The percentage of biochar compost in the soil significantly affected the stem length (H = 12.04, p = 0.0005, fig. 1) of the barley plants in the phytotoxicity trial. Plants with the longest stems grew in the soil with 60:40 or 40:60 compost ratios, regardless of biochar particle size. Meanwhile, plants with the shortest stems were grown in 100% compost. The interaction between biochar particle size and the proportion of compost in the soil had a significant effect on the barley's wet weight (H = 4.19, p = 0.04, fig. 2). Plants grown in 100% compost with fine biochar had the lowest wet weights, and those grown in 60:40 or 40:60 compost ratios with medium biochar particle size had the highest wet weights.

Both biochar particle size and the percentage of compost in the soil affected the barley dry weight (H = 4.41, p = 0.04, and H = 10.94, p = 0.0009, fig. 3). Barley grown in media with coarse or medium biochar had the most biomass (dry weight), while those grown in media with the control (no biochar) compost produced the least. Plants grown with 20% compost accumulated the highest dry weights, while those grown with 100% compost accumulated the least.

Visual rankings for barley differed depending on the percent compost in the growing media and biochar particle sizes (*H* = 6.52, *p* = 0.01). Plants grown in soil with 40% fine biochar compost had the highest growth scores, while those grown in 100% of the same treatment had the lowest.

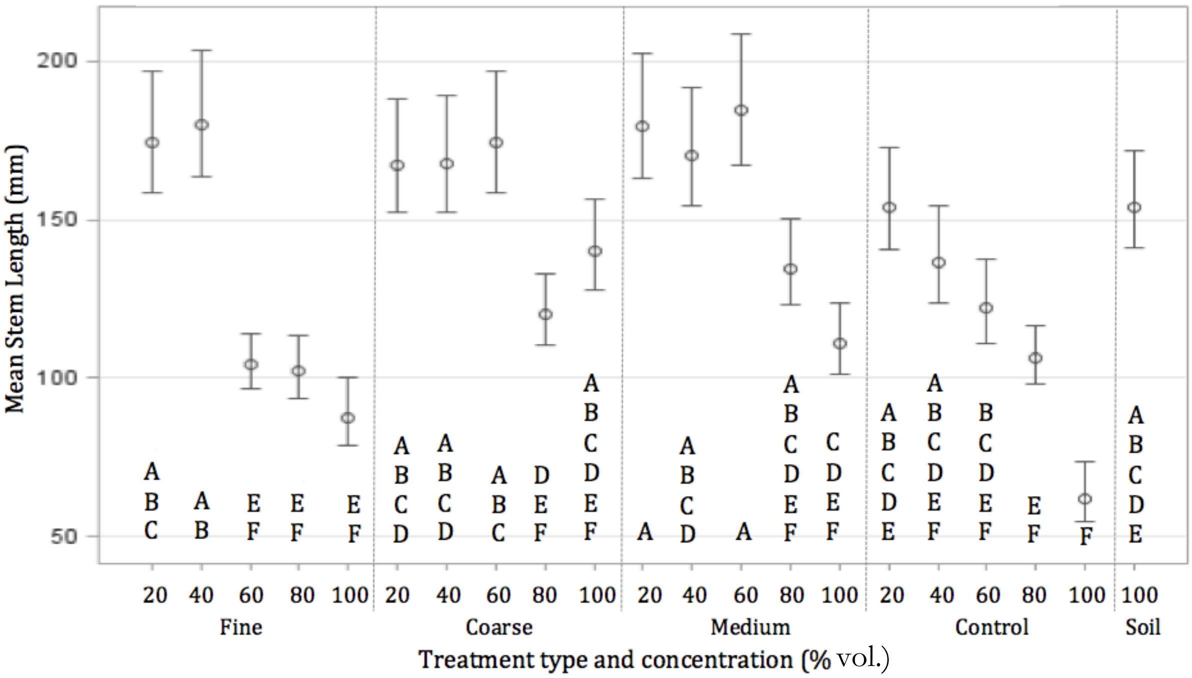

Figure 5.1. Least square means of barley stem length as affected by biochar compost. Soil control (no compost), Control (compost without biochar), Fine (<1.6 mm), Medium (3.2 – 6.4 mm) and Coarse (12.8 – 19.2 mm) particle size. Bars represent the 95% confidence limits, n = 60. Letters indicate statistical relationships and points with the same letter are not statistically different.

