University of Southern Queensland

Faculty of Health, Engineering and Sciences

Reduction of Fertiliser Losses in Agriculture

A dissertation submitted by

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Abstract

Fertiliser losses in agriculture constitute a global economic and environmental issue. Nutrient runoff readily pollutes watercourses and causes eutrophication, damaging riverine and coastal ecosystems. Leaching of nutrients ensures groundwater is also impacted, and that fertiliser thought to have been taken up by plants is lost forever. Flow-on economic effects of this environmental damage are often considerable, necessitating the need to reduce fertiliser losses. Sugarcane in particular, is grown in areas which receive high rainfall, and soils that require large fertiliser loads. A possible means of reducing fertiliser losses is biochar, a carbon product produced through pyrolysis which may be used as both a soil amendment and carbon sink. Field trials have shown that the use of biochar – even with reduced fertiliser application – can actually increase the yield of sugarcane crops. This investigation aimed to investigate the merits of biochar through similar tests conducted on a laboratory scale with a focus on reducing nutrient losses rather than increasing yield. Through accelerated leaching column tests using commonly used urea fertiliser, it was determined that the addition of biochar in a subsurface layer would provide significant nutrient retention benefits. Biochar is hardly an instant solution however, with current prices all but eliminating it from consideration. This investigation has uncovered numerous avenues of further research which must be explored before biochar can become a viable mainstream soil amendment product.

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Matthew Hafey

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1: Introduction

Pollution from fertilisers is a global issue, with around half the fertilisers applied to some popular crops being washed away. Being essentially nutrients, these fertilisers pollute water courses by causing excessive growth of algae and macrophytes (Higashino & Stefan 2014). Such rapid growth causes these blooms of algae to starve of oxygen and die, leaving behind dead zones where little can survive (NASA 2003). Other environmental impacts may also be seen, such as soil acidification and groundwater pollution (Lines-Kelly & Vimpany 2004). As is to be expected, these environmental effects have similarly negative economic implications as well, providing further motivation to reduce fertiliser losses in agriculture.

1.2: Objectives

The primary objective of this investigation is to determine if the addition of biochar to soil can be effective in reducing fertiliser losses through both runoff (across the surface) and leaching (through the soil profile). This will be achieved by using accelerated leaching tests to examine the effect of the addition of biochar on a variety of parameters such as pH, electrical conductivity (EC), and (most importantly) nutrient retention. The application method of biochar will also be considered, with biochar either applied in layers or incorporated throughout the soil profile.

While it is most certainly expected that this investigation reveals if some of the aforementioned parameters affect – for better or worse – fertiliser losses, it may be unable to produce a specific relationship. For example, it is expected to determine if the addition of biochar reduces fertiliser losses, but not the optimal ratio of fertiliser to biochar to achieve this. Such limitations are due to the need for adequate control treatments as well as statistical replicability. These factors exponentially increase the scale of any experiments to beyond achievable levels, necessitating the need to reduce

the scope. It is for this reason that research (in section 2) will be used to select a field of particular interest, allowing the investigation to focus on this area in appropriate detail.

2: Literature Review

2.1: Introduction to Fertiliser Runoff and Leaching

In 1991 a blue-green algae bloom covered a 1000km stretch of the Darling River. This resulted in the deaths of more than 1600 sheep and cattle, even leading to Australian Embassies receiving enquiries about potential health risks of eating foods grown in Australia (Howard & McGregor n.d.).

For a more international perspective, one might consider the Caspian Sea, the world's largest inland body of water (Huseynov 2011). A similar problem to the Murray-Darling may also be seen in the Northern Caspian Sea, around the mouth of the Volga River. Here – in a process called eutrophication – excess nutrients allow rampant algal growth to take place. This algae quickly dies however, leaving the water starved of oxygen and compromising aquatic life (NASA 2003). Eutrophication is a global issue, with 400 such dead zones at the mouths of rivers around the world. Perhaps more alarmingly, this figure increases at a rate of 40 per decade or four each year (Cho 2013), highlighting the scale of the issue. Economic impacts of eutrophication are just as concerning, with estimates indicating the problem costs the United States' economy $2.2 billion annually. Although eutrophication may be instigated by pollution from detergents in sewage, as well as animal manure, it is pollution from fertilisers (Cho 2013) that may be the most avoidable cause.

In the most basic sense, fertilisers are nutrients added to crops and pastures to increase their productivity. They are primarily composed of nitrogen, phosphorous and potassium, with each of these nutrients having its own environmental impacts (Lines-Kelly & Vimpany 2004). Nitrogen is mineralised into ammonium or nitrate before being taken up by plants. Unfortunately, this nitrate is readily leached from soils, polluting groundwater and leading to soil acidification. As a result, nitrogen is potentially the biggest polluter of the three (Lines-Kelly & Vimpany 2004). Phosphorous is more readily absorbed but is vulnerable to being washed away during heavy rainfall events. As the primary cause of eutrophication, it is highly desirable to minimise phosphorous runoff

in agriculture, particularly considering that large quantities of phosphorous reach waterways via sewage and waste from intensive livestock systems (Lines-Kelly & Vimpany 2004). It is important to reiterate the different mechanisms of loss for both these ingredients, with nitrogen leaching downwards through the soil and phosphorous running off the surface (Paterson et al. 2014). The third primary ingredient is potassium which is readily absorbed by plants, provided it is applied in multiple small doses as opposed to a single large one (Lines-Kelly & Vimpany 2004). As a result, potassium is relatively easy to manage, and thus presents little environmental threat (Lines-Kelly & Vimpany 2004), meaning it can be largely ignored in this investigation.

It should be noted that massive rainfall events are not the only hydraulic cause of fertiliser pollution. In 2001, Shortle & Griffin (2001) noted that approximately 70% of all water drawn from aquifers, lakes and rivers is employed in irrigated agriculture, making it the largest anthropogenic use of water. They also observed massive increases in the area of land irrigated for agriculture over the 20th century, while noting that irrigated agriculture provides 40% of the world's food, despite comprising just 17% of cropped land. As one would expect, this results in increased return runoff, delivering growing quantities of pesticides, salts and fertilisers to watercourses (Shortle & Griffin 2001). In the western United States, irrigated agriculture is responsible for 40% of degraded lakes and 89% of degraded river sections. With both rain-fed and irrigated agriculture contributed to serious environmental pollution, it becomes increasingly important to implement mitigation strategies. Point sources of pollution, such as industrial and municipal sectors have their pollution more stringently examined and controlled than non-point sources such as agriculture (Shortle & Griffin 2001). This is likely due to the fact that point sources are much more readily managed but does not diminish the importance of reducing pollution from agriculture. While Shortle & Griffin (2001) place considerable emphasis on minimising runoff through regulation, this investigation will focus on means which may actually minimise fertiliser losses while improving crop productivity in the hope of producing a "win-win" outcome.

Given the global nature of modern agriculture, natural processes are disrupted in that nutrients are no longer returned to soils by plant decomposition. This gradually drains

soils of nutrients, often requiring continuous application of fertiliser in some areas (Cho 2013). Pollution from excess application of fertilisers is a global issue, with application rates currently almost double what plants can absorb. As a result, around 50% of the fertiliser applied to crops such as corn and rice remains on the field as waste. This excess fertiliser is highly susceptible to runoff, leading to an overabundance of both algae and macrophytes in watercourses. One should note however, that in dry weather, the uptake of nitrogen by other, wild plants may reduce pollution of waterways (Higashino & Stefan 2014).

In 2009, 19.5% of fertiliser applied was lost to leaching while 1.7% was washed away through runoff (Wang et al. 2014). Groundwater is the main source of drinking and irrigation water for most regions. Leaching has already proved to be an issue in agricultural areas where nitrate-nitrogen levels are much higher. Nitrate-nitrogen is regarded as a strong carcinogen, highlighting not just environmental risks, but public health ones as well. Nitrogen uptake by crops in China's Baiyangdian Basin has been found to be just 23-47%. Both soil nitrogen concentration and soil water movement contribute to nitrate pollution (Wang et al. 2014).

In New Zealand, nitrogen and phosphorous added to improve productivity has been shown to impact on water quality. While phosphorous is typically lost through surface runoff, nitrogen losses generally occur through infiltration. A continuing issue in New Zealand is the continual decline of water quality. Water nutrient loads can impact oxygen, geochemistry, and the growth of algae and plants, affecting ecosystem health (Paterson et al. 2014).

In Europe, the Nitrates Directive limits organic nitrogen application to 170kg/ha in a bid to reduce runoff and keep water nutrient levels below 50 ppm to avoid eutrophication (Crosson et al. 2007).

Investigations of rice paddy fields in Japan revealed that excessive application of fertiliser results and coastal pollution. A correlation between greater rainfall intensity

and increased runoff was also confirmed (Higashino & Stefan 2014), while Crosson et al. (2007) also states that high rainfall makes nitrates prone to being leached from the soil. This is belied to be caused by raindrop-induced pumping of water over paddy fields, and means that nutrient loadings may increase with the growing likelihood of extreme rainfall events due to climate change (Higashino & Stefan 2014).

Another – often overlooked issue – is where the nutrients in fertilisers actually come from. Although all three major ingredients cycle constantly through the biosphere, this is not necessarily the case in an economic sense. This is particularly true for Phosphorous which is mined from rocks, leading to the concept of 'peak phosphorous', an idea that commercially available reserves might be exhausted (Cho 2013). While a number of academics dismiss this theory, citing that the rate of rock formation approximately matches the current rate of extraction, many acknowledge that the quality and accessibility of phosphate rock reserves is declining. As a result, it is thought that future costs of mining, refining and transporting phosphorous will climb (Cho 2013).

Rising oil prices in 2008, combined with other factors, managed to increase the price of phosphate rock by 800%. Due to being closely linked to global food prices, such surges in the value of phosphate rocks can compromise food security in developing countries (Cho 2013). These economic concerns are only amplified by an expanding world population and claims the United States only has enough reserves for 25 years. Like most mining enterprises, it is possible to progressively move to lower grade phosphate rock, but these are more expensive to access and process, and have negative health implications. Lower grade rocks are laden with the heavy metals cadmium and uranium, materials toxic to both humans and soil (Cho 2013). Interestingly, the vast majority of phosphorous consumption is due to inefficiency, with just a fifth of mined phosphorous reaching the dinner plate. Over 30% of mined phosphorous is lost during mining and processing with a further 50% wasted from the farm onwards (Cho 2013). Such wastefulness only emphasises the motivation to reduce fertiliser losses.

2.2: Cation Exchange Capacity (CEC)

Perhaps a little known soil property, cation exchange capacity, or CEC is a soil's ability to retain positively charged ions, or cations. This represents the ability of the soil to provide plants with essential nutrients such as calcium, magnesium and potassium (Lines-Kelly 2002). An important relationship is that cation exchange capacity increases with soil pH, meaning acidic soils are less likely to provide nutrients. In addition, soils with high CEC are less susceptible to nutrient loss via leaching. Most importantly – as far as this investigation is concerned – is that CEC can be enhanced through the addition of lime or organic matter (Lines-Kelly 2002). Therefore, the addition of organic matter may be a decisive means of reducing soil nutrient losses.

2.3: Introduction to Biochar

Biochar is a charcoal created from biomass that is primarily used as a soil amendment, but has many other possible applications. Although it is a relatively new area of study, there is potential for biochar to improve soil properties such as soil fertility and water holding capacity while providing environmental services such as carbon sequestration (University of California, Davis 2016). The biosphere produces and absorbs 20 times the carbon dioxide as the anthroposphere. As a result, the proper use of biomass could prove vital in combating immediate climate change (Read n.d.).

Pyrolysis may be used for both energy production and the creation of biochar, with the char essentially being the residue of the process. Low temperature pyrolysis produces around 50% biofuel and 50% Biochar. Temperatures above 700°C (where the process is instead called gasification) increase energy yields at the cost of char production (Lehmann 2007b). As a process, pyrolysis produces between three and nine times the energy required to initiate it, emphasising its efficiency (Lehmann 2007b).

While biochar is an emerging field, it has considerable potential to both sequester carbon and reduce fertiliser pollution (Lehmann 2007b). Even sources of biofuel can be over exploited however, as excessive removal of crop residues (supposedly a waste product) increases dust and therefore wind erosion (Lehmann & Joseph 2009).

There are four key motivating factors for developing biochar technology. These include energy production, soil improvement, waste management, and the mitigation of climate change (Lehmann & Joseph 2009). A fledgling biochar industry must be economically feasible to have any chance of widespread success (Lehmann & Joseph 2009). To be financially viable, exhaust gases must also be captured for energy production. That being said, adding biochar to soil could reduce emissions by 12-84% more, providing the groundwork for a carbon-negative industry. The addition of biochar improves both the structure and fertility of soil, increases fertiliser retention, and decreases fertiliser runoff (Lehmann 2007a).

2.4: Application of Biochar in Reduction of Fertiliser Losses

Biochar may be used as a soil amendment to improve soil fertility while also acting as a carbon sink. By simply burying char, it becomes possible to sequester decades' worth of emissions. As a material, biochar is both stable and able to retain large quantities of nutrients (Read n.d.). This ability means that biochar – when used as a soil additive – has the potential to reduce nitrous oxide and methane emissions from plants, decrease fertiliser needs, and alleviate the pollution of waterways (Lehmann 2007b).

Biochar is one of the most stable forms of organic carbon, able to persist in the soil for thousands of years. It should be noted that biochar will eventually decay to carbon dioxide – because otherwise it would make up the majority of soil organic matter – though the exact half-life remains unknown. This is largely due to the endless number

of biological materials that biochar can be made from although production conditions, soil properties and climate can also be expected to play a role (Lehmann 2007b).

Biochar is a particulate, heterogeneous material, meaning that it will decay through oxidation of the surface, with different areas decaying at different rates and the centre largely unaffected even after centuries. Biochar is known to last longer, and retain cations better than other forms of soil organic matter. Cation retention of fresh biochar is less than char which has been in soil for a time (Lehmann 2007b).

Biochar is capable of retaining nutrients in the soil without compromising the ability of plants to access it. This allows for both reduced environmental pollution and improved crop yields. Phosphate is also readily absorbed by biochar, something which does not occur with other soil organics. Similar benefits are even seen in the absorption of atmospheric nitrogen, with bean plants in weathered savannah soil demonstrating greater fixation ability after biochar has been added. Another unexpected ability is the retention of potent greenhouse gasses such as nitrous oxide and methane. In fact, experiments involving forage grass indicate that adding just 20g/kg of biochar to the soil can eliminate methane emissions and reduce nitrous oxide emissions by 80% (Lehmann 2007b).

As stated earlier, increases in soil organic matter, including application of biochar generally increases the amount of cations available to plants. Cation exchange capacity (CEC) of soil organic matter increases with pH. Although the properties of biochar change considerably once added to the environment, it has been observed that pH (and hence CEC) increase with production temperature. This comes at a cost of carbon yield however, making 450-550°C something of an optimal temperature range (Lehmann 2007b). Bacterial growth rates are also improved by biochar's pore structure – providing both protection and attachment opportunities for microorganisms (Lehmann 2007b). A means of incorporating biochar in the soil needs to be developed however, as surface char is likely to be washed away (Lehmann 2007b).

The ability of biochar to adsorb nitrate (NO_3^-) does seem to vary according to char type and pyrolysis temperature. In tests of sugarcane bagasse derived biochar, Kameyama et al. (2010) discovered that biochar loads of up to 10% by weight reduced nitrate losses by just 5%. It was still concluded however, that the addition of bagasse charcoal would provide plants with greater access to NO_3^- by increasing the residence time (Kameyama et al. 2010). Tests conducted by Yao et al. (2012) had varied results when examining the ability of biochar to reduce the leaching of nitrate ammonium and phosphate. While nine of 13 biochars tested exhibited an ability to adsorb ammonium, few could adsorb nitrate or phosphate. Two chars in particular, created from peanut hull Brazilian pepperwood managed to reduce the leaching of nitrates by 34% (Yao et al. 2012). While the peanut char managed to reduce phosphate losses by 20.6% and ammonium losses by 34.7%, the Brazilian pepperwood char could only reduce ammonium losses by 14% and actually caused additional phosphate release. This led Yao et al. (2012) to conclude that the ability of biochar to reduce nutrient leaching depends on both nutrient and char type and that the properties of a given biochar should be examined before applying it to a given task.

2.5: A Focus on Sugarcane

Production of sugarcane often occurs in areas which suit fertiliser losses. Together with pesticides and sediments, fertilisers washed out of cane fields cause serious environmental damage to marine environments such as Queensland's Great Barrier Reef (Queensland Government 2016). Although industry practice is improving, in 1987 it would not be uncommon for growers to apply over 200kg of nitrogen per hectare, forming a major component of crop production costs (Prammanee, Wood & Saffigna 1988). Even an application rate more common in today's world of 140kg N/ha would still require significant outlay.

A recent (2013) grower group trial in the Herbert region used the addition of biochar to the soil, combined with around 50% of the usual nitrogen fertiliser load to increase the sugar yield by over 19% at harvest (Morley 2015). It was the success of this trial which turned the focus of the investigation to sugarcane with the possibility of not only replicating the fertiliser leaching which occurred during this trial, but also producing laboratory scale results which accurately replicate a much more costly field trial.

3: Methodology

3.1: Design of Column Tests

After some initial consideration of experimental design concerning rainfall simulations and other test methods, it was decided to use column tests to study the effect of adding biochar. These small-scale tests are used to test leaching by filling a vertical tube with soil and adding water to the top. Water percolates down through the soil to the bottom where it is collected for analysis. A simple diagram of this test is presented below:

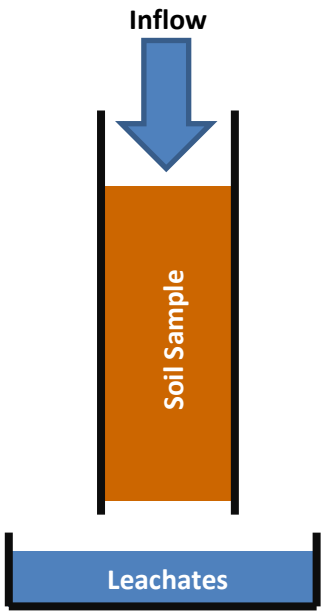

Figure 1: General Column Test Concept

This set-up may be achieved using simple – but highly suitable – items such as PVC pipe, as well as assorted plastic bottles funnels and containers. The following diagram demonstrates a typical column testing apparatus using these items:

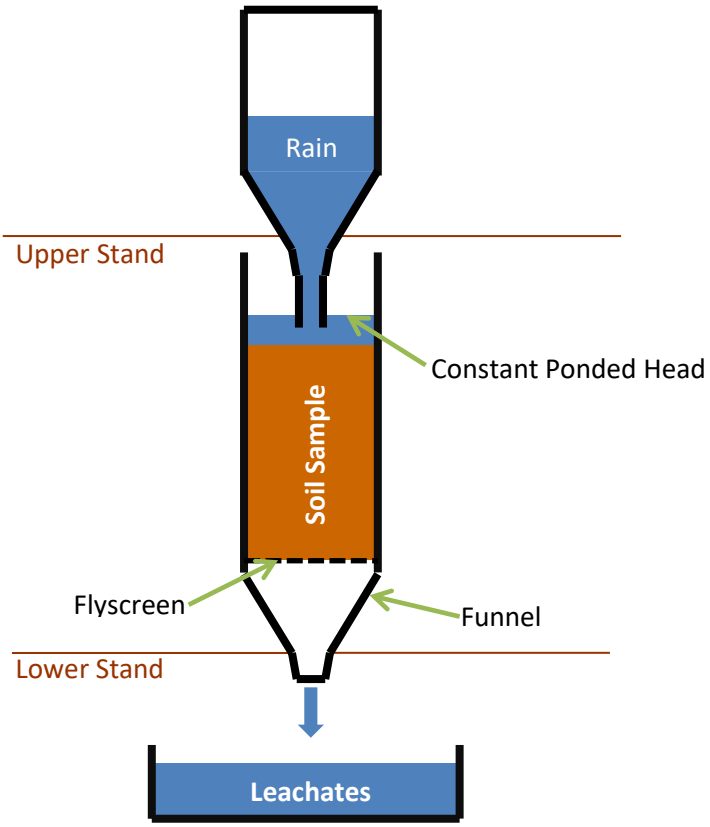

Figure 2: Column Testing Apparatus

90mm PVC pipe (internal diameter 86.2mm) may form the basis of the soil column. Attaching flyscreen to hold the soil, and a funnel to direct the leachates makes for a simple yet effective design. While making the PVC pipe long enough to accommodate the full load of rainfall would be easier to achieve, the use of a bottle as seen in the diagram allows the ponded head to be kept at or below a certain level. This is highly desirable as it should be remembered that increasing the ponded head makes the test less like a real-world rainfall event. By using the walls of the pipe to prevent runoff, these tests are primarily concerned with examining leaching behaviour, though it is likely that materials usually lost in runoff will instead percolate downwards when forced to do so.

A design of an idealised column test was developed and then refined as available resources dictated. As discussed earlier, it was decided to focus on sugarcane

production, with the chosen soil coming from the Ingham region of Northern Queensland and a particular focus on a recent grower group project in the Herbert region (Morley 2015). The desire to replicate this field trial necessitated keeping the experimental design as close to the application end as possible, largely dictating design specifics.

It was initially proposed to utilise columns with soil 200mm deep to match the primary root zone, and in fact, the soil used in the tests was originally collected from this region of the soil profile. The longest available column testing apparatus only allowed for 100mm columns however, though this should place more emphasis on the performance of the biochar as the ratio of biochar to soil would be effectively doubled. Soil was air dried to ensure that soil microbes were still available to break fertiliser down into plant accessible – not to mention detectable – forms. Biochar used matched the field trial, as did the doses at 10 tonnes per hectare. The specific biochar used was Carbon 8, produced by a company called RCRA, Renewable Carbon Resources Australia, based in Charleville, Queensland and sold for around $1/L. Carbon 8 is intended for agricultural applications and made from the Stinking Gidgee tree, *Acacia cambagei* a tree found in arid regions and notable for its characteristic odour.

It was decided to steer away from the field trial on fertiliser loads however, given that the objective there was to grow crops rather than examine leachates. This resulted in roughly half the usual fertiliser load being used in the grower trial (Morley 2015), while this investigation will use the industry recommended 140kg N/ha (Wood, Schroeder & Stewart 2003). Also unlike the grower trial, was the decision to focus specifically on nitrogen losses and omit other nutrients. At 46% nitrogen, urea is both the most concentrated and the most popular solid nitrogen fertiliser (Incitec Pivot Fertilisers 2012), making it an ideal choice for this experiment. The aforementioned application rates scale to 5.836g of biochar and 0.1776g of urea per column. While it would have been possible to increase the dosages to focus on the effect of each ingredient, it was decided to keep things as close to field application as possible.

Although some sources recommend a $CaCl_2$ solution to be used as artificial rain, distilled water was chosen in this case to more closely replicate real-world situations. In order to simulate drought-breaking spring rainfall occurring after the soil had been fertilised, it was decided to start with the soil pre-wet to field capacity before waiting 24 hours and applying the first rainfall event of 50mm with dissolved fertiliser load. After 48 hours, any leachates would be collected and refrigerated before another rainfall event was added. This would simulate a field receiving 50mm, or coincidentally, one pore volume of rain every second day.

Laboratory tests could then be conducted with enough precision that the seemingly minute quantities of urea and biochar would not be of concern. These tests would measure the pH, electrical conductivity and volume, as well as the nitrogen and carbon levels of the leachates. A nitrification inhibitor (2-chloro-6 (trichloromethyl) pyridine) would be added to the collection buckets to prevent nitrates in the leachates from volatilising and being lost.

