Czech University of Life Sciences Prague

Faculty of Environmental Sciences

Department of Environmental Geosciences

Diploma Thesis

Environmental and Economic Potential of Co-Composted Biochar for Agriculture and Soil Remediation

Author: Brett Nolan Gallagher
Supervisor: doc. Mgr. Lukáš Trakal, Ph.D.

CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Environmental Sciences

DIPLOMA THESIS ASSIGNMENT

Brett Nolan Gallagher

Environmental Geosciences

Thesis title

Environmental and Economic Potential of Using Co-Composted Biochar for Agriculture and Soil Remediation

---

Objectives of thesis

Thesis aim is to examine biochar-compost practical application as a replacement from using peat through the lens of sustainability and economics.
The case study will measure:
1. how well the resulting biochar amended compost retains water
2. nutrients stability and retention
3. how well C+B supports plant growth
4. is it possible to decrease composting time with the addition of biochar
Additionally, the thesis will provide an environmental-economic analysis comparing the life cycles of biochar and peat and the costs linked to their production, transportation and application.
The hypothesis is as follows: Compost amended with biochar will provide an environmentally and economically sustainable replacement of using peat as a growing substrate in commercial and domestic horticulture needs.

Methodology

This thesis is not an attempt to confirm these studies, but rather to examine the practical application of biochar's benefits through the lens of sustainability and economics. Additionally, part of the analysis of the experiment described above will include an environmental-economic assessment of the cost effectiveness of biochar: at what level does it need to be added to speed up composting, retain water and nutrients, and support plant growth. These results will also be compared to the environmental-economic cost of using peat and savings that come from preserving peatland habitats.

The proposed extent of the thesis

50-60

Keywords

Compost; Biochar; Economic assessment; Retention capacity

Recommended information sources

Daniel Fischer and Bruno Glaser (2012). Synergisms between Compost and Biochar for Sustainable Soil Amelioration, Management of Organic Waste, Dr. Sunil Kumar (Ed.), ISBN: 978-953-307-925-7, InTech. 198s.

EPSTEIN, E. *The science of composting.* Lancaster: Technomic publishing co., 1997. ISBN 1-56676-478-5.

Erisman, Jan Willem; Sutton, Mark A.; Galloway, James; Klimont, Zbigniew; Winiwarter, Wilfried (28 September 2008). "How a century of ammonia synthesis changed the world". Nature Geoscience. 1 (10): 636–639.

HAUG, R T. *Practical handbook of compost engineering.* Boca Raton: CRC, 1993. ISBN 0-87371-373-7.

JOSEPH, S. – LEHMANN, J. *Biochar for environmental management : science and technology.* London ; Sterling: Earthscan, 2009. ISBN 978-1-84407-658-1.

RYNK, R. *On-Farm composting Handbook.* Ithaca: NRAES, 1992. ISBN 0-935817-19-0.

Expected date of thesis defence

2018/19 SS – FES

The Diploma Thesis Supervisor

doc. Mgr. Lukáš Trakal, Ph.D.

Supervising department

Department of Environmental Geosciences

Advisor of thesis

doc. PhDr. Michal Lošťák, Ph.D.

Electronic approval: 5. 3. 2019

prof. RNDr. Michael Komárek, Ph.D.

Head of department

Electronic approval: 6. 3. 2019

prof. RNDr. Vladimír Bejček, CSc.

Dean

Prague on 15. 04. 2019

I declare that my thesis "Environmental and Economic Potential of Using Co-Composted Biochar for Agriculture and Soil Remediation" was worked out by myself, alone, under the supervision of the head of the thesis and using literature and other sources that are cited in the work and listed in the bibliography at the end of the thesis. As the author of the thesis, I further declare that I did not violate any copyrights of any third parties.

In Prague, the 17 of April 2019 ____________________________

Abstract:

Transitioning to agricultural systems less dependent on fossil fuels is necessary for sustainable production of food in the future. Free sources of organic materials are widely available and can be composted or turned into biochar to provide long term fertility and soil remediation. The experiment conducted was designed to test the limits of compost and biochar's ability to remediate even the most polluted, lifeless soil. Co-composting small amounts of biochar (2-5%) sped up the composting process, reduced unwanted odors and gases, and appears to have a beneficial effect on plant growth and increased biomass. The addition of biochar had mixed results on the uptake of Pb, Zn, and Cd, however, the addition of compost always had a beneficial effect. Homemade green-waste compost outperformed commercially bought packaged compost in all comparisons. Additionally, a macro-economic discussion is made about the role of energy in agriculture using an "energy returned on energy invested" (EROI) framework. We conclude that the costs to people and the planet of a broken nutrient cycle is a root cause of ecological degradation. Fixing the nutrient cycle by properly composting organic matter mixed with biochar is a cost-effective solution to solving many of the world's most pressing ecological and economic issues such as soil degradation, polluted water systems, and eutrophication. Going forward, a paradigm shift in social perspective is needed, from "dirt", to a living, breathing soil that supports all life on earth.

Key words:

Compost, Biochar, Cycle, Energy, Terra Preta, Risk Elements, Heavy Metals, Nutrients, Value

Souhrn:

Přechod na zemědělské systémy méně závislý na fosilních palivech je nezbytný pro udržitelnou výrobu potravin v budoucnu. Zdroje organických materiálů jsou volně a široce dostupné. Mohou být kompostovány nebo přeměněny na biochar, zajisťující dlouhodobou úrodnost a sanaci půdy. Provedený experiment byl navržen tak, aby otestoval limity schopnosti kompostu a biocharu napravit i tu nejznečištěnější půdu. Přidáním malého množství biocharu (2 – 5 %) do kompostování se kompostovací proces urychlil, snížilo se množství nežádoucích pachů a plynů a ukázalo se, že takový postup má příznivý vliv na růst rostlin a zvýšení biomasy. Přidání biocharu mělo smíšené výsledky na příjem Pb, Zn a Cd rostlinami, avšak přídavek kompostu měl vždy příznivý účinek. Domácí kompost z ekologického odpadu překonal komerčně kupovaný balený kompost ve všech srovnáváních. Dále je vypracována makroekonomická diskuse o úloze energie v zemědělství s využitím rámce „EROI“ (Energy Returned on Energy invested). Došli jsme k závěru, že náklady pro společnost a planetu spojené s přetrháním koloběhu živin, jsou základní příčinnou ekologické degradace. Napravení koloběhu živin řádným kompostováním organické hmoty s přidáním biocharu, je nákladově efektivním řešením mnoha nejnaléhavějších ekologických a ekonomických problémů světa, jako je degradace půdy, znečištěné vodní systémy a eutrofizace. Pro udržitelnou budoucnost je zapotřebí změna paradigmatu vnímání společnosti, z „hlíny“, k živé, dýchající půdě podporující veškerý život na Zemi.

Klíčová slova:

Kompost, Biochar, Cyklus, Energie, Terra Preta, Rizikové prvky, Těžké kovy, Živiny, Hodnota

Table of Contents

1 Life Beneath Our Feet

"Human", "humble" and "humus" derive from the same root Latin word meaning "from the Earth". It takes a bit of humility to admit that the current way we are treating our humus, or soils, needs some fundamental rethinking. The "Green Revolution" has certainly increased agricultural output, but its focus on petrol-chemical solutions has degraded soils, poisoned aquifers and has led to vast reduction of species diversity, costing people and planet enormously. Ninety-five percent of the food eaten worldwide comes from the ground, which contains its own universe of bacteria, algae, fungi, protozoa, worms, etc. There are more living organisms in a teaspoon of healthy soil than all the people on our planet. Yet very little care is being paid to the bottom of our food chain.

The United Nations declared 2014 the "Year of Soil" and released a report claiming that at the current rate of soil depletion there are now a countable number of harvests left on Earth, sixty. It turns out that soil is not a renewable resource on a human scale of time; it takes about one thousand years to create three centimeters of topsoil. The United Nations predicts human population will reach over 9 billion by 2050, more than a threefold increase in less than a century. Eighty-five million new people are at the dinner table each year and the amount of arable land is shrinking at an alarming rate due to pollution, erosion, poor irrigation practices, construction, and a changing climate. Population growth plus continued resource depletion is, by pure arithmetic, unsustainable even at modest rates in the very short term.[1] The sad reality is that we are in danger of collapsing the complex web of life that we depend on, and are a part of, simply due to our own stupidity. However, unlike an asteroid collision or some catastrophe beyond our control, we are entirely capable of reversing course by simply changing our values and behavior.

In the slew of academic specialties, we often lose sight of how intertwined various fields of study are. This is especially seen in the disconnect between environmental studies and economics. We cannot discuss economic policy without addressing its effects on the environment. All goods and services are derived from functional ecosystems; money, science, art and culture all amount to nothing in a

[1] The current 1.1 % per year growth in population equates to a doubling time of about 64 years.

world without arable soil, drinkable water and breathable air. Therefore, it is imperative to seriously question and redefine our current value systems and measurements for success.

In 2009, the report of the Stiglitz Commission on the Measurement of Economic and Social Progress stated, "What we measure shapes what we collectively try to pursue, and what we pursue determines what we measure." The report examined the long unquestioned assertion that Gross Domestic Product (GDP) is a good indication of the well-being of a nation. GPD, as it stands today, is strongly correlated with energy consumption; a percentage increase in GDP corresponds with an increase in energy consumed (Hall, Lambert, & Balogh, 2014).

Production, packaging, transport, marketing, and application of synthetic fertilizers certainly increase GDP. However, chemical fertilizers bleach the soil of life, runoff into streams and rivers, poisoning aquifers, affecting the health of humans, fish and animals. Fertilizer runoff incites massive algae blooms visible from space that suck oxygen from the water, creating dead zones, which in turn destroy fishermen's' livelihoods and our freedom to swim and enjoy our natural world safely. Even the resulting cleanup attempts and increases in healthcare drive GDP upward because more energy must be consumed. It is evident that fertilizers use is not in our best interest, regardless of increases in GDP, and their use is fueling our drive off an ecological cliff. Careful energy accounting in the form of energy returned of energy invested (EROEI) is needed to assess the ecological impact of all economic and policy decisions. In a world with decreasing energy supplies and damaged ecology, societies of today must change their values to respect the natural world and, in turn, economies of the future will inevitable be built around saving energy rather than consuming it.

Without synthetic fertilizers and a decreasing energy supply, how can we feed the growing population on shrinking arable land? Rather than treating the symptoms, let us deal with the causes. One of the key solutions to repairing our failing ecosystems remains astoundingly simple: fixing the broken nutrient cycle. This will require humans to stop wasting valuable resources in the form of organic residues, "When our food refuse is instead discarded as waste, the nutrient cycle is broken, creating problems such as pollution, loss of soil fertility, and abuse of water resources" (Jenkins, 2005). As Joseph Jenkins (2005) so eloquently put it, the human nutrient cycle consists: 1. Grow food 2. Eat that food 3. Collect and process organic residues (manure, food scraps, urine, agricultural byproduct, yard trimmings) 4. Apply the organic material back to the soil, thereby enabling more food to grow. 5. Repeat this process sustainably forever.

We can look to an unlikely place for a model of long-term sustainable agriculture, the Amazon basin. The peoples of pre-Columbian South America managed to create what has become known as “terra preta”, or Amazonian dark earth. In the last few decades, teams of curious scientists of various fields have unearthed evidence of large-scale civilizations on the Amazonian basin, an area previously thought to be impossible for supporting large civilizations because of its notoriously poor soil. These dark soils, at places 2 meters deep, are man-made from generations of farmers returning food scraps, urine, bones, broken ceramics, agricultural by-product, human and animal manure, and most importantly to its longevity, charcoal, to the top soil. Various crop residues, tree trimmings, even human waste can be pyrolyzed (heated up without oxygen) and turned into charcoal, otherwise known as biochar (BC), a carbon rich, porous material which harbors soil life, traps risk elements such as toxic heavy metals, and stores carbon in the soil. After over 500 years of neglect, islands of highly fertile soil remain, unlike unaltered Amazonian jungle soils which quickly leach nutrients in the constant rain, humidity, and acidity. By prizing what today we call “waste”, Amazonian agriculture thrived, fueling the rise of highly intelligent, complex societies in otherwise infertile land.

This thesis claims that co-composting biochar addresses many of the prevalent ecological, energy and economic issues of our time. All organic material can be composted safely given the right temperature and enough time. Co-composting organic matter and charcoal is a long-term solution that can be used as a soil amendment to increase soil life, nutrient availability, water retention capacity, avoid uptake of risk elements into plant tissue and increase crop yields. To examine if these claims are true and can be mimicked using local materials, an experiment was conducted in which heavily contaminated soil (Pb, Zn, Cd) was mixed with varieties of compost with different levels of biochar. Our hope is that co-composted biochar can decrease the composting time, retain water and nutrients, and reduce the uptake of heavy metals into plant tissue. The poor soil represents a “worst case scenario”, in an attempt to push co-composted biochar to its remediation limits.

2 Literature Review

2.1 Terra Preta: Designed Long Term Soil Fertility

The recent interest in biochar stems from the discovery of "terra preta" and other "dark earth" finds. This highly fertile soil is found in places where ancient agricultural civilizations thrived, even in poor soil like the Amazon. Images of the Amazon rain forest bring to mind lush jungle and green landscapes, full of a countless diversity of life. However, the soils of the Amazon are acidic and nutrient poor because of the soil type (in the Amazon, Oxisols), heavy rainfall, and consistently high temperatures cause quick breakdown of organic matter (OM). Compost, fertilizer, manure, and organic litter from plants all quickly decompose and the nutrients they contain leach away (Barrow, 2012). Terra preta soil is remarkable because it is rich, dark, nutrient dense soil, sometimes several meters deep with high amounts of soil organic matter (SOM) and nutrients: nitrogen, calcium, potassium (Glaser et al., 2001). It is typically found on low bluffs on the edge of flood plains. Sites often cover 5-15 acres, but sometimes as much as 700 (Denevan & Woods, 2009). This land was once cultivated by ancient civilizations but was abandoned to the jungle for hundreds of years after the arrival of Europeans caused the demise of their cultures by disease and war. Yet even after years of neglect, the soils in these areas remain highly fertile.

The key difference of terra preta soil is the large quantity of charcoal (biochar) which comprises up to 35 % of terra preta soils (Glaser et al., 2001), 64 times more charcoal than the surrounding red earth (Mann, 2006). Biochar is able to persist in the soil for millennia. Makoto Ogawa (1999) demonstrated that carbon in charcoal is retained up to 50,000 years. Organic matter absorbs to charcoal, rather than being washed away or attaching to other non-available compounds. "Simply adding charcoal to the soil is not enough to create Terra Preta. Charcoal contains few nutrients, so high nutrient inputs such as excrement and waste such as turtle, fish, and animal bones are necessary" (Mann, 2006). The charcoal in the soil has "stored" these nutrients for centuries, cycling them into plant matter then capturing the nutrients again in the soil when the plant dies and is decomposed. Lehmann et al, (2007) found that terra preta has more phosphorous, calcium, sulfur, and nitrogen than is common in the rain forest. More importantly, terra preta is a living soil, hosting an astonishing array of soil life. In 2010, a Brazilian-U.S. team of archaeologists, soil scientists and molecular biologists found that terra preta had as much as a hundred times more bacteria than adjacent soils and that the bacteria are totally different than those nearby (Mann, 2006).

Despite the charcoal in the soil, terra preta is not a product of “slash and burn” agriculture. When wood is burned, the carbon is released as carbon dioxide into the atmosphere and not stored in the soil. Ancient farmers intentionally burnt the wood at lower temperatures and longer time so that the wood was not burnt completely and the result was charcoal (highly porous carbon), not ash.

Terra preta was almost certainly intentionally created by humans, “It is not associated with a particular parent soil or condition.” Suggesting that it was not produced by natural processes. Another clue to its human origins is the broken ceramics (Mann, 2006). Additionally, natives have been observed to still char vegetative waste and add it to planting areas (Hemming, 2008). Some archeologists and soil scientists theorize that terra preta was a byproduct of a waste management technique used by the ancients that involved added charcoal and ash to human and animal waste to solidify it and absorb unpleasant odors. This mixture was then applied to the agricultural fields. They claim that the people understood the benefits of adding biochar and OM to the soil and intentionally applied it to fields to improve the poor fertility of the jungle soil for intensive agriculture that managed to support a large civilization for centuries before Columbus arrived (Barrow, 2012). One of the biggest patches of terra preta was mapped by Wim Sombroek in the 1960’s. It is situated on the high bluffs at the mouth of the Tapajos near Santarem and 3 miles long and half a mile wide (4.8 x 0.8 km). “If the agricultural practices of the lower Tapajos were as intensive as the most complex people in pre-Columbian agriculture, this land is capable of feeding 200,000-400,000 people. This would have been one of the most populated places on the planet at that time” (Mann, 2006).

To test the effects of biochar, Steiner et al., (2014) applied a variety of treatments involving charcoal and fertilizers for 3 years to rice and sorghum plots. In the first year there was little difference among the treatments (in control plots almost nothing grew). Plots with charcoal alone grew little but those treated with a combination of charcoal and fertilizer yielded a much as 880 % more than fertilizer plots alone. Terra preta is estimated to make up somewhere between 0.1 - 10 % of Amazonian soil basin. The difference in these estimates is irrelevant because only a few thousand square kilometers of farmland would have been enough to feed millions of people that made up these ancient civilizations (Mann, 2006).

What is truly amazing about these finds is that people of the Amazon practiced agriculture in the same areas for centuries, yet rather than degrading the soil, they improved it. This is in stark contrast to just about any other place on the planet that is experiencing large scale degradation of arable land due to thousands of years of continual grazing, plowing, and not recycling organic matter.

The research on terra preta proves that by carefully recycling of nutrients we can create long-term sustainable agriculture even in poor soil and, perhaps to the perplexment of multinational corporations, we can do this in local, low tech and energy efficient ways.