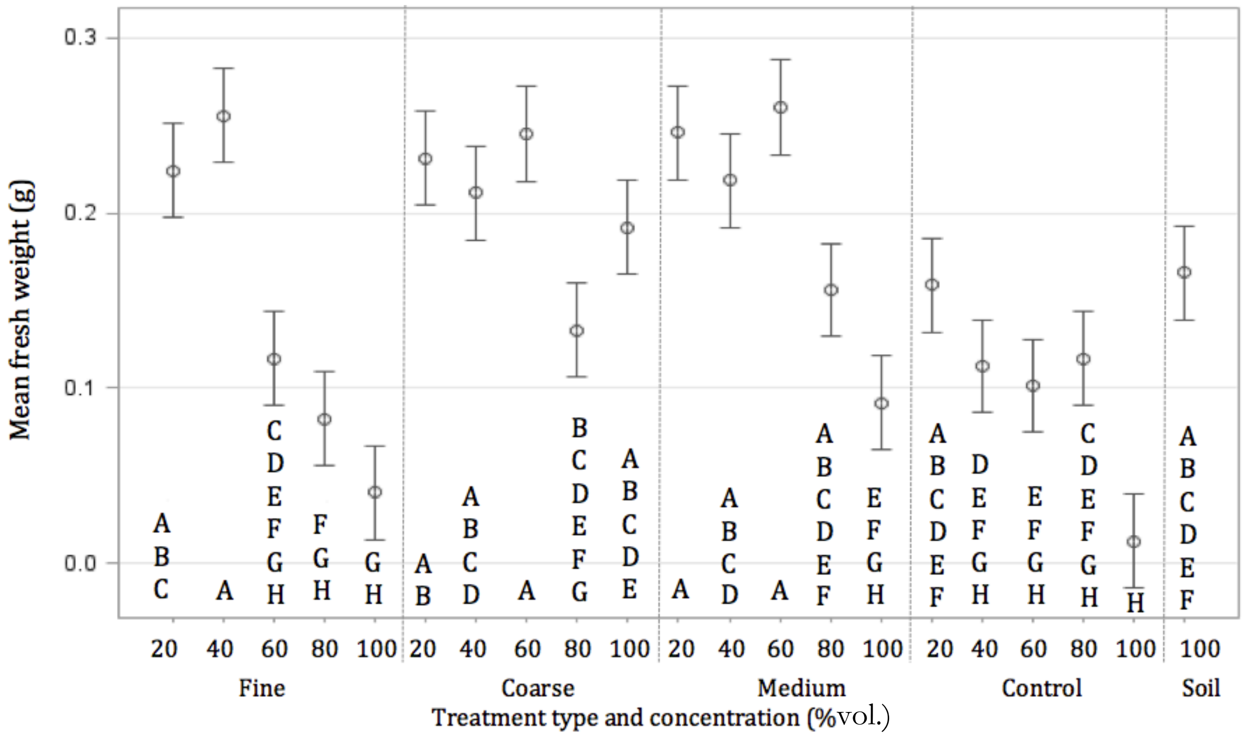

Figure 5.2. Least square means of barley fresh (wet) weight, as affected by biochar compost. Soil control (no compost), Control (compost without biochar), Fine (<1.6 mm), Medium (3.2 – 6.4 mm), Coarse (12.8 – 19.2 mm) particle size. Bars represent the 95% confidence limits, n = 60. Letters indicate statistical relationships and points with the same letter are not statistically different.