In terms of actual soil treatments, the experiment was designed to closely replicate the field trial, while including the necessary controls and also examining the merits of layered vs incorporated biochar. The experimental procedure is detailed in a following section.

3.2: Tenosols, the Chosen Soil Type

This subsection describes the soil type used, descriptions of other soil types considered are provided in Appendix B.

Of all the soil orders in Australia, Tenosols are the most widespread, covering over a quarter of the continent. Though mainly found in arid western areas of the country, these soils are a diverse group, and may even be seen in alpine regions (McKenzie et al.

2004). Tenosols are characterised by their limited pedological development – with the frequent exception of the upper A horizons – which leads to them being referred to as slightly developed soils. The geographic distribution of Tenosols facilitates a rainfall range of 200mm to over 2000mm. While these soils are typically used for extensive livestock production due to low rainfall, water retention and fertility, higher rainfall areas are open to cultivation if the topography is suitable (McKenzie et al. 2004).

The particular Tenosol being used in this investigation is chernic, meaning it possesses dark organic upper horizons and underdeveloped lower horizons (McKenzie et al. 2004). Being located in northern Queensland provides enough rainfall for sugarcane production. These underdeveloped soils are formed along river channels such as Herbert River, the Stone River and Trebonne Creek. Occurring at the highest parts of a floodplain, these yellowish-brown soils are made from relatively recent sandy alluvial material yet have formed over a long enough time period that they possess a dark surface horizon (Wood, Schroeder & Stewart 2003) indicating large quantities of organic matter. These soils are well drained due to their sandy nature, though the organic topsoil ensures moderate levels of fertility. They are typically very acidic with a moderately low cation exchange capacity, caused by the acidic cations which make up some 40% of the soil's CEC (Wood, Schroeder & Stewart 2003). Being composed primarily of fine sand, these soils are weakly structured, making them prone to compaction and vulnerable to loss of both organic matter and water through tillage operations. Most importantly, the aforementioned properties make these soils prone to leaching (Wood, Schroeder & Stewart 2003). The high probability of leaching, together with the lack of organic matter and use in the sugarcane industry make these soils an excellent choice for investigation.

3.3: Field Capacity Testing Method

The field capacity test was a relatively simple procedure first recommended by Professor Bernard Schroeder which involved adding some cotton wool and plastic tubing to a large measuring cylinder. So that one end of the tubing was buried in wool

at the base. Soil would then be placed on top of the cotton wool and the whole cylinder dropped from two centimetres three times to simulate the level of compaction typically experienced in the topsoil at field conditions. Water was then added to the measuring cylinder at a slow rate so that there was no ponded head, with the progress of the wetting front being observed through the clear sides of the measuring cylinder. The plastic tubing prevented air from being trapped beneath the advancing wetting front and impeding its progress by allowing the air to move through the cotton wool and out through the plastic tubing. When the wetting front had almost reached the cotton wool, the soil was removed, with the partially wet soil being taken away to be weighed, dried and weighed again. The difference in weights indicated the amount of water needed to bring that quantity of soil to field capacity. It was also decided to oven dry the already dried soil as a simple addition to this test to determine the quality of the original drying process. Once field capacity and the weight of soil used was known, the columns could then be wetted up ready for the leaching tests.

3.4: Column Testing Method

The chosen column testing method is presented below, note the number of samples column of Table 1 increases rapidly with the length of the experiment.

Treatments

1. Control – 6g biochar but no fertiliser
2. Control – 0.18g urea but no biochar
3. Control – No char or fertiliser
4. Trial replication, 6g incorporated char, 0.18g urea
5. 6g char layered 4cm below surface, 0.18g urea

Note that there will be 3 replicates of each treatment to provide statistical power without dramatically affecting the scale of the experiment.

The sample nomenclature used is described in the following diagram for future reference:

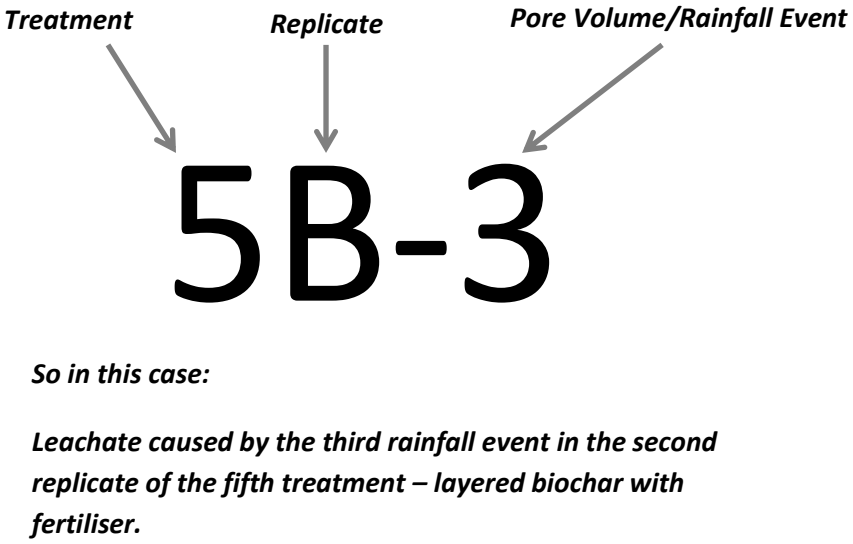

Figure 3: Description of Sample Nomenclature.

Materials

- Urea fertiliser, chemical formula $CO(NH_2)_2$
- Soil
- Distilled water
- Biochar
- Soil column testing apparatus
- pH and EC meters
- a Shimadzu TOC-V with built-in TNM-1

- Ammonium probe and ion chromatograph (both were not used in the final analysis due to unforeseen complications)
- Containers and refrigerator access to store samples

Method

1. Conduct preliminary tests to determine soil field capacity.
2. Set up columns with a soil depth of 100mm, this should take roughly 0.5kg of soil, varying according to char load. The set-up used is presented in the following photograph with additional images in Appendix C:

Figure 4: Column Testing Set-up, note the use of common household materials is extremely unlikely to compromise accuracy.

3. Pre-wet columns to field capacity.
4. Set up bottles with initial loading of water (0.292L) and urea. All subsequent water application will also feature 0.292L, giving the equivalent of a 50mm rainfall event or one pore volume.
5. Apply the first 50mm of water (and fertiliser).

6. Wait 48 hours before retrieving the leachates and adding another 50mm of rain. Repeat until enough rainfall has been added (see table 1, though 11 days was deemed adequate). Refrigerate leachates until they can be analysed at an appropriate time.

Table 1 - Rainfall					
Rain Event no.	**Day**	**Cumulative Rainfall (mm)**	**Cumulative Volume (L)**	**Pore Volumes**	**No. of samples**
1	1	50	0.291792696	1	15
2	3	100	0.583585393	2	30
3	5	150	0.875378089	3	45
4	7	200	1.167170786	4	60
5	9	250	1.458963482	5	75
6	11	300	1.750756179	6	90
7	13	350	2.042548875	7	105
8	15	400	2.334341572	8	120
9	17	450	2.626134268	9	135
10	19	500	2.917926965	10	150
11	21	550	3.209719661	11	165
12	23	600	3.501512358	12	180
13	25	650	3.793305054	13	195
14	27	700	4.08509775	14	210
15	29	750	4.376890447	15	225
16	31	800	4.668683143	16	240

Table 1: Rainfall application options

3.5: Laboratory Analysis Method

Laboratory analysis generally followed standard procedure. First, each sample was weighed to determine the volume of leachates. Then each sample was strained through fiberglass filters into three vials. The filtered samples could then be used for pH and EC tests with a combined pH and EC probe. The most important analysis would involve determining total nitrogen and carbon analysis using a Shimadzu TOC-V with built-in TNM-1. An image of the sample vials loaded into the aforementioned machine is presented below:

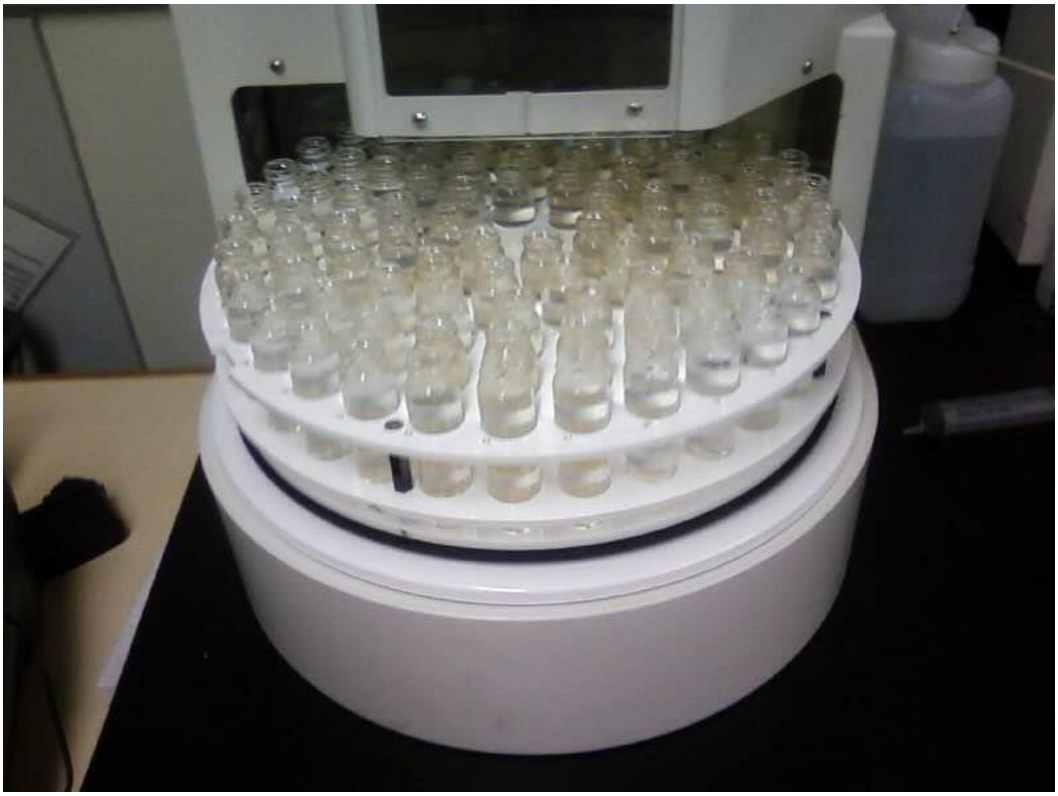

Figure 5: Sample Vials Ready for Analysis

4: Results

Results are presented in this section in graphical from, broken down by parameter, and will be discussed in the subsequent section. Tables of the original results are displayed in Appendix D for conciseness. Other observations are outlined in Appendix E.

4.1: Field Capacity Test Results

The field capacity test results are presented here. The following table details the change in weights of partially wet and dry soil samples (including container weights) over three days of oven drying.

Table 2- Field Capacity Results

Sample	Initial Mass (g)	Mass after 1 day (g)	Mass after 2 days (g)	Mass after 3 days (g)
Field Capacity	273.2	235.64	233.20	235.46
Dry	119.58	119.50	119.80	119.50

Table 2: Results of field capacity test

It was decided to ignore the small increases in weight observed as measurement error, allowing calculations to proceed. Subtracting container weights gives 37.63g of water in 203.04g of field capacity soil and 0.08g in 87.20g of “dry” soil. Standardising these ratios to 760g of soil (the amount applied to the columns to give 10cm depth) gives 140.85g of water in field capacity soil and 0.697g of water in dry soil. Evaluating the difference in these water contents gives the amount of water required to bring the dry soil up to field capacity: 140.16g or 140.16mL.

4.2: Mass/Volume Results

Graphs of sample mass (or leachate volume) follow. The first five plots compare the three replicates of the individual treatments to allow outliers to be spotted and removed from further calculations. The sixth plot takes the mean of the replicates for each treatment and presents them together, allowing the different treatments to be compared. See the later section 4.8 for a summary of the notable outliers.

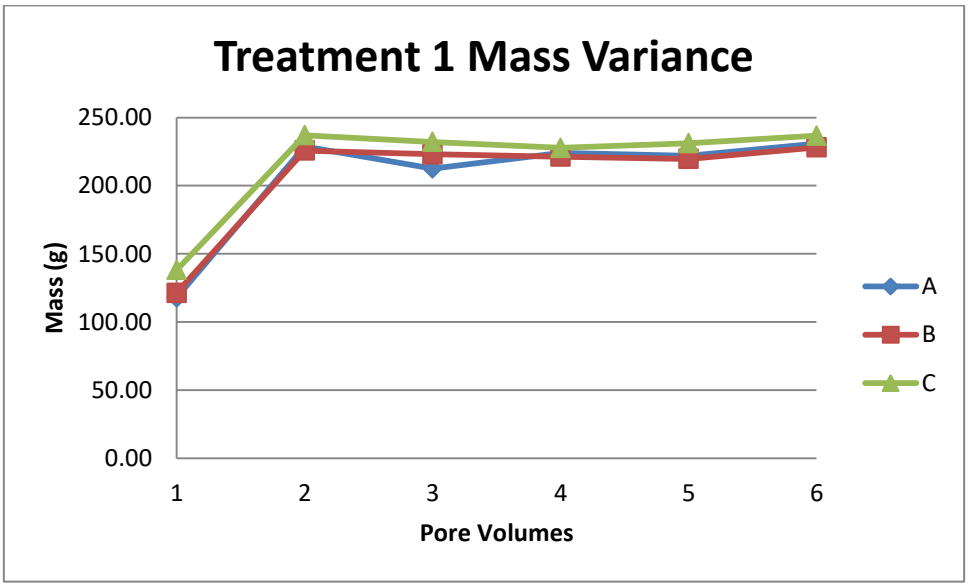

Figure 6: Comparison of mass variance in the treatment 1 replicates.

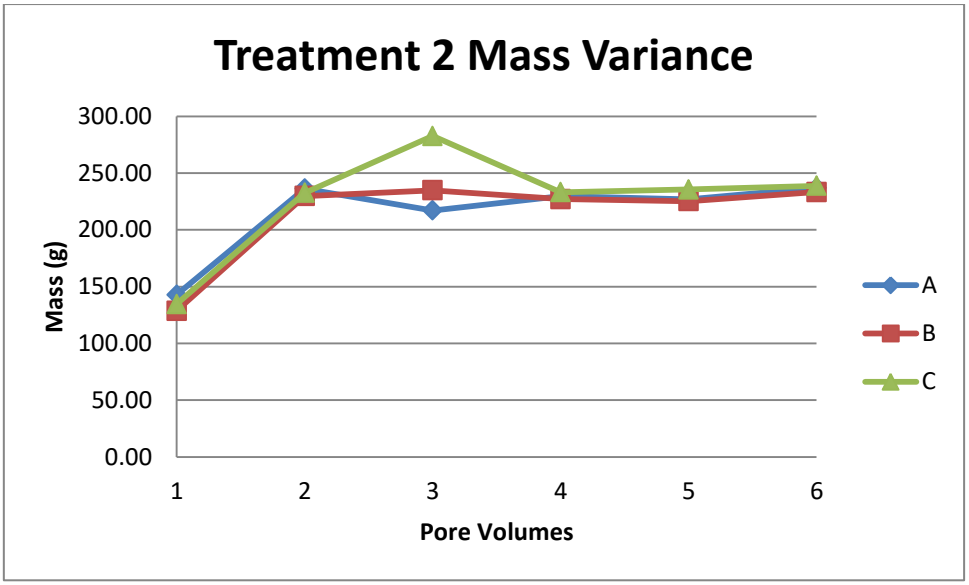

Figure 7: Comparison of mass variance in the treatment 2 replicates. Note the outlier.

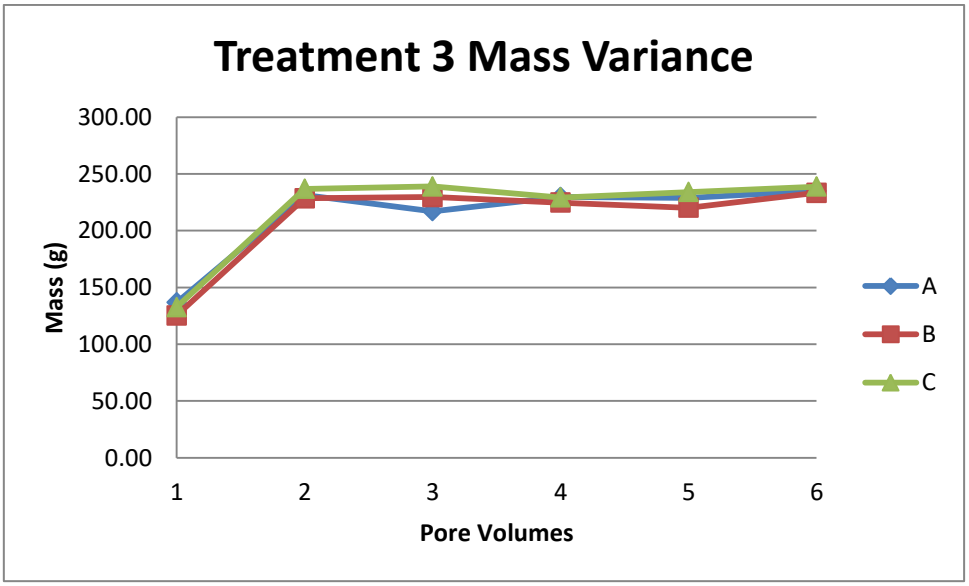

Figure 8: Comparison of mass variance in the treatment 3 replicates.

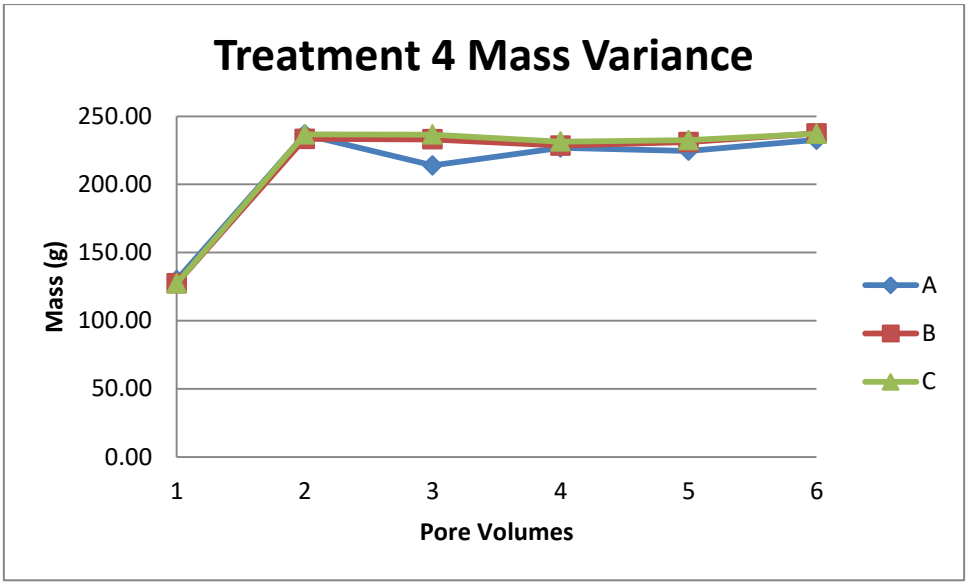

Figure 9: Comparison of mass variance in the treatment 4 replicates.

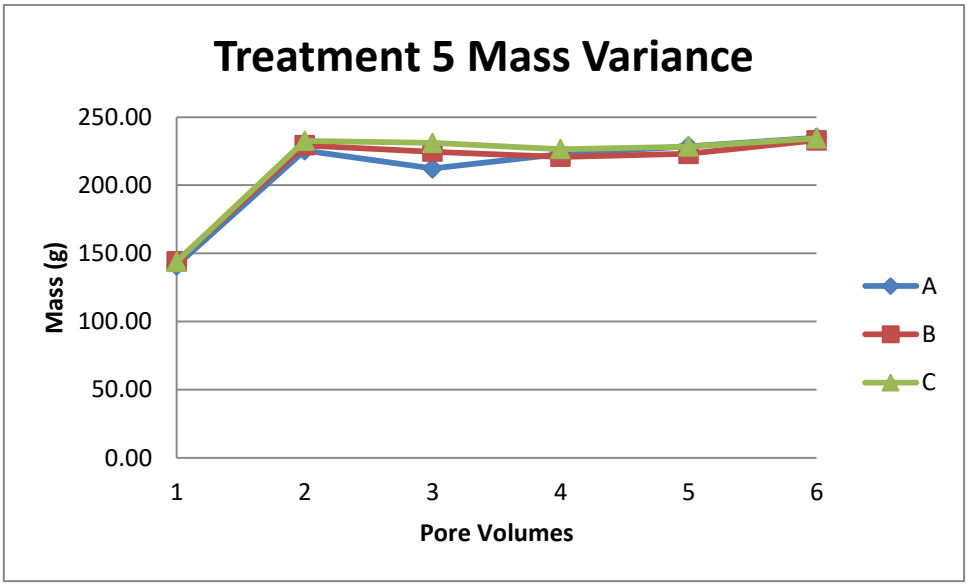

Figure 10: Comparison of mass variance in the treatment 5 replicates.

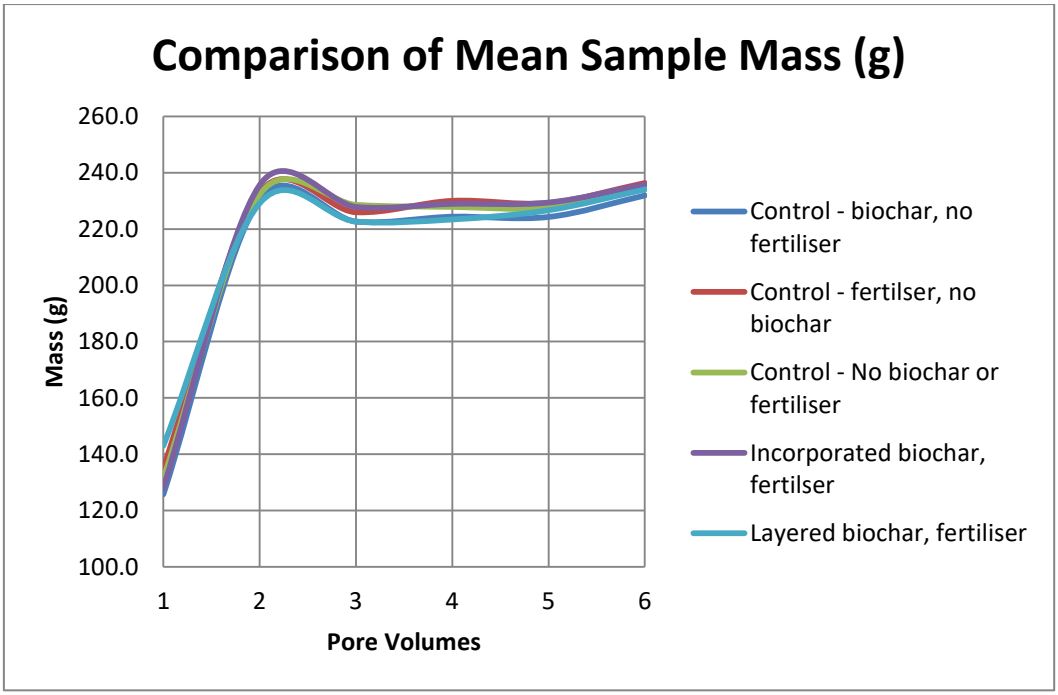

Figure 11: Comparison of mean leachate mass (or volume) between treatments. Note outliers have been removed from consideration.