2.2 Compost: Feed the Soil, Not the Plant

Alchemists of the middle ages obsessed over turning base metals into gold. What they missed were the right materials. We can turn our waste into something much more useful than gold. Food scraps, paper, sticks, cardboard, egg shells, bones, even sewage sludge, can all be composted and turned back into life. Every apple core, onion peel and fallen branch is stored solar energy. When returned to the soil, we are feeding the circle of life.

Compost is any group of organic residues that have been piled, moistened, and allowed to undergo aerobic biological decomposition (Smith & Collins, 2007). We can think of the composting process as providing the right conditions to harness a microscopic army that breaks down OM through a series of steps. Thermophilic (heat producing) composts' microbial activity can be so great in a well composed pile that if you were to reach your hand to the middle, it would be uncomfortable warm, reaching temperatures as high as 72 °C (162F). This is far above the temperature required to kill most human pathogens and weed seeds (Camps & Tomlinson, 2015). Pathogenic organisms cannot survive compost temperatures of 55-60 °C (131-140F) for more than 1 hour (Jenkins, 2005). Reaching such high temperatures is not always necessary. Low temperature composting, given enough time, will yield compost also suitable for agriculture (Jenkins, 2005).

The generally used method for composting seeks a carbon (C) to nitrogen (N) ration (C/N) of the source materials to be around 25:1 (Jenkins, 2005). Carbon sources are made up of mostly dead leaves, cardboard, wood chips, branches, egg cartoons, paper and toilet roles. Nitrogen sources are typically fresh cut grass or leaves, food refuse, urine and manures. Finding the right ratio is important in creating quality compost. Manure and urine by themselves will not compost; they are too high in nitrogen so all what is left is a slimy, smelly mess. Hot composting involves finding the right C/N ratio in a pile of compost that is at least one cubic meter with a sufficient supply of moisture. Compost requires moisture and can shrink from 65 % to 25 % in under a week (Jenkins, 2005). An accurate field measurement is the “squeeze test”; a handful of material should give a drop of water when squeezed (Hagemann et al., 2017). The final product of this process is a humus-like, stable substrate that is free of pathogens and plant seeds and can be applied to land to enrich the soil as an organic fertilizer (Smith & Collins, 2007). Well-made compost has all the nutrients a plant needs (Bot & Benites, 2005), and it does not leach these nutrients like raw manure, instead holds it in the soil (Jenkins, 2005).

As with anywhere in nature, the edges contain the most interesting interactions and greatest diversity of life (Hemenway, 2011). The uppermost soil boundary is where the line becomes blurred between living organisms and decomposed dead matter returning to stable elements, referred to as humus (Bot & Benites, 2005). Plants obtain nutrients from both organic matter and minerals, that form from the weathering of rocks and make up most of soil matter. Organic matter consists of any plant or animal that returns to the soil and goes through decomposition (Bot & Benites, 2005), a biological process that results in the breakdown of complex organic molecules of non-living materials into simpler organic and inorganic molecules (Juma, 1998). Most soils contain only 2 - 10% OM (Bot & Benites, 2005). Despite being present in such small amounts, OM plays a crucial role in feeding the biology of the soil. Healthy soil is teaming with microscopic organisms which feed on OM, breaking down the materials to their basic elements, allowing plants to access the nutrients that are otherwise unavailable, locked up in their mineral states. Returning and nurturing SOM is critical for soil biology, which consequently influences chemical and physical processes in soils.

By applying OM, we can: feed soil organisms, supply and retain nutrients available to plants, increase the water holding capacity (WHC) of soils, prevent erosion, and store carbon. Additionally, by using OM to feed plants we can avoid the unsustainable and toxic use of chemical fertilizers, which are enormously costly in energy to produce, transport and apply.

2.2.1 Compost Effects on Soil Biology & Nutrient Availability

Imagine a pyramid with layers of increasing complexity of organisms. Countless bacteria, microbes, fungi, are at the bottom, followed by worms and insects, then plants of all kinds, and finally animals, including humans. The wider the base of the pyramid, the more life supported in the upper layers. Without the immense diversity of bacteria, microbes, and mycelium (fungi) found in the base, the rest of the pyramid collapses (Hemenway, 2011). Soil organisms use OM as food, releasing nitrogen, phosphorous, sulfur, potassium and various other micro-nutrients during the process (Bot & Benites, 2005). When OM is not returned to the fields in the form of crop residue, aged manure or compost, soil loses its ability to naturally release mineral elements to the plants through the herds of living organisms. When OM is kept in the soil or fed in the form of soil amendments, soil organisms decompose the matter in a series of steps. The result is humus. Humus cannot be used by most microbes as an energy source, so it stays in the soil and accumulates over time. In extreme situations microbes will begin to feed on humus, however this is a sign that the soil is in very bad shape due to lack of OM (Hemenway, 2011).

Vogtmann et al. (1991) found that compost improves productivity in terms of quantity and quality of agricultural crops. The more diverse the compost is, the better it supplies the plants with all the essential nutrients. In trials comparing compost to chemical fertilizers, potatoes and beats had higher dry matter, starch and vitamin C grown in compost Fricke et al. (1990). The loss of OM both reduces the soil nutrient retention and decreases the absorption of applied mineral fertilizes (Agegnehu et al., 2016c; Glaser et al., 2002). This ultimately creates a positive feedback loop in which plant growth becomes dependent on increasing amounts of fertilizer, most of which are leached from the soil.

There is immediate need to establish long term, energy efficient, low cost methods of building and enhancing soils across the world, and that begins with repairing our broken nutrient cycle by composting our organic waste. French writer, Victor Hugo, recognized the broken nutrient cycle as early as the 1860’s. He found it so important at the time he included it in *Les Miserables*:

Science…knows that the most fecundating and the most efficacious of fertilizers is human manure. The Chinese, let us confess it to our shame, knew it before us. Not a Chinese peasant…goes to town without bringing back with him, at the two extremities of his bamboo pole, two full buckets of what we designate as filth. Thanks to human dung, the earth in China is still as young as in the days of Abraham. Chinese wheat yields a hundred fold of the seed. There is no guano comparable in fertility with the detritus of a capital. A great city is the most mighty of dung-makers. Certain success would attend the experiment of employing the city to manure the plain. If our gold is manure, our manure, on the other hand, is gold.

Hugo recognized that people in Europe at the time were breaking from the natural cycle of nutrients by importing guano rather than using local organic resources. He was evoking humility in appealing to people to understand the value in what is now seen as "filth".

2.2.2 Compost / OM effects on Water Holding Capacity & (in)Filtration

The key element of climate change is largely a major shift in the world's precipitation patterns. Based on the current observations and modeling, we can expect to see areas of the world facing increasing levels of drought while other parts will see an increase in rainfall, however, it may become less frequent but more intense (Schlenker et al., 2007; Vano et al., 2010; O'Neill & Dobrowolski, 2011).

Compost can hold 9 times (900 %) its weight in water, compared to sand which holds 2 % and clay 20 % (Jenkins, 2005). Fischer & Glaser (2012) found that OM addition through compost can absorb 3 to 20 times its weight in water.

OM changes the physical structure of soil by creating aggregates and thus pore spaces. These pore spaces are essential for the water infiltration and directly affect the water holding capacity (WHC), a soil's ability to retain water for extended periods of time after rainfall or irrigation. Sandy soil has too large of pore spaces for water to be retained and clay, too small for water to infiltrate well. OM improves infiltration by improving aggregation and feeding soil organisms such as worms, who form macro pores, allowing water to infiltrate deep into the subsurface (Carter et al., 2004). (Baronti et al., 2014) found that the depletion of OM in the last century, in combination with chemical fertilizers has dramatically decreased soils' water holding capacity around the world, effecting crops ability to adapt to a changing climate.

2.2.3 Compost / OM ability to Degrade Toxic Chemicals and Bind Heavy Metals

A responsible society bans the use of resources that permanently reduce yields of sustainable resources such as pollutants, persistent poisons, radioactive material, large areas covered by concrete and sewers into the sea (Mollison, 1978). Modern agriculture is one of the heaviest sources of pollution, “agriculture constitutes one of the most important non-point sources of metals pollutants. The main sources are impurities in:

a. Fertilizers: Cd, Cr, Pb, Mo, U, V, Zn,
b. Pesticides: Cu, As, Hg, Pb, Mn, Zn
c. Fungicides: Cu, Zn and Mn” (Hassaan et al, 2016).

Composting not only converts OM to humus but also degrades toxic chemicals, such as gasoline, diesel fuel, oil, grease, wood preservatives, PCB’s, coal gasification wastes, refinery wastes, insecticides, herbicides, TNT, and other explosives, into simpler, benign, organic molecules (Jenkins, 2005).

In Jenkins’s (2005) experiment where insecticides and herbicides were intentionally added to compost piles, the insecticide (carbofuran) was completely degraded and the herbicide (triazine) was 98.6 % degraded after 50 days of composting. Soil contaminated with Dicamba herbicide at a level of 3,000 parts per million showed no detectable levels after only 50 days of composting. Huu-Taun Tran et al (2018) conducted a study where soil heavily contaminated with diesel fuel was composted for 45 days and the toxic elements were reduced by 93 %.

Heavy metals are elements that cannot be created or destroyed. However, they can be altered and bound to other elements which prevents them entering ground water or being taken up by plants, essentially locking them up in the soil where they will not harm plants or animals. Holmgren et al. (1993) tested a range of different soils through the USA and found “significant correlations between the solubility of Cd, Cu, Zn, Pb and Ni and SOM content.” Meaning, the more organic matter applied, the better the ability of the soil to lock up harmful compounds. Application of compost reduced Pb and As uptake in lettuce and mustard greens in an experiment conducted with highly contaminated soil (Mcbride, Simon, Tam, & Wharton, 2016). The effects of compost additions are long term, “organic matter applied by compost even effectively prevents mobilization of heavy metals for a long time after the cessation of compost addition (Mondini et al., 2003).

Some bacteria can even digest uranium. A certain strain of bacteria (Saccharomyces cerevisieae) lives hundreds of meters below ground and will eat, then extreme uranium. The discarded uranium is made water insoluble by the digestion, making it much easier to remove from water sources (Jenkins, 2005). The work that armies of microorganisms and fungi can do in restoring damaged landscapes is extraordinary and still being discovered.

2.2.4 Compost /OM effect on Soil Structure & Porosity: Preventing Erosion

The main source of soil loss is erosion caused by agrochemicals (destroying soil life and removing water, see below), tilling of fields, and over grazing of animals (Agegnehu et al., 2017). Lal et al (2015) traced a direct link between declining SOM contributing to increasing rates of erosion, more intense compaction of soil from machinery and livestock, loss of nutrients, drop in biodiversity and desertification, all of which result in reduced soil fertility

Soil organic components, along with micro-organisms, bind soil particles into aggregates and these aggregates bind to each other more strongly than adjacent particles (Agegnehu et al., 2017). OM changes the physical characteristics of soil. As microbes feed, they secrete enzymes in the form of gels and waxes, which allow tiny particles to bind together into loose crumbles and larger aggregates. The space between aggregates is the pore space. The process of aggregation is necessary for healthy soil structure, allowing aeration, water filtration, root penetration and resistance to erosion (Bot & Benites, 2005). Aggregates that break apart when brought in contact with water, clog pore spaces, forming a crust that makes it difficult for water and oxygen to infiltrate or for seedlings to emerge. A soil laden with OM will easily form a variety of aggregate shapes and pore spaces. This relationship is associated with a higher active surface area for storage and exchange processes in soil (Fischer & Glaser, 2012). Amlinger et al. (2007) found that an increase of SOM: reduced soil density, stopped soil erosion, and water runoff. This was supported by a 5-year follow-up study that measured these effects. Yearly compost additions yielded 67 % reduction in soil erosion, 60 % reduced run-off, 8 % lowered bulk density and 21 % higher OM content compared to controls (Fischer & Glaser, 2012). Without soil life, earth dries up and blow away or forms impenetrable clumps of clay after heavy rains (Hemenway, 2009).

2.3 Synergetic Effects of Biochar and Compost

In the last two decades, interest in biochar has grown considerably as a strategy to simultaneously address a number of urgent global issues: enhancing crop production and soil fertility, water retention and purification (decreased irrigation costs and drought protection), decrease nutrient leaching, sequester carbon while avoiding the release of other greenhouse gases, and to remediate soils polluted with risk elements from human activities (Camps & Tomlinson, 2015) (Baronti et al., 2014).

Biochar is charcoal that has been made for the purpose of soil improvement. It is essentially any carbon rich OM (most commonly: wood, manure, sewage sludge, crop residue such as nut shells and rice hulls (Ahmad et al., 2012; Hussain et al., 2016; Inyang et al., 2016; Stefaniuk and Oleszczuk, 2015; Usman et al., 2015; Zielińska et al., 2015a.; Godlewska, Schmidt, Ok, & Oleszczuk, 2017) that is heated in the absence of oxygen, in a process called pyrolysis (Lehmann and Joseph, 2009).

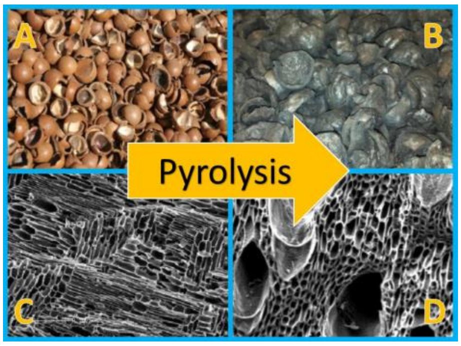

Figure 1: A: Walnut shells B: Turned into biochar through pyrolysis C: Zoom in on the pore structure D: An up lose looks shows the enormous porosity of the char surface.

Biochar on its own is not a fertilizer. It provides a highly porous (see figure 1) and negatively charged surface where microbes, bacteria and fungi can flourish, greatly increasing the biomass and fertility of the soil. Several studies have found an initial decrease in soil fertility when biochar is added to soil due to its ability to absorb water and microbes. If the charred material is free of heavy metals or other toxins and is "charged" with OM before application, it seems to only benefit the soil in the long term (Agegnehu et al., 2017).

Biochar varies widely in quality based on the parent material, temperature, length of pyrolysis, size, and if it is enriched with other compounds, like compost or urine (Barrow, 2012). By changing these parameters, it is possible to customize biochar for the desired treatment of the soil.

There is a wealth of historical and scientific evidence supporting the overall positive effects of activated charcoal on soil life and processes. But improving soil quality is as varied an experiment as examining every type of soil so we must remain careful of "one-size-fits-all" solutions and can hedge our bets by diversifying biochar source material.

Biochar use and its production can be divided into five categories: rehabilitation of damaged ecosystems, improved fertility, mitigation of climate change, and waste management, energy production.

2.3.1 Remediation of Risk Elements

One of the greatest potentials of biochar is its use in polluted or degraded soils to remediate them, bringing back soil life, functionality and thus economic value. Unlike organic pollutants, heavy metals are not biodegradable and persist in soils for decades or even centuries (Zhang et al. 2013). The impact of biochar on heavy metals immobilization depends on various factors such as soil properties, feedstock, pyrolysis temperature, particle size, application rate, and metal species (Lu et al., 2014;Xu etal. 2016; Yang et al., 2016; Ahmad et al., 2014a).

Biochar, like compost has a unique ability to "lock up" heavy metals and persistent organic pollutants because of its negative charge resulting in drastically reduced uptake of metals into plants and increase in plant growth soils (Houben et al. 2013a; Kimet al. 2015;Lu etal. 2014). Many of these elements are positively charged so when they become bound to BC they are no longer free to move through water systems or be taken up into plant tissue.

This study will focus exclusively on lead (Pb), cadmium (Cd), and zinc (Zn) contamination. These metals cause various health problems when consumed in excess and were all very prevalent in the Litavka soil (see chapter 3.2.2 for details) that was used in the study experiment.

The source of these contaminants is mining, smelting, industry, waste incineration and agriculture. Agricultural soils are particularly affected by heavy metal contaminants in pesticides and fertilizers, irrigation with contaminated surface or groundwater, surface runoff from localized industrial facilities, mineral ore extraction and subsequent waste disposal (Candeias et al., 2014; Li et al., 2014), road dust, sewage sludge and livestock manures, and atmospheric deposition (Ke-Lin et al., 2006; Micó et al., 2006; Nicholson et al., 2003; Pagotto et al., 2001).

According to the World Health Organization, Pb is a neurotoxin, capable of impairment of neurodevelopment in children. Lead accumulates in the skeleton, and its mobilization from bones during pregnancy and lactation causes exposure to fetuses and breastfed infants. There are indications that lead is harmful even at low concentrations, considerably below 100 μg/l. Food is the predominant source of lead uptake in the general population (WHO, 2019).

Cadmium targets kidney and bones, causing osteoporosis and an increase risk in lung cancer if inhaled. The World Health Organization warns, “Food is the main source of cadmium exposure in the general population (representing > 90 % of the total intake in non-smokers). In heavily contaminated areas, dust resuspension can constitute a substantial part of the crop contamination and exposures via inhalation and digestion. Cadmium is accumulating in soils and catchments under certain environmental conditions, thus increasing the risk of future exposure through food.” (WHO, 2019) It is abundantly clear that we should seek to altogether stop the use of Pb and Cd and limit Zn in agricultural products as they pose a serious threat to human health and the quality of wellbeing.

Unlike Pb and Cd that have no known benefit to humans, plants or animals, Zn is an essential micro-nutrient for booth humans and plants. However, as with anything the dose makes the poison. If consumed in too high amounts risk of infection is increased and flu-like symptoms may occur (WHO).

Vegetables are an essential component to a healthy diet because the are rich in vitamins, minerals and fiber. However, certain vegetables readily accumulate high levels of metals in their root systems and leaves (Zhou, 2016). Different metals tend to accumulate in different plants, even in the same species. Alexander et al. (2006) found that Pb accumulated in lettuce and onion while Cd accumulated in spinach and lettuce. In many parts of the world, the demand for land and food production are so great that farmers cannot afford to leave fields fallow for remediation and instead, continue to farm even though the food harvested is contaminated with risk elements.