Plants grown in biochar compost at the same concentrations but with different biochar particle sizes were not statistically different, with the exception of the 60:40 treatment. The plants did not grow as well in the fine biochar and control compost (no biochar) treatments as compared to the soil control or coarser biochar composts (Fig. 1 and 2). Plants in the 100% control compost and the 100% fine biochar compost grew significantly less than those in the control soil.

Our study did not show a positive influence of any biochar compost on the growth of barley, regardless of the concentration ratio or particle size. It was apparent that growth was greater in the biochar compost treatments, relative to the controls, especially at ratios lower than 60:40, but the effect was not statistically significant.

For selecting which concentration ratio to use for the subsequent growth trials, 80:20 and 100% concentrations were excluded due to lower barley growth than the other concentrations. These differences, however, were not statistically different from other concentrations. Plant growth at the 60:40 ratio was variable and statistically indistinct from the other ratios. The 20:80 and 40:60

ratios supported higher growth in several instances and, although the mean differences was not statistically significant, were selected as the best mix ratios to use in the subsequent growth trials.

Plant Growth in Biochar Compost Amended Soil

The biochar particle size affected the number of leaves on lettuce plants during the growth trials ($F_{4,71} = 5.28$, $p = 0.0009$, fig. 3). Regardless of the mixture ratio, plants grown in soil with fine biochar compost produced 7-86% more leaves than those grown in potting soil only (Bonferroni-adjusted $p = 0.0052$), and plants grown in soil with the medium biochar compost produced 95-13% more leaves than plants grown in potting soil only ($p = 0.0009$). Compost alone produced lettuce with 89-9% more leaves than lettuce grown in potting soil only ($p = 0.0028$).

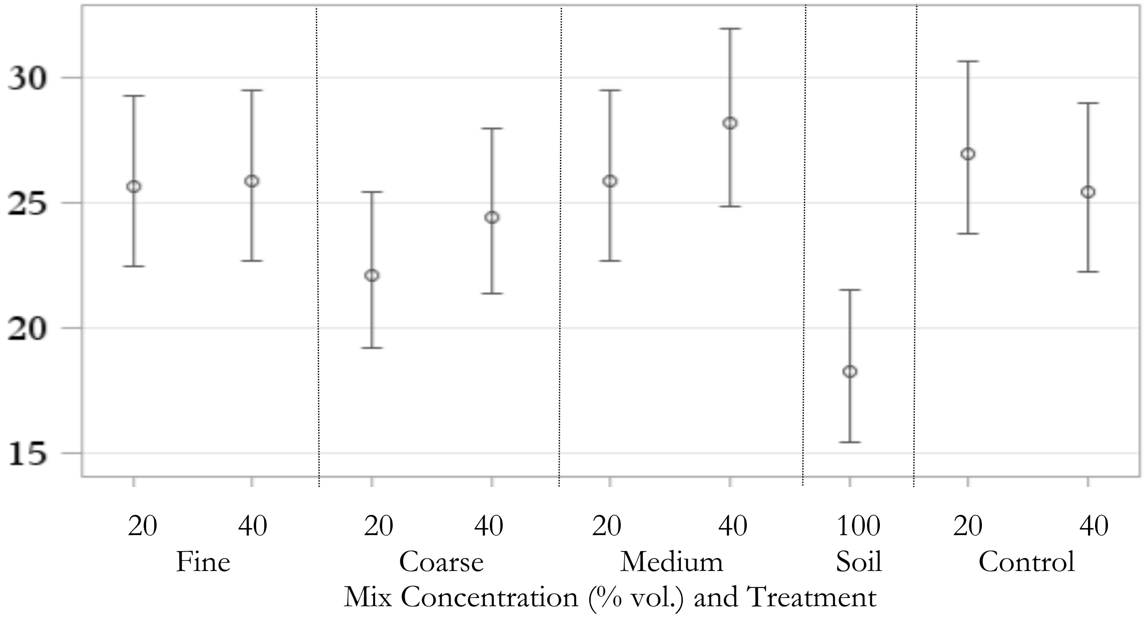

Figure 5.3. Least square mean of lettuce plant's leaf count. n = 4. Bars represent the 95% confidence limits. Control (no biochar added), fine (<1.6 mm), medium (3.2 – 6.4 mm) and Coarse (B 12.8 – 19.2 mm) particle size.