4.3: Nitrogen Results

Similarly to the previous subsection, graphs of leached nitrogen (by ppm and mg) are presented. For both concentration and mass: the first five plots compare the three replicates of the individual treatments to allow outliers to be spotted and removed from further calculations. The sixth plot takes the mean of the replicates for each treatment and presents them together, allowing the different treatments to be compared. The first six plots present leached nitrogen in parts per million or mg/L:

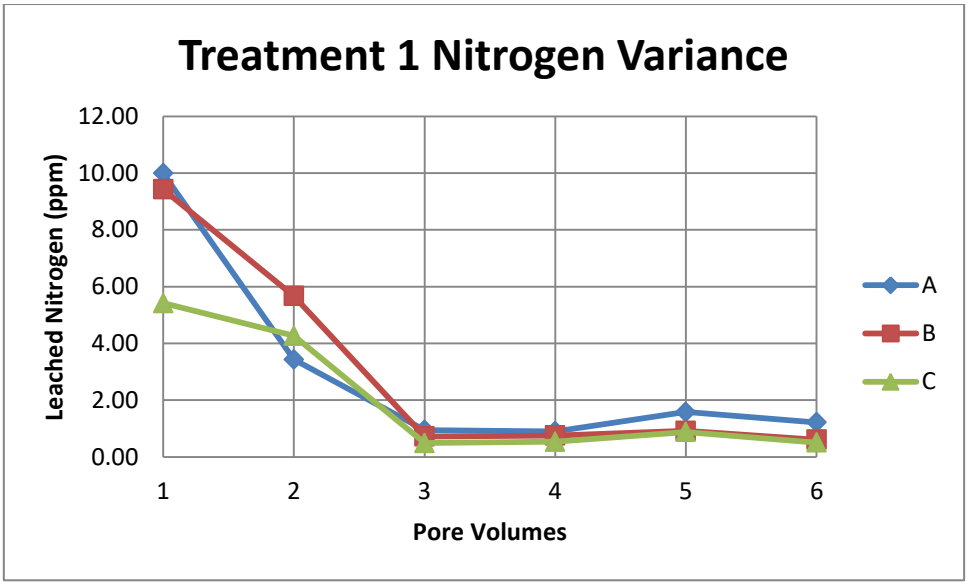

Figure 12: Comparison of Nitrogen concentration variance in the treatment 1 replicates.

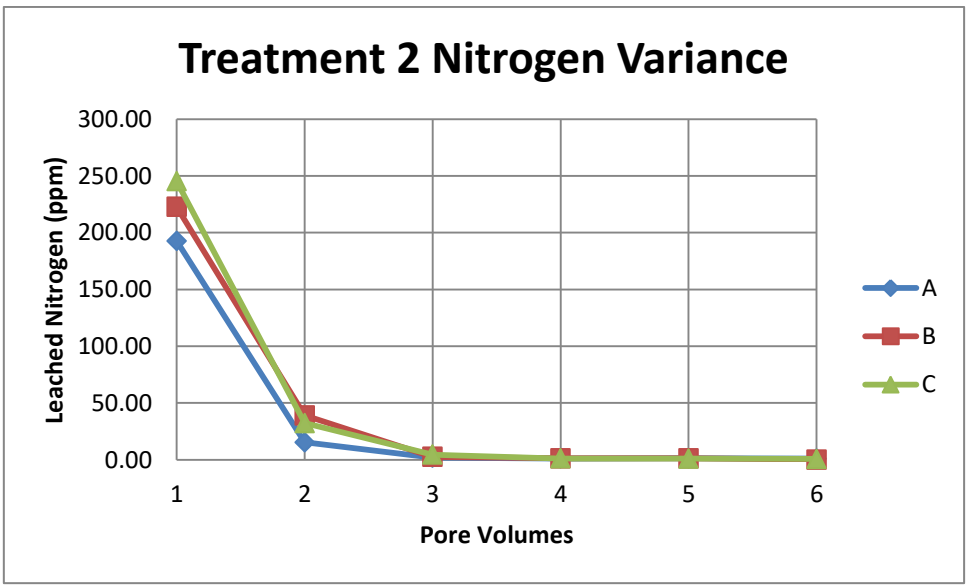

Figure 13: Comparison of Nitrogen concentration variance in the treatment 2 replicates.

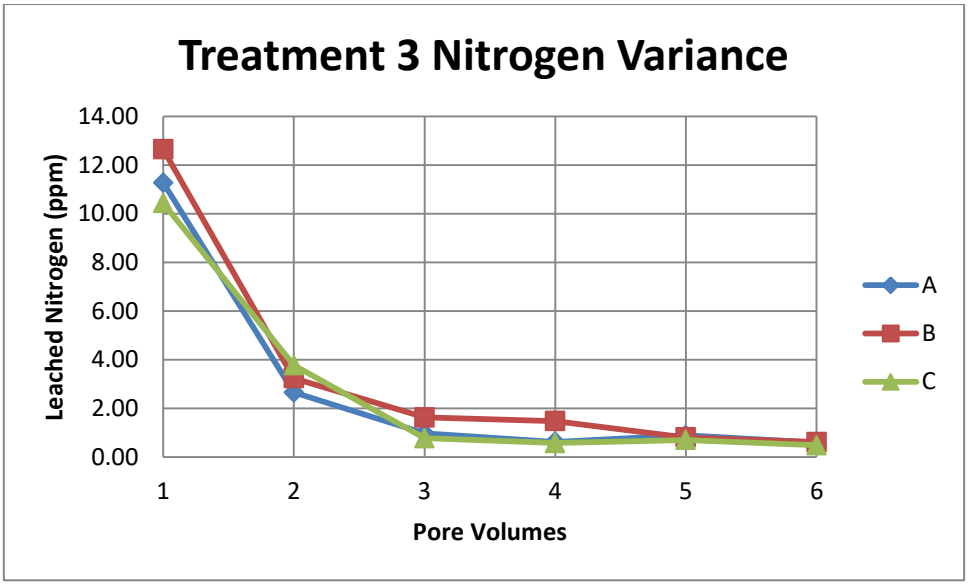

Figure 14: Comparison of Nitrogen concentration variance in the treatment 3 replicates.

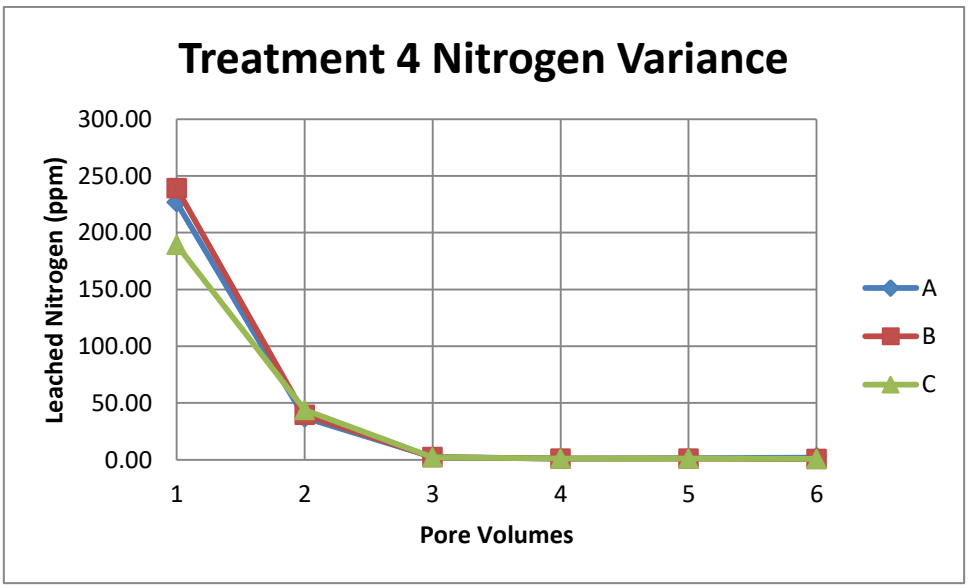

Figure 15: Comparison of Nitrogen concentration variance in the treatment 4 replicates.

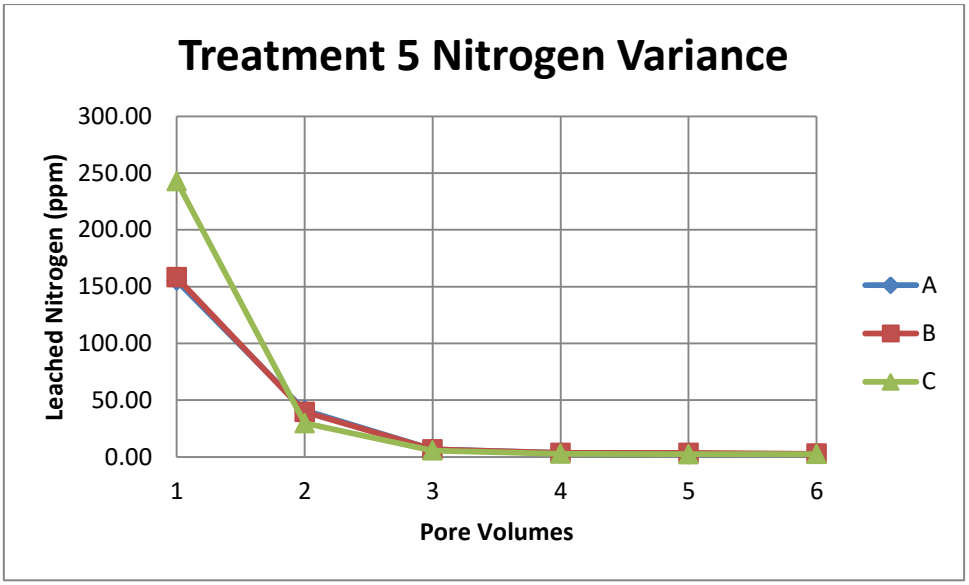

Figure 16: Comparison of Nitrogen concentration variance in the treatment 5 replicates. Note the presence of a significant outlier.

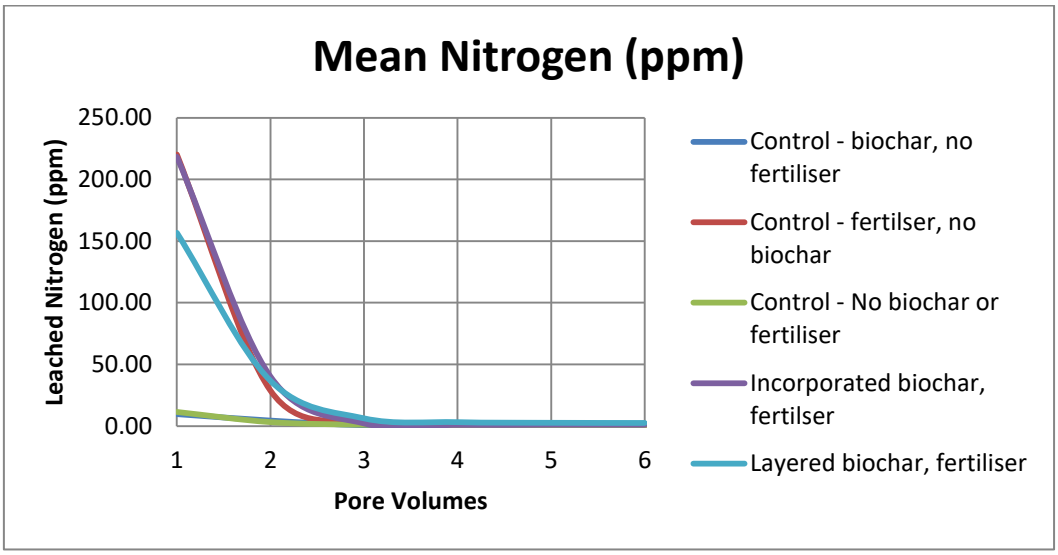

Figure 17: Comparison of nitrogen concentration in the leachates over time for the five treatments. Note outliers have been removed from consideration.

Multiplying the leachate volume by the nitrogen concentration for each sample allows the mass of nitrogen leached to be determined, resulting in the following six plots:

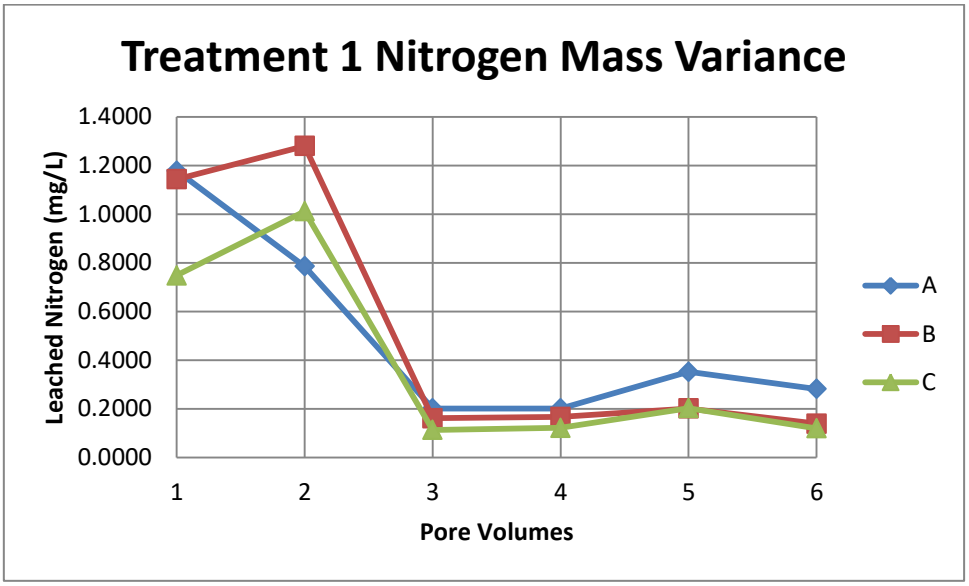

Figure 18: Comparison of variance in the mass of leached nitrogen amongst treatment 1 replicates.

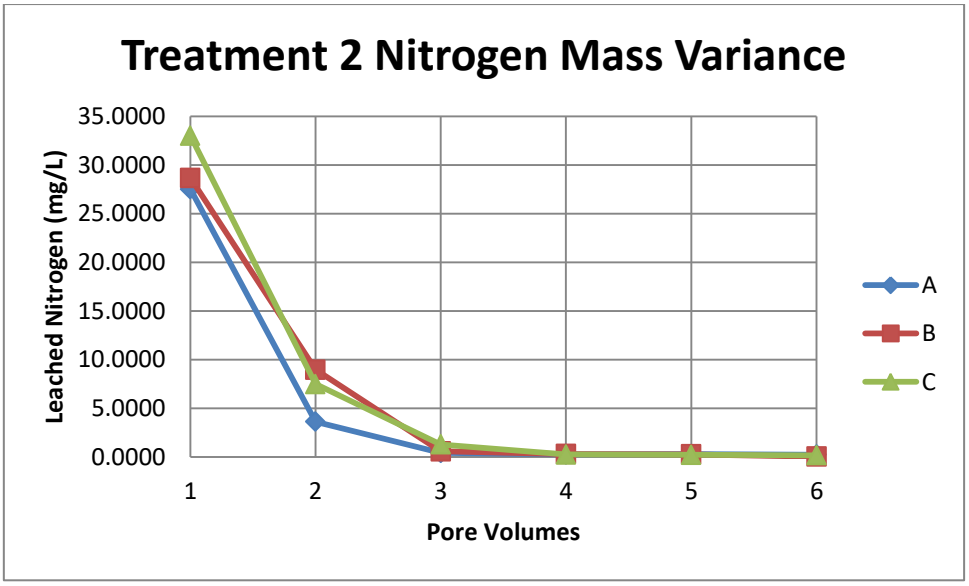

Figure 19: Comparison of variance in the mass of leached nitrogen amongst treatment 2 replicates.

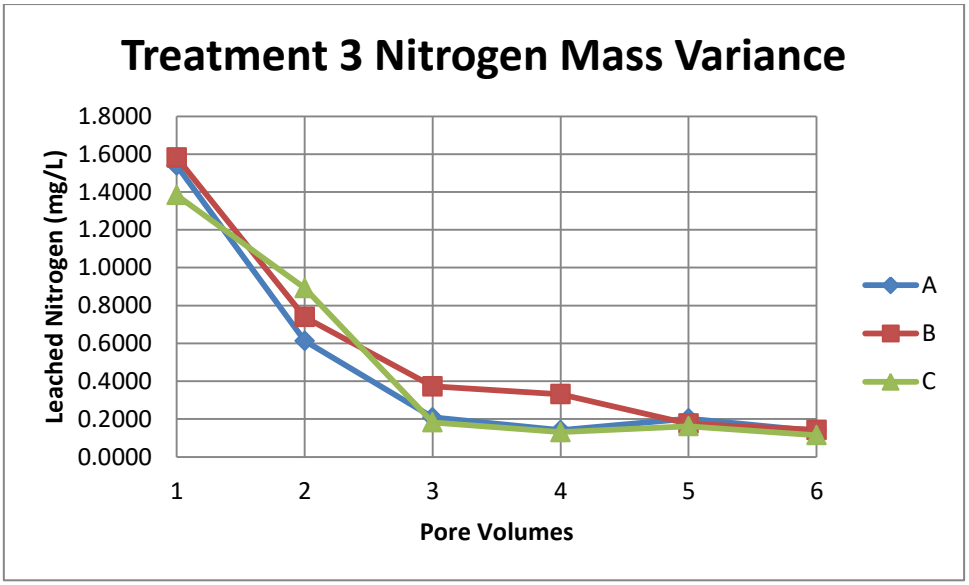

Figure 20: Comparison of variance in the mass of leached nitrogen amongst treatment 3 replicates.

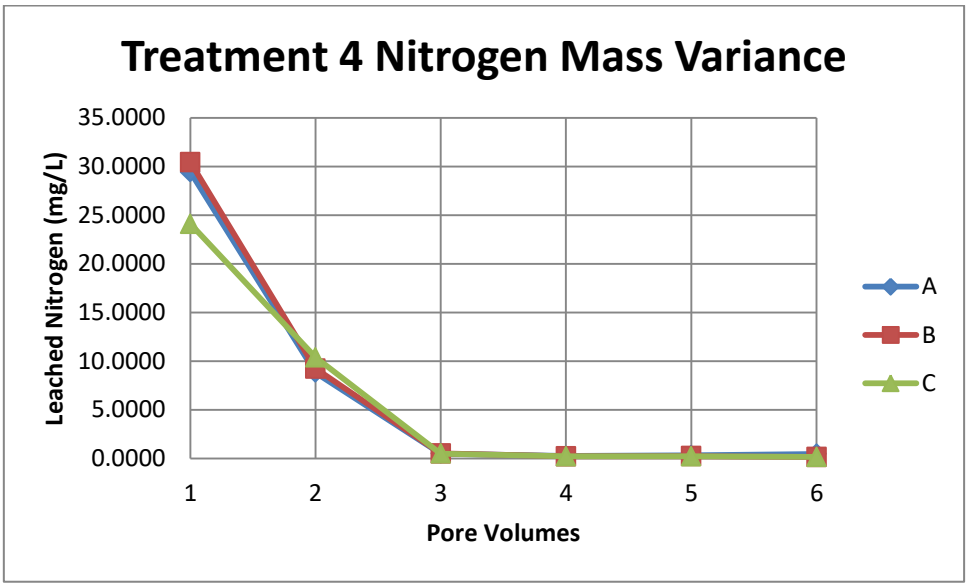

Figure 21: Comparison of variance in the mass of leached nitrogen amongst treatment 4 replicates.

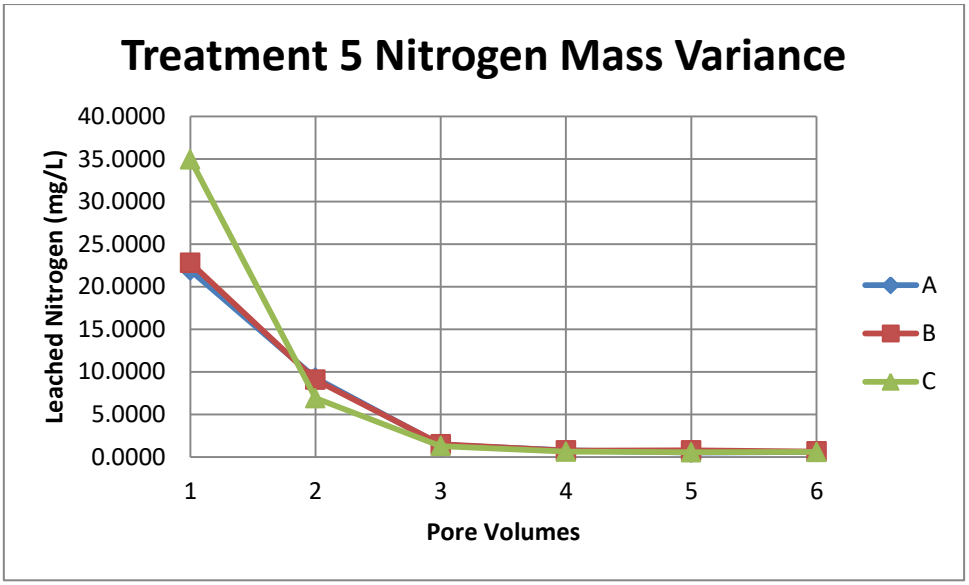

Figure 22: Comparison of variance in the mass of leached nitrogen amongst treatment 5 replicates.

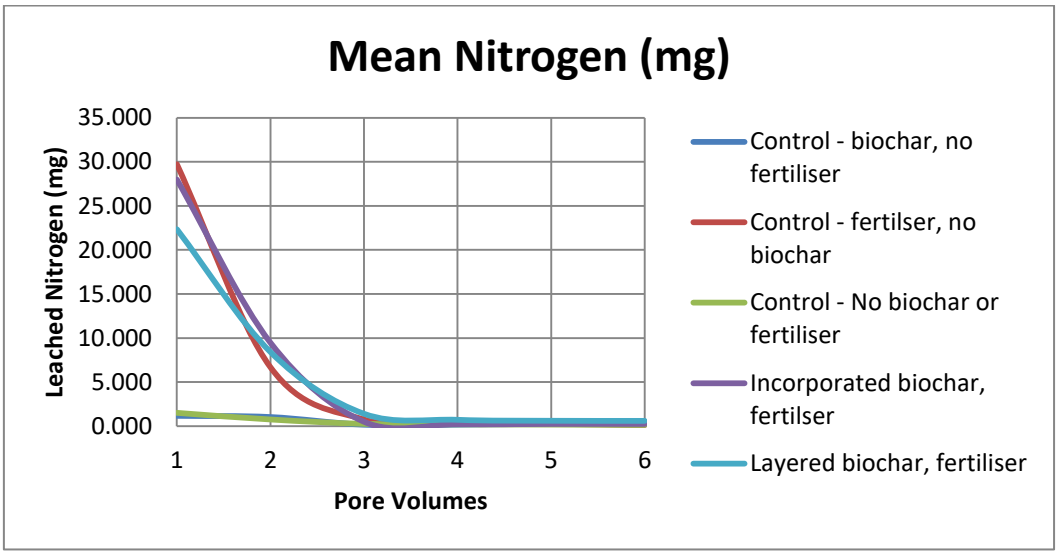

Figure 23: Comparison of leached nitrogen over time for the five treatments. Note outliers have been removed from consideration.