Ahmad et al. (2012) found that adding 5 % biochar to the soils decreases the bioavailability and bio-accessibility of Pb and Cd by 75.8 % and 12.5 %, respectively, compared to unamended soil. Jiang et al. (2012) investigated the effect of biochar on the mobility and bio-availability of Cu, Pb, and Cd in soil. They observed that the acid soluble Cu and Pb significantly reduced, while the reducible and oxidizable Cu and Pb increased responding to biochar addition. Cui et al. (2011) assessed the effect of biochar on Cd uptake by rice in a 2-year field experiment. They found a great reduction in Cd concentration of rice grain in soils amended with 40 ton per hectare biochar. Similar results are confirmed by Bian et al. (2013), who suggest that biochar at 40 t ha−1 can allow grain Cd level to meet a safe rice production (< 0.4 mg kg−1). They also conduct a 3-year field experiment in contaminated rice paddy and find that biochar reduces Cd and Pb bioavailability to rice (Bian et al. 2014). In the previous field study, biochar applied at rates of 10–40 t ha−1 efficiently immobilizes Cd and Pb in paddy soil and decreases their bioavailability by 15 – 27 % and 18 – 31 %, respectively (Cui et al. 2013; Wu, He, Inthapanya, & Yang, 2017).

Beesley et al. (2014) concluded that biochar can mitigate free metal concentrations of Cu, Cd, and Pb and that combing compost with biochar gave the best results because it was able to decrease extractable metals while at the same time increase the solubility of nutrients. Sizmur et al. (2011) findings concluded that the use of biochar and compost in combination is effective in reducing the bioavailability and mobility of heavy metals (Zn, Pb, and Cu). They suggest future experiments with varying levels of biochar in order to determine the most efficient doses. This is something we attempted to find in our experiment explained in detail later.

2.3.2 Enhancing Soil Fertility & Crop Yield

Biochar has a high cation exchange capacity (CEC) because it is negatively charged. Soil with a high CEC has the “ability to hold or bind plant nutrient cations to the surface of biochar particles, humus and clay, so nutrients are retained rather than leached and therefore more available for up- take by plants” (Glaser et al., 2002; Laird et al., 2010a; Lehmann et al., 2003a). Co-composting biochar allows the BC to absorb water and nutrients. These nutrients can then be held in the top soil rather than leached away out of the reach of plants’ roots. “Moreover, biochar substrate or more specifically its surface property stimulates microbial activity, facilitating the composting process” (Jindo et al. 2012; Khanetal. 2014; Wu et al., 2017).

Biochar has a high specific surface area, 400 – 800 m^2 (Agegnehu et al., 2017). This means that a single spoonful of BC can have the surface area of a football field. All this surface area can be colonized by countless microorganisms and mycelium, greatly enhancing the fertility of the soil, but also speeding up the breakdown of composting materials (Thies and Rillig, 2009; Jindo et al. 2012a). “Moreover, carbonaceous dark biochar makes the topsoil absorb more solar energy, which results in higher soil temperatures (Krull et al., 2004) causing higher activity of soil biota (Paul 2014) and, consequently, a longer vegetation period” (Marousek et al.2015; Vochozka, Plachy, & Marous, 2017).

“Apart from direct application of biochar for environmental protection, it also has an indirect effect on agricultural production in case of less fertile soils. Biochar may improve such soil properties like ion exchange capacity, porosity, water holding capacity, retention of nutrients or microbial activity (Hussain et al., 2016). The above benefits are of enormous importance as they determine the agronomic productivity, solving problems related with farming on soils poor in nutrients.” (Godlewska et al., 2017).

In a field study testing amendment on average yield of barley, Agegnehu et al., 2016, compared biochar alone, co-composted biochar, and biochar plus mineral fertilizer. The addition on co-composted biochar promoted better plant growth and carbon sequestration than biochar alone or with mineral fertilizer. With the co-composted BC, a significant part of the initial total C content remained after the second harvest, whereas only 58 % remained.

Biochar greatly reduces nutrients lost. In a study by Hua et al. (2009), they reported that a 9 % biochar amendment decreased loss of nitrogen in the soil by 64.1 % compared to a no biochar control. Similar studies confirm such results (see for example Lehmann, 2007). The potential for BC to capture nutrients that would otherwise end up in streams and rivers is a major factor in why it should be applied to agricultural fields.

2.3.3 Water: Porosity, Capillary Action, Purification

Water is the greatest limiting factor of any agricultural system around the world. Approximately 70 % of the world’s demand for fresh water is for agriculture (SIWI-IWMI, 2004). Even if there is ample rainfall in a region, if the soil cannot retain the rainfall, plant growth will suffer. We can imagine biochar as a very porous sponge in the soil. Compost and BC together can greatly expand soils’ ability to store water, most biochars made from plant materials have a high porosity and surface area (Downie et al., 2009) and thus a large capacity to hold water at field capacity (Glaser et al., 2002). As noted before, however, it is not advisable to apply fresh biochar to fields as crops may suffer in the short term because of biochar's sponge-like behavior. Fresh biochar may suck the water and nutrients from the soil, only releasing them when it is saturated, which could take several seasons depending on conditions. Hagemann et al., 2017 found this effect can be avoided by co-composting biochar or otherwise treating it with nutrient rich waste streams, such as liquid manure.

Biochar may provide a solution to restoring desert areas. Due to its porosity and composition, biochar can increase water retention capacity when added to sandy soils (Case et al., 2012; Basso et al., 2013; Conte et al., 2013). A great study conducted by Mulcahy, Mulcahy, & Dietz (2013) looked for solutions to increasing water capacity in arid lands to help sustenance farming women in eastern and southern Africa become more resilient to drought. Because biochar is too expensive for these farmers, they made cooking stoves that produced enough biochar to help seedling tomatoes become established. The results demonstrated that in sandy soils, a 30 % addition of biochar to the root zone of seedling tomatoes significantly increased the seedlings ability to resist wilting of death from drought.

Liu et al. (2012) found a positive synergistic effect of compost and biochar mixtures on soil OM content and water retention capacity and nutrient levels in sandy soil. The addition of co-composted biochar increased the yield of both rainy and dry season maize and the absorption of phosphate on calcareous soil (Nur et al. 2014).

Biochar application can change the physical structure of soil. Since BC is usually applied in small chunks, it creates pores in the soil that allow water and air to infiltrate more easily. This allows plants to draw the soil to a lower water content before wilting (Koide et al., 2015). Asai et al. (2009) found that additions of biochar to the topsoil caused a decrease in bulk density, increase in water holding capacity and permeability of water accelerated.

2.3.4 Adding BC decrease Composting Odor & Time

Research conducted by (Dias et al. 2010; Sánchez-García et al. 2015; Steiner et al. 2010; Zhang et al. 2014a; Zhang and Sun 2016) have all confirmed BC's ability to speed up the composting process. Sánchez-García et al. (2015) found a significant decrease in composting time with only a 3 % BC addition. "In a research conducted by Zhang et al. (2016a), adding 10 – 15 % straw biochar to pig manure led to faster OM degradation and the concentrations of DOC in such compost decreased by 37.5 – 62.0 % compared to the control" (Wu et al., 2017).

This has obvious economic benefits; more compost in less time. It also means that BC can be used in places where a lot of organic matter is received and the turnover needs to be sped up, such as a city compost facility that is laden with refuse because people in the city do not have gardens or yards where they can have their own compost piles.

Odor can be a deciding factor in accepting a compost facility in a densely populated place, since no one wants to live next to a smelly compost pile. Ammonia is not a pleasant odor and represents loss of nitrogen into the atmosphere. Dias et al. (2010) found that biochar reduced odors and N losses in compost piles. The reduction in time and odor with a BC addition is something we set out to test when creating our own compost piles (see 3.2.1).

2.3.5 Reduced/Ceased Agro-Chemicals usage

Gross application of agro-chemicals is a key factor in soil depletion around the world. That World Health Organization (WHO) estimates that over 300,00 people die each year because of exposure to pesticides. Nitrogen fertilizer applied to soil increases the yield of plants in the short term. However, the nutrients bleach the soil, killing bacteria and fungi that would otherwise support plant growth. By applying fertilizers year after year, a dependence develops. Only 15 – 30 % of applied phosphorus fertilizer and only 20 – 35 % of nitrogen is taken up by harvested crops (FAO, 2006).

The demand for fertilizers worldwide is increasing exponentially, "The total global demand for NPK fertilizer was 180 million tons in 2012, of which nitrogen fertilizer alone constituted 110 million tons (~61%). The world nitrogen fertilizer demand is expected to be around 116 million tons in 2016 at an annual growth rate of 1.3 %. Of the overall increase in demand for 6 million tons nitrogen between 2012 and 2016, 60 % will be in Asia, 19 % in America, 13 % in Europe, 7 % in Africa and 1 % in Oceania (FAO, 2012). Assuming a 33 % N recovery efficiency (Raun et al., 2002) and \$USD 255 ton−1 (World Bank, 2015) this equates to an \$18.8 billion annual loss in N fertilizer costs" (Agegnehu et al., 2017).

The Green Revolution's focus on chemical fertilizers and seed genetics certainly increased yields worldwide. However, we are now seeing diminished returns and negative consequences of not focusing on the soil biology. Returning OM in the form of compost and biochar has been found in multiply studies to reduce nutrient leaching. The application of Brazilian pepperwood biochar significantly reduced the total amount of nitrate, ammonium and phosphate in the leachates by 34 %, 34.7 %, and 20.6 %, respectively, compared to the soil alone. Similarly, peanut hull biochar also reduced the leaching of nitrate and ammonium by 34 % and 14 %, respectively (Yao et al., 2012). Other studies also indicated that addition of biochar to a typical U.S.A Midwestern agricultural soil substantially reduced leaching of N, P and Mg (Laird et al., 2010a) and Ca and Mg (Major et al., 2012).

3 Co-Composted Biochar Experiment

3.1 Aim of the experiment

The experiment conducted was designed to test the abilities of compost and biochar's ability to remediate even the most polluted lifeless soil. This experiment examined changes in values specifically of lead (Pb), cadmium (Cd), and zinc (Zn), all of which were present above agricultural limits in the tested soil. Also, retention changes of nutrients, nitrate, sulphate and calcium were measured under tested conditions.

The experiment was divided into two stages. Preparatory stage of preparing an on-site created compost allowing the co-composting experiment of charging compost with BC in the process of composting. An additional goal in making own compost was to show that high quality compost can be made with free, local organic waste, without high-tech equipment or any source of energy. For this stage of the experiment the following research questions were asked:

1. Is it possible to decrease composting time with the addition of biochar? How much by percentage of weight is needed?
2. Does co-composting BC improve the compost quality in terms of consistency, smell and nutrient content

After that, the experiment was conducted, with the aim to treat low-organic contaminated soil by the prepared compost for possible plant growth. The following research questions were asked:

3. Does addition of C + BC improve retention of water and nutrients in soil?
4. Does addition of C + BC increase yields even in contaminated soil?
5. Can C + BC decrease uptake of risk elements in plants?
6. How much, if any, BC is needed (% weight) to improve results?
7. What kind of difference can be seen between homemade and commercially bought compost?

Additionally, an a brief discussion is had on the energy economics comparing current industrial models of fertilizing with the recycling of organic matter.

3.2 Materials & Methods

3.2.1 Experimental Soil

The soil used was highly contaminated with risk elements (Zn, Pb, Cd, Cu, As, Cr, Ni) and is referred to as “Litavka soil” as it comes from a site nearby Litavka river. The site is located near the city of Příbram, Czech Republic, 8 km downstream of a lead smelter. After centuries of mining and smelter activities, the area surrounding Příbram is one of the most lead, zinc and cadmium contaminated regions in the Czech Republic, as well as in Europe.

This site presents many challenges for remediation mostly because it is a populated agricultural area. Over 50,000 people inhabit Příbram and the surrounding area and it is estimated that two-thirds of the agricultural land, 990 km^2, is contaminated from the smelter (Komarek, 2007). Additionally, flooding from the Litavka river greatly increases the mobility of the risk elements and makes it difficult to predict their movements.

The soil used in the growing experiment was taken from several sampling locations at various depths up to half a meter deep. It was mixed together, dried, then sieved (2 mm). Average pH was 5.6, indicating highly acidic soil. The soil was analyzed using ICP-OES with the average levels of Cd, Pb, and Zn given below.

Table 1: Litavka Cd, Pb, and Zn levels compared to the permissible limit standards of the World Health Organization

Metal	Cd (mg/kg)	Pb (mg/kg)	Zn(mg/kg)
Litavka Soil	50.7	4565.8	4749.6
WHO limits	0.08	50	85

The levels of contamination in this soil far exceed the permissible limit by the World Health Organization (WHO) for Cd, Pb and Zn.

3.2.2 Retail-Compost

A control was used to test the difference between a professional commercially produced compost bought at a garden center to our own homemade compost from locally sourced materials. The retail compost (RC) was Agro Zahradnický Kompost (garden compost) made by Agro CS.

3.2.3 Biochar

The biochar used in the experiment was a mixture of soft wood, mostly spruce. It was made in the CHP plant Kozomín (Czech Republic) in the gasifier GP 750. GP 750 is an atmospheric, fixed-bed, multi-stage gasifier, which uses air as a gasifying medium. The biochar was heated for 6 hours between 500 – 600 °C. Initial biochar characteristics are in Table 2.

The following pristine biochar analysis were conducted: water content (W) determined by the standard ČSN EN 15414-3; the ash content (A) according to the standard ČSN EN 15403 at the temperature 550 °C; the volatile content measured on the basis of ČSN EN 15148 standard at 900 °C. The biochar surface (SBET) was performed by automated volumetric gas adsorption instruments ASAP 2020 and ASAP 2050.

Table 2: Initial biochar characteristics

Kozomín - Biochar		
Property	Unit	6 □□ 10 mm
Moisture	wt. %	3.75
Total combustibles, h^d	wt. %	94.32
Ash, A^d (550 °C)	wt. %	5.68
Volatile combustibles, V^d	wt. %	**3.80**
Fixed carbon, FC^d	wt. %	90.52
Loose poured bulk density^r	$kg.m^{-3}$	142
Specific surface area - BET, S_{BET}^d	$m^2.g^{-1}$	**615**

3.2.4 Experimental homemade compost and charger compost

Three composts were made with the only difference being the percentage of biochar: A (No Biochar), B (2 % BC), C (5 % BC), all by weight.

The compost experiment began on November 1, 2017. Fallen leaves from a grove of oak and maple trees, small sticks, and freshly cut grass were collected on the campus of Czech University of Life Sciences in Prague. The leaves, twigs and grass were shredded and added to a 200-liter plastic drum at a ratio of 5:1 (leaves to grass). This ratio was determined to be approximately the 25:1 carbon to nitrogen ratio necessary for optimal breakdown of organic materials into compost. Three drums (A, B, C) were filled with 25 kg of leaves and 5 kg of grass.

Photo 1, 2: (Left) Shredded and moistened OM on the first day of composting. (Right) 3 composters: A, B, and C.

Three liters of water were added to each container during shredding to saturate the materials. This amount of water passed the "squeeze test" in which a handful of the material, when squeezed, produced just a few drops of water. This ensures that the materials are moist but not soaked. Prior to filling the drums, each were drilled with holes to allow airflow and excess water to drain out. A metal pipe was run down the center of the drum and fixed on a wooden stand to allow spinning of the container to mix the materials. Container A contained 0 % of BC, container B contained 2 % of BC and container C 5 % of BC, all by percentages of total weight of leaves, twigs, and grass. The containers were placed in a greenhouse at approximately 20°C and spun to mix and aerate materials 3 times per week for the duration of the experiment, approximately 16 weeks.

Table 3: Initial weight (kg): Nov 2,2017

	Weight Leaves	Weight Grass	Weight Biochar	Total Start Weight
A 0 %	25	5	0	30
B 2 %	25	5	0.5	30.5
C 5 %	25	5	1.25	31.25

The original ratio of leaves to grass was lacking nitrogen to generate optimal composting. On November 29, 2017, 2.21 kg of additional fresh grass was added to each container with the corresponding percentage (0 %, 2 %, 5 %) weight of BC (see table 4).

Table 4: Extra grass & biochar added (kg) Nov 29, 2017

	Weight of grass	Weight BC (%)	Total weight added	Total weight 29/11
A	2.21	0	2.21	32.21
B	2.21	0.044	2.254	32.754
C	2.21	0.111	2.321	33.571

On December 4, 500 ml of water was added to each container to pass the squeeze test. Further observations are noted in the results.

The Co-composting experiment ended February 12, 2018 when all materials had broken down and reached a stable state where no heat was being generated by the decomposition and the compost as mostly homogeneous except for larger sticks. All containers were emptied, weighed and sieved individually.

3.2.5 Seeds

Two types of plants were grown for the experiment, yard grass and arugula (*Eruca sativa*). The grass was common perennial garden grass typical of that bought in any garden center. The Arugula seeds were from the seed supplier, Seminko.

3.2.6 Experimental substrates

After the composting was completed, compost created in container A (with 0 % of added BC) was divided into 3 substrates:

- compost with no additions (further referred as A),
- finished compost to which 2 % of BC were added after composting process has been finished (further referred as FC2),
- and finished compost to which 5 % of BC were added after composting process has been finished (further referred as FC5).

This additional biochar was added just prior to the greenhouse growing experiment to compare the effect of “charging” the biochar during the composting process before applying it to soil rather than adding it to finished compost and applying it directly to a field. The only difference between B & C and FC2 & FC5 is that in the latter, the BC was added at the end of the composting and was not co-composted. Retail compost (RC) came packaged from a garden nursery.