Regardless of biochar particle size, compost had a significant effect on lettuce wet weight ($F_{4,70} = 4.78$, $p = 0.0018$, fig. 4). For example, the wet weight of lettuce grown in 20:80 fine biochar compost was 121.6-14.9 g heavier than those grown in potting soil alone (Scheffé's-adjusted $p = 0.0082$). Similarly, plants grown in 40:60 fine biochar compost were 10.0-1115.8 g heavier than those grown in soil alone ($p = 0.016$). Similar trends were observed for lettuce dry biomass, and moisture content.

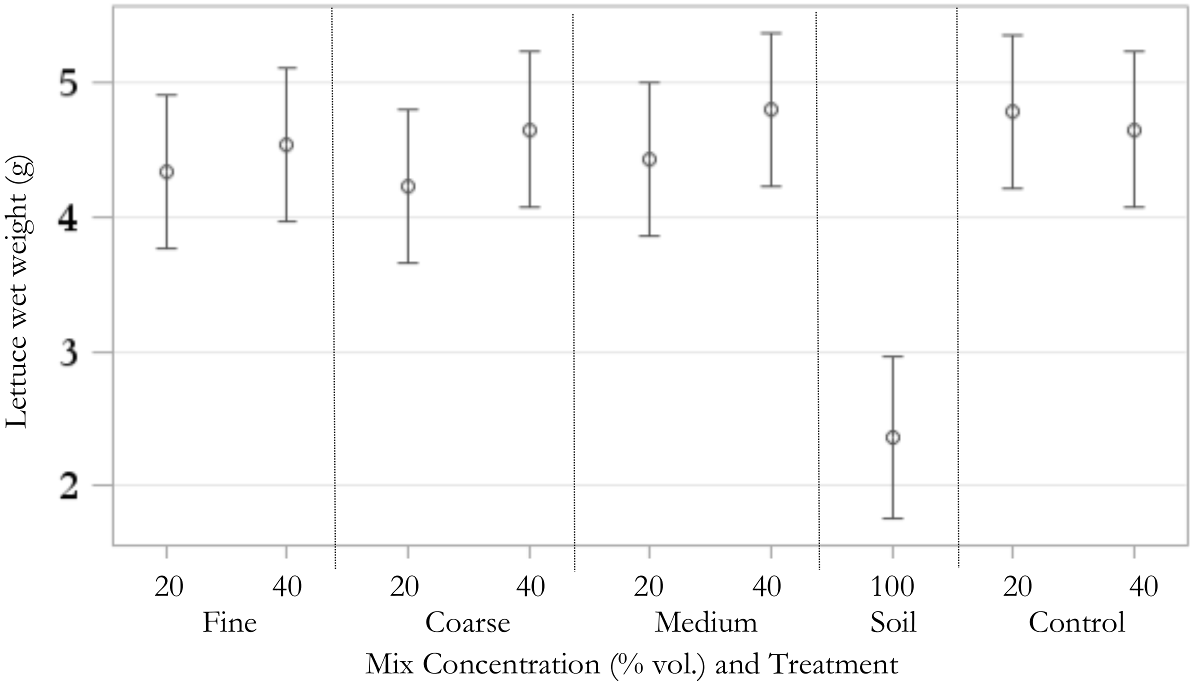

Figure 5.4. Least square mean wet (fresh) weight of lettuce plants. n=4. Bars represent the 95% confidence limits, n = 4. Control soil (without compost), control compost (without biochar), fine (<1.6 mm), medium (3.2 – 6.4 mm) and coarse (12.8 – 19.2 mm) particle size.