Additional plots may then be constructed by subtracting values of control treatments as baselines and considering the original quantity of nitrogen applied, 81.7mg to determine the quantity retained.

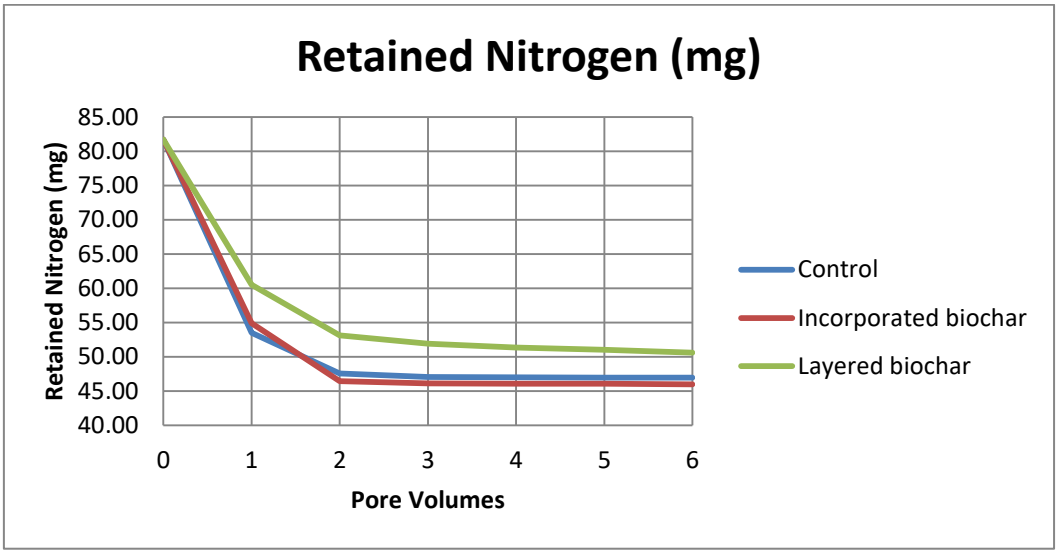

Figure 24: Comparison plot of mass of nitrogen retained between the unaltered soil and the two different biochar treatments. It can be clearly seen that layered biochar performs better. Note that major outliers were removed to generate this result.

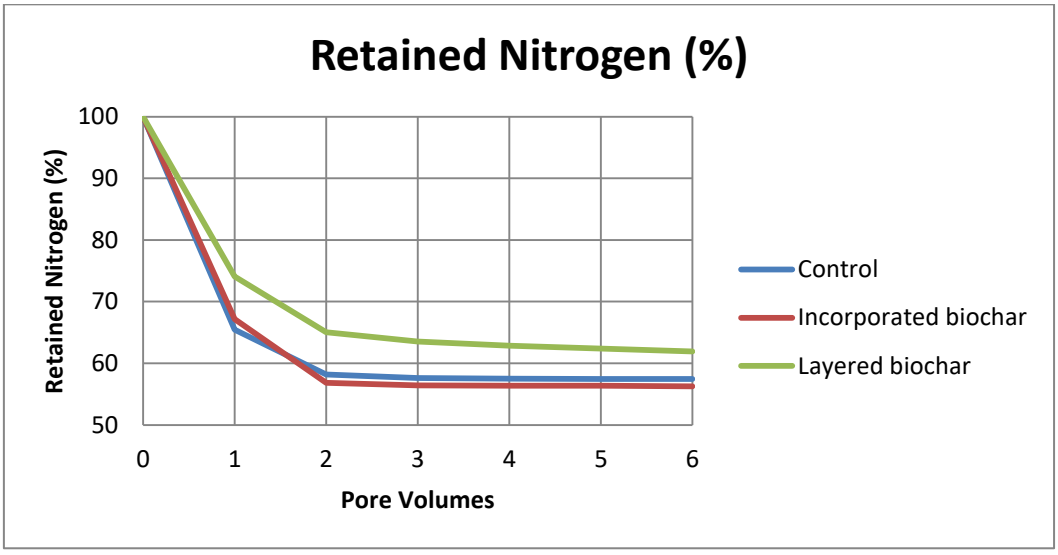

Figure 25: Comparison of the retained nitrogen as a percentage of the original amount applied. Recall that outliers were removed to generate this result.

4.4: Carbon Results

Graphs of leached carbon (by ppm and mg) follow. For both concentration and mass: the first five plots compare the three replicates of the individual treatments to allow outliers to be spotted and removed from further calculations. The sixth plot takes the mean of the replicates for each treatment and presents them together, allowing the different treatments to be compared. The first six plots present leached carbon in parts per million or mg/L:

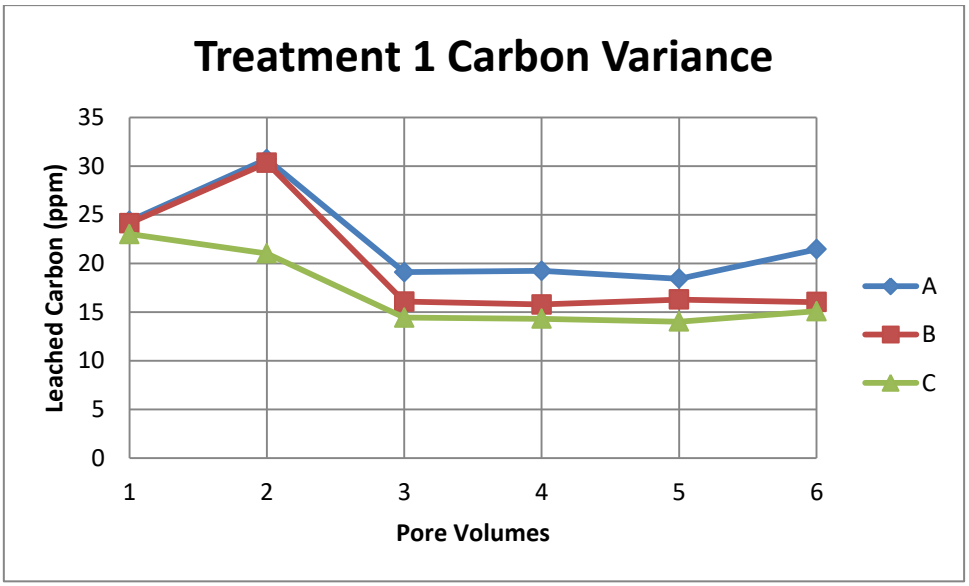

Figure 26: Comparison of Carbon concentration variance in the treatment 1 replicates.

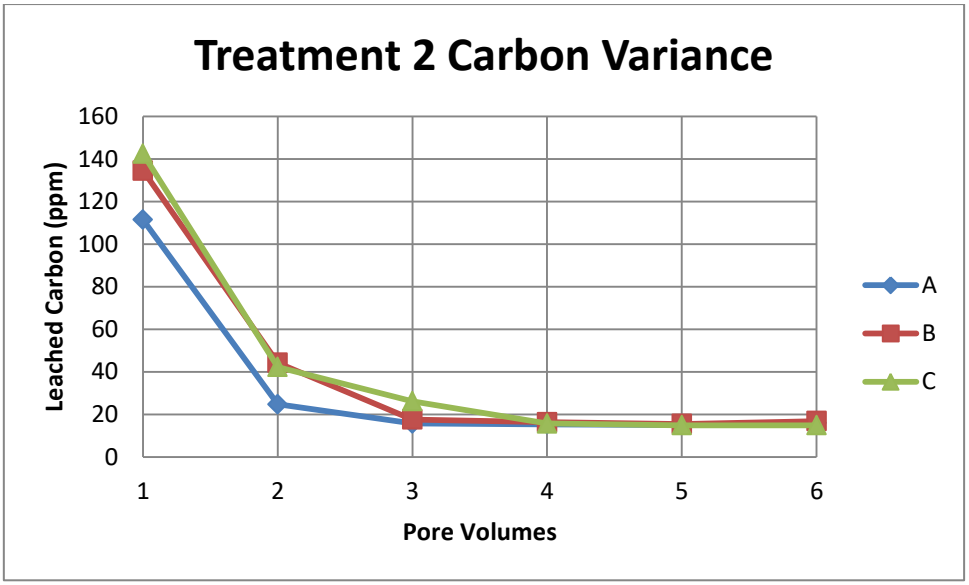

Figure 27: Comparison of Carbon concentration variance in the treatment 2 replicates.

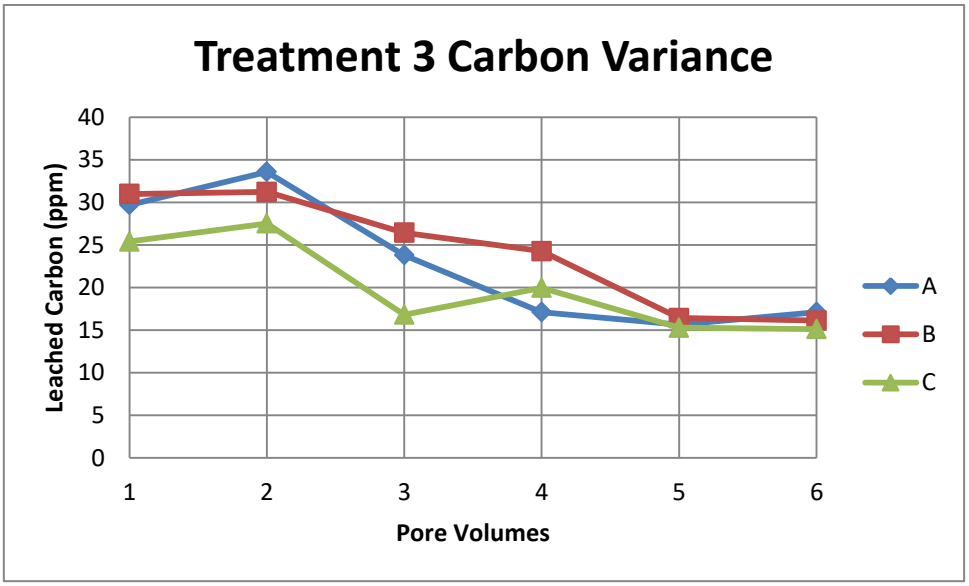

Figure 28: Comparison of Carbon concentration variance in the treatment 3 replicates.

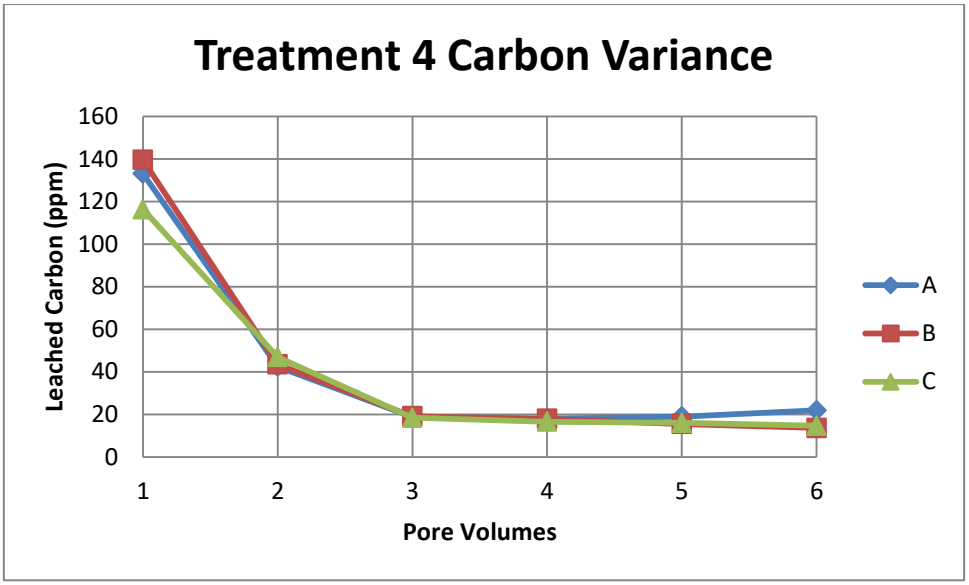

Figure 29: Comparison of Carbon concentration variance in the treatment 4 replicates.

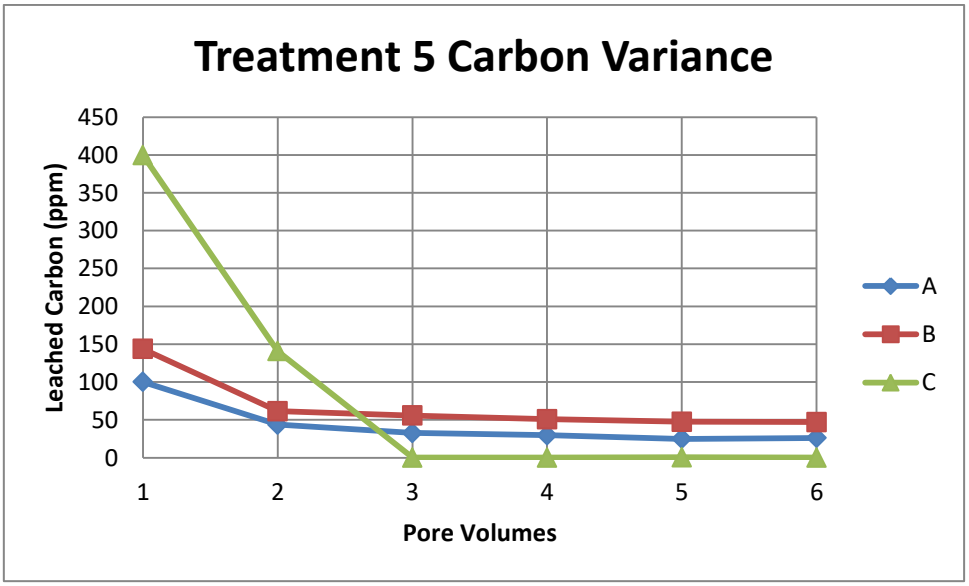

Figure 30: Comparison of Carbon concentration variance in the treatment 5 replicates. Note the presence of significant outliers.

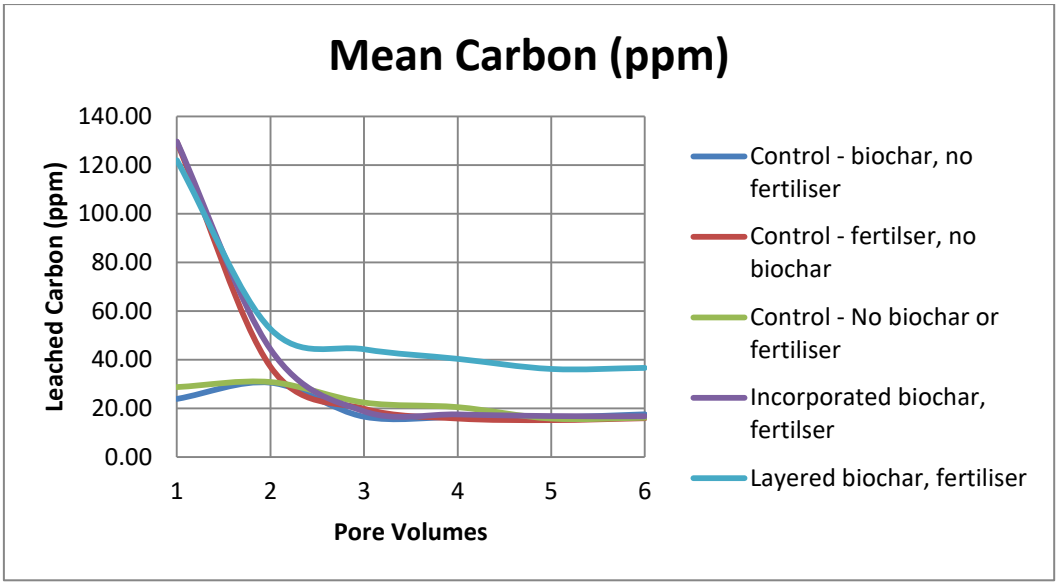

Figure 31: Comparison of carbon concentration in the leachates over time for the five treatments. Note outliers have been removed from consideration.

Multiplying the leachate volume by the carbon concentration for each sample allows the mass of carbon leached to be determined, resulting in the following six plots:

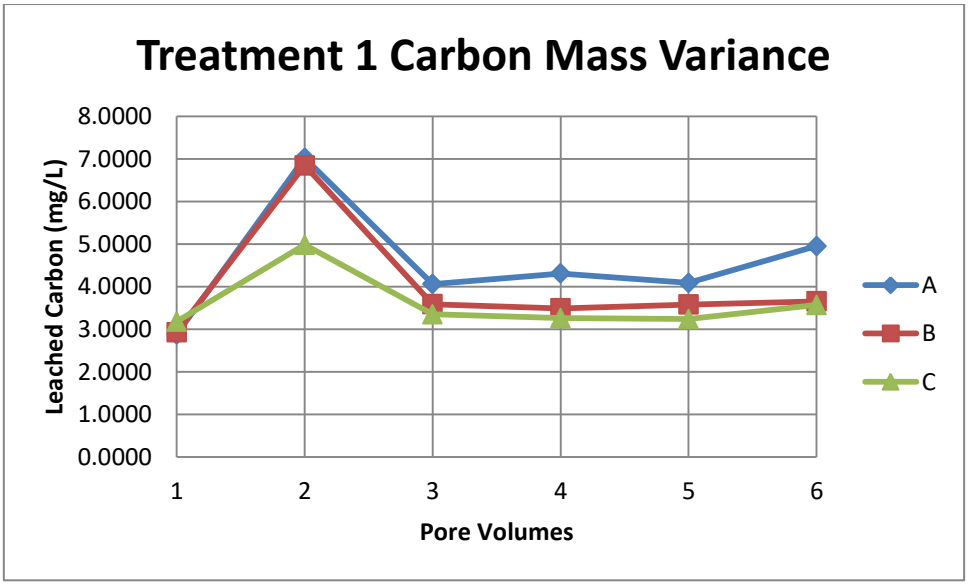

Figure 32: Comparison of variance in the mass of leached carbon amongst treatment 1 replicates.

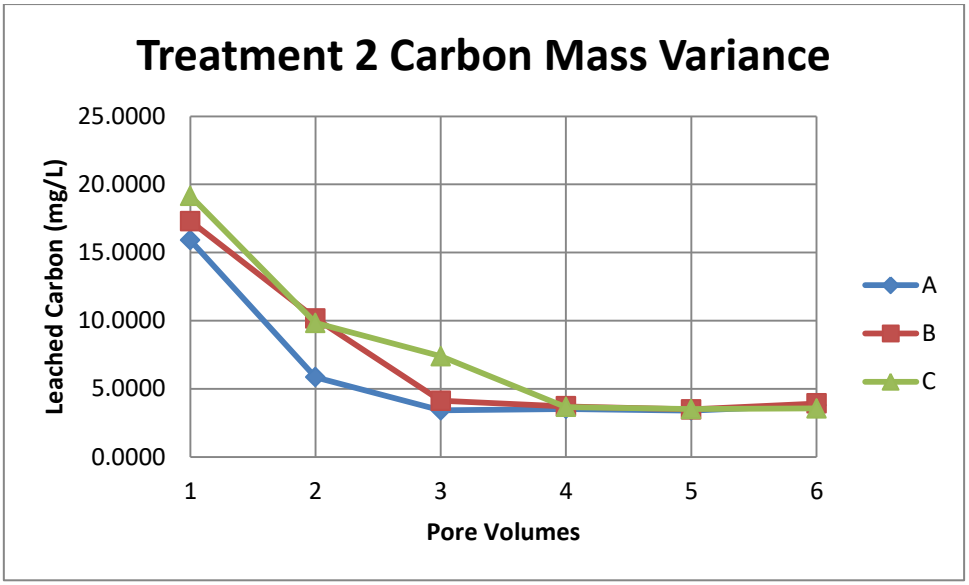

Figure 33: Comparison of variance in the mass of leached carbon amongst treatment 2 replicates.

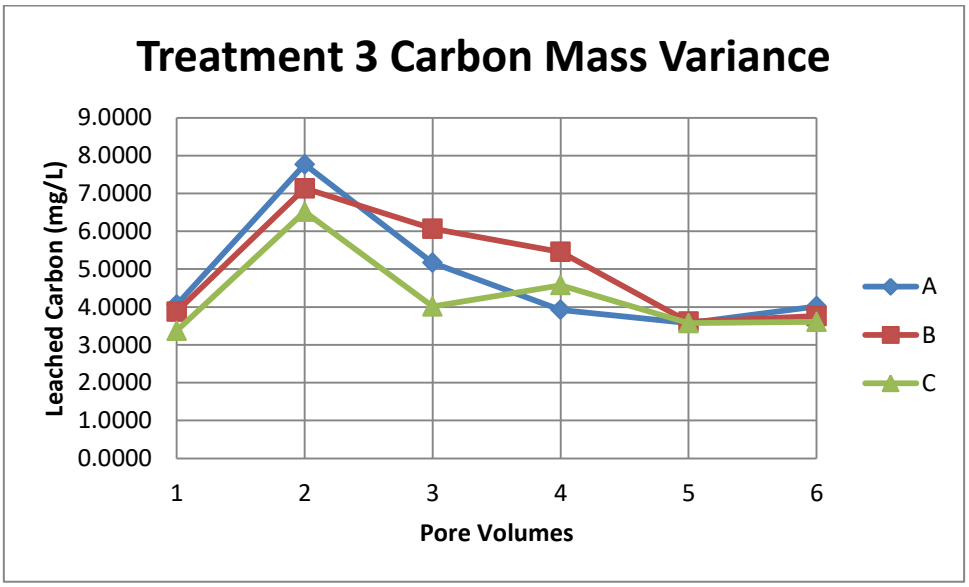

Figure 34: Comparison of variance in the mass of leached carbon amongst treatment 3 replicates.

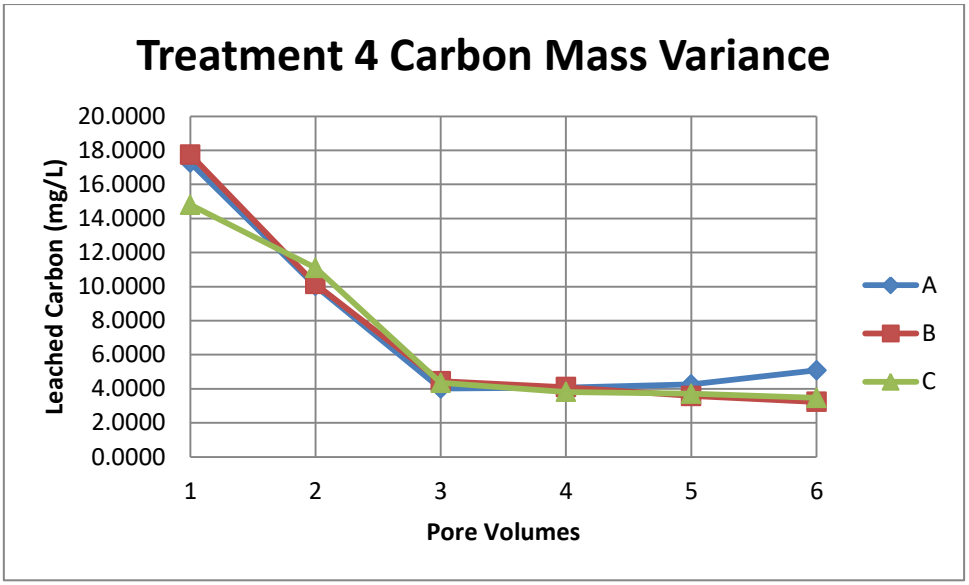

Figure 35: Comparison of variance in the mass of leached carbon amongst treatment 4 replicates.