7 substrates were prepared for the growing experiment and will be referred to as follows (see Table 5 for all details):

1. LIT: contaminated soil from Litavka site
2. RC: retail compost
3. A: compost, 0 % BC
4. B: co-composted BC 2 %
5. C: co-composted BC 5 %
6. FC2: finished compost + 2 % BC
7. FC5: finished compost + 5 % BC

Table 5: Breakdown of 7 substrates used in the growing experiment

Litavka	Purchased Agro	A. Compost	B. Compost /BC 2%	C. Compost /BC 5%
↓	↓	↓	↓	↓
1. Litavka soil (LIT)	2. Retail Compost (RC)	3. Compost (A)	4. C/BC 2% (B)	5. C/BC 5% (C)
		6. Finished compost + 2%BC (FC2)		
		7. Finished compost + 5%BC (FC5)		

3.2.7 Experimental setup

Two growing experiments ran in parallel; one growing standard perennial yard grass (further referred as grass) and one growing arugula. Both experiments were identical except for the plants being grown. All substrates were mixed 50 % by weight with Litavka soil (LIT), except LIT which was 100 % contaminated Litavka soil as a control.

Table 6: Pot setup

Substrate samples	# of replicas	Total # pots	Litavka soil	Compost	Retail Compost	Compost removed	BC added per pot
1. LIT	4	8	5.76	0	0	0	0
2. RC	4	8	2.88	0	2.88	0	0
3. A	4	8	2.88	2.88	0	0	0
4. B	4	8	2.88	2.88	0	0	0
5. C	4	8	2.88	2.88	0	0	0
6. FC2	4	8	2.88	2.88	0	0.0072	0.0072
7. FC5	4	8	2.88	2.88	0	0.018	0.018

Each 1 liter pot was filled to 720 g. For LIT all 720 g was LIT soil. 720 g x 8 = 5.76 kg. Therefore, half (2.88 kg) LIT soil and half compost were mixed in bulk. For FC2 and FC5, 2 & 5 % compost were removed before mixing and the corresponding weight in BC was added to keep all weights the same. In the end, 56

1l pots were filled; 28 were seeded to grass (0.5 g grass seed per pot), and 3 holes with 3 arugula seeds in each hole. Upon germination seedlings were thinned to only 3 plants per pot (1 per each hole).

Each pot's dry weight was 720 g. Water was added to a test pot of C until fully saturated and excess water could drain out. It was determined that 100 % saturation weight was about 1040 g. For the duration of the experiment, each pot was filled until 880 g weight (50 %) saturation during each watering.

The growing experiment was conducted in the green house of the Czech University of Life science between March 1 - April 5, 2018. The greenhouse temperature averaged around 20 °C between day and night temperatures. HCL lights were above set to 12 hours on and 12 hours off. Seeds for both arugula and grass began sprouting after 4 days. All pots were mixed around each time of watering (approximately 2 times per week) to ensure that lighting availability in the greenhouse was not a factor on growth.

3.2.8 Pore-Water Analysis

On April 5th, the final day of the growing experiment, rhizon soil moisture samplers were inserted into each pot 6 hours after watering to ensure that all excess water had drained out. The rhizons were inserted horizontally under vacuum by attaching it to a plastic syringe. The rhizons were then collected after 4 hours under vacuum and the water samples were refrigerated until the following day when they were analyzed in the lab.

The following day, April 6th, 2018, the samples were diluted to have conductivity smaller than 300 micS/cm and were analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-OES). Collected pore water from the rhizons was diluted 10x to have a conductivity lower than 500 microS/cm and the glass vials with each solution were then analyzed by the Total Organic Carbon Analyzer.

3.2.9 Plants Digestion

To determine nutrient and metal content of both grass and arugula, the biomass dried for 3 weeks. The dried biomass was then machine ground and weighed to 200 mg of each sample. 2 ml H202 and 8 ml HNO3 were added to each sample and allowed to react before enclosed with a Teflon lid. All samples were placed on a hot plate set to 150 °C where they heated for approximately 16 hours. Samples were filtered and diluted to 25 ml. They were then analyzed by ICP-OES.

3.2.10 Statistical Analysis

All data was analyzed by performing Analysis of Variance (ANOVA) to assess the differences of group means in in the study. Additionally, a Tukey's Honest Significance Test was run to find the means that are significantly different than each other when $p < 0.05$. This test identifies any difference between two means that is greater than the standard expected error. Statistical analyses were done using the software R 3.5.

4 Results of Experiment

Photo 2: Grass is visible in A and B but not in C after only 1 week of composting.

Although no quantifiable data was taken on the chemical decomposition, some observation notes (see Photo 3) can add to our analysis. By December 4, after a month of composting, the grass was visible in A and B, but hardly present in C. A was clearly the least decomposed and the smelliest. B was less smelly and C (5 %) had no unpleasant smell and the middle bar fixing the barrel to the stand was visible, signifying that the materials had broken down the furthest in the 5 % BC compost.

On December 12, the decomposition had evaporated much of the moisture, slowing the decomposition so 2 l of water were added again to pass the “squeeze test”. C had a nice earthy smell, while A & B smelled like a stagnant pond, evidence of ammonia gas being released and a loss of nitrogen. By January 4, A had a slimy texture and smelled quite bad, B & C had no smell and were very homogenous in texture. A was still warm when reached into, B and C were no longer generating heat. Again, signifying that they had already reached a steady state and decomposition had ended. By January 12, all 3 mixtures were nearly broken down completely, A no longer smelled, however, many flies were hovering around the container, but not around B and C.

C had the least weight and volume lost, losing only 24 % of its weight while A & B lost 38 % and 39 % respectively. A&B lost the same weight, however, B (2 % BC) had significantly more volume than A.

Table 3:Initial and final compost weights and volumes

Treatment	Weight Feb 12	% weight lost	Volume (l)
A (0% BC)	17.4	38%	40
B (2% BC)	17.7	39%	51
C (5% BC)	23.3	23%	60

B & C were much easier to sieve partly due to being drier, but also because the larger materials had broken down further.

4.1 Pore water

4.1.1 Nutrient Retention

Retail Compost (RC) had the most nitrate present in the pore water, followed by Litavka. Although A, B, C, FC2, and FC5 had low concentration of nitrate present, B and C had slightly more with A, FC2 and FC5 having no statistically significant difference (see Figure 2).

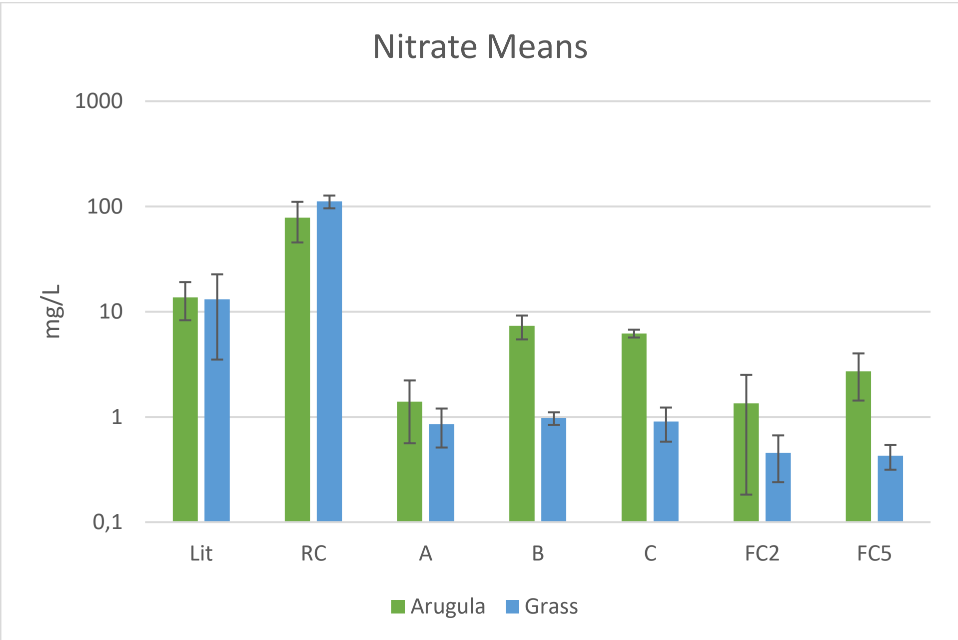

Figure 2: Nitrate Means

A similar trend can be seen (Figure 3) for sulphate presence in pore water with RC leaching the most. However, between all compost and compost/BC mixtures, there was no statistically significant difference. The lower available sulphate in Litavka soil is due to its low original level.

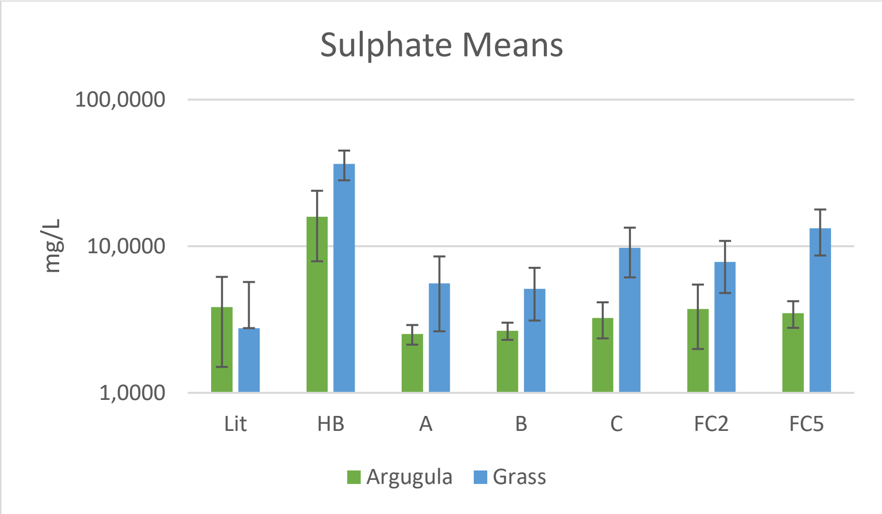

Figure 3: Sulphate Means

There was a large standard deviation in the results of Ca present in pore water (see Figure 4). However, the general pattern is the same; Litavka and RC have much more mobile levels of Ca than any of the other treatments with no statistical difference between A, B, C, FC2, FC5.

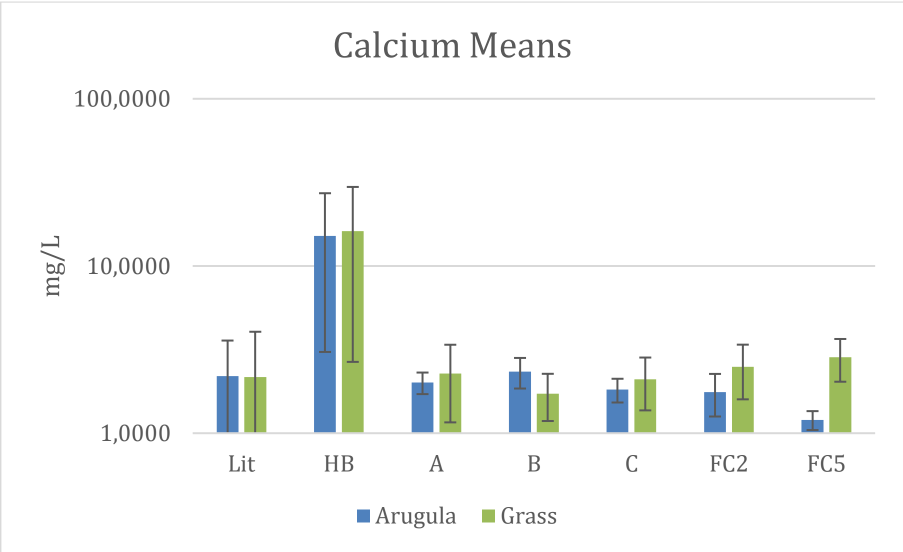

Figure 4: Calcium Means

4.1.2 Availability of Metals

For lead (Pb) availability in pore water, no useful data was gathered from grass because of such a low amount in all samples. For arugula, A and B had statistically significant less amounts of lead present compared to the rest of the treatments. However, the values Pb in all treatments is very low. More details in Figure 5.

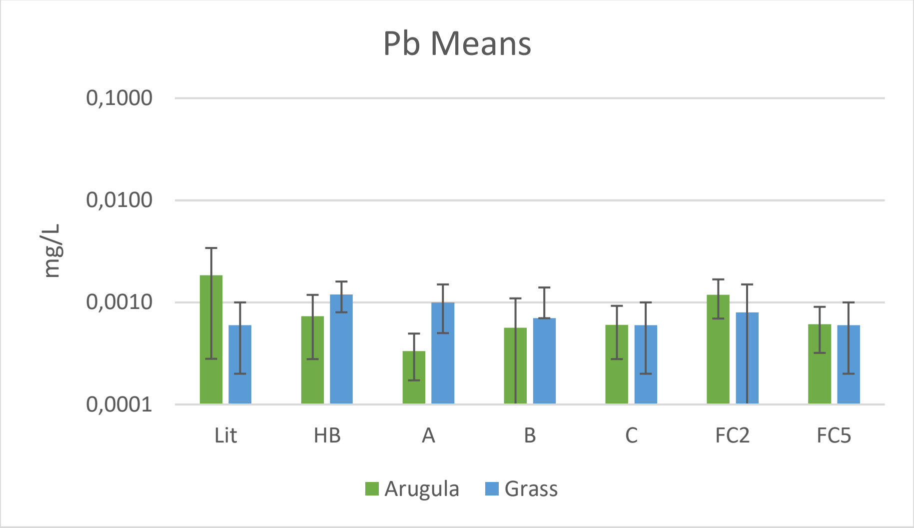

Figure 5: Pb Means

In comparing the different treatments' availability of Cd, we can observe that RC had higher level than any of the homemade compost mixtures (Figure 6). The difference between A, B, C, FC2 and FC5 were not significantly different and all had very low levels available in the porewater.

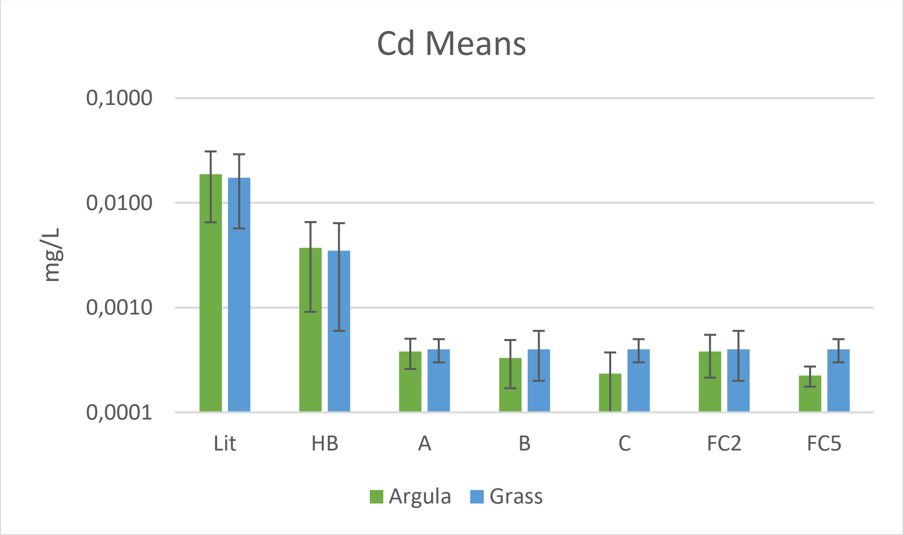

Figure 6: Cd Means

Zn followed a similar pattern as Cd (see Figure 7). All treatments in for both plants had significantly lower levels than the Litavka control. RC again had slightly higher levels of Zn availability than A, B, C, FC2, and FC5. There was no statistically significant difference between all the homemade treatments.

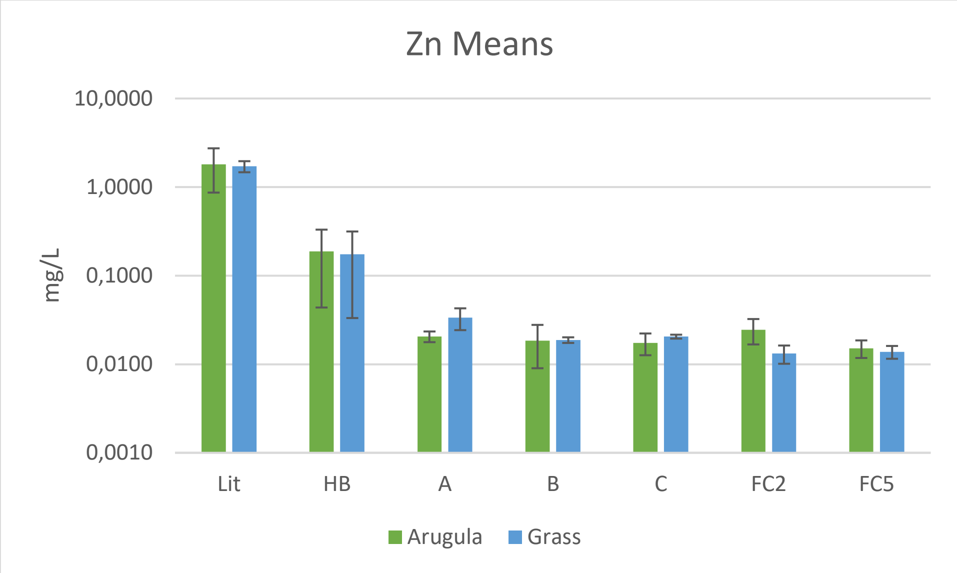

Figure 7: Zn Means

4.2 Influence of Compost/Biochar on pH

The organic matter in compost and biochar raised the pH of the substrate by nearly 2 orders of magnitude, from 6.4 in the pure Litavka soil to nearly 8.4 in FC5 (see Figure 8).