The biochar particle size and the percentage of compost in the soil each affected lettuce growth scores at the 5% level of significance. Growth scores for plants grown in soil alone were significantly higher than the scores for those grown in media with the 40:60 coarse biochar compost to soil ratio. These results indicate that biochar can have both positive and negative effects on plant growth. Due to the equivocal nature of reported effects, there is still no consensus regarding the direction of the effect of biochar compost, and biochar variability there-in, on the growth of plants. When the body of evidence has reached sufficient proportions, conclusive evidence should be based on a meta-analysis approach.

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Chapter 6 - General Summary and Conclusions

Due to increasing demand for food, agronomic production efficiency has been emphasized. However, the current strategy for maximizing production might be flawed. Increasing chemical and energetic inputs can increase crop yields in the short term, but such increases are not sustainable. A more prudent strategy would maximize outputs while respecting the global energy balance and material cycles.

Compost is an effective agricultural fertilizer that is produced from organic waste products. Composting increases the chemical stability of the organics, decreases their biohazards, and returns a nutrient-rich soil amendment. Yet, the use of compost as a soil amendment has been criticized because the composting process releases gases that are both environmentally detrimental and decrease the nutrient value of the compost product (Godbout et al., 2010). Several methods for retaining these gases have been proposed, including co-composting with biochar.

Published literature claims that biochar can increase composting efficiency, while reducing some of the negative effects. Biochar has been reported to benefit compost aeration and microbial communities, decrease emissions of nuisance gases, and yield compost that is higher in nutrients relative to non-biochar compost (Prost et al., 2012, Li et al., 2014, Sanchez-Garcia et al., 2015). When the compost is subsequently used as a soil amendment, additional benefits are reported. These include increased soil fertility, moisture retention, C sequestration, and plant growth, as well as decreases nutrient leaching (Asai et al., 2009, Tenenbaum, 2009, Van Zwieten et al., 2010, Lehmann et al., 2011).

While there are many reports of positive effects from co-composting with biochar, neutral or negative effects have also been reported (e.g. Cheng et al., 2006, Rogovska et al., 2012). As such, understanding of the effects of co-composting with biochar and, subsequently, how biochar compost effects plant growth is incomplete. This is due, in part, to physiochemical differences in biochar, which result from variations in its parent material, pyrolysis temperature, and postproduction processing treatments (Li et al., 2014, Zhang et al., 2014b). Key composting variables, such as temperature, pH, bulk density, moisture content, and microbial community composition and abundance, have all been shown to be affected by the presence of biochar (Lehmann et al., 2009, Dias et al., 2010, Steiner et al., 2010, Spokas et al., 2012, Prost et al., 2012, Atkinson et al., 2010). The magnitude of these effects is a function of the physiochemical state the compost, biochar, and the amount of biochar being used (Chen et al., 2010, Khan et al., 2016). Biochar, in turn, may be affected by the composting process. Composting can degrade, saturate, or clog biochar, decreasing its nano-porosity, upon which many of the composting benefits depend (Kuzyakov et al., 2009), yet understanding of biochar degradation is still developing.

There is a large and growing body of scientific literature about the effects of co-composting with biochar and biochar compost on plant growth. With this in mind, the research presented here was designed to investigate the relative effects of biochar particle sizes on gas emissions from composting, nutrient retention, and plant growth. With this purpose, we composted poultry manure with 3 sizes of biochar, and examined *in situ* gas emissions and several metrics of compost quality. Once the compost had matured, we examined its effect on the growth of plants in a greenhouse.

It was hypothesized that the particle size of the biochar would have an influence on the compost processing. For instance, it seemed reasonable to expect that smaller particles would cause relatively greater reductions of gas emission through adsorption mechanisms. Further, it was hypothesized that for similar reasons, the compost containing different biochar particle sizes would affect plant growth differently when used as a soil amendment. However, the results that we attained were sufficiently variable that corroborating these hypotheses was difficult.