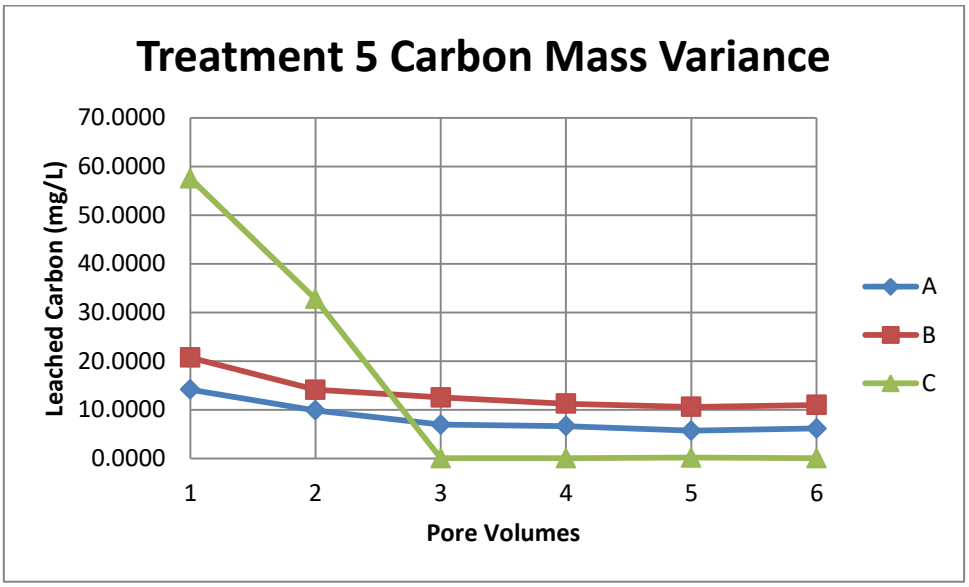

Figure 36: Comparison of variance in the mass of leached carbon amongst treatment 5 replicates. Note that all values for replicate C are outliers.

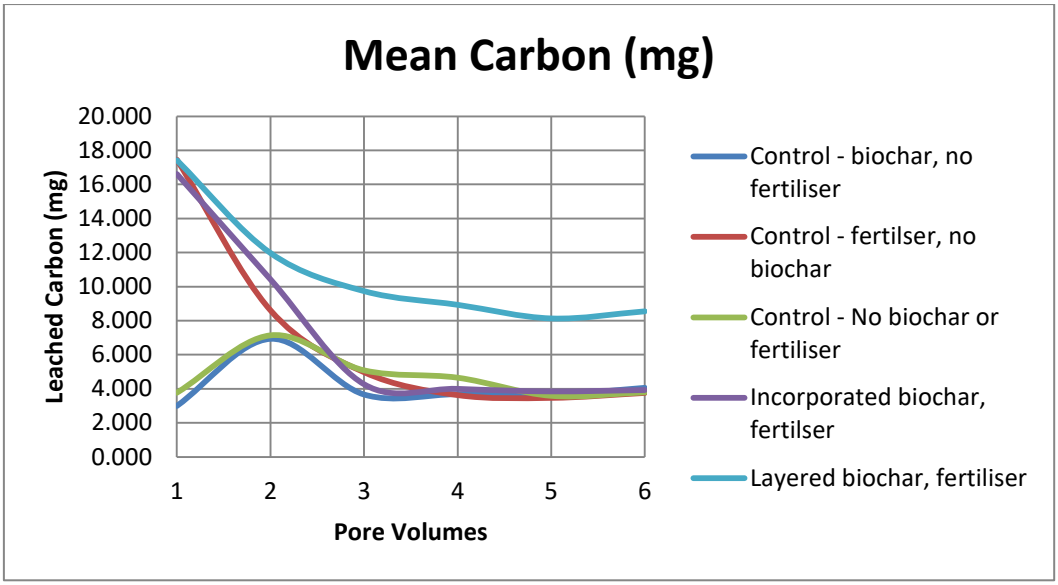

Figure 37: Comparison of leached carbon over time for the five treatments. Note outliers have been removed from consideration.

Additional plots may then be constructed by subtracting values of control treatments as baselines and considering the original quantity of carbon applied, 40.8mg (half the amount of N applied as urea has one carbon atom and two nitrogen atoms) to determine the quantity retained.

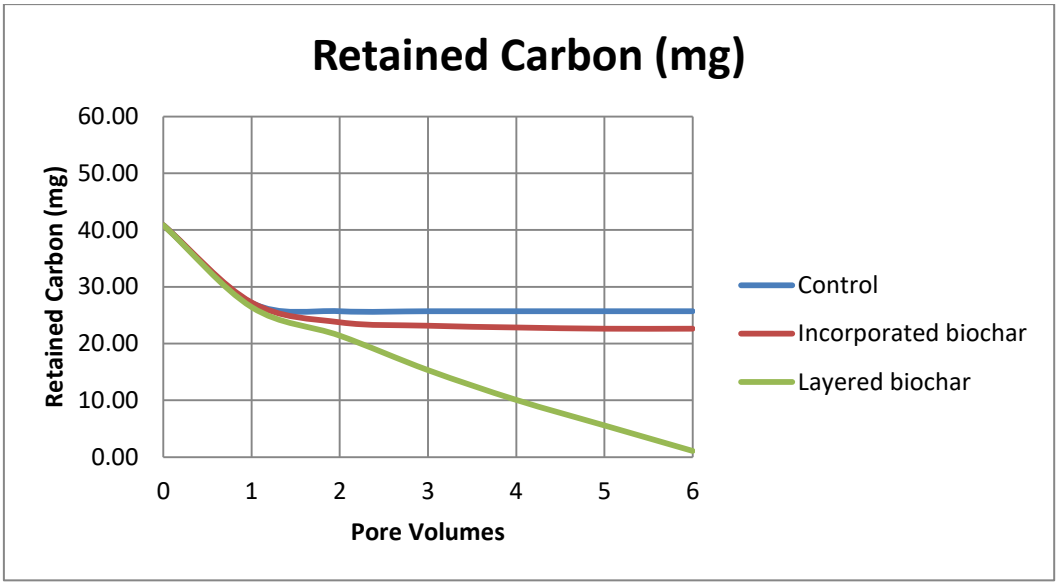

Figure 38: Comparison plot of mass of carbon retained between the unaltered soil and the two different biochar treatments.

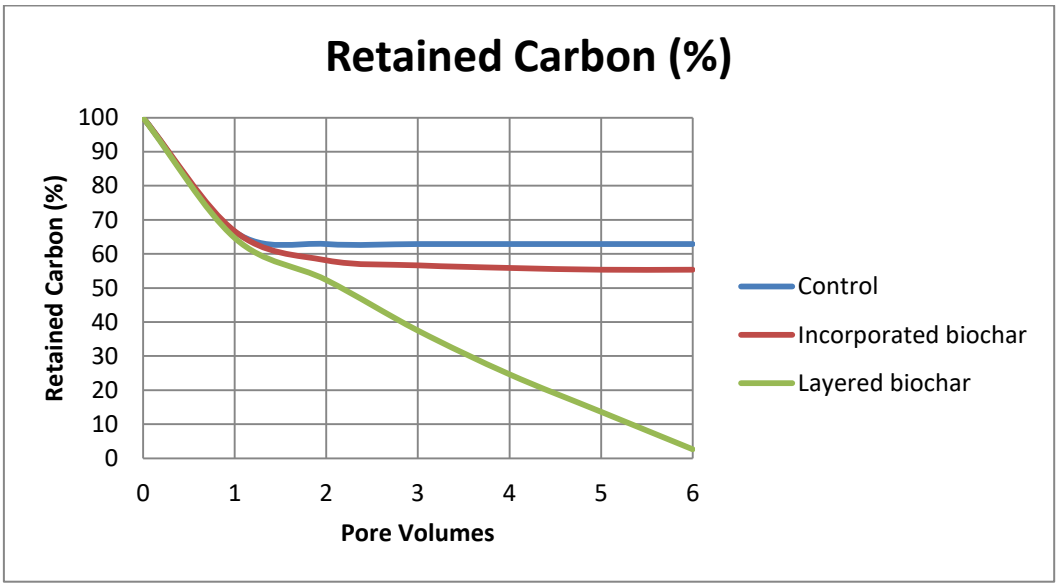

Figure 39: Comparison of the retained carbon as a percentage of the original amount applied.

4.5: Nitrogen to Carbon Ratio

After acquiring data on both nitrogen and carbon leaching, it is possible to evaluate the nitrogen to carbon ratio. If the amount of nitrogen is double the amount of carbon, it is a possible indication that the applied urea has washed straight through the soil. Table 3 summarises this data for the three treatments with fertiliser applied.

Table 3 – Nitrogen/Carbon						
Treatment	Pore Volumes					
	1	2	3	4	5	6
No biochar	1.7027	0.7761	0.1502	0.0702	0.0713	0.0350
Incorporated biochar	1.6846	0.9079	0.1152	0.0548	0.0639	0.0624
Layered biochar	1.2826	0.7026	0.1435	0.0798	0.0743	0.0694

Table 3: The ratio of leached nitrogen to carbon

4.6: pH Results

Graphs of sample pH are presented below. The first five plots compare the three replicates of the individual treatments to allow outliers to be spotted. Unlike previous parameters, however, pH is not essential to further calculations so it was decided to leave the outliers unamended for the sake of keeping the data unaltered. The sixth plot takes the mean of the replicates for each treatment and presents them together, allowing the different treatments to be compared.

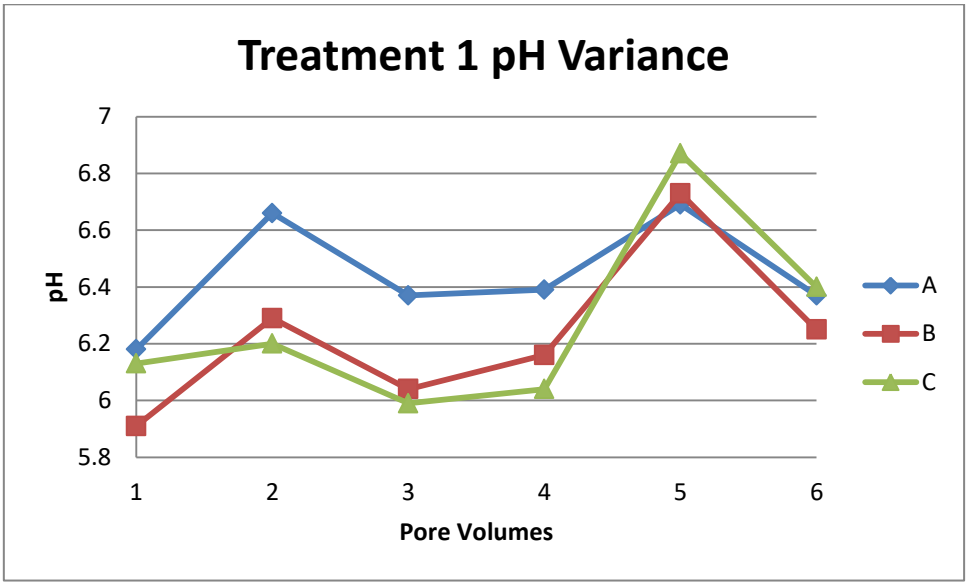

Figure 40: Comparison of the pH values of treatment 1 replicates.

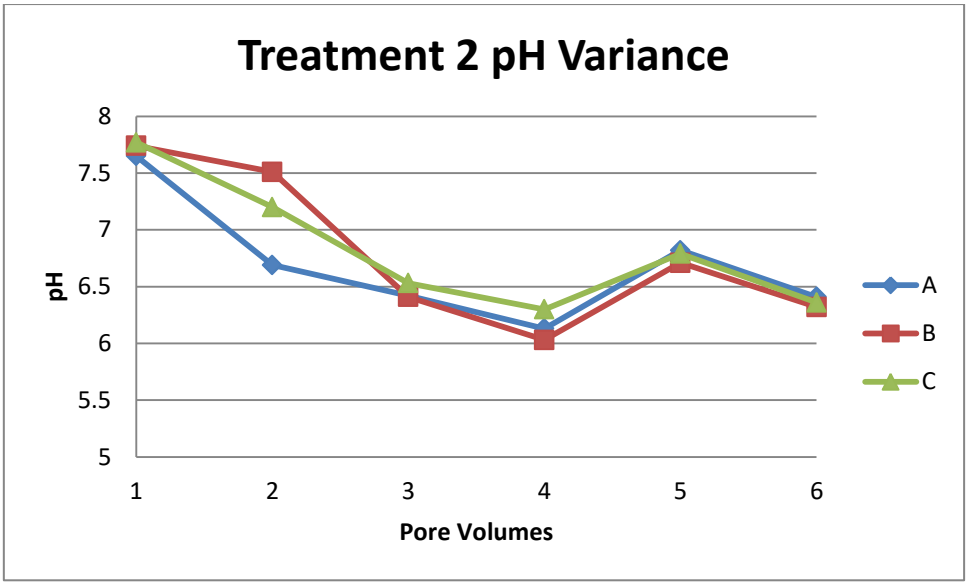

Figure 41: Comparison of the pH values of treatment 2 replicates.

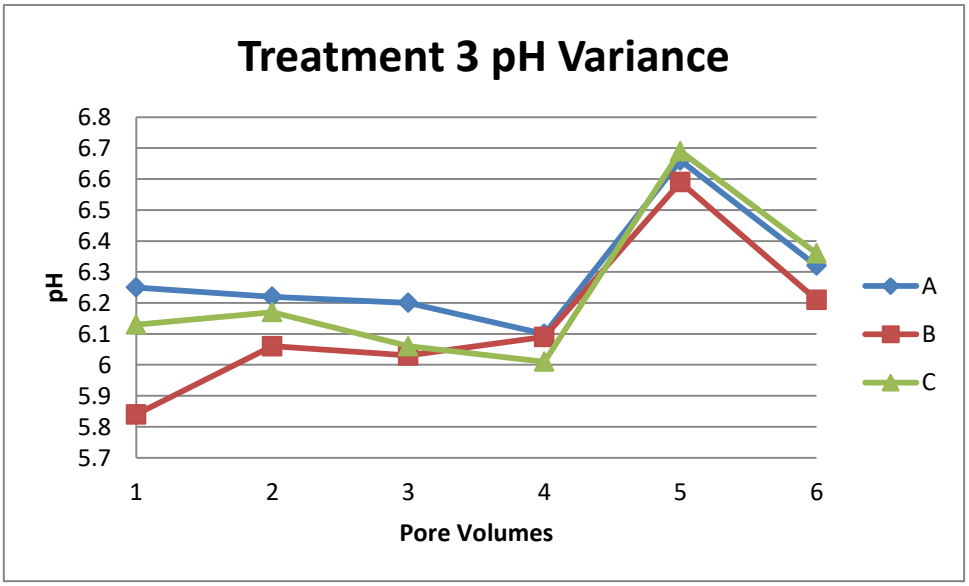

Figure 42: Comparison of the pH values of treatment 3 replicates.

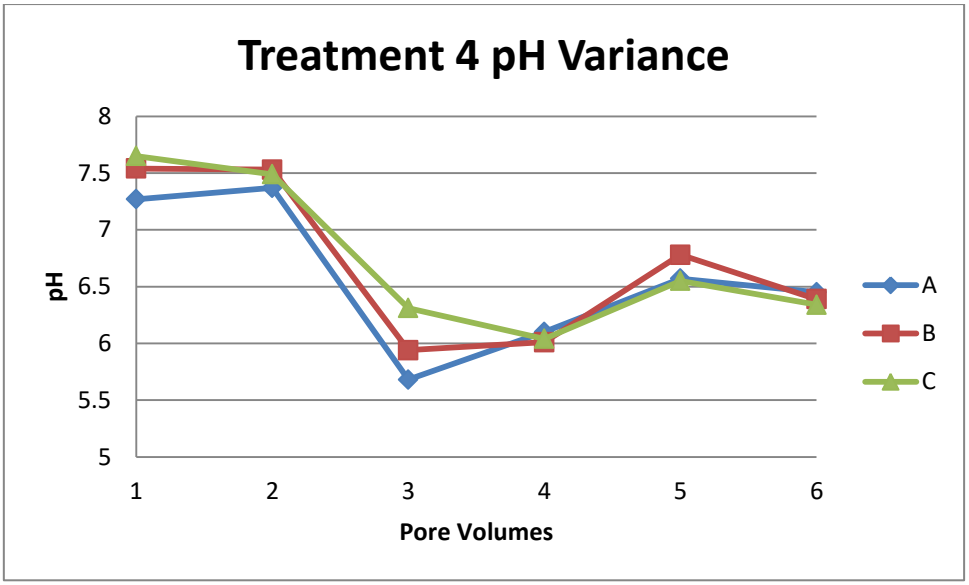

Figure 43: Comparison of the pH values of treatment 4 replicates.

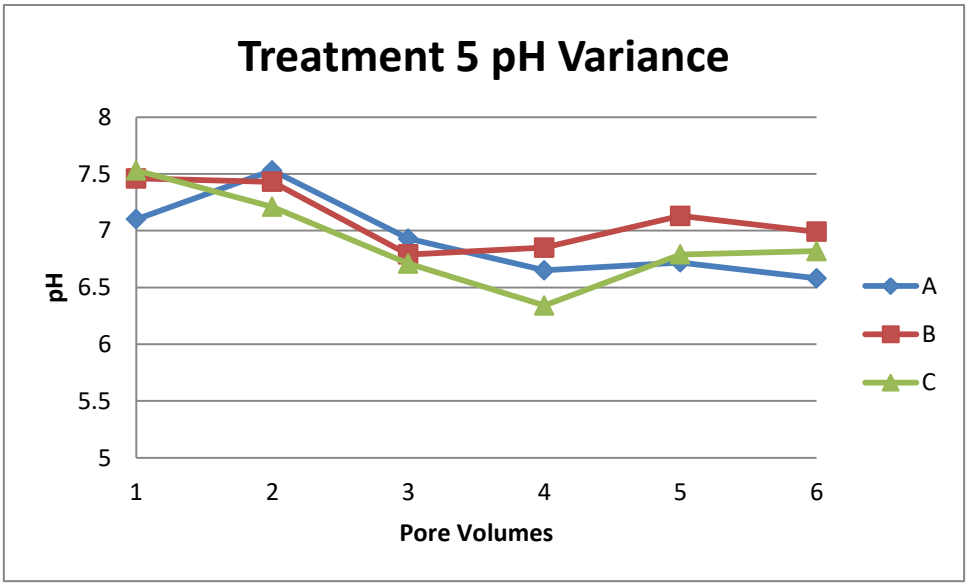

Figure 44: Comparison of the pH values of treatment 5 replicates.

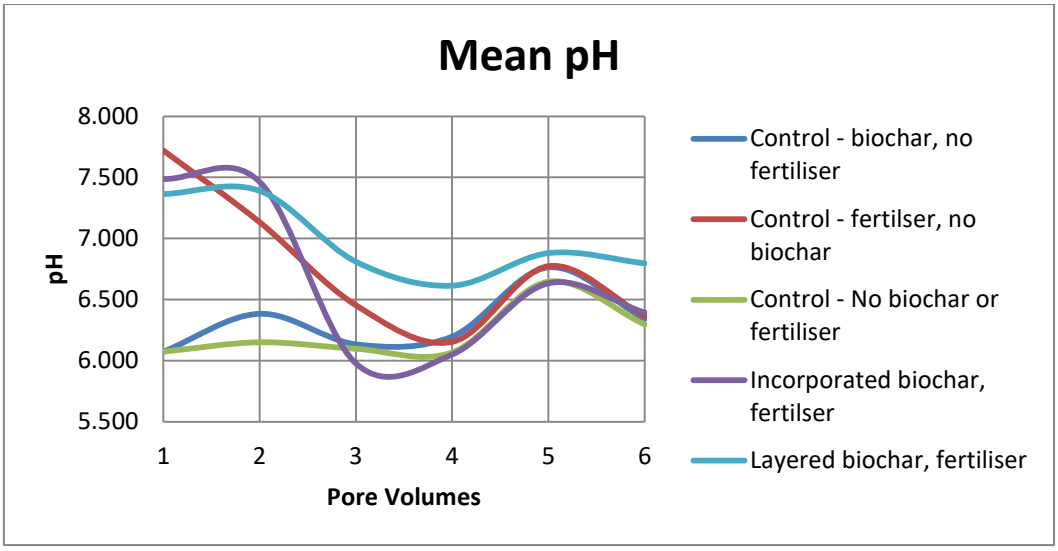

Figure 45: Sample pH averaged across the three replicates of each of the five treatments. Note the very different results.

4.7: Electrical Conductivity Results

Graphs of sample electrical conductivity, or EC follow. The first five plots compare the three replicates of the individual treatments to allow outliers to be spotted. Like pH, EC is not essential to further calculations so it was decided to leave the outliers unamended for the sake of keeping the data unaltered. The sixth plot takes the mean of the replicates for each treatment and presents them together, allowing the different treatments to be compared.

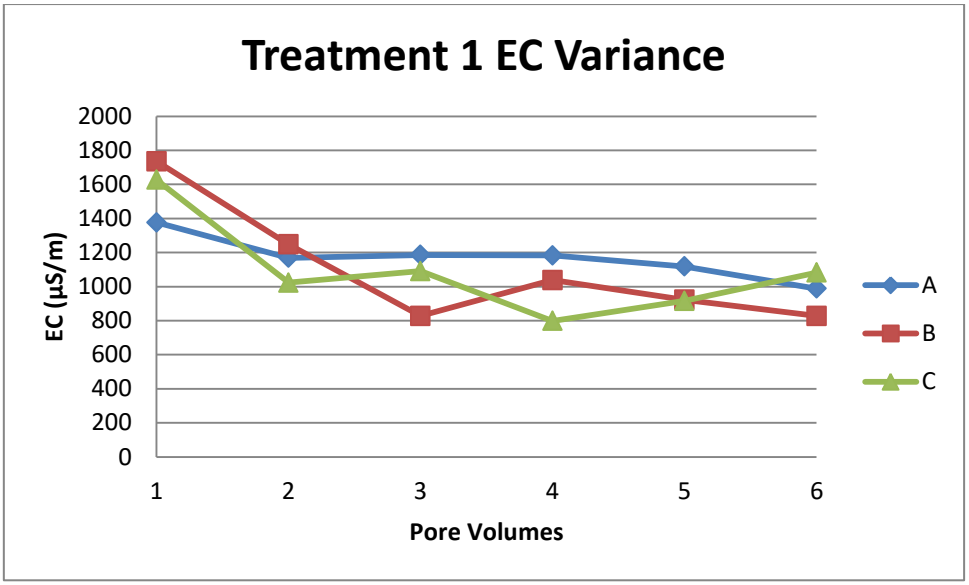

Figure 46: Comparison of the electrical conductivity values of treatment 1 replicates.