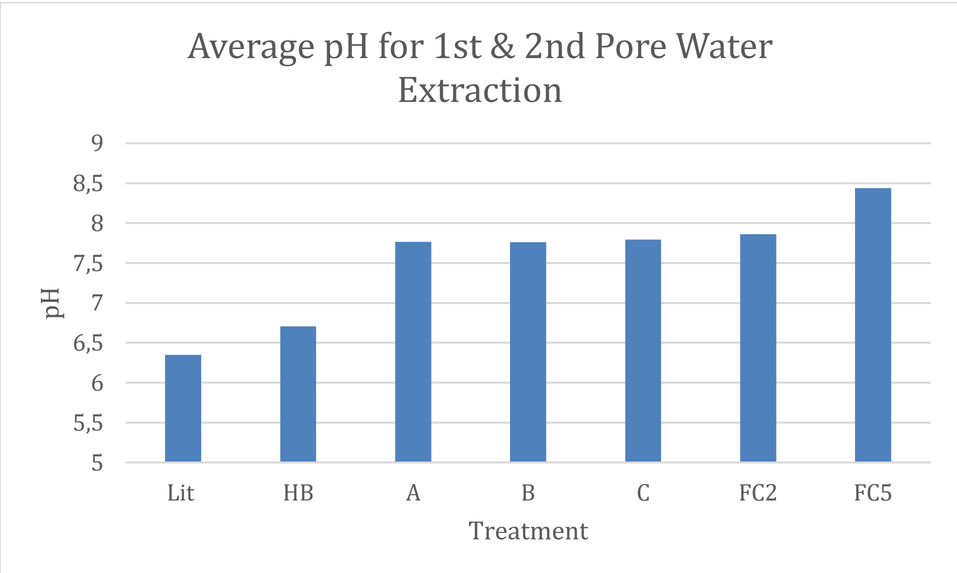

Figure 8: Average pH for 1st and 2nd Pore Water Extraction

4.3 Observed Biomass

From germination, it was very clear that the treatment of soils effected germination rate and subsequent grown. Litavka treatments in both grass and arugula had poor germination. For grass, there was at least enough biomass at the conclusion of the experiment to analyze for metal content. For arugula, only several seeds germinated, and all died within 10 days. Only 1 arugula pot germinated for FC5.

By the end of 1 month growing experiment, the differences in growth were very evident as can be seen in Photos 4 - 5. For arugula, the yield in biomass can be charachterized as: B=C>FC2>A>FC5>RC>Litavka. B and C clearly had the most biomass, closely followed by A and FC5 which were relatively the same. There was a definite underperformance in the RC when compared to all other treatments (see Photo 6).

Photo 3: 2 weeks after germination. From left to right: Lit, RC, A, B, C, FC2, FC5. Only 1 pot germinated in FC5.

Photo 4: Arugula 5 weeks after germination. Left to right: Lit, RC, A, B, C, FC2, FC5

Photo 5: Harvested arugula biomass. Note absence of Lit because of death after germination. (HB = RC)

The differences were also noticiable for grass which appeared to have very similar results from A, B, C, & FC2, but a clear drop off for FC5, followed by RC and lastly Litavka (see Photos 7 – 8). Grass can be characterized as: A=B=C=FC2>FC5>RC. Litavka and RC both had poor germination rates and poor growth with much less vigor than the rest of the treatments.

Photo 6: 2 weeks after germination. From left to right: Lit, RC, A, B, C, FC2, FC5

Photo 7: Grass 5 weeks after germination. Left to right: Lit, RC, A, B, C, FC2, FC5

4.4 Pb, Cd, Zn, Content in Plant Tissue

Pb, Cd, and Zn content of digested plants were analyzed. All data are compared to the World Health Organization's (WHO) permissible limits of content in plants shown by the yellow bar spanning the graph. For all Pb, Cd, & and Zn. Any amount over this bar has exceeded the limit and there is a high risk of adverse health effects at these levels of consumption. No data was available for LIT arugula because no seedlings survived more than 10 days after germination.

Figure 9 shows the levels of Pb taken into the plant tissue of both grass and arugula. All except the mean of C (2% co-composted) were above the WHO threshold for permissible levels. In all cases where organic matter was added (every treatment except Litavka), there was a decrease in the levels of Pb taken up into the plant tissue.

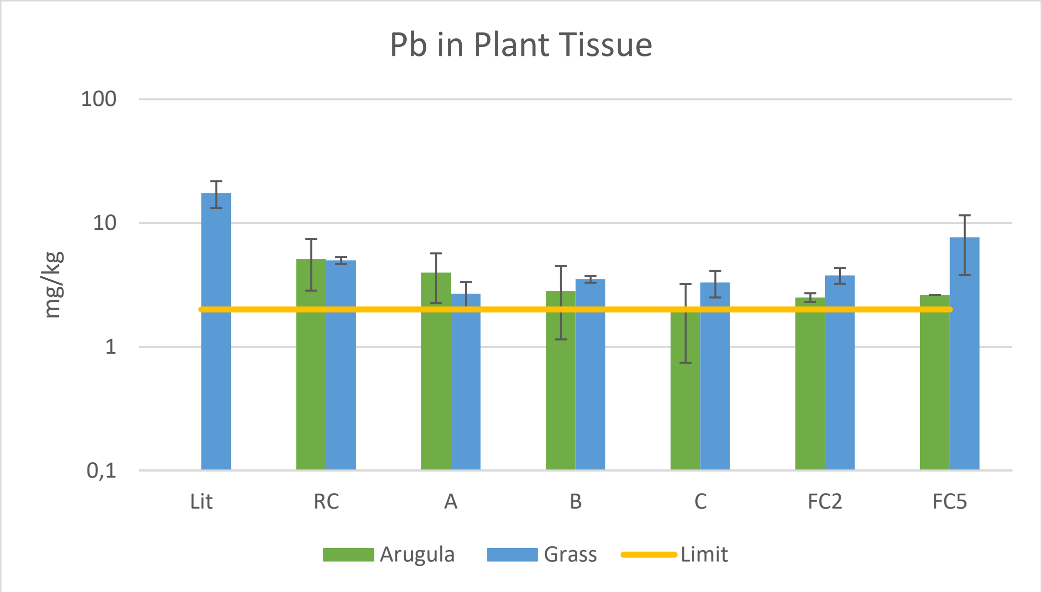

Figure 9: Pb in Plant Tissue

RC had higher levels of Pb in both grass and arugula except grass FC5 that spiked above the rest. In Figure 10 we can see a gradual decrease in Pb in arugula plants from A to B to C and then a slight increase in FC2 and FC5.

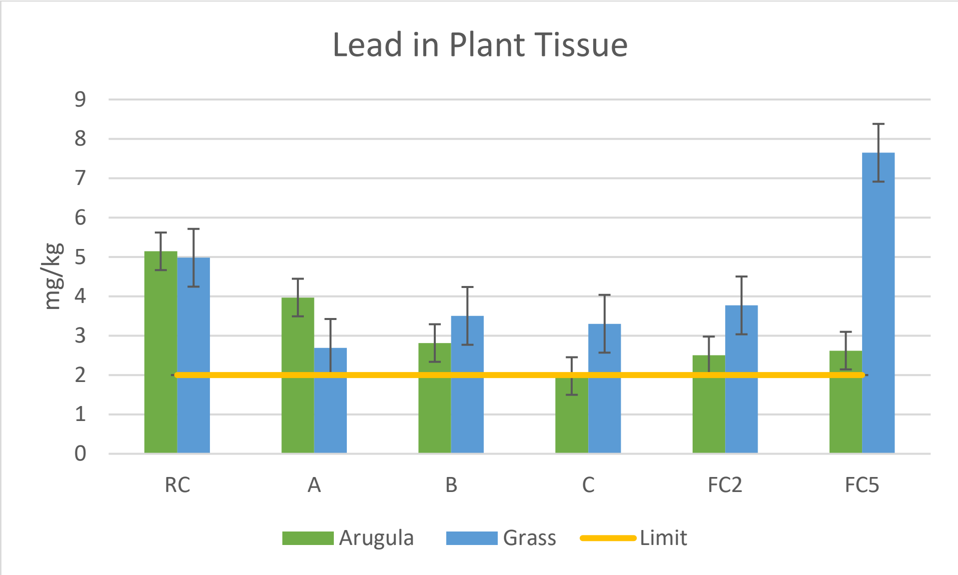

Figure 10: Lead in Plant Tissue

All treatments of both plants exceeded the WHO (2019) permissible limits for Cd (Figure 11). There was a noticeable difference in uptake between grass and arugula, with arugula absorbing much more than grass. This could be telling that in areas contaminated with Cd, it is better to use compost/biochar to remediate the soil to grow grass for livestock rather than crops that would be directly consumed by people.

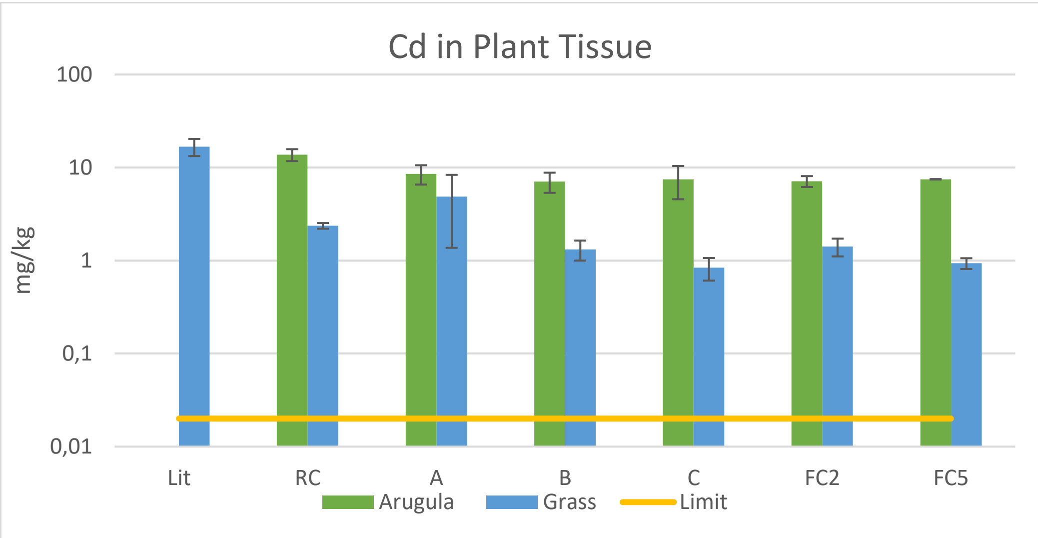

Figure 11: Cd in Plant Tissue

A closer look (Figure 12) reveals that for arugula, we see high intake with RC, followed by subsequently lower uptake in A and a leveling off for the rest of the treatments. The opposite effect can be seen for grass, with a lower amount of Cd in RC, an increase in A, a level decrease between the rest of the treatments.

For Zn we see a similar pattern to Pb. All organic matter dramatically decreased the amount of Zn taken up into plant tissue.

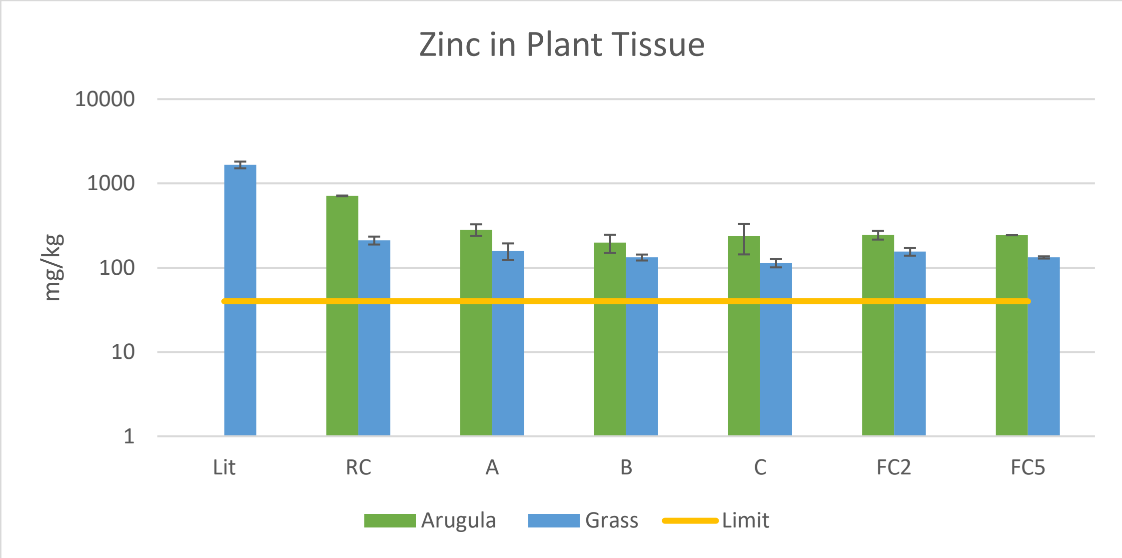

Figure 12: Zinc in Plant Tissue

A closer look reveals a start decrease in Zn between RC and the rest of the treatments. Between A, B, C, FC5, FC2, only B (2%) was statistically significant with a clear decrease in the amount of Pb present. The rest were more or less the same.

4.5 Statistic Results

All statistical results can be found in the appendix. See appendix tables 1, 2 & 3 for data.

5 Experiment Discussion

5.1 Is it possible to decrease composting time with the addition of biochar? How much by percentage of weight is needed?

Co-composting biochar indeed sped up the composting process, confirming the findings of (Fischer & Glaser, 2012; Chen, 2016, Lohri, Rajabu, Sweeney, & Zurbrügg, 2016). Both B (2 % BC) and C (5 % BC) reached a stable state full 3 and 2 weeks earlier than A (0% BC), respectively. C reached a stable temperature and homogeneous state one week before B. However, the temperature could be due to the increased drying effect the BC had on the compost since it acts as a sponge, soaking up excess moisture. More tellingly was the speed at which the additional grass that was added a month into the experiment was digested noticeably faster in B and C than in A. In only a week the added grass was not visible in C, somewhat in B and virtually undigested in A (see Photo 3).

Based on the observations of the experiment, it can be concluded that the ideal percentage of BC needed to speed up decomposition lies somewhere between 2 – 5 %. However, this is also most likely dependent on the initial composition of the feedstock materials for the compost. Our experiment was fairly carbon heavy, more nitrogen material (grass) was needed after a month of composting to keep the decomposition going. In very nitrogen rich materials, such as manure, fresh cut grass, catering or food refuse, the composting could benefit from more BC by percentage of weight because it would act as a bulk source of carbon. Co-composting chicken manure, for instance, requires a larger amount of biochar in order to see results; Agegnehu et al. (2017) found a 20 % additional of BC decreased nitrogen loss by 52 %. Carbon heavy materials such as wood chips could possibly due with even less.

Decreasing the time necessary for finished compost has obvious advantages practically and economically, as long as there is no sacrifice in the quality of the finished material, which was only seen in C and FC5 during the growing experiment. There seemed to be adverse effects with FC5 for both grass and arugula. Arugula had poor germination and less biomass yield and was not at the same level of growth as the other treatments with BC. This might simply be based on the size of biochar we used in the growing experiment. It’s possible that the larger pieces obstructed germinating seeds’ sprouting and root formation.

Since biochar can be costly in certain regions (depending on availability of feedstock and production methods), it is advisable for home and commercial composters who wish to add BC to first make sure that there is enough free carbon material in the compost and not solely rely on BC as a source of high carbon material since low doses of biochar can still speed up the process without raising the input costs.

Faster turnover reduces the amount of space needed to handle the same amount of OM. Smaller facilities could handle more OM and generate more compost in a given time which allows for less startup costs in terms of land needed and more revenue generated. Based on our experiment, even a small addition of 2 % BC, reduced the production time by 14 %. If biochar is sourced locally from what would otherwise be waste materials, there is no reason that a 2 % addition would offset the economic benefit of decreasing production times. In fact, compost facilities (as well as backyard gardeners) could turn biochar production into a profitable aspect of composting. BC parent material can be sourced locally for free, which is often the case with agricultural residues, and tree trimmings from road ways. The cost of transport could be offset by the energy production from the charcoal process and the carbon capture of biochar could offset the carbon emitted into the atmosphere during local transport. Additionally, the heat generated when making BC could be used to heat homes or greenhouses and the biooil and syngas oil could be collected in the proper facilities to capture an additional yield of biofuels (Vochozka et al., 2017, Koide et al., 2015; Roberts, Gloy, Joseph, Scott, & Lehmann, 2010).

5.2 Does co-composting BC improve the compost quality?

Compost quality from a fertility and aesthetic perspective is vital for any sustainable production whether it is backyard or commercial. B & C had noticeable less smell than A. Both treatments with biochar smelled earthy and soil-like, while A smelled like a stagnant pond and had a slimy texture during the first several weeks of decomposition and especially after the second round of grass was added. Biochar acts as a sponge and can soak up excess moisture that could otherwise cause the compost to go anaerobic. This could have adverse effects if there is little moisture in the parent material and rainfall is inadequate to hydrate the compost heap. In this case, water might have to be added to compensate BC's absorption. We saw this drying effect when comparing the finished composts; C was significantly drier than B and A. It is advisable to vary the amount of BC based on local conditions rather assume that there is a specific target percentage of biochar.

The smell from A is very likely due to the release of nitrous oxide, (N_2O), reduced ammonia (NH_3) and methane (CH_4) (Cornelissen et al., 2016), all of which are greenhouse gases. Some release of gases during composting is inevitable but can be greatly reduced by co-composting biochar (Camps & Tomlinson, 2015). These gases represent a loss in quality to the finished compost because nutrients are being lost in gaseous form which has the double-sided effect of entering the atmosphere and warming the planet. Methane alone is more than 30x more potent as a heat-trapping gas than CO_2 ((Vandecasteele et al, 2016) and is created during anaerobic decomposition, when there is insufficient oxygen present during decomposition. This is what occurs when OM is landfilled, the gases released are detrimental to the environment. Not only we are wasting precious nutrients, but they are being converted into harmful gases. The addition of BC to compost can simultaneously trap greenhouse gases and save nutrients that can then be used by soil life and translates to an increase in plant yields and a cleaner atmosphere.