Results from the compost experiment showed that biochar influenced gas emissions, and other physical aspects, during composting of poultry manure, but with variable magnitude and certainty. Large sized biochar reduced gas emission concentration of CO_2, NO and NH_3 during composting (non-parametric, $p < 0.05$). Conversely, the same size biochar had less of an effect than smaller grain sizes on the emission of N_2O and CH_4 gases. Small gain sized biochar resulted in slightly higher concentrations of SO_2 in compost emissions. Biochar particle size also had significant effect on compost bulk density; all biochar treatments were consistently less dense than the no-biochar control (non-parametric, $p < 0.05$). Medium biochar compost was consistently less dense than fine biochar, while the effect of the coarse biochar was ambiguous. Further, particle size had an effect on compost temperature (Spearman's $r = -0.31$, $p < 0.0001$). Compost that included either of the two larger sized biochars experienced greater peak temperatures, followed by a more rapid return to ambient temperatures than the smaller sized biochar treatments. This can be taken as a proximate indicator that larger sized biochar has a greater effect on compost microbial activity, and subsequently on the rate of organic matter degradation, relative to smaller. The effect of biochar particle size on the concentrations of CH_4, CO, and SO_2 gas emissions, as well as on compost pH, was statistically negligible.

Biochar compost has variable effects on the growth of barley plants. Generally, barley plant growth was not affected by biochar particle size. The percentage of biochar compost in the soil significantly affected the barley stem length ($H = 12.04, p = 0.0005$). Plants with the longest stems grew in the soil with 60:40 or 40:60 compost ratios, regardless of biochar particle size. Further, the proportion of biochar compost in soil had a significant effect on the barley's wet weight ($H = 4.19, p = 0.04$). Plants grown in 100% compost with fine biochar had the lowest wet weights, and those grown in 60:40 or 40:60 compost ratios with medium biochar particle size had the highest wet weights. Both biochar particle size and the percentage of compost in the soil affected the barley dry weight ($H = 4.41, p = 0.04$, and $H = 10.94, p = 0.0009$). Plants grown in media with coarse or medium biochar had the most biomass (dry weight), while those grown in media with the control (no biochar) compost produced the least. Plants grown with 20% compost accumulated the highest dry weights, while those grown with 100% compost accumulated the least. Based on these results we determined that 20:80 and 40:60 compost ratios were best suited for plant growth.

In the longer-term lettuce growth test compost had a significant effect on lettuce wet weight ($F_{4,70} = 4.78, p = 0.0018$). For example, the wet weight of lettuce grown in 20:80 fine biochar compost was 12.2-14.9 g heavier than those grown in potting soil alone (Scheffé's-adjusted $p = 0.0082$). Similarly, plants grown in 40:60 fine biochar compost were 10.0-11.6 g heavier than lettuce grown in soil alone ($p = 0.016$). Similar trends were observed for lettuce dry biomass, and moisture content. The biochar particle size affected the number of leaves on lettuce plants during the growth trials. Plants grown in soil with the medium biochar compost produced 9.5-13% more leaves than plants grown in potting soil only ($F_{4,71} = 5.28, p = 0.0009$). Regardless of the mixture ratio, plants grown in soil with fine biochar compost produced 7-8.6% more leaves than those grown in potting soil only ($p = 0.0052$). The two concentration levels of compost and the non-biochar compost controls all positively affected the growth of the lettuce, with no statistically significant differences between them. Particle size had no statistically significant effect. These results affirm that compost, when used in appropriate quantities, is a beneficial soil amendment.

Due to problems with equipment, the start of the experiment was delayed for roughly 30 days after the poultry manure and biochar were mixed. The compost was then remixed at the actual start of the experiment. It is possible that any differences in the effects of the biochar compost and the particle sizes of the biochar were diminished by the 30-day delay in the start of the experiment.

Studies similar to the one presented here have yielded both positive and negative results. Taken together, therefore, the literature about the effects of biochar on compost and plant growth remains inconclusive. The results of this study, despite having had instances of clarity, yet when taken as a whole are similarly inconclusive.

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