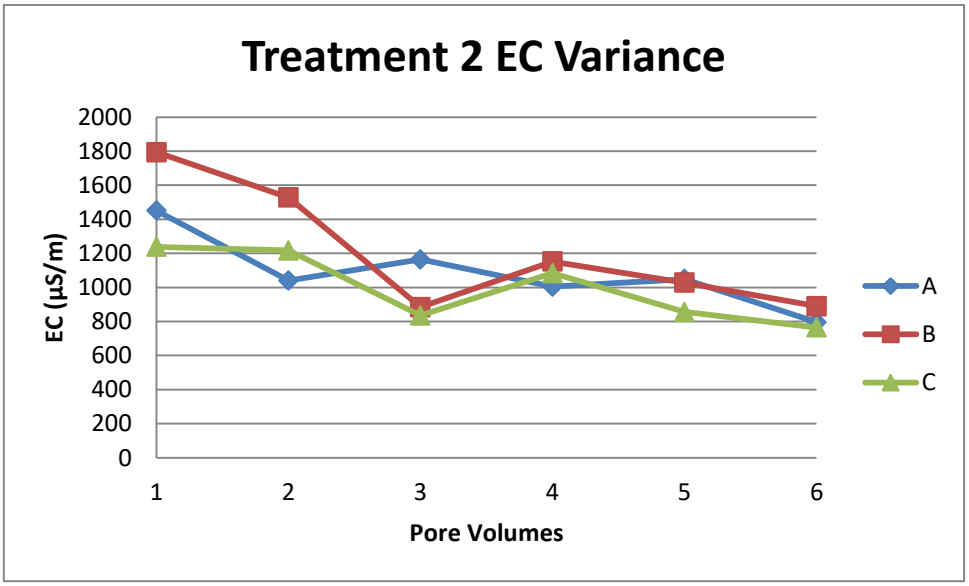

Figure 47: Comparison of the electrical conductivity values of treatment 2 replicates.

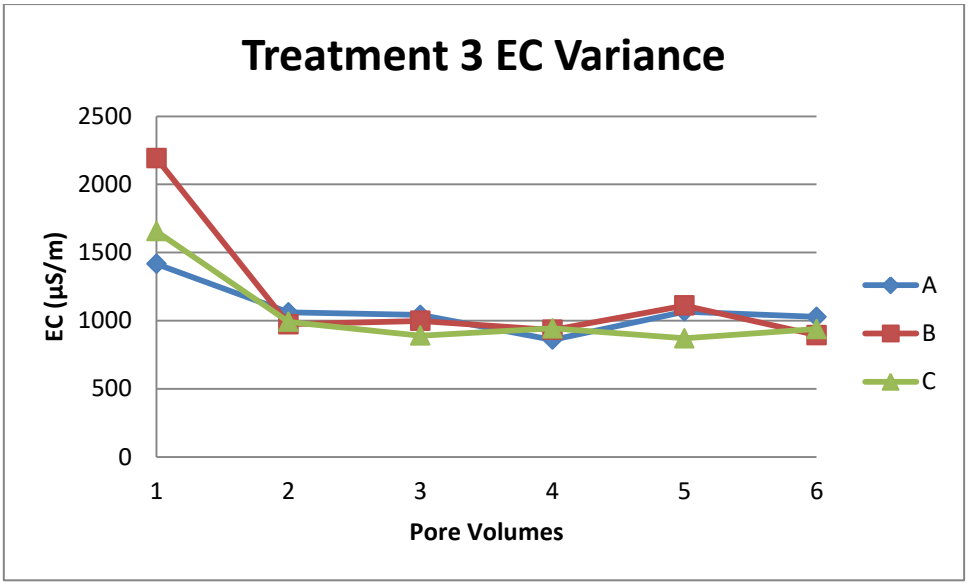

Figure 48: Comparison of the electrical conductivity values of treatment 3 replicates.

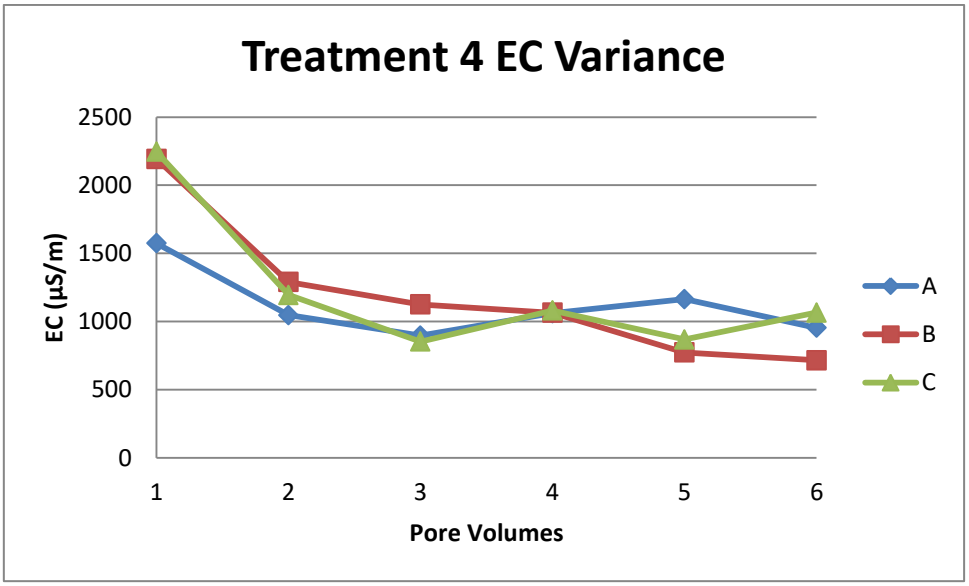

Figure 49: Comparison of the electrical conductivity values of treatment 4 replicates.

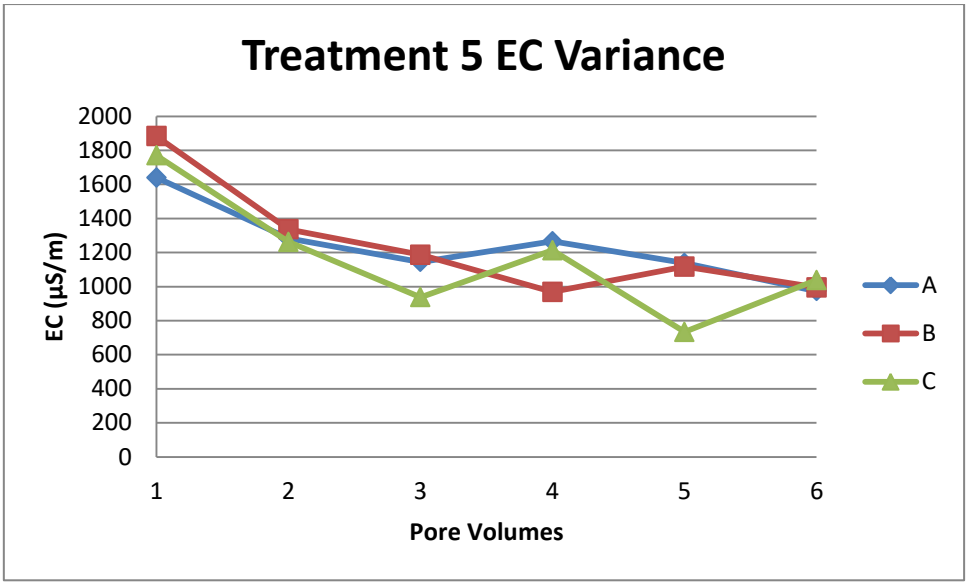

Figure 50: Comparison of the electrical conductivity values of treatment 5 replicates.

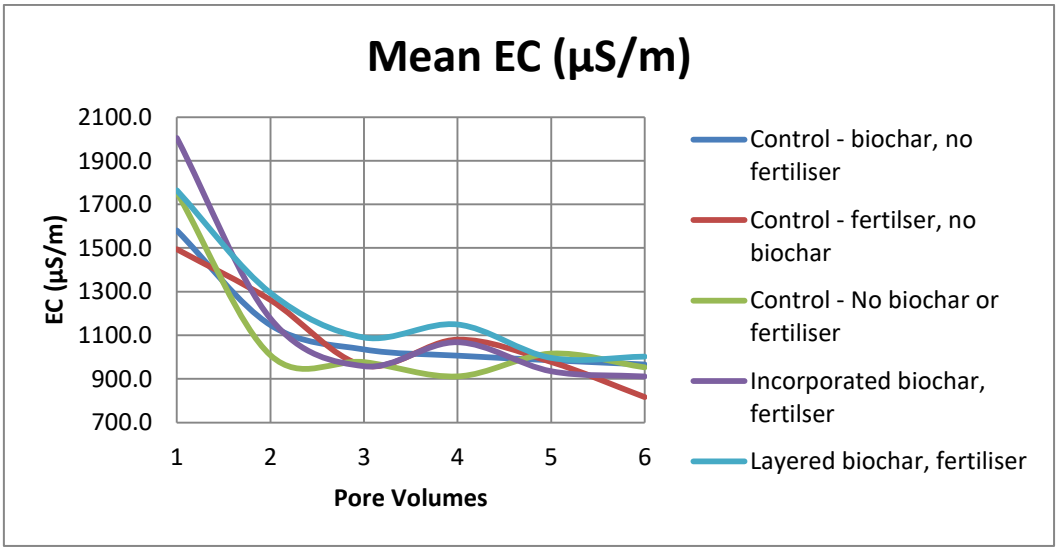

Figure 51: Sample electrical conductivity averaged across the three replicates of each of the five treatments. While each curve is distinct, they generally follow the same overall function.

4.8: Summary of Major Outliers

Notable outliers are listed in the following table by parameter. The removal of outliers from future calculations is also documented. As discussed earlier, it was decided to leave pH and EC data unaltered as these values were not required for further calculations.

Table 4 – Notable Outliers		
Parameter	**Sample**	**Remove from Calculations of Mean and Other Values?**
Nitrogen (ppm)	1C-1	Yes
	5C-1	Yes
Nitrogen (mg)	1C-1	Yes
	5C-1	Yes
Carbon (ppm)	1C-2	Yes
	All of 5C	Yes
Carbon (mg)	1C-2	Yes
	All of 5C	Yes
Mass	2C-3	Yes
pH	2A-2	No
	2A-3	No
	2A-4	No
	3B-1	No
Electrical Conductivity	3B-1	No
	4A-1	No
	5C-5	No

Table 4: Summary of notable outliers

4.9: Deconstructed Columns

This section presents photographs of the deconstructed soil columns.

Figure 52: Columns of Treatment 1. From left to right: 1A, 1B, 1C. These columns have biochar but no fertiliser applied.

It can be seen that all three of the above columns have formed a hard cylindrical structure, albeit with coarse, almost loose aggregates at the base. Pieces of incorporated biochar are just visible as dark areas, particularly in 1C.

Figure 53: Columns of Treatment 2. From left to right: 2A, 2B, 2C. These columns have fertiliser but no biochar applied.

It can be seen that the above columns have a similar overall structure to the previous set but no visible biochar, as none was added. The filter paper on these columns is also badly damaged, possibly by the fertiliser.

Figure 54: Columns of Treatment 3. From left to right: 3A, 3B, 3C. These columns have no fertiliser or biochar applied.

The columns seen above are similar to the previous two sets but exhibit a weaker structure, being much easier to break.

Figure 55: Columns of Treatment 4. From left to right: 4A, 4B, 4C. These columns have fertiliser and incorporated biochar applied.

The above columns were noted for their combination of visible biochar, damaged filter paper and coarser structure overall.

Figure 56: Columns of Treatment 5. From left to right: 5A, 5B, 5C. These columns have fertiliser and layered biochar applied.

The above columns are similar to those of treatment four with the exception of a clear biochar layer, which allows the column to be easily split in half. The interior of column 5B is presented in an additional image on the following page where the biochar is clearly visible:

Figure 57: View of the two broken halves of 5B. As expected the biochar layer created a point of structural failure.

5: Discussion

Results and other aspects of the experiment will be discussed in this section. These include the limitations in the applicability of the results to real-world situations and the various potential sources of error. As in the previous section, results will be broken down by parameter.

5.1: Discussion of Mass/Volume Results

Recalling figure 11, it can be seen that all treatments produce similar quantities of leachates.

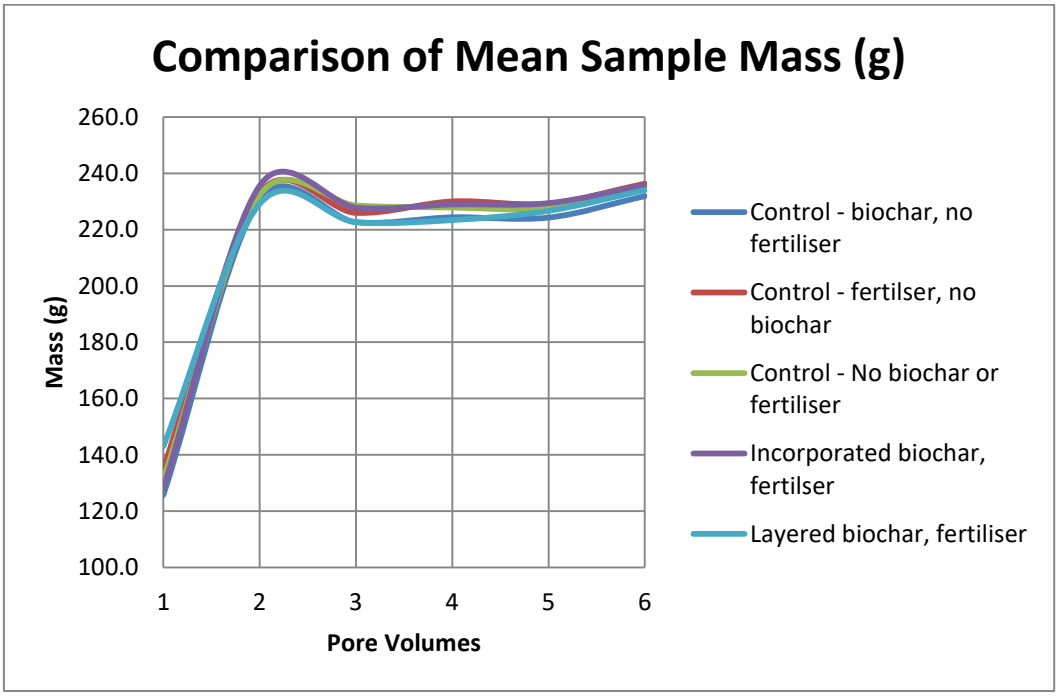

Figure 11: Comparison of mean leachate mass (or volume) between treatments. Note outliers have been removed from consideration.

Starting with the soil at field capacity rather than saturation meant that the full 292mL of the first storm would not flow through the columns, but that a good portion of it would become trapped instead. This is reflected in the low volume of leachates produced by the first pore volume. It can be seen that the rate of leaching peaks at the second rainfall event as the soil jumps towards saturation. Leachate volume then reduces to around 225mL before slowly climbing towards 235mL. Although the initial peak at 2.5 pore volumes is greatly exaggerated by the graphing software, a cursory check of the earlier straight-lined plots reveals similar – albeit smaller – peaks. The gradual increase over later pore volumes is likely caused by rate of "rainfall" exceeding the rate at which smaller soil pores can absorb water, causing more leachates to wash out.

Most interesting however, is that the full volume of 292mL is never leached through, implying some 60mL of water is either evaporating or becoming trapped in the soil columns. Even though the experiment was conducted indoors, some level of evaporation would still be expected, particularly given the 48 hour gap between rainfall events. The fact that all water was observed to disappear into the soil column within half an hour of being applied also indicates that there was plenty of time for leachates to evaporate. It is also likely that some of the missing 60mL went into filling soil pores as it would take many pore volumes of wetting for the soil to reach saturation.

Of course, it should also be remembered that converting mass to volume relies on some assumptions which could reduce the accuracy of further calculations. The first of these is that the density of water does not change with temperature, or even that 1g of water equals 1mL regardless of temperature. While this is largely the case, the presence of nutrients and other impurities in the leachates slightly reduces the accuracy of this assumption.

5.2: Discussion of Nitrogen

Certainly the most important parameter in this case, nitrogen content of the leachates denotes the quantity of fertiliser washed out, and hence the capacity of biochar to reduce these losses. It is for this reason that figure 25 is perhaps the most important of this entire investigation, highlighting that biochar can reduce fertiliser losses.

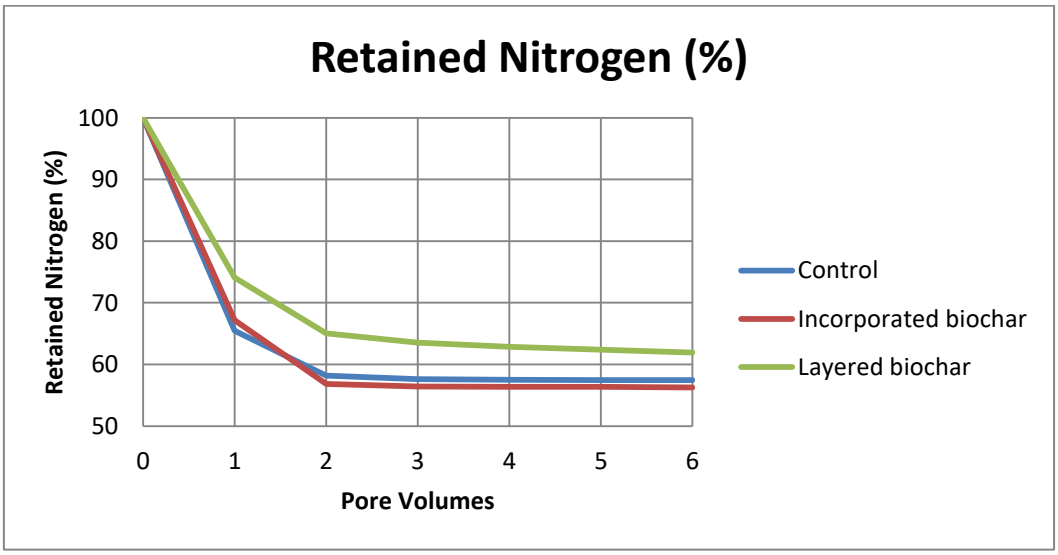

Figure 25: Comparison of the retained nitrogen as a percentage of the original amount applied. Recall that outliers were removed to generate this result.

As seen above, the addition of layered biochar can improve the nitrogen retention by almost 5% after six pore volumes. Benefits are even more pronounced after one or two pore volumes, where an additional 10% of the original nitrogen applied is available to plants. In effect the area between the layered biochar and control curves is extra time and nutrients available to plants. Although it is the least realistic of the two application methods, with a fine layer of biochar being carefully arranged 4cm below the surface, it may actually represent a scaled down model of the original field trial which used a rotary hoe to incorporate biochar throughout the top 20cm of soil. More research would be required however, to investigate if columns can be scaled in the vertical

direction to simulate larger soil profiles. A more likely means of achieving this process in the field is simply applying biochar to the surface (where it is more likely to encounter fertiliser) and waiting several years for it to move down through the soil profile. It may also be possible to integrate a layer of biochar into the soil using a plough or other piece of existing agricultural equipment. Another possible flaw in the layered treatment is that spreading the biochar as a layer over the whole soil column effectively creates a filter, which may simulate the behaviour of the biochar exclusively, rather than the relationship between the soil and biochar which is being examined.

It can also be seen that all the two lower curves are converging on a near steady retained nitrogen level of 56%, perhaps indicating the addition of biochar is not worth the small gains. Given that the biochar used costs $10 for a 10L bag weighing approximately 5kg, achieving an application rate of 10 tonnes per hectare would require $20,000 per hectare of crop. Although biochar persists in the soil for thousands of years, the time taken to see a return of the investment may be too long for many producers, even when considering a possible reduction in fertiliser application rates.

It is possible – if not necessarily probable – that if the incorporated biochar had not performed so poorly during the second rainfall event that it may have proven to be a functional solution as well. This is particularly apparent when one considers that incorporated biochar performed slightly better than untreated soil during the first rainfall event. Focusing on the four events produces the following figure:

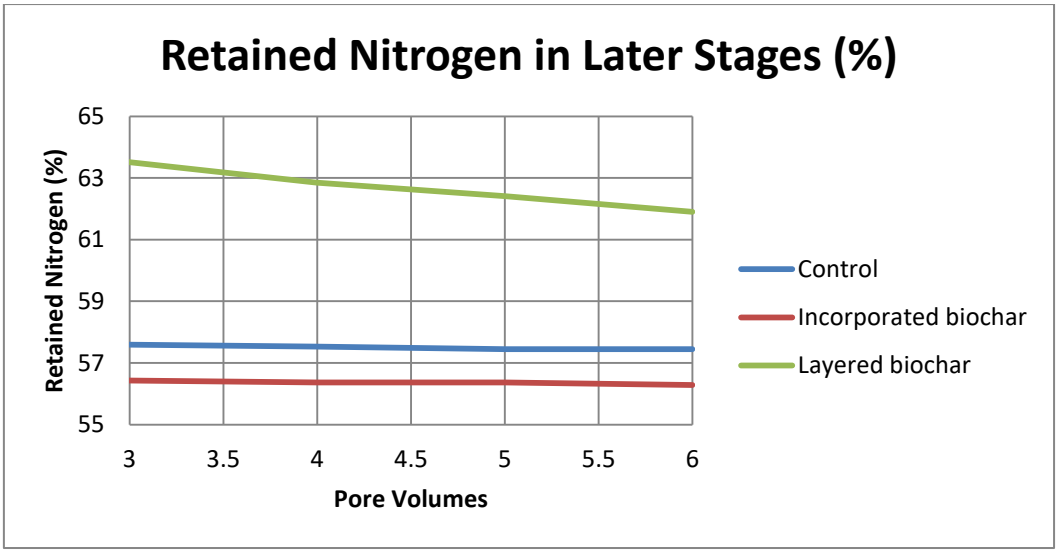

Figure 58: A close up of nitrogen retention in the later stages of the experiment.

The above figure shows that the curves of the control and the incorporated biochar are more parallel than converging, with the layered biochar curve moving to either converge or intersect. Despite convergence being more likely, it would be beneficial to conduct longer experiments to confirm layered biochar does not actually perform worse than unaltered soil in the long term.

5.3: Discussion of Carbon

Figure 37 is the first chart to be examined when considering the carbon leaching results to see if large quantities of biochar have leached through.

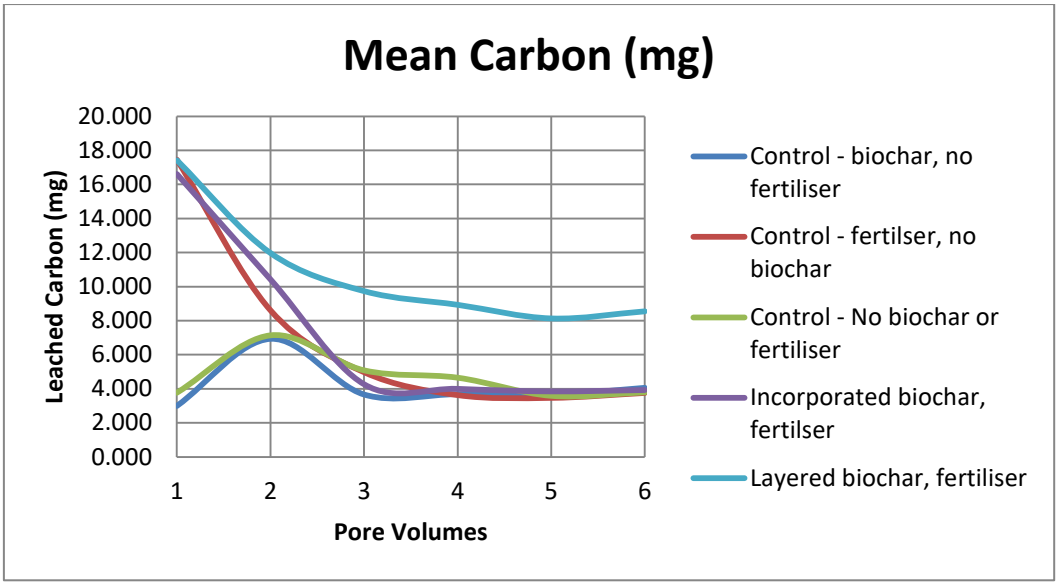

Figure 37: Comparison of leached carbon over time for the five treatments. Note outliers have been removed from consideration.