Additionally, biochar had a bulking affect, greatly reducing the loss of weight and volume during decomposition. A and B had similar amount of weight lost, however B maintained 26 % of its volume compared to 21 % in A. C maintained 32 % of its initial volume and lost significantly less overall weight than A and B. Less weight loss means more final compost, clearly a desirable outcome. Higher volume means more pore spaces in the substrate. These results show that BC creates gaps and pore spaces, preventing the clumping of wet materials in the compost so that moisture is more evenly distributed, and rainwater and oxygen can more freely infiltrate. Mixed with surface soil, this can have a long-term effect of remedying and preventing compaction, allowing plants' roots to reach deeper in subsoil which can have major consequences during droughts when water is unavailable in the surface soil.

It appears that even a low 2 % biochar addition to compost can go a long way in eliminating unpleasant odors and unwanted emissions. Increasing the frequency of turning the compost could also have a similar effect because of the increased aerobic decomposition. Although, this was not seen in our experiment as all composts were turned several times per week. There might have been different results if the compost was turned by hand with a fork or machine rather than rotated in the barrels. The circular rotation might have caused some material to clump together rather than mix properly. Increasing aeration means an increase in energy used to complete the composting, whether human or machine, and therefore an increase in cost. The addition of biochar also represents a cost, however the energy generated during biochar production can offset the cost in time and materials of its addition. And as we will examine later, biochar production can be a very low tech/low cost technology.

Aesthetically, smell can be a major issue in whether local communities adopt composting facilities for their locally produced organic waste. In densely populated urban areas, this can mean the difference between having a local compost facility to convert organic matter into organic fertilizers or spending energy, money, and generating pollutants on collecting and transporting all the waste out of the area only to have to transport it back in for urban parks, farms and gardens. Smaller, local composting facilities are more desirable than larger centralized facilities because there is less transport required, less material means more human scaled operations which can provide meaningful employment. Most importantly, when “waste” is treated locally, communities are much more aware of their consumption and amount of waste because they see where it goes and how it is treated, they know the people who work there, and ultimately, their communal “waste” will go back into their gardens, or parks. This creates “skin in the game” where people are motivated to properly sort and reduce their waste because it is not simply exported out to pollute some other community or place. In this way, the idea of waste is eliminated and is instead seen for what it really is, a valuable resource.

If biochar is simply added at the end of the composting process, we lose the benefits of its ability to retain nutrients and avoid gaseous loss. Furthermore, if co-composted, bacteria and fungi have time to colonize the surface and water can be absorbed. This creates a so called “charging” effect and avoids many downsides of applying fresh biochar to agricultural land.

5.3 Does the addition of C+BC improve retention of water and nutrients in soil?

Both nutrients and metals are undesirable in large amounts in pore water. Nutrients in pore water are likely easily leached from the soil, reducing yield potential and creating water problems in too high amounts. A general pattern seen in the results of the experiment was that RC consistently had higher levels of N, S, Ca, Mg, Mn in the pore water when compared to the rest of the treatments. No statistically different results were seen between A, B, C, FC2, & FC5. RC might have simply had more nutrients in available form that were then easily leached into pore water because it was much more broken down and aged than the homemade composts. Although it is not stated on the packaging of RC, it is also possible that soluble nutrients are added to the compost to improve growing.

Based on our finding, we did not observe any statistically significant differences between the homemade treatments for both nutrients and metals in the pore water. A serious limitation to this study was the small sample sizes. Only 4 replicas for each soil treatment and plant were tested and for FC5 arugula only 1 pot could be used. Possible explanations for our results could be the short testing period (less than 1 month), small sample sizes, and not enough biochar.

What is certain is that fresh composts and OM additions to polluted soils can reduce metal availability of Pb, Cd, and Zn and retain nutrients better than the polluted soil on its own. In contrast to our findings, many other studies have found significant differences in retaining nutrients and locking up harmful metals with the addition of biochar ((Hagemann et al., 2017; Beesley et al., 2011; Gul & Whalen, 2016; Roy, 2017). Roy (2017) and Agegnehu et al (2016), among many others, found that biochar can be a key component in capturing nitrogen and phosphorous, locking it in the soil and preventing the runoff and leaching of these 2 key nutrients. The introduction of fertilizers, often seen as an easy way to increase yields and profits, can set off a chain reaction that leaves lifeless soil, and plants entirely reliant on increasing amounts of fertilizer in order to survive. Termorshuizen et al. (2005) found that decreasing SOM around the world is largely caused by over tilling and over application of mineral fertilizers. The unsustainability, environmentally and economically, of agrochemicals is very clearly displayed by examining the life cycle of phosphorous and the subsequent gross application of agro-chemicals.

Phosphorous (P) is a key element for life, providing an essential part of DNA and RNA. It is the “P” of the NPK ratio found on the labeling of any fertilizers. P is naturally occurring in soils through the weathering and breakdown of rocks which occurs over a geological time scale. Although phosphorous is relatively common in most soils, it is in a form unavailable to plants so the available form can be easily depleted around plant root zones if nutrients are not returned to the soil. Currently, the vast majority of P is extracted from mines in the US, Russia, China, and Morocco and the demand is greatly increasing throughout the world (Cordell et al., 2009). About 90 % of worldwide demand for rock phosphate is for food production (Rosmarin, 2004; Smil, 2002; Cordell et al., 2009).

The fertilizer industry recognizes existing reserves could be exhausted in the next 50 - 100 years (Steen, 1998; Smil, 2000b; Gunther, 2005). Arguments over the exact year only distract from the undeniable reality that our current model of industrial food production is heavily reliant on nonrenewable resources such as mined phosphate and the fossil fuels used to mine, refine, package, transport and apply it. Unlike fossil fuels where there is potential to transition to different forms of energy, P is an element. It cannot be created from something else. However, unlike fossil fuels, it can be recycled and used again and again by simply treating our waste as a resource and source of fertility. Currently, increasingly large amounts of energy are going into mining and refining P and conservative analysis predicts peak P production in 2033 (Cordell et al., 2009). Peak production means a decrease in supply even as demand will rise, ultimately increasing the price of P. This effect could be seen when gas prices reached record highs in 2007/2008 and the price of mined phosphate jumped 700 % in a 14-month period (Minemakers Limited, 2008). The application of chemical fertilizers invites a host of problems that inevitably reduce soil life over time. When soil organisms are gone, the natural breakdown of minerals into their plant available form ceases and the nutrients that are available are leached from the soil. Consequently, even if there is phosphorous present in the soil, fungi and soil organisms are needed to turn mineral phosphorous into soluble phosphate that can be used for plant growth (Smith, Jakobsen, Gronlund, & Smith, 2011). Throughout millions of years of co-existence, mycorrhizal fungi developed the ability to provide phosphate directly to the root zones in exchange for nutrients from the plant (Smith, Jakobsen, Gronlund, & Smith, 2011). Their removal creates a positive feedback loop in which it becomes necessary to apply ever increasing doses of P to maintain yields, while more and more P leaches from the soil.

Most farmers look for easy ways to increase yields, a very reasonable undertaking. When fertilizers are brought to a farm they resemble salt. Nitrogen on its own degrades and breaks down. A fresh cut pile of grass will be a smelly, slimy mess in a couple days because there is too much nitrogen and not enough carbon to decompose properly. The nutrients are stable in granular form in the bag of fertilizers because of the addition of cadmium (Cd) salt. Cadmium is a very mobile risk element shown to have negative health effects on people and animals even in very small amounts (Bolan et al., 2013c; Moreno-Jiménez et al., 2016).

The fertilizers are then applied to the field. The water solubility of NPK fertilizers means that they provide nothing to the plant until it is mixed with water and washed through the soil. The plant must drink the solution to uptake the nutrients which requires much more water and causes the plant grow quickly, mostly because it is bloated with salt and water. Only 26 – 28 % of N is taken up by the plants (Miao et al., 2011), the rest is leached away and enters water bodies. Lehmann et al (2003) found that application of biochar led to a 60 % reduction in nitrogen leaching.

The leached P (and N) flow into waterways where the nutrients fuel huge growths of algae, visible from space. The algae growth sucks oxygen from the water in a process called eutrophication, creating aquatic dead zones that can stretch for 100’s of kilometers.

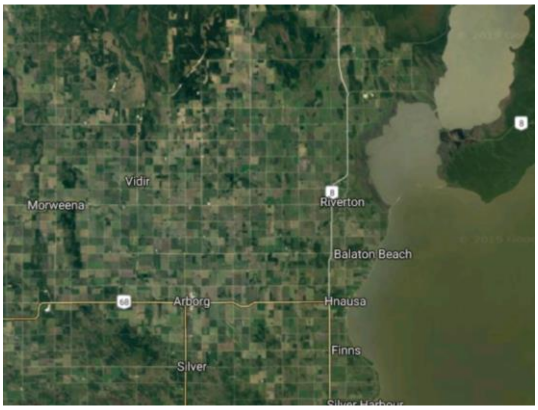

Photo 8: Mississippi delta eutrophication visible from space (left). Lake Winnipeg in Canada is green from algae blooms. Not the expanse of farmland where all run-off drains into the lake (right). Source: Google Maps

Pests do not see plants the way humans do. Instead, they observe and are attracted to the water and nutrients in a bloated plant. Combine this pest attraction with monoculture food production in which a single crop is planted for square kilometers and very soon farmers are faced with a choice of spraying pesticides or losing the investment of their crops. Pesticides kill the pests eating the crops but also kill the life in the soil. With the soil life gone, all the micronutrients necessary for a healthy plant are unavailable, leaving the plant vulnerable to fungal problems. Enter fungicide, which now kills the beneficial fungal connection in the soil that, among many other benefits, provide the plant naturally with phosphates. If a P deficiency develops in the soil, plants send out molecules through their roots that attract mycorrhizal fungi who release organic acids that make P soluble. In exchange, the plant exudes sugars to feed the fungi (Smith, Jakobsen, Gronlund, & Smith, 2011). When we forgo this naturally symbiotic relationship and apply P fertilizer, there is too much water-soluble P present and the plant emits enzymes, which repel the helpful fungi, treating it as a pathogen.

After the application of fungicide, we are left now with a completely lifeless soil. The structure of the soil begins to collapse, losing the pore spaces created by worms and other soil organism as discussed in the previous section. Without pore spaces, water infiltration significantly decreases, requiring increasing amounts of irrigation, resulting in more runoff, eroding the topsoil with it. Nature's response to damaged soil is a reparative function; pioneering 'weeds' (an entirely subjective term, many plants considered weeds are edible and medicinal) emerge, sending taproots deep into the soil, drawing up nutrients from below, breaking up the compacted ground and holding on to what is left of the topsoil (Hemenway, 2001). The cocktail is now completed with an addition of herbicide to kill the 'weeds'.

This downward ecological spiral starts with a seemingly harmless NPK fertilizer application to boost profits, but over several years becomes increasingly expensive and creates a cycle of dependence. Fertilizers, pesticides, fungicides, herbicides, extra water, and eventually decreased yields are costly to the environment, farmers, consumers and taxpayers. Additionally, our entire model of industrial agriculture in "developed" countries will undoubtedly become less and less economically viable and finally impossible once fossil fuels increase in price and we reach the limits of phosphorous mining. The *Lake Winnipeg Basin Initiative Report* assessed the damage of algae blooms (seen in photo 9). They found that $ 18 million dollars spent on restoration had removed less than 1% of phosphorous from the lake.

It’s clear that the gross application of agrochemicals is devastating to the environment and this in turn means that it is also detrimental to society and subsequently economies in the long run. The price of mining, refining, packaging, transporting, applying, water treatment, sickness and healthcare, loss of biodiversity, and loss of use of water ways for fishing, recreation and aesthetics comes at an enormous cost, one that is truly incalculable.

All of these “ negative externalities” (unaccounted costs) can be avoided by recycling and investing organic ‘waste’ locally back into our fields, feeding soil life with OM that we produce, (food scraps, yard trimmings, manure, etc). Cordell et al., (2009)’s study concluded that small scale (human scale) organic agriculture uses less energy per crop output than industrial agriculture. Our focus must switch from feeding the plants to feeding the soil life. Compost and biochar offer a return to a natural approach that simultaneously addresses the problems with our currently unsustainable agricultural and waste management.

5.4 Does addition of C + BC increase yields even in contaminated soil?

The biomass weight was lost in a computer mishap, but the photos and observations speak for themselves. In both grass and arugula, B & C outperformed RC, A, FC2, and FC5. The general conclusion that can be made in terms of biomass for the 7 treatments is: B=C>A=FC2>FC5>RC. B and C had very similar yields and growth patterns. Likewise, there was not much discernable difference between the yields of A and FC2. There was a clear drop off in growth with FC5, especially regarding germination of arugula. Grass also looked stunted in growth. Quite surprisingly, RC performed the worst of all the treatments. The growth was poor, with very small, weak plants that had yellowish discoloration on the leaves of arugula that was not present on any other treatments.

The Litavka soil used in the experiment can be seen as a worst-case scenario for growing crops. The soil contained little organic matter, had no signs of macro life (worms, centipedes, etc.) and was highly contaminated with a variety of metals and metalloids. Yet, with an addition of co-composted biochar and OM in general, significant growth was possible. A limitation to our study was that 50 % of the weight was our treatments of composts. In a field scenario this amount of OM would be too costly and energy intensive to be used at a large scale for immediate remediation. It is entirely possible however, that if we reverse our current mismanagement of soil and take a long-term approach, there is no reason why we cannot slowly rebuild damaged or infertile soils just as the ancient Amazonian peoples did over generations.

5.5 Can C + BC decrease uptake of risk elements in plants?

The results from the experiment were largely inconclusive regarding metal content in plant tissues. All plants and treatments were at or exceeded WHO's recommended limits for Pb, Cd, and Zn, meaning these plants were not safe to eat by people or livestock. The addition of organic matter in all treatments certainly lowered the amount of metals taken up by the plants, but this could be because half the substrate was compost, there were less metals available. For both arugula and grass, Pb and Zn only showed significant differences between the control (Lit) and the rest of the treatments. With Cd, the results showed that for arugula, B and FC2 had statistically significant less Cd, followed by A and C, and then FC5.

Many factors can affect the bioavailability of metals, such as soil pH, soil organic matter (SOM) and clay contents, as well as many other independent variables such as soil temperature, moisture, and aeration (Bolan et al., 2013b). Again, the small sample size and short duration of the experiment could have affected our results. There appears to be a consensus throughout scientific studies that organic matter on its own reduces the bioavailability of risk elements and many studies have found that biochar adds additional benefits. Organic matter decomposes in several months or years, whereas BC can remain in the soil for at least half a millennium, so the additional of biochar adds long term benefits in locking up heavy metals.

Remediation is simply treating the symptoms of the problem. The foundational strategy for human society should be to deal with the causes and reduce and eliminate the source of risk elements by fundamentally changing our industrial, mining, and agricultural practices which, currently, are costing us and future generations enormously. According to calculations by Bationo et al (2006), more than half of all African people are affected by land degradation, making it one of the continent's most urgent development issues. An estimated US $42 billion in income and 6 million ha of productive land are lost every year due to land degradation and declining agricultural productivity (Agegnehu et al., 2017). Because of short term thinking and a search for immediate returns land degradation is a global issue. Application of organic matter and biochar can be a tool to remediate soils for long term improvement, but the core strategy should be to cease to emit toxic materials in the first place.

5.6 How much, if any, BC is needed (% weight) to improve results?

It appears that the difference between 2 % and 5 % of co-composted biochar did not significantly affect the results of the study. However, co-composted biochar (B&C) performed better at both amounts than finished compost + BC. FC2 plants performed better than FC5 and a slight decrease in growth of grass for FC5 and poor germination for arugula; only 1 out of 4 pots germinated. It is possible that the larger biochar pieces blocked the germinating seedlings and or root development. Regardless, a clear case can be made that the 2 % BC additional performed significantly better than just compost alone.

Clearly, there is an economic advantage out of getting the same results with less biochar. The ideal amount, however, is likely dependent on various factors such OM content, source rock of soil, parent material for composts, etc. The conclusion we can draw from this experiment is that 2 % appeared to be the lower limit for our context, while with 5 % we began to see a plateau in risk elements avoided, nutrients retained, and even a decrease in plant growth and biomass yield. The ideal amount of BC appears to lie somewhere between 2 – 5 %.

5.7 What difference can be seen between homemade and commercially bought compost?

Certainly, the most unexpected result was the very stark difference in growth comparing A (homemade made compost with no biochar) and RC (retail compost). Both treatments contained no BC. We included RC in the experiment to act as a control for A but also to test the difference between professional, store bought compost with simple, homemade green waste compost. There is no way to know what the parent material of RC was, but it is very likely that it is a mix of various types of woody materials and green waste. RC was expected to perform better mostly because the materials were aged properly and fully decomposed, whereas A still have some partially intact sticks and woody material that could lock up nitrogen in the soil. We also assumed a more variable mix of materials that would likely contain more micronutrients in a more available form.

In both grass and arugula, A outperformed RC quite substantially. There was a clear difference in growth from start to finish. This might be due to the acidity of the soil and composts. Litavka soil was acidic; the average pH of the 3 soil layers was 6.3. The average pH of RC and A was 6.5 and 7.7 respectively. The ideal range of pH for most plants in most growing conditions is between 6.5-6.8. It's possible that when mixed together, A and Litavka provided a more ideal pH than that of Litavka and RC. However, arugula and grass can both tolerate a wide range of soil types and range of pH, so it seems that there were other factors influencing the growth beyond pH.

RC was made up of very small particles, a similar consistency to that of soil. Whereas A was much more heterogenous and contained particles of various sizes. During watering, RC would often pool at the soil surface, while A would readily accept the water and allow it to infiltrate the medium. RC and Litavka soil appeared compacted after several watering's, with a slightly crusty surface. It's likely that the bigger particle size in A made root development easier because of the larger pore spaces. And since water easily infiltrated, the roots could chase the water downwards instead of remaining at the surface. See Photo 10 comparing root growth in A (left) and RC (right).

Photo 9: Left: poor root growth in RC. Right: better root growth with homemade compost, no biochar

What is clear is that the difference in yield was not simply dependent on nutrient availability. In the pore water sampling, RC had significantly more nutrients available in the pore water than A, yet A yielded much more. There are complex biological and physical processes at play. This comparison of these treatments demonstrates that yield is not simply related to nutrient availability, in contrast to the dominant thinking throughout industrial agriculture where soluble chemical nutrients are applied in hopes of a bigger yield. Agriculture of the future must move away from the reductionist thinking that treats soil as a lifeless medium in which to grow plants and instead respect the complex interactions of organic matter, weathered minerals, and soil biota.

Homemade compost outperforming professionally made, packaged compost should be inspiring to home-scale gardening and community-scale farming. No one has ever walked through a forest and scolded the trees for all their leaf waste. Yet, throughout most of the United States in the fall, suburban families often spend many hours raking and bagging leaves, then paying for green waste companies to truck the leaves away, essentially raking away the fertility of their gardens. Many of these people then go to a garden center where they purchase bagged compost for their gardens. This could very well be that they are buying back their own leaves and mowed grass. It makes much more sense to designate a meter squared (10.7 ft^2) of garden and simply add any garden refuse and food scraps to a pile throughout the year. Two square meters is enough to have a “finished” pile in 6 months to a year, of already mostly decomposed compost and an “at work” pile of actively decomposing material. No equipment is necessary except perhaps a garden fork for turning the pile every couple weeks. This is not to say that commercially made, packaged compost cannot be useful in certain situations, just that composting in a low-tech, low-energy way, on a family and community scale can create similar or even better-quality composts while also recycling nutrients and dealing with waste streams locally.

Many garden soil and compost mixes bought in packages contain peat moss. Wetlands in northern America or Europe are drained of water, clear cut and the peat is extracted with large machinery, packaged and transported across the continent. All the costs, financially, energetically, and ecologically can be avoided by simply composting food and yard scraps at a locally.

6 Economic Discussion

All fundamental economic questions, such as “what is value and where does it come from?” were originally philosophical and ethical questions. Economics as a field of study has become so laden with complex models, and lengthy formulas that make all kinds of assumptions with so many variables that, in many ways, it has become disconnected from reality; analogous to how many people confuse money with wealth. In the spirit of the roots of economic study (and for the sake of the reader), we will not get bogged down in complex formulas attempting to factoring in all variables, assume humans are totally rational creatures, and that the idea and value of money is unchanging, all of which are untrue assumptions. Adam Smith’s *Wealth of Nations*, considered a cornerstone of modern economics, had few formulas and certainly no complex calculations. Significant insights can be had at a macro level of analysis.

6.1 The Oil We Eat

Instead of prizing the complex web of biology in the soil, industrial agriculture has been reduced to chemistry, analogous to a shale oil mining operation. Enormous amounts of energy are used to pump water and chemical nutrients underground, poisoning aquifers and extracting, large, but unhealthy plants while damaging the soil biology.

“Economics in the future will inevitably be tied to yield judged on energy rather than monetary return. In the present economy we waste energy to make money. In the future, any system that wastes energy must fail” (Mollison, 1978). The cost of energy in monetary terms matters little (especially when value of money is constantly changing), what is worth counting is energy returned on energy invested (EROI). In other words, when making decisions about future investments, it is fundamental to ask the question, “will we obtain or save more energy in the long run than we are investing today?” If the answer is “no”, most likely acting is foolish.

Mining and manufacturing fertilizers, refrigerating and transporting food across countries is only possible with cheap fuel sources, like oil (Cordell et al., 2009). According to data from the USDA, agriculture is becoming increasingly dependent on fossil fuels. In 1910, the EROI of food was 1.4:1, reaching 10:1 calories by 1950 and 14:1 by 2007. Meaning that 14 calories of fossil fuel energy are invested in every food calorie we eat (Garza, 2015). In the last 100 years, farming has turned into an energy sink, in which we are eating fossil fuels. This system is inherently unsustainable and increasingly fragile as fossil fuel production has already peaked (Royal Dutch Shell, 2008) and bound to increase in price, subsequently increasing the price of food. The timeline is debatable, but the result is inevitable; we will not always be able to use fossil fuels to produce food so we must begin transitioning to a sustainable method.

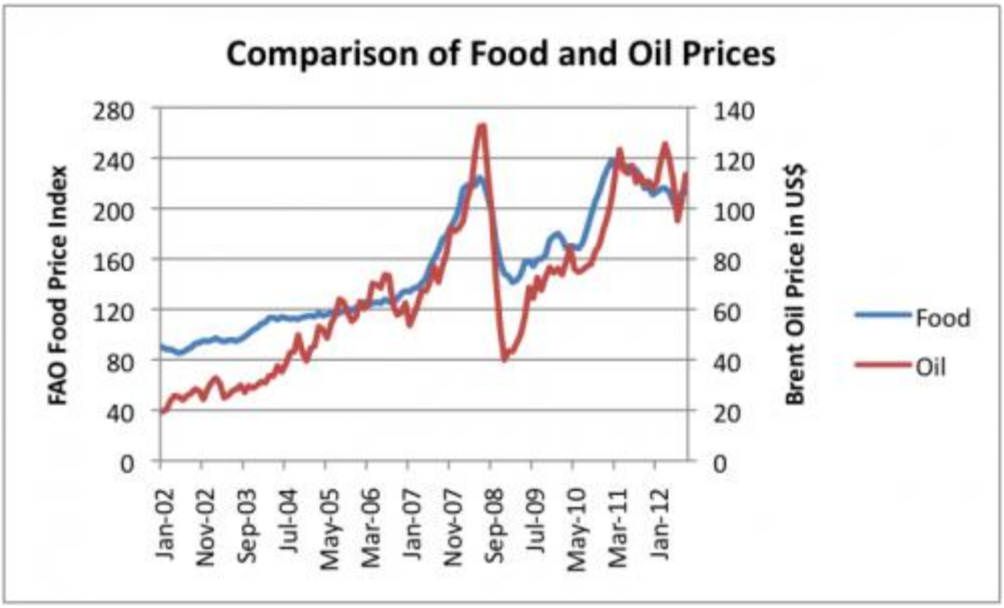

Figure 13: Comparison of Food and Oil Prices. Food Prices indices are as published by the Food and Agriculture Organization (FAO) of the United Nations. Oil prices are monthly average Brent Oil spot prices, as published by the US Energy Information Administration. Source: Ourfiniteworld.com

Binding the cost of food to oil has vast social, geopolitical and economic consequences. In the U.S., people spent on average nearly 18 % of income on food in 1960, compared to 6.6 % in 2014 (USDA). Compare this to the average Egyptian who spends 43 % of yearly income on food (USDA). For the vast majority of people around the world, a small change in the price of staple foods can be the difference between feeding their family or not. In 2010, record draughts across Europe, Russia, Ukraine and China dramatically reduced the wheat harvest, driving prices up. This hit North Africa, the Levant and Arabian Peninsula particularly hard. The World Bank reported in 2008 that the region imports over 50 % of its food, the highest rate in the world[2] (World Bank, 2008). Increases in wheat prices in 2010 became the straw that broke the camel's back. The Arab Spring began when Mohamad Bouazizi, a Tunisian vegetable vendor self-immolated, triggering riots and uprisings in Tunisia, Yemen, Bahrain, Jordan, Egypt, and Morocco. Although usually reduced to natural disasters by politicians and media, it is largely our own mismanagement of land, resources and degradation of soil that are causing social unrest and famine.

Barring some radical technological development in harvesting energy, agriculture of the future will be small scale, organic, and locally consumed. The reason is simply because the current industrial model is consuming more energy than it is generating. This is not to say that we are "going back". In fact, human scale agriculture is how that majority of the world currently grows and eats food. Peasant farmers today grow 70 % of the world's food on 30 % of the land, and almost all is consumed within 100 km (Hilmi, 2012). A growing number of small scale, organic farms are springing up across North America and Europe. People are beginning to understand and see the harmful health and planetary effects of industrial agricultural.

Unlike pre-industrial small-scale farmers that relied only on observation, today, we are armed with an incredible wealth of scientific knowledge. We understand that the foundation of healthy plants (and in turn healthy people and animals) is a living soil. We know how to test and remedy nutrient deficiencies without simply guessing when a whole year's crop relies on getting it right. We know that we can safely compost our organic waste and recycle the nutrients to grow more food without poisoning water tables and harming soil life.

6.2 Cost of Compost and BC Production

Both composting and making biochar require no expensive, high-tech equipment or significant labor inputs to produce and both can be energy generating activities. Composting can be as simple as throwing food scraps and yard trimmings into a pile in the backyard, or on a large scale it could require large machinery for shredding and turning materials, irrigation lines, and underground fans that force air through the bottom. The type and scale of composting facility must fit the demands and resources of the household, community or region and will vary widely from

[2] The World Bank recommends "sending better price signals to farmers" and "consider improving the use of financial instruments (hedging, futures, and others) to manage exposure to international price volatility", but amazingly, nothing regarding land management or the preservation of resources.

place to place. Regardless of the scale of the operation, turning what would be waste, into organic fertilizer simply makes sense. A yield can be had in the heat generated by large compost piles. In many places around the world, copper coils are wound through compost piles and water is ran through the coils, picking up the heat along the way. This heat can be used for warming greenhouses or even homes. A year later there is a pile of finished compost.

The biochar used in our experiment was produced using modern kiln technology in a highly controlled process with low emissions of noxious gases and can produce quality char consistently. However, the technology involved requires high investment costs for large equipment, facilities and maintenance. Charcoal has been made for thousands of years using very basic systems, some as easy as digging a cone shaped hole, managing the burn and then extinguishing the fire when the charcoal is ready. A low-tech cone shaped metal flame curtain called a "Kon-Tiki Kiln" was developed recently and is being used to produced biochar from agricultural residues (Cornelissen et al, 2016). The process is low-cost, efficient, avoids the release of greenhouse gases, and able to produce biochar at the standards of the International Biochar Initiative (IBI).

Inevitably the issue of cost will arise if there is a community or city effort to establish compost and biochar facilities. Determining the monetary costs for these facilities is certainly necessary. However, follow-up questions should carry equal weight: "what is the long-term cost to our community, planet, people and animal health if we do not recycle our waste?" What is the cost savings in final waste disposal from landfilling or incineration? What amount of greenhouse gases are avoided by composting? How much carbon can be stored in the soil by making biochar? How much carbon are we reducing from the atmosphere by not burning organic waste and instead pyrolyzing it? What amount of organic fertilizer can be produced and how much chemical fertilizers can be avoided? What would be the impacts to the environment and water ways from the runoff of the chemical fertilizers? What savings in water treatment can be had by avoiding chemical fertilizers?

Many studies have tried to calculate these costs. Lehmann et al (2003) found that application of biochar led to a 60 % reduction in leached nitrogen, increases in crop productivity by 38 – 45 % and a 20 % cost saving on fertilizer and 10 % on irrigation. This is certainly a good starting point for convincing farmers and policy makers to adopt more sustainable methods of farming. However, these estimates do not consider the enormous ecological and economic savings of reducing eutrophication in lakes, rivers, and seas or the decreased health care costs of people poisoned by excess nitrates in drinking water or the habitat restoration that could occur if water ways are cleaned. These questions are complicated to answer because there are so many constantly changing variables that are extremely hard to arrive at a fixed value, especially in monetary terms. What is clear is that the cost of setting up systems and facilities to compost and produce biochar far outweigh the negative externalities of not recycling organic waste.

6.3 Valuing Our Source of Wealth

If we are to transition to a new paradigm of sustainable agriculture that focuses on feeding and restoring the Earth's soils, we need to change our methods of accounting and our values. As film maker and habitat restorer, John D. Liu put it,

"We have only just begun to recognize the value of natural capital. Surely investing in the recovery of damaged environments is a cost-effective way of solving many of the problems we face today. The source of wealth is the functional ecosystems. The product and services that we derive from those are derivatives. It's impossible for the derivatives to be more valuable than the source. And yet, in our economy now as it stands, the products and services have monetary values, but the source - the functional ecosystems - are zero! This cannot be true. It's False. We've created a global institution of economics and economic theory based on a flaw in logic. If we carry that flaw in logic from generation to generation, we compound the mistake."

The value of goods and services are derivatives of functional ecosystems and we readily assign a value to the products. However, we do not assign a value to the source of our wealth, functional ecosystems. Fields of study have arisen to attempt to place dollar values on ecosystem services. The purpose of these studies is well meaning; to show the immense wealth we derive from the planet and give a starting point for policy makers and decision-making processes. The result, however, often ends up in disputes about calculations and complex formulas which is ultimately a distraction from the issue being addressed. In an article responding to Robert Constanza's "Twenty Years of Ecosystem Services" $33 trillion dollar estimate of ecosystem services, Michael Toman (1998) said, “Leaving aside technical quarrels about the estimate in the paper, the fundamental problem is that there is little that can usefully be done with a serious underestimate of infinity” Biodiversity comes in systems, rather than individual units so the traditional cost-benefit analysis and marginal analysis is very limited in value. And here lies the fundamental problem. Can we place a monetary value on breathable air that allows the idea of “value” and “money” to exist in our heads? What amount of money is your family’s health worth? If a species goes extinct (we are currently living through the largest mass extinction in 65 million years) what is the cost when we consider the loss of value from all future generations of humans, let alone the cost to the environment? This is incalculable.

Economics of soil does not exist in thinking terms of money. Healthy soil is as much a necessity of life as air. Unclean air and soil are not bad economics but bad life. The economist, historian and philosopher, Karl Polanyi, argued in his 1944 work, *The Great Transformation* that if we turn the natural environment and human beings into pure commodities, we assure the destruction of both society and the natural environment. Polanyi further asserts that the “economy” is not autonomous, as is proposed in economic theory, but is subordinate to society, e.g. politics, religion, and social relations (Polanyi, 1944). Societal values should shape our economics and institutions, not the other way around as is increasingly happening. By recognizing the infinite value of functional ecosystems that support all life on earth, we must shift our perspective from the left diagram to the right (see Figure 14).

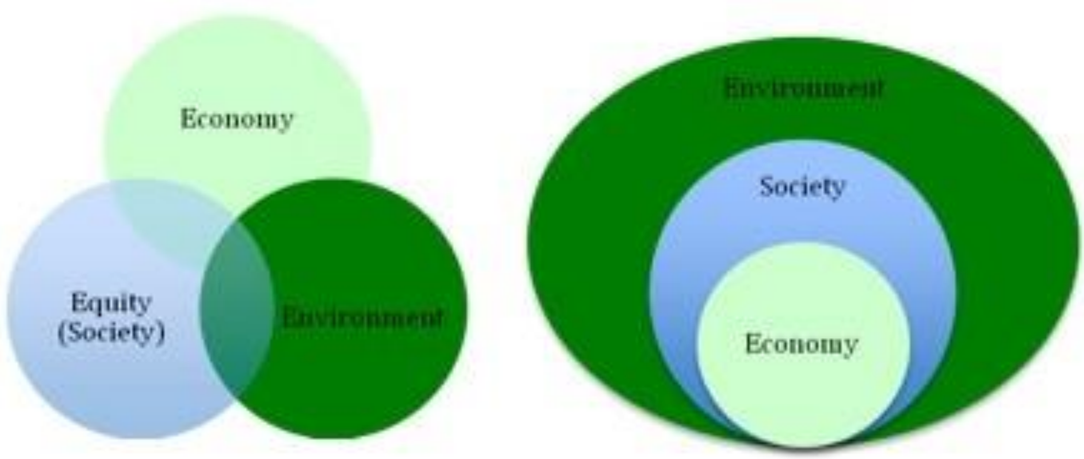

Figure 14: (Left) diagram depicting economy, society and environment as equals. (Right) diagram depicting the reality that society, and therefore, economics, are results of a habitable environment.

Economics is a subset of society and society is a product of a habitable environment. What this amounts to is, what is good for the environment (all ecological systems) is good for society, which in turn is good for the economy. However, the reverse is not necessarily true.

Current values seem to be unchanging and fixed in time as we are born into a given historic reality and it perhaps seems naive to think that significant value changes can occur rapidly. However, this is not the case as humans are uniquely capable of rapidly adapting new ideas. Bees have very complex, highly organized societies but are not capable of overthrowing the queen bee and establishing a representational democracy. Humans can do this simply by changing the stories we tell ourselves. Less than 160 years ago the buying and selling of human beings was common place and endorsed by governments around the world. Women in the U.S. have only had the right to vote for 100 years and views on homosexuality have shifted rapidly in the last several decades. To argue against these changes would seem absurd by today's standards and we can hope that future generations will look back at the degradation of the environment with the same level of confusion for how it could have happened at all. Bill Mollison, the co-author of Permaculture claimed that early societies developed principles and rules that dictated that we leave any natural system alone until we must use it. When we do, we conserve it as much as possible. This amounts to reducing pollution, replacing lost minerals and nutrients, careful energy accounting, and making assessment of long term negative social effects on society and act to eliminate those (Mollison, 1978). We can learn much from the respect and intimacy with nature shared by many native and aboriginal societies around the world and reflect these values in our actions, laws, and policies. Mollison went on the say that, "Unity in people comes from a common adherence to a set of principles, each of us perhaps going our own way, at our own pace, and within the limit of our resources, yet all leading to the same goals. In our case, a living, complex, sustainable Earth". The methods and ingredients for building and restoring soil health will be different across the planet, based on local climate, biology, cultures, politics and religion, but the question driving the goal should be the same; how can we meet the needs of today, without destroying the opportunities of future generations?

7 Conclusion: Shifting Paradigms

Co-composting biochar is an effective way to simultaneously reduce our waste and pollution and yield organic fertilizer that can then grow food. Our experiment demonstrated that co-composting biochar sped up the composting process, reduced odor and greenhouse gases, retained nutrients in the soil, and increased the biomass of the plants.