It can be seen that the biochar in soil control actually performs better than the plain soil control, indicating that no biochar is lost. A possible exception to this may be the layered biochar with fertiliser treatment. Despite retaining much more nitrogen than the other treatments, it appears this has been somehow compensated for with carbon losses. Although such high values may point to an outlier, all results from column 5C were already removed from consideration for this reason. Reviewing figure 36 highlights this inconsistency and proves the high rates of carbon leaching in layered biochar columns.

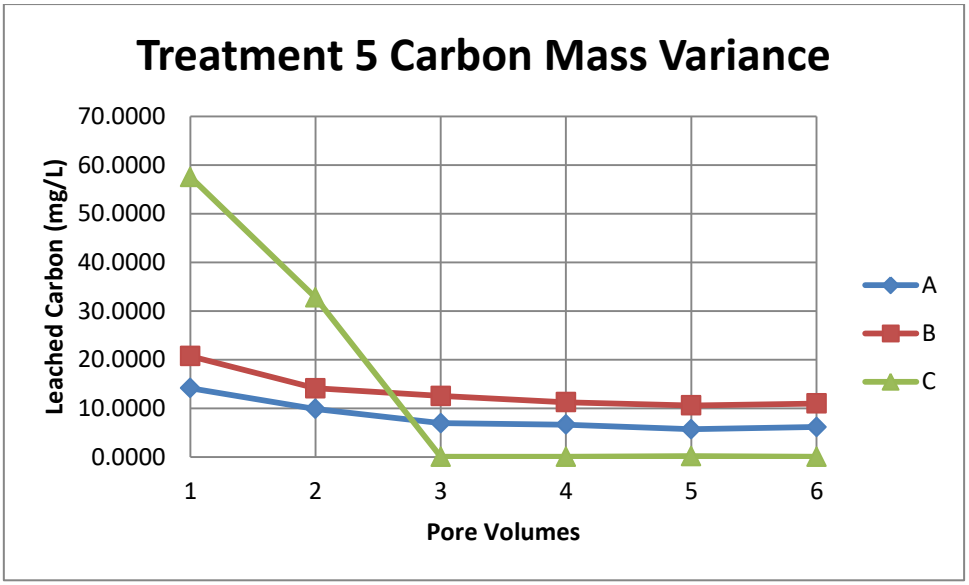

Figure 36: Comparison of variance in the mass of leached carbon amongst treatment 5 replicates. Note that all values for replicate C are outliers.

Sample 5C carbon leaching is excessive in early stages then reduces almost to nothing. This may indicate a poorly constructed column where large quantities of fine biochar – or some other form of carbon – are leaching out. It should be noted however, that there is still considerable variance in the level of carbon leaching between all three layered biochar replicates, even if they all present a picture of heavy carbon leaching compared to the other treatments. While all three treatments involving fertiliser exhibit high levels of carbon leaching on the first few days, the continued losses from layered biochar treatments is concerning. Even considering replicates A and B as outliers and taking 5C as the definitive value would do nothing to reduce the overall carbon lost, but simply move the losses to earlier rainfall events. Inspecting figure 39 further highlights the extent of this issue:

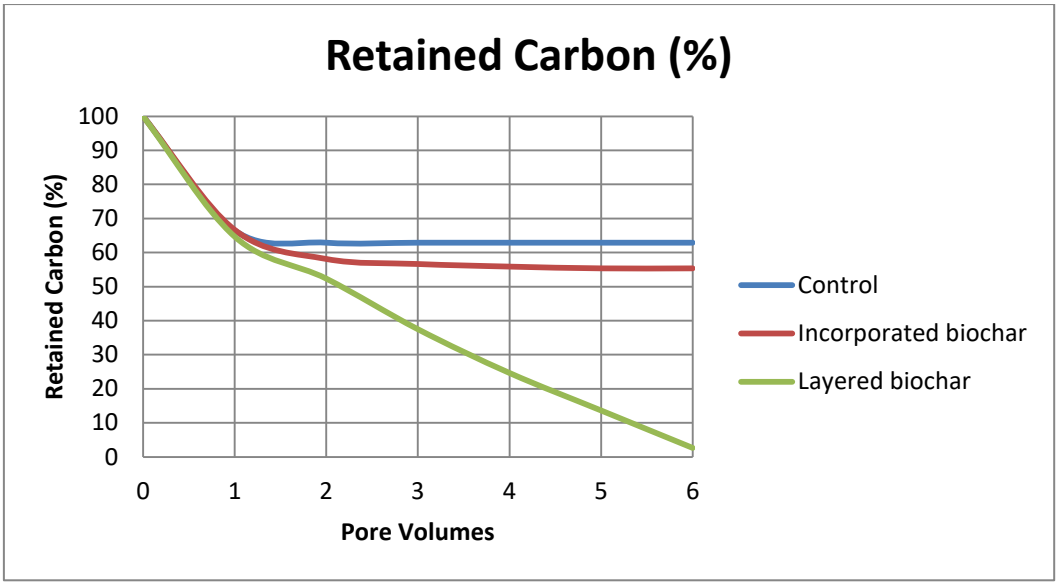

Figure 39: Comparison of the retained carbon as a percentage of the original amount applied. This plot takes into account the carbon leached from biochar and soil without fertiliser applied to focus on the retention of fertiliser.

Both biochar treatments leached more carbon, however the layered biochar treatment managed to lose all but 2.6% of the additional carbon applied in fertiliser. The loss of so much additional carbon in the otherwise successful layered biochar treatments may indicate that some of the benefits gained by using biochar to increase soil carbon and organic matter may actually have been lost. This would be particularly concerning in instances in where biochar has been applied with the additional goal of sequestering carbon, possibly to offset costs via government subsidies. If all the carbon were to wash out, there is a chance it would make its way back into the carbon cycle much sooner than anticipated, potentially having serious consequences for any established biochar industry.

5.4: Discussion of the Nitrogen to Carbon Ratio

The ratio of nitrogen to carbon may be discussed by examining table 3. This data serves as indicator of the amount of carbon relative to nitrogen that has been lost from the

fertiliser applied. Values closer to two (the ratio of nitrogen to carbon in urea) may indicate the amount of fertiliser that has leached without being broken down by soil microbes.

Table 3 – Nitrogen/Carbon

Treatment	Pore Volumes					
	1	2	3	4	5	6
No biochar	1.7027	0.7761	0.1502	0.0702	0.0713	0.0350
Incorporated biochar	1.6846	0.9079	0.1152	0.0548	0.0639	0.0624
Layered biochar	1.2826	0.7026	0.1435	0.0798	0.0743	0.0694

It can be seen that all three of the treatments with fertiliser applied initially leach more nitrogen than carbon but the reverse quickly becomes true. By the end of the test the no biochar columns are losing carbon at over 28 times the rate of nitrogen leaching.

Although the ratio of nitrogen to carbon approaches 2 initially, it is unlikely that large quantities of straight urea have been leached. For fertiliser added in the first rainfall event to leach through on the first day, it would need to somehow overtake the existing soil water which would be in the process of being pushed out. One possible explanation is that the water used to bring the soil to field capacity had not spread uniformly, allowing urea to pass through “dry patches” during the first rainfall event. The fact that many columns started leaching dirty water immediately after the first rainfall event was applied may support this. Inconsistent wetting is somewhat unlikely however, as it implies that the water containing the urea would wash straight through the soil while contributing little to wetting up the dry patches. In addition, the experiment was designed to ensure that water was applied as uniformly as possible across the soil surface by using a small ponded head, meaning – at least near the surface – that dry patches are unlikely.

Another possible explanation is that the boundary between the soil media and the wall of the column itself is more hydraulically conductive than the main body of the soil, acting as a path of least resistance. Such “edge effects” are often exaggerated however, and if such behaviour was occurring, it is likely that large quantities of the field capacity water would be stored in this boundary region and needing to be displaced before any urea fertiliser would be able to leach through. A third explanation could be that some other forms of nitrogen and carbon are leaching through. The main obstacle to this hypothesis is that more carbon *and* nitrogen was washed out of columns with fertiliser applied, indicating some dry patches, edge effects or some other phenomena may be responsible after all.

5.5: Discussion of pH

This subsection will refer heavily to the earlier graphs of pH results. While it can be seen in figure 45 (below) that pH values appear inconsistent, figures 40-44 reveal remarkable consistency across the replicates of individual treatments. Although pH is something of a supplementary parameter in this investigation, the fact that the strangely unique behaviour of each treatment is not random is fascinating. Although mean values in figure 45 have not been altered by the removal of outliers, the consistency amongst replicates indicates this would be largely unnecessary. The only real correlation between the various treatments occurs between 4 and 6 pore volumes, with all treatments exhibiting a curious rise in pH during the fifth rainfall event. Additionally, the columns with fertiliser applied do exhibit higher pH values in earlier stages, with layered biochar displaying a higher pH in later stages as well. This contrasts with the incorporated biochar and fertiliser curve, which reaches the lowest overall pH during the middle of the experiment. Reassuringly, it can be seen that the addition of biochar to plain soil does provide a slight increase in pH across the board, indicating a possible application in acidic soils. This still pales in comparison, however, to the clear relationships seen among the replicates of all the treatments, giving rise to a possible area of further study.

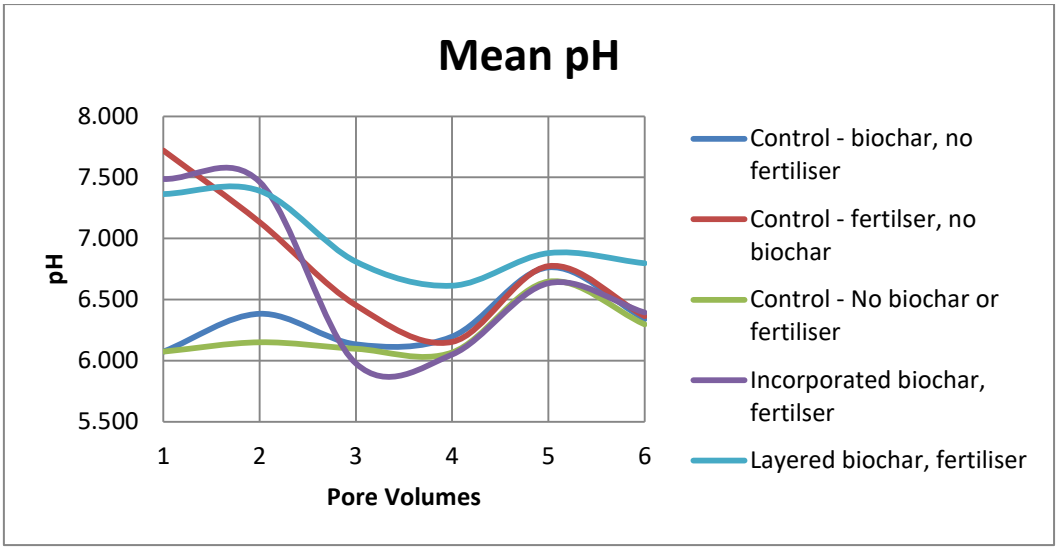

Figure 45: Sample pH averaged across the three replicates of each of the five treatments. Note the very different results.

5.6: Discussion of Electrical Conductivity

EC results are best summarised by figure 51 below:

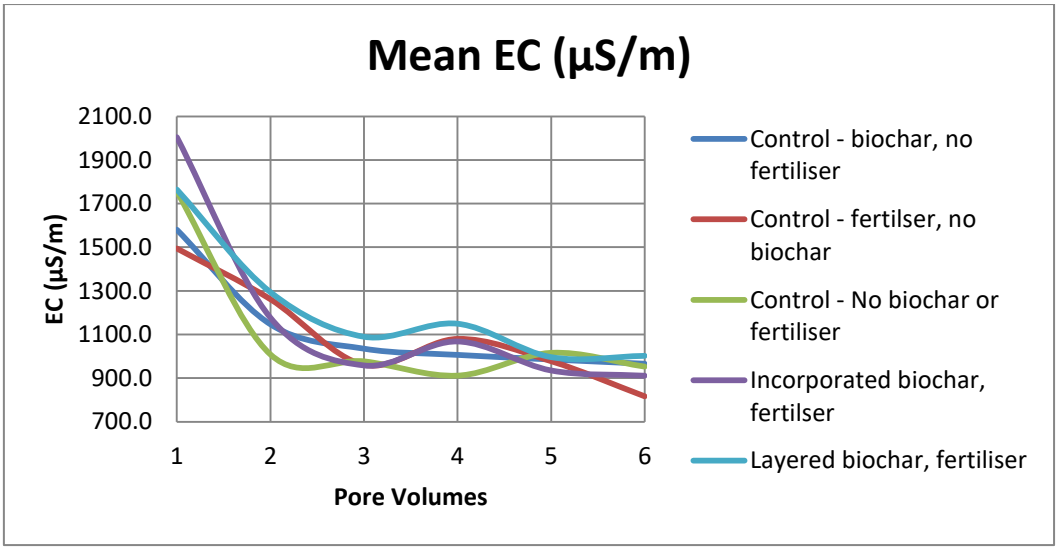

Figure 51: Sample electrical conductivity averaged across the three replicates of each of the five treatments. While each curve is distinct, they generally follow the same overall function.

While – like pH – there was limited variance among the replicates of the individual treatments, there seemed to be much less in the way of distinct patterns forming. This is largely the result of the similar curve shape seen across the treatments. Despite initially appearing as something of a tangled mess, it quickly becomes apparent the EC curves for each treatment start high and end low, with the exception of small fluctuations. It can be seen that the two treatments involving biochar and fertiliser increased the EC in the initial stages, though it is surprising that the controls with fertiliser and biochar individually display lower values of EC. Leachates from the plain soil had a high initial EC, but this quickly fell away to be among the lowest overall. The same is true for the incorporated biochar with fertiliser columns, which start with the highest EC and end with the second lowest. The layered biochar treatment generally exhibits a high EC across the board, possibly coinciding with the high quantities of lost carbon.

5.7: Limitations of the Experimental Design

Though all aspects of the experimental design were thoroughly considered, there were several compromises made which may impose limitations on the accuracy and/or applicability of the results to real world situations. One of these limitations was caused by the decision to use urea rather than a nitrate salt. While the use of urea would accurately reflect on-farm operations, the trade-off is that microbial breakdown of the fertiliser would be required before any ammonium or nitrate would be detected. Had the analysis strategy not later been changed to focus on total nitrogen, this issue would likely have led to questionable results.

Another issue is the concept of the column tests themselves. Designed to simulate accelerated leaching under rainfall, these tests have many qualities that are rather unlike rain. These include the forced infiltration and resulting ponded head, as well as the lack of raindrop impact effects.

Determining which treatments would be included, as well as the number of replicates and number of rainfall events also required compromise. For example, there was no control treatment of layered biochar without fertiliser, leaving it unknown if layered biochar performs markedly differently in the absence of fertiliser. The inclusion of only six rainfall events (which somewhat coincidentally gives six pore volumes) is another limitation as the full leachate composition over time remains unknown. While efforts were made to simulate 50mm spring rainfall on alternate days, it may be possible to have 200mm in a single event, or even several weeks between rainfall events, in which time nitrates could easily be lost to the atmosphere. This goes without reiterating that the column tests themselves are hardly an exact representation of rainfall events.

Statistical power of the experiment is also somewhat limited due to the use of only three replicates. Although adding more replicates would dramatically increase the volume of work required for potentially minimal gains in accuracy, it would have further validated the results. For example, it is possible – but extremely unlikely – that all replicates in this test are in fact outliers on many parameters and the only means of completely confirming otherwise would be the inclusion of more replicates. With these limitations in mind, it should be emphasised that the final experimental procedure was deemed the best solution using the resources available.

5.8: Comments on the Scale of Laboratory Work

It seems the most difficult aspect of this experiment is the level of laboratory work required to properly analyse the results. Several days of tedious filtering, measuring and analysing highlighted that the greatest obstacle to further research in this field is the need for more efficient means of analysing many samples. Leachate samples had to be strained through fiberglass filters before they could be used in most analysis machines. This involved the use of a screw-together mechanism and required the filter paper to be replaced and the mechanism rinsed with distilled water after every sample. Five treatments, three replicates and six rainfall events equated to 90 samples which needed to be strained by this method. Furthermore, the fact that the laboratory

machines used often consumed some or all of the samples necessitated the filtering of three vials' full of each sample, equating to 180 vials as illustrated in the image below:

Figure 59: Boxes of filtered sample vials ready for analysis.

Each of the boxes above contains 40 vials with all 180 vials taking two days and 90 pieces of fiberglass filter paper to complete.

Once the samples had been filtered into vials, they could be analysed by the various laboratory pieces of laboratory equipment. While the original three devices considered were a combined pH and EC probe, ammonium probe, and Thermo Fisher ICS 2000 ion chromatograph, complications with the latter two necessitated the use of alternate hardware. In the spirit of expedience, it was decided to use a Shimadzu TOC-V with

built-in TNM-1 as an alternative method of measuring leached nitrogen and – as something of a bonus – non purgeable organic carbon. While this machine proved much more reliable and consistent in its results, it still took almost two days of continuous operation to analyse 90 samples and three quality standards. Even before it was decided not to use the ICS 2000, the machine's long warmup time had a notable effect on the timelines of laboratory work. Furthermore, the combined EC and pH probe, while simple in operation and reliable in results, proved tedious to operate, taking roughly one minute to determine a result. The outcome of this was several hours of holding probes in vials, waiting for a result. Although this may appear to be an indictment of current laboratory procedures and equipment, it merely serves to emphasise the need for efficiency gains in this area. Reducing analysis times by 50% - not just for this investigation but others as well – would permit twice the number of samples. This would allow for a potential broadening of the scope to consider other parameters or a dramatic increase in statistical power by doubling the number of replicates. While the laboratory work performed here delivered the desired results, the development of more efficient analysis methods would be a wholly beneficial area of future study.

5.9: Potential Sources of Error

Although this may appear to be a relatively simple experiment, there are numerous potential sources of error which must be discussed.

There is a good chance some measurement error occurred over the course of the experiment, particularly in setting up the column tests. The very small quantities of urea and biochar added to the soil necessitated the use of very precise laboratory scales. 176.6mg of urea and 5.836g of biochar needed to be accurately measured nine times each, and then transported a considerable distance to another laboratory so they could be applied to the soil columns. The inconsistent aggregate size of both these materials – with the urea being a granulated fertiliser, as well as the biochar particles

taking a wide variety of shapes and sizes – made measuring the same precise quantities multiple times particularly difficult.

This was a particular problem with the urea, with 176.6mg being just a few granules. The inconsistency in particle sizes, though small, meant that one extra-large grain could increase the mass by as much as 10mg. While this was an issue, due diligence was taken to switch out pieces of fertiliser until the desired 176.6g was reached. In the timeframe practically available, this allowed for an accuracy of ±4mg to be achieved. While this may sound like a low accuracy threshold, the shape of the particles made significant further improvements almost impossible. The degree of consistency amongst the results also indicates that the correct quantities of fertiliser and biochar were measured.

Other sources of possible measurement error should also be noted including the measurement of water and soil. 292mL of water needed to be accurately measured 15 times for each rainfall event. While the repetitive nature of this task was a potential source of human error, and the measuring cylinder used had only 5mL increments, it is unlikely any significant mistakes were made. With the possible exception of one outlier, the sample mass results indicate that the volume of water applied in each event was consistent across samples, if not exactly 292mL. Measuring soil was another potential source of error due to the inherent compaction issues. Although it was decided to base the quantity of soil used around volume, 100mm deep in an 86.2mm diameter column, soil was primarily measured by mass for practicality reasons. This meant that even if the same amount had been applied to each column, every bump and jolt could have compacted the soil, reducing the volume.

While most columns appeared to be adequately constructed – and the results largely reflect this – it – was noted that column 4B did not have a level surface. This may have been indicative of an error while constructing the columns, a large amount of compaction on one side, or (unlikely given the results) a large amount of clay particle leaching on one side of the column. Of these three alternatives, the former is the most likely, with an error made in failing to level the column's surface before the beginning

of the experiment. Although no major mistakes seem to have occurred while conducting the column tests, the subsequent analysis work would have a number of potential sources of error.

In addition, the scale and repetitive nature of the analysis work discussed earlier makes human error a distinct possibility. While the upmost care was taken to avoid mistakes, there was always a chance that the samples could be labelled incorrectly or otherwise placed in the wrong vial. This would result in results from one sample being recorded for another. That being said however, the cohesive nature of the results indicates that such mistakes did not occur in this case. A combination of diligence, as well as strategies such as conducting analysis and bookwork simultaneously is believed to have reduced the likelihood of such errors to a satisfactorily low level of probability.

6: Conclusions

This study has proven conclusively, that biochar is a potential – if not necessarily viable – means of reducing fertiliser losses in agriculture. In the sugarcane industry in particular, high rainfall can cause significant fertiliser losses, causing economic and environmental damage. The addition of a layer of biochar to the soil profile provides a noticeable increase in the nitrogen retention ability of a well-drained soil used in sugarcane production. Unfortunately, biochar's utility is limited by its prohibitive price, with the specific biochar and application rate used in this investigation costing $20,000/ha. Although biochar would be expected to improve yields and reduce fertiliser requirements, it may take too long for many producers to see a return on their investment. This may necessitate the use of biochar with the secondary goal of carbon sequestration, however the results of this investigation indicate carbon leaching from biochar may preclude this. If anything, biochar has serious potential but will require significant further research and investment before widespread adoption.

6.1: Further Work

Even before completing this investigation, many other areas of study for future biochar research were apparent. By the end of the experiment, several additional pathways of further exploration had been uncovered. Running the same experiment over more rainfall events (or simply more rainfall overall) would be a highly beneficial, if perhaps tedious area of future investigation. Getting to the bottom of the leaching curve where no more fertiliser washes out would paint a more complete picture of the performance of biochar. Placing multiple small containers at the bottom of columns would be a means of measuring leachate distribution over a field, as well as the impacts of any edge effects caused by the column walls. Much wider columns – and hence more soil – would be recommended to achieve this with significant accuracy.

Further research using lysimeters would be extremely valuable, if expensive work as it would provide a much more complete picture of biochar's effects on the soil-water-nutrients relationship. Examining the effect of the biochar to fertiliser ratio, as well as looking at different environments would be other important areas, allowing agricultural scientists to recommend loadings to farmers based on their type of crop, soil and climate. How biochar functions alongside other soil additives such as calcium carbonate could also be examined. A more complex investigation would involve the manufacture of fertiliser itself and examine the merits of biochar coated fertiliser pellets, pre-loaded biochar and other composites. Ultimately, it will be the performance of biochar in expensive field trials – and just as importantly its price – which will determine if this carbon product ever sees mainstream use.

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Appendices

Appendix A: Project Specification

ENG4111/ENG4112 Research Project

Project Specification

For: Matthew Hafey

Title: Amelioration of Fertiliser Runoff in Agriculture

Major: Environmental Engineering

Supervisors: Thomas Banhazi, Les Bowtell

Enrolment: ENG4111 Semester 1 2016, ENG4112 Semester 2 2016

Project Aim: Investigate the use of biochar soil additives to reduce fertiliser runoff (and probably leaching) in agriculture. Using cost-effective and easily applicable products to improve fertiliser retention will provide both financial and environmental benefits.

Programme: Issue A, 16th March 2016

1. Research background information regarding fertiliser runoff, biochar, and typical fertiliser loadings.
2. Use rainfall and/or runoff data, along with available equipment to develop an experimental procedure.
3. Use research – and possibly initial testing – to determine most important parameters and reduce scope.
4. Undertake experiments and compile results.
5. Study experimental results and discuss in report format.

If time and resources permit:

6. Undertake further experimentation by investigating previously cut parameters, further optimising parameters which have already been investigated, or simply repeating tests to ensure reliable results.

Appendix B: Alternative Soil Types

Across the globe there are many different types of soils and surrounding environments. Even within Australia itself there is considerable variety, opening the possibility that environment, and – by extension – soil type may be a limiting factor on the effectiveness of biochar to withhold nutrients. While the focus on sugarcane led to this investigation using Tenosols, a variety of other agricultural soils were considered. These have been discussed below:

Type 1 – Black Vertosols

These are clay rich soils found throughout Australia, particularly in the eastern interior. Characterised by cracks which occur in dry conditions, Vertosols are known for shrinking and swelling (The Australian Soil Classification n.d.). Generally brown grey or black in colour, they constitute the most common soils in Queensland, being highly regarded for their fertility and water holding capacity (Queensland Government 2013). Interestingly, Australia possesses both the greatest variety and the greatest area of these cracking clay soils on the planet (The Australian Soil Classification n.d.). Seasonal shrinking and swelling of Vertosols often leads to the formation of hummocky reliefs known as Gilgai (Bennett n.d.). Queensland boasts more than half of the country's Vertosols which cover 28% of the state's area and are utilised for 58% of its crops (Soil Science Australia 2015). With the exception of crusty surface horizons, Vertosols may be characterised by a clay content greater than 35% (The Australian Soil Classification n.d.). These soils exhibit a moderate degree of leaching, leading to a higher concentration of silica, as well as cations such as calcium and magnesium (McKenzie et al. 2004). Carbonate is often present in varying quantities with strongly acidic and sodic subsoils also being common (McKenzie et al. 2004).

Highlighting their utility, Vertosols are subjected to a range of agricultural practices including both dryland and irrigated cropping, as well as with grazing operations on

native, improved or irrigated pastures. Agriculture on Vertosols is highly dependent on rainfall as they are primarily found in arid and semi-arid regions with average rainfalls as low as 200mm annually (McKenzie et al. 2004). As would be anticipated, the extent of cracking prior to rain events affects water infiltration. Due to the shrink-swell behaviour of Vertosols, low intensity rainfall often closes the cracks before large quantities of water can run in. This is only exacerbated by the poor permeability of swollen soils (McKenzie et al. 2004) meaning water is liable to runoff once cracks have closed. When cleared, Vertosols become vulnerable to sheet erosion whereby the finest (and most nutritious) soil particles are washed away by raindrop impact and shallow surface flow (Alt, Jenkins & Lines-Kelly 2009). This phenomenon may have interesting impacts on phosphorous runoff which should be examined. That being said, soils of this type in the Darling Downs region exhibit reduced nitrogen levels when subjected to cropping, while being naturally deficient in sulphur and zinc. Black Vertosols are the most frequent in this of soils group, with yellow varieties being much less common (McKenzie et al. 2004). As such, black Vertosols – the likes of which may be seen on the Darling Downs (McKenzie et al. 2004) – could yield valuable information if investigated.

Type 2 – Calcarosols

Found over a swathe of land around the Great Australian Bite, Calcarosols are characterised by the presence of calcium carbonate. Located in the semi-arid, Mediterranean climatic zone of South Australia and Western Australia, these soils typically receive annual rainfalls of 200 to 350mm (McKenzie et al. 2004). Although they are used in irrigated horticulture, Calcarosols are most commonly used for cereal growing. They exhibit shallow depth, low water retention, and often chemical problems such as sodicity, salinity and alkalinity. As far as fertilisers are concerned, Calcarosols are often phosphorous deficient, as well as requiring the addition of nitrogen when growing legume pastures (McKenzie et al. 2004). Despite exhibiting reduced levels of traced elements of copper, zinc and manganese (McKenzie et al. 2004), these soils are considered moderately fertile (Soil Science Australia 2015). The strong presence of calcium carbonate, combined with the need for phosphorous and frequent use in cropping enterprises, would make Calcarosols an interesting soil to examine.

Type 3 – Ferrosols

As the name suggests, Ferrosols are soils rich in iron, bestowing them with particular chemical and physical properties. While they can exhibit high clay contents of up to 70%, most varieties remain fairly permeable (McKenzie et al. 2004). In coastal Queensland in particular, Ferrosols can be blessed with high rainfall of over 3000mm annually, though much lower values of 500mm are also common. Ferrosols are spread across several distinct areas, leading to a variety of land uses including dairying on improved pastures, horticulture, forestry, and beef cattle grazing on native pastures. Most interesting however, is the production of sugarcane on Ferrosols around Innisfail and Bundaberg (McKenzie et al. 2004). Erosion, compaction and acidification are common issues on Ferrosols, particularly when cropping practices are involved. Many Ferrosols under cropping enterprises require application of nitrogen and phosphorous fertilisers to compensate for otherwise low fertility. Leaching can also be an issue on some red Ferrosols (McKenzie et al. 2004), marking them of particular interest to this investigation.

Appendix C: Photographs

Interesting supplementary photographs are presented in this section.

Figure 60: Up-close image of the biochar used. The lighter coloured pieces appear to be uncooked plant material.

Figure 61: Soil and biochar together for comparison. While this is the amount of biochar applied to the columns, the amount of soil is typically much greater.

Figure 62: The granulised urea fertiliser. This was dissolved in the water applied during the first rainfall event.

Figure 63: The experiment in action, water can be seen inside the bottles.

Figure 64: A close up of the working experiment. The lengths of poly pipe extend from the bottles to control the depth of ponded head.

Appendix D: Tables of Results

Raw Data

Raw results are presented here in table form:

Table 5 – Leachate Mass (g)							
Treatment	Replicate	Pore Volumes					
		1	2	3	4	5	6
1	A	117.93	228.68	212.64	224.07	221.89	230.77
	B	121.31	225.76	223.10	221.25	219.69	228.16
	C	138.09	237.03	232.11	227.75	231.21	236.73
2	A	142.77	236.28	217.05	229.72	226.90	236.92
	B	128.67	229.77	234.82	227.14	225.24	233.28
	C	134.54	232.55	282.65	233.14	235.55	238.75
3	A	136.67	231.36	217.12	229.67	228.92	234.95
	B	125.21	228.45	229.67	224.67	220.22	233.33
	C	132.66	236.74	238.92	229.16	233.93	238.73
4	A	129.80	236.62	213.86	226.90	224.58	232.68
	B	127.27	233.38	233.01	228.46	231.07	237.44
	C	127.28	236.71	236.54	231.42	232.48	237.20
5	A	141.02	225.52	212.28	222.86	228.48	234.78
	B	144.12	229.26	224.58	220.82	223.08	232.94
	C	143.93	232.60	231.05	226.45	228.39	234.35

Table 5: Mass of leachates

Table 6 – Nitrogen (ppm)							
Treatment	Replicate	Pore Volumes					
		1	2	3	4	5	6
1	A	9.99	3.433	0.9442	0.8973	1.585	1.218
	B	9.425	5.669	0.7213	0.7509	0.916	0.6081
	C	5.415	4.269	0.4855	0.5321	0.8755	0.5051
2	A	192.7	15.27	1.825	1.018	1.222	0.9517
	B	222.7	38.98	2.421	1.249	1.147	0.08214
	C	245.3	32.16	4.519	1.056	0.8748	0.6269
3	A	11.27	2.649	0.9612	0.6125	0.8836	0.58
	B	12.64	3.233	1.621	1.474	0.7969	0.61
	C	10.43	3.767	0.7639	0.5688	0.6945	0.48
4	A	226.6	37.2	2.273	1.083	1.389	1.942
	B	239.2	39.5	2.191	0.9194	0.9517	0.5674
	C	189.3	43.82	2.022	0.87	0.8847	0.6254
5	A	155.2	41.17	6.724	3.45	2.216	2.458
	B	158.2	39.49	6.615	3.397	3.424	2.711
	C	242.8	29.65	5.532	2.736	2.373	2.431

Table 6: Nitrogen concentration of leachates

Table 7 – Carbon (ppm)							
Treatment	Replicate	Pore Volumes					
		1	2	3	4	5	6
1	A	24.36	30.7	19.09	19.23	18.41	21.45
	B	24.13	30.32	16.07	15.76	16.28	16.01
	C	23	21.01	14.42	14.3	14	15.07
2	A	111.4	24.74	15.71	15.34	15.01	16.01
	B	134.5	44.19	17.56	16.3	15.47	16.79
	C	142.4	42.25	26.14	15.69	14.88	14.89
3	A	29.7	33.57	23.79	17.09	15.61	17.1
	B	30.97	31.22	26.42	24.27	16.4	16.1
	C	25.39	27.52	16.8	19.96	15.27	15.11
4	A	133.1	42.39	18.75	17.98	18.93	21.85
	B	139.5	43.46	19.08	17.9	15.48	13.61
	C	116.3	46.89	18.37	16.49	15.96	14.6
5	A	100.1	43.69	32.67	29.7	24.82	26.14
	B	143.8	61.46	55.81	50.91	47.48	47.04
	C	399.6	140.8	0.09687	0.09687	0.6091	0.09687

Table 7: Carbon concentration of leachates

Table 8 – Nitrogen (mg)							
Treatment	Replicate	Pore Volumes					
		1	2	3	4	5	6
1	A	1.1782	0.7851	0.2008	0.2011	0.3517	0.2811
	B	1.1434	1.2799	0.1609	0.1661	0.2012	0.1387
	C	0.7478	1.0119	0.1127	0.1212	0.2024	0.1196
2	A	27.5124	3.6080	0.3961	0.2339	0.2773	0.2255
	B	28.6556	8.9566	0.5685	0.2837	0.2584	0.0192
	C	33.0035	7.4789	1.2773	0.2462	0.2061	0.1497
3	A	1.5403	0.6129	0.2087	0.1407	0.2023	0.1363
	B	1.5827	0.7386	0.3723	0.3312	0.1755	0.1423
	C	1.3837	0.8918	0.1825	0.1303	0.1625	0.1146
4	A	29.4134	8.8024	0.4861	0.2457	0.3119	0.4519
	B	30.4438	9.2186	0.5105	0.2100	0.2199	0.1347
	C	24.0947	10.3728	0.4783	0.2013	0.2057	0.1483
5	A	21.8868	9.2848	1.4274	0.7689	0.5063	0.5771
	B	22.8003	9.0536	1.4856	0.7501	0.7638	0.6315
	C	34.9470	6.8967	1.2782	0.6196	0.5420	0.5697

Table 8: Leached nitrogen (mg)

Table 9 – Carbon (mg)							
Treatment	Replicate	Pore Volumes					
		1	2	3	4	5	6
1	A	2.8729	7.0206	4.0594	4.3089	4.0851	4.9501
	B	2.9273	6.8451	3.5853	3.4870	3.5766	3.6529
	C	3.1761	4.9801	3.3471	3.2569	3.2370	3.5676
2	A	15.9049	5.8456	3.4099	3.5240	3.4058	3.7931
	B	17.3066	10.1537	4.1235	3.7024	3.4845	3.9168
	C	19.1590	9.8254	7.3886	3.6580	3.5050	3.5550
3	A	4.0592	7.7669	5.1654	3.9251	3.5735	4.0177
	B	3.8779	7.1323	6.0680	5.4528	3.6117	3.7567
	C	3.3683	6.5152	4.0139	4.5741	3.5722	3.6073
4	A	17.2768	10.0305	4.0099	4.0797	4.2514	5.0841
	B	17.7546	10.1428	4.4459	4.0895	3.5770	3.2316
	C	14.8031	11.0995	4.3453	3.8162	3.7104	3.4632
5	A	14.1164	9.8531	6.9353	6.6190	5.6710	6.1372
	B	20.7249	14.0905	12.5340	11.2421	10.5920	10.9577
	C	57.5158	32.7505	0.0224	0.0219	0.1391	0.0227

Table 9: Leached carbon (mg)

Table 10 – pH							
Treatment	Replicate	Pore Volumes					
		1	2	3	4	5	6
1	A	6.18	6.66	6.37	6.39	6.69	6.37
	B	5.91	6.29	6.04	6.16	6.73	6.25
	C	6.13	6.2	5.99	6.04	6.87	6.4
2	A	7.65	6.69	6.42	6.13	6.82	6.41
	B	7.74	7.51	6.41	6.03	6.71	6.32
	C	7.77	7.2	6.53	6.3	6.79	6.36
3	A	6.25	6.22	6.2	6.1	6.66	6.32
	B	5.84	6.06	6.03	6.09	6.59	6.21
	C	6.13	6.17	6.06	6.01	6.69	6.36
4	A	7.27	7.37	5.68	6.1	6.57	6.45
	B	7.54	7.53	5.94	6.01	6.78	6.39
	C	7.65	7.49	6.31	6.04	6.55	6.34
5	A	7.1	7.53	6.93	6.65	6.72	6.58
	B	7.46	7.43	6.79	6.85	7.13	6.99
	C	7.53	7.21	6.71	6.34	6.79	6.82

Table 10: pH of leachates

Table 11 – EC (µS/m)							
Treatment	Replicate	Pore Volumes					
		1	2	3	4	5	6
1	A	1377	1169	1186	1183	1118	988.2
	B	1736	1248	827.7	1038	922.4	827.7
	C	1628	1023	1091	798.2	915.9	1082
2	A	1451	1040	1164	1004	1049	795.3
	B	1794	1528	884.5	1152	1028	889.5
	C	1238	1217	835.1	1083	855.6	764.5
3	A	1417	1061	1042	859.1	1066	1027
	B	2192	973	998.4	932.3	1111	893.4
	C	1656	991	889.9	942.6	870.6	937.8
4	A	1574	1046	896.5	1060	1164	953
	B	2193	1290	1125	1064	772.6	715.1
	C	2246	1194	852.9	1080	868.2	1065
5	A	1640	1284	1144	1266	1138	973.5
	B	1883	1336	1187	968.9	1117	994.7
	C	1770	1262	937.9	1213	733.4	1038

Table 11: Electrical conductivity of leachates

Mean Values

Mean values of parameters are presented in the following tables:

Table 12 – Mean Sample Mass (g)							
Treatment		Pore Volumes					
		1	2	3	4	5	6
Control - biochar, no fertiliser	1	125.8	230.5	222.6	224.4	224.3	231.9
Control - fertiliser, no biochar	2	135.3	232.9	225.9	230.0	229.2	236.3
Control - No biochar or fertiliser	3	131.5	232.2	228.6	227.8	227.7	235.7
Incorporated biochar, fertiliser	4	128.1	235.6	227.8	228.9	229.4	235.8
Layered biochar, fertiliser	5	143.0	229.1	222.6	223.4	226.7	234.0

Table 12: Mean mass of leachates (g)

Table 13 – Mean Nitrogen (ppm)							
Treatment		Pore Volumes					
		1	2	3	4	5	6
Control - biochar, no fertiliser	1	9.71	4.46	0.72	0.73	1.13	0.78
Control - fertiliser, no biochar	2	220.23	28.80	2.92	1.11	1.08	0.55
Control - No biochar or fertiliser	3	11.45	3.22	1.12	0.89	0.79	0.56
Incorporated biochar, fertiliser	4	218.37	40.17	2.16	0.96	1.08	1.04
Layered biochar, fertiliser	5	156.70	36.77	6.29	3.19	2.67	2.53

Table 13: Mean nitrogen in leachates (ppm)

Table 14 – Mean Carbon (ppm)							
Treatment		Pore Volumes					
		1	2	3	4	5	6
Control - biochar, no fertiliser	1	23.83	30.51	16.53	16.43	16.23	17.51
Control - fertiliser, no biochar	2	129.43	37.06	19.80	15.78	15.12	15.90
Control - No biochar or fertiliser	3	28.69	30.77	22.34	20.44	15.76	16.10
Incorporated biochar, fertiliser	4	129.63	44.25	18.73	17.46	16.79	16.69
Layered biochar, fertiliser	5	121.95	52.58	44.24	40.31	36.15	36.59

Table 14: Mean carbon in leachates (ppm)

Table 15 – Mean Nitrogen (mg)							
Treatment		Pore Volumes					
		1	2	3	4	5	6
Control - biochar, no fertiliser	1	1.161	1.026	0.158	0.163	0.252	0.180
Control - fertiliser, no biochar	2	29.724	6.681	0.747	0.255	0.247	0.131
Control - No biochar or fertiliser	3	1.502	0.748	0.255	0.201	0.180	0.131
Incorporated biochar, fertiliser	4	27.984	9.465	0.492	0.219	0.246	0.245
Layered biochar, fertiliser	5	22.344	8.412	1.397	0.713	0.604	0.593

Table 15: Mean nitrogen in leachates (mg)

Table 16 – Mean Carbon (mg)							
Treatment		Pore Volumes					
		1	2	3	4	5	6
Control - biochar, no fertiliser	1	2.992	6.933	3.664	3.684	3.633	4.057
Control - fertiliser, no biochar	2	17.457	8.608	4.974	3.628	3.465	3.755
Control - No biochar or fertiliser	3	3.768	7.138	5.082	4.651	3.586	3.794
Incorporated biochar, fertiliser	4	16.612	10.424	4.267	3.995	3.846	3.926
Layered biochar, fertiliser	5	17.421	11.972	9.735	8.931	8.131	8.547

Table 16: Mean carbon in leachates (mg)

Table 17 – Mean pH							
Treatment		Pore Volumes					
		1	2	3	4	5	6
Control - biochar, no fertiliser	1	6.073	6.383	6.133	6.197	6.763	6.340
Control - fertiliser, no biochar	2	7.720	7.133	6.453	6.153	6.773	6.363
Control - No biochar or fertiliser	3	6.073	6.150	6.097	6.067	6.647	6.297
Incorporated biochar, fertiliser	4	7.487	7.463	5.977	6.050	6.633	6.393
Layered biochar, fertiliser	5	7.363	7.390	6.810	6.613	6.880	6.797

Table 17: Mean pH of leachates

Table 18 – Mean EC (µS/m)							
Treatment		Pore Volumes					
		1	2	3	4	5	6
Control - biochar, no fertiliser	1	1580.3	1146.7	1034.9	1006.4	985.4	966.0
Control - fertiliser, no biochar	2	1494.3	1261.7	961.2	1079.7	977.5	816.4
Control - No biochar or fertiliser	3	1755.0	1008.3	976.8	911.3	1015.9	952.7
Incorporated biochar, fertiliser	4	2004.3	1176.7	958.1	1068.0	934.9	911.0
Layered biochar, fertiliser	5	1764.3	1294.0	1089.6	1149.3	996.1	1002.1

Table 18: Mean electrical conductivity of leachates

Tables of Further Calculations

The following tables contain data that was produced through further calculations:

Table 19 – Mean Nutrients released from biochar						
	Pore Volumes					
	1	2	3	4	5	6
Mean Carbon Released from biochar (mg)	-0.776	-0.205	-1.419	-0.966	0.047	0.263
Mean Nitrogen Released from biochar (mg)	-0.341	0.278	-0.096	-0.038	0.072	0.049

Table 19: Nutrients released by biochar

Table 20 – Nitrogen Losses from Fertiliser (mg)							
		Pore Volumes					
	Treatment	1	2	3	4	5	6
Control	2	28.22	5.93	0.49	0.05	0.07	0.00
Incorporated biochar	4	26.82	8.44	0.33	0.06	0.00	0.07
Layered biochar	5	21.18	7.39	1.24	0.55	0.35	0.41
Note negative values were set to zero							

Table 20: Nitrogen lost from fertiliser applied

Table 21 – Carbon Losses from Fertiliser (mg)							
		Pore Volumes					
	Treatment	1	2	3	4	5	6
Control	2	13.69	1.47	0.00	0.00	0.00	0.00
Incorporated biochar	4	13.62	3.49	0.60	0.31	0.21	0.00
Layered biochar	5	14.43	5.04	6.07	5.25	4.50	4.49
Note negative values were set to zero							

Table 21: Carbon lost from fertiliser applied

Table 22 – Retained Nitrogen (mg)							
	Pore Volumes						
	0	1	2	3	4	5	6
Control	81.70	53.48	47.55	47.05	47.00	46.93	46.93
Incorporated biochar	81.70	54.88	46.44	46.11	46.05	46.05	45.98
Layered biochar	81.70	60.52	53.13	51.89	51.34	50.99	50.58

Table 22: Retained Nitrogen (mg)

Table 23 – Retained Nitrogen (%)							
	Pore Volumes						
	0	1	2	3	4	5	6
Control	100	65.46	58.20	57.59	57.53	57.44	57.44
Incorporated biochar	100	67.17	56.84	56.43	56.36	56.36	56.28
Layered biochar	100	74.07	65.03	63.52	62.84	62.41	61.91

Table 23: Retained Nitrogen (%)

Table 24 – Retained Carbon (mg)							
	Pore Volumes						
	0	1	2	3	4	5	6
Control	40.85	27.16	25.69	25.69	25.69	25.69	25.69
Incorporated biochar	40.85	27.23	23.74	23.14	22.83	22.61	22.61
Layered biochar	40.85	26.42	21.38	15.31	10.07	5.57	1.08

Table 24: Retained Carbon (mg)

Table 25 – Retained Carbon (%)							
	Pore Volumes						
	0	1	2	3	4	5	6
Control	100	66.49	62.89	62.89	62.89	62.89	62.89
Incorporated biochar	100	66.66	58.11	56.64	55.88	55.35	55.35
Layered biochar	100	64.68	52.34	37.48	24.64	13.63	2.64

Table 25: Retained Carbon (%)

Appendix E: Additional Experimental Observations

Observations made whilst conducting the experiment but not relevant enough to be included in the main text are outlined in this section.

Notes on the Biochar Used

Several observations were made of the appearance and texture of the biochar. For convenience these have been listed below:

- Pieces were very inconsistent in size
- Biochar was mostly black in colour, with some grey and brown
- Some of the lighter brown constituents may indicate a lack of full pyrolysis as they still resemble pieces of plant material.

Round 1 Observations

The following observations were made when applying the first rainfall event.

- Columns 1A, 2A, 2Band 2C all immediately started leaching dirty water, despite the presence of filter paper.
- 3A was the last sample to begin leaching.
- The surface of column 4B is not level.
- On collection, 1A and 2A were noticeably dirtier than other samples.

Round 2 Observations

The following observations were made when applying the second rainfall event.

- Some of the water was spilled when applied to 2B.
- Sample sizes were much larger than round 1 as expected.
- Column 1C produced an exceptionally clean sample.

Round 3 Observations

The following observations were made when applying the third rainfall event.

- Column 1C again produced an exceptionally clear sample.

Round 4 Observations

The following observations were made when applying the fourth rainfall event.

- An impurity – likely a piece of poly pipe – was spotted in the water applied to column 4B. This was unlikely to affect the results.
- On collection, a dead insect was seen in the leachate from column 1B.
- 1C again produces a noticeably clearer sample than the other columns.

Round 5 Observations

The following observations were made when applying the fifth rainfall event.

- Too much nitrification inhibitor may have accidentally been applied to column 1A.
- On collection 1C was once again a clean sample, though 4B was almost as clear.

Round 6 Observations

The following observations were made when applying the sixth rainfall event.

- On collection, samples with no biochar were observed to be cleaner for all A and B samples, with 4B being the only clean sample of these replicates with biochar applied.
- 1C was still clear with 2C and 3C coming close.