A CEO who extracts more and more money from a business without investing back into it will eventually ruin his/her company. Likewise, in agriculture, we cannot continue to extract food year after year without returning OM (reinvesting) back to the soil and expect to be able to continually increase yields, which will be needed in the coming years with the population expected to increase to over 9.5 billion by 2050 (UN 2015). Based on these numbers, food production worldwide will have to increase by 70 % of current levels to satisfy needs (FAO, 2009) It is becoming very clear that industrial agriculture's use of fertilizers is unsustainable, and this is detrimental to the environment, human health, and subsequently, economic systems. When synthetic fertilizers are applied to agricultural land, not only does the farmer pay the cost of the initial fertilizers, but society pays for the externalities that result in: energy intensive and expensive water treatment facilities, healthcare costs (brought on by diseases caused by nitrates, pesticides and other chemicals found in agrochemicals), loss of fish and wildlife in runoff areas, and loss of use when swimming and drinking water is contaminated. Damaged ecosystems result in damaged economies.

Fixing the broken nutrient cycle by restoring OM to the soil, is a sustainable, and cost-effective solution to addressing a myriad of issues around agriculture and soil degradation. Biochar can be added to compost to speed along the decomposition, reduce unwanted greenhouse gases and odor, store carbon, retain nutrients, and build long term soil fertility. Organic matter is free and largely available in the form of human and animal manure, food scraps, paper products and yard trimmings. Humans now have the scientific understanding of how biological soil properties provide the necessary foundation for a healthy ecosystem and fortified with this knowledge we must shift our perspective from "dirt" to a living, breathing soil that supports all life on earth.

Einstein once remarked, “A new type of thinking is essential if mankind is to survive and move toward higher levels.” We must shift the paradigm if we are to effectively address the global ecological issues of our age. This shift comes when we understand energy flows that dictate our world and changing what we value; in a sense, developing ethics that reflect our interdependence with the natural world. The core of the terrestrial web of life is a living soil and it is as fundamental to our existence as air and water. When we stop to examine our source of wealth and prosperity, it can only be concluded that all life, goods, and services derive from functional ecosystems and our behavior must adapt to reflect this. If not now, then when?

9 References

Agegnehu, G., Bass, A. M., Nelson, P. N., & Bird, M. I. (2016). Benefits of biochar, compost and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Science of the Total Environment*, *543*, 295–306. https://doi.org/10.1016/j.scitotenv.2015.11.054

Agegnehu, G., Srivastava, A. K., & Bird, M. I. (2017). The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Applied Soil Ecology*, *119*(June), 156–170. https://doi.org/10.1016/j.apsoil.2017.06.008

Ahmad M, Soo Lee S, Yang JE, Ro HM, Han Lee Y, Sik Ok Y (2012) Effects of soil dilution and amendments (mussel shell, cow bone, and biochar) on pb availability and phytotoxicity in military shooting range soil. Ecotoxicology and Environ- mental Safety, 79, 225–231

Amlinger, F.; Peyr, S.; Geszti, J.; Dreher, P.; Karlheinz, W. & Nortcliff, S. (2007). Beneficial effects of compost application on fertility and productivity of soils. Literature Study, Federal Ministry for Agriculture and Forestry, Environment and Water Management, Austria

Asai, H., Samson, B. K., Stephan, H. M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., et al. (2009). Biochar amendment techniques for upland rice production in Northern Laos 1. Soil physical properties, leaf SPAD and grain yield. Field Crops Research, 111(2009), 81e84

Baronti, S., Vaccari, F. P., Miglietta, F., Calzolari, C., Lugato, E., Orlandini, S., … Genesio, L. (2014). Impact of biochar application on plant water relations in Vitis vinifera (L.). *European Journal of Agronomy*, *53*, 38–44. https://doi.org/10.1016/j.eja.2013.11.003

Barrow, C. J. (2012). Biochar: Potential for countering land degradation and for improving agriculture. *Applied Geography*, *34*, 21–28.

https://doi.org/10.1016/j.apgeog.2011.09.008

Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J. L., Harris, E., Robinson, B., & Sizmur, T. (2011). A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environmental Pollution*, *159*(12), 3269–3282. https://doi.org/10.1016/j.envpol.2011.07.023

Bian RJ, Chen D, Liu XY, Cui LQ, Li LQ, Pan GX, Xie D, Zheng JW, Zhang XH, Zheng JF, Chang A (2013) Biochar soil amendment as a solution to prevent Cd-tainted rice from China: results from a cross- site field experiment. Ecol Eng 58:378–383

Bot, A., & Benites, J. (2005). *The importance of soil organic matter: Key to drought-resistant soil and sustained food and production*. Rome: Food and Agriculture Organization of the United Nations.

Bolan, N., Makino, T., Kunhikrishnan, A., Kirkham, M., 2013a. Cadmium contamination and its risk management in rice. Adv. Agron. 119, 183.

Camps, M., & Tomlinson, T. (2015). The Use of Biochar in Composting. *International Biochar Initiative*, (February), 1–4.

Candeias, C., Melo, R., Ávila, P.F., da Silva, E.F., Salgueiro, A.R., Teixeira, J.P., 2014. Heavy metal pollution in mine–soil–plant system in S. Francisco de Assis–Panasqueira mine (Portugal). Appl. Geochem. 44, 12–26.

Chen, Y.-T. (2016). A Cost Analysis of Food Waste Composting in Taiwan. *Sustainability*, *8*(11), 1210. https://doi.org/10.3390/su8111210

Cordell, D., Drangert, J. O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, *19*(2), 292–305. https://doi.org/10.1016/j.gloenvcha.2008.10.009

Cornelissen, G., Pandit, N. R., Taylor, P., Pandit, B. H., Sparrevik, M., & Schmidt,

H. P. (2016). Emissions and char quality of flame-curtain “Kon Tiki” kilns for farmer-scale charcoal/biochar production. *PLoS ONE, 11*(5), 1–16. https://doi.org/10.1371/journal.pone.0154617

Cui H-J, Wang MK, Fu M-K, Ci E (2011) Enhancing phosphorus availability in phos- phorus-fertilized zones by reducing phosphate adsorbed on ferrihydrite using rice straw-derived biochar. Journal Soils Sediments, 11, 1135–1141.

Erisman, Jan Willem; Sutton, Mark A.; Galloway, James; Klimont, Zbigniew; Winiwarter, Wilfried (28 September 2008). "How a century of ammonia synthesis changed the world". Nature Geoscience. **1** (10): 636–639.

FAO, 2009. How to Feed the World in 2050. High-Level Expert Forum, Rome, Italy.

Fischer, D., & Glaser, B. (2012). Synergisms between Compost and Biochar for Sustainable Soil Amelioration. *Management of Organic Waste*. https://doi.org/10.5772/31200

Glaser, B., Haumaier, L., Guggenberger, G. et al. Naturwissenschaften (2001) 88: 37. https://doi.org/10.1007/s001140000193

Garza, Eric. The Role of Energy in Food Production. Agriview. Volume 71. January, 2015. http://ericgarza.info/wp-content/uploads/2015/10/Agriview- 1-26-2015-for-web.pdf

Godlewska, P., Schmidt, H. P., Ok, Y. S., & Oleszczuk, P. (2017). Biochar for composting improvement and contaminants reduction. A review. https://doi.org/10.1016/j.biortech.2017.07.095

Gomez-Eyles, J.L., Sizmur, T., Collins, C.D., Hodson, M.E., 2011. Effects of biochar and the earthworm Eisenia fetida on the bioavailability of polycyclic aromatic hydrocarbons and potentially toxic elements. Environmental Pollution 159, 616e622.

Gul, S., & Whalen, J. K. (2016). Biochemical cycling of nitrogen and phosphorus in biochar-amended soils. *Soil Biology and Biochemistry, 103*, 1–15. https://doi.org/10.1016/j.soilbio.2016.08.001

Hagemann, N., Joseph, S., Schmidt, H. P., Kammann, C. I., Harter, J., Borch, T., … Kappler, A. (2017). Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. *Nature Communications*, *8*(1). https://doi.org/10.1038/s41467-017-01123-0

Hall, C. A. S., Lambert, J. G., & Balogh, S. B. (2014). EROI of different fuels and the implications for society. *Energy Policy, 64*, 141–152. https://doi.org/10.1016/j.enpol.2013.05.049

Hassaan, Mohamed & El Nemr, Ahmed & Madkour, Fedekar. (2016). Environmental Assessment of Heavy Metal Pollution and Human Health Risk. American Journal of Water Science and Engineering. 2. 14-19. 10.11648/j.ajwse.20160203.11.

Hemenway, Toby, 1952-. (2001). Gaia's Garden : a guide to home-scale permaculture. White River Junction, Vt. :Chelsea Green Pub. Co.,

Hilmi, A. (2012). *Agricultural Transition – a different logic*. The More and Better Network.

Huu-Tuan Tran, Chi-Thanh Vu- Chitsan Lin, Xuan-Thanh Bui, Wen-Yen Huang, Thi-Dieu-Hein Vo, Hong-Giang Hoag, Wen-Yi Liu. (2018). Remediation of highly fuel oil-contaminated soil by food waste composting and its volatile organic compound (VOC) emission. Biosource Technology Reports, Volume 4 p. 145-152.

Hussain, M., Farooq, M., Nawaz, A., Al-Sadi, A.M., Solaiman, Z.M., Alghamdi, S.S., Ammara,U., Ok,Y.S., Siddique, K.H.M., 2016. Biochar for cropproduction:potential benefits and risks. J. Soil Sediment.

Houben D, Evrard L, Sonnet P (2013a) Beneficial effects of biochar application to contaminated soils on the bioavailability of Cd, Pb and Zn and the biomass production ofrapeseed (Brassica napus L.) Biomass Bioenergy 57:196–204

Jenkins, J. (2005). The humanure handbook a guide to composting human manure. Grove City, PA: Jenkins Publ.

Juma, N.G.1998. The pedosphere and its dynamics: a systems approach to soil science. Volume 1. Edmonton, Canada, Quality Color Press Inc. 315 pp.

Jindo K, Suto K, Matsumoto K, Garc?ıa C, Sonoki T, Sanchez-Monedero MA (2012) Chemical and biochemical characterisation of biochar-blended composts pre- pared from poultry manure. Bioresource Technology, 110, 396–404

Kimetu, J. M., Lehmann, J., Ngoze, S. O., Mugendi, D. N., Kinyangi, J. M., Riha, S., et al. (2008). Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. Ecosystems, 11,726e739.

Koide, R. T., Nguyen, B. T., Skinner, R. H., Dell, C. J., Peoples, M. S., Adler, P. R., & Drohan, P. J. (2015). Biochar amendment of soil improves resilience to climate change. *GCB Bioenergy*, *7*(5), 1084–1091. https://doi.org/10.1111/gcbb.12191

Komarek, Chrastny, Stichova, (2007). Metal/metalloid contamination and isotopic composition of lead in edible mushrooms and forest soils originating from a smelting area. Environmental International Volume 33, Issue 5 p. 677-684.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627.

Lehmann, J., & Joseph, S. (2015). *Biochar for environmental management: Science, technology and implementation*. New York: Routledge, Taylor & Francis Group/Earthscan from Routledge.

Lu SG, Sun FF, Zong YT (2014) Effect ofrice husk biochar and coal fly ash on some physical properties ofexpansive clayey soil (Vertisol). Catena 114:37–44. doi:10.1016/j.catena.2013.10.014

Lohri, C. R., Rajabu, H. M., Sweeney, D. J., & Zurbrügg, C. (2016). Char fuel production in developing countries - A review of urban biowaste carbonization. *Renewable and Sustainable Energy Reviews*, *59*, 1514–1530. https://doi.org/10.1016/j.rser.2016.01.088

Mann, C. C. (2006). *1491: The Americas before Columbus*. London: Granta.

Mcbride, M. B., Simon, T., Tam, G., & Wharton, S. (2016). HHS Public Access, *224*(1), 1–18. https://doi.org/10.1007/s11270-012-1378-z.Lead

Mollison, B., & Holmgren, D. (1978). *Permaculture*. Stanley, Tasmania: Tagari.

Mondini, C., M. T. Dell'Abate, L. Leita, and A. Benedetti. 2003. An Integrated Chemical, Thermal, and Microbiological Approach to Compost Stability Evaluation. J. Environ. Qual. 32:2379-2386. doi:10.2134/jeq2003.2379

Montgomery, D. R. (2012). *Dirt: The erosion of civilizations*. Berkeley, CA: University of California Press.

Mulcahy, D. N., Mulcahy, D. L., & Dietz, D. (2013). Biochar soil amendment increases tomato seedling resistance to drought in sandy soils. *Journal of Arid Environments*, *88*, 222–225. https://doi.org/10.1016/j.jaridenv.2012.07.012

O’Neill M, Dobrowolski J (2011) Water and agriculture in a changing climate. Hort-Science, 46, 155–157.

Ogawa M (1999) Utilization of symbiotic microorganisms and charcoalin tropical agriculture and forestry, and CO2sequestration.SoilMicroorganisms53(2), 73–79. [in Japanese]

Polanyi, K. (2014). *The Great Transformation*. Boston: Beacon Press.

Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life cycle assessment of biochar systems: Estimating the energetic, economic, and climate change potential. *Environmental Science and Technology*, *44*(2), 827–833. https://doi.org/10.1021/es902266r

Rosmarin, A., 2004. The Precarious Geopolitics of Phosphorous, Down to Earth: Science and Environment Fortnightly, 2004, pp. 27–31.

Roy, E. D. (2017). Phosphorus recovery and recycling with ecological engineering: A review. *Ecological Engineering*, *98*, 213–227. https://doi.org/10.1016/j.ecoleng.2016.10.076

Schlenker W, Hanemann WM, Fisher AC (2007) Water availability, degree days, and the potential impact of climate change on irrigated agriculture in California. Cli- matic Change, 81,19–38

SIWI-IWMI, 2004. Water—More Nutrition Per Drop, Towards Sustainable Food Production and Consumption Patterns in a Rapidly Changing World. Stockholm International Water Institute, Stockholm

Smil, Vaclav (1999). "Detonator of the population explosion" (PDF). *Nature. 400 (6743): 415.* Bibcode*:*1999Natur.400..415S. doi*:*10.1038/22672.

Smil, Vaclav (2004). Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production. Cambridge, MA: MIT Press.

Smil, Vaclav (2011). "Nitrogen cycle and world food production" (PDF). *World Agriculture. 2: 9–13.*

Smith, S. E., Jakobsen, I., Gronlund, M., & Smith, F. A. (2011). Roles of Arbuscular Mycorrhizas in Plant Phosphorus Nutrition: Interactions between Pathways of Phosphorus Uptake in Arbuscular Mycorrhizal Roots Have Important Implications for Understanding and Manipulating Plant Phosphorus

Acquisition. *Plant Physiology*, *156*(3), 1050–1057. https://doi.org/10.1104/pp.111.174581

Steiner, C., & Harttung, T. (2014). Biochar as a growing media additive and peat substitute. *Solid Earth*, *5*(2), 995–999. https://doi.org/10.5194/se-5-995-2014

Stiglitz, Joseph E.; Sen, Amartya Kumar; & Fitoussi, Jean-Paul. (2009). *Report by the commission on the measurement of economic performance and social progress.* . Commission on the Measurement of Economic Performance and Social Progress, Paris.

Termorshuizen, A. J.; van Rijn, E. & Blok, W. J. (2005). Phytosanitary risk assessment of composts. Compost Science & Utilization 13, 108-115

Toman, M. (1998). Why not to calculate the value of the world's ecosystem services and natural capital. *Ecological Economics*, *25*(1), 57–60. https://doi.org/10.1016/S0921-8009(98)00017-2

UN, 2015. United Nations (UN), Department of Economic and Social Affairs, Population Division 2015, World Population Prospects: The 2015 Revision. UN, New York, USA.

Vandecasteele, B., Sinicco, T., D'Hose, T., Vanden Nest, T., & Mondini, C. (2016). Biochar amendment before or after composting affects compost quality and N losses, but not P plant uptake. *Journal of Environmental Management*, *168*, 200–209. https://doi.org/10.1016/j.jenvman.2015.11.045

Vano JA, Scott MJ, Voisin N et al. (2010) Climate change impacts on water management and irrigated agriculture in the Yakima River Basin, Washington, USA. Cli- matic Change, 102, 287–317. Veihmeyer

Vochozka, M., Plachy, J., & Marous, J. (2017). Glory and misery of biochar, 311–317. https://doi.org/10.1007/s10098-016-1284-y

Vogtmann, H. (1991). W: Lassen J. Paper- Food Quality and the Consumers. 1993

Worrell, D. Phylipsen, D. Einstein, N. Martin, "Energy Use and Energy Intensity of the U.S. Chemical Industry" (Lawrence Berkeley National Laboratory, LBNL- 44314, 2000);

Woods W., Denevan W. (2009) Amazonian Dark Earths: The First Century of Reports. In: Woods W.I., Teixeira W.G., Lehmann J., Steiner C., WinklerPrins A., Rebellato L. (eds) Amazonian Dark Earths: Wim Sombroek's Vision. Springer, Dordrecht

Wu, S., He, H., Inthapanya, X., & Yang, C. (2017). Role of biochar on composting of organic wastes and remediation of contaminated soils — a review, 16560–16577. https://doi.org/10.1007/s11356-017-9168-1

Wu, Shaohua & He, Huijun & Inthapanya, Xayanto & Yang, Chunping & Lu, Li & Zeng, Guangming & Han, Zhenfeng. (2017). Role of biochar on composting of organic wastes and remediation of contaminated soils-a review. Environmental science and pollution research international. 24. 16560-16577. 10.1007/s11356-017-9168-1.

Zhang, X.K., Wang, H.L., He, L.Z., KP, Lu, Sarmah, A., Li, J.W., et al., 2013. Using biochar for remediation ofsoils contaminatedwith heavy metals and organic pollutants. Environ. Sci. Pollut. Res. 20, 8472–8483.

Zhou H, Yang WT, Zhou X, et al. Accumulation of Heavy Metals in Vegetable Species Planted in Contaminated Soils and the Health Risk Assessment. Int J Environ Res Public Health. 2016;13(3):289. Published 2016 Mar 4. doi:10.3390/ijerph13030289