The Use of Organic and Mineral Amendments to Improve Zimbabwean Soil Health Utilising Plant Growth and Hydrocarbon Breakdown as Indicators

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The Use of Organic and Mineral Amendments to Improve Zimbabwean Soil Health Utilising Plant Growth and Hydrocarbon Breakdown as Indicators

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Summary

Southern Africa faces a great problem threatening the sustainability of maize crops because of the inability of African soils to grow said plants and their deficiency in many different factors such as water holding capacity, nutrients availability, and aggregate stability, amongst others. The hypothesis behind this study is that mineral and organic matter amendments can improve soil health and thereby increase potential hydrocarbon bioremediation, since this is only possible in a well structured, healthy soil. Soil health is measured in this study using plant health itself as an indicator, as well as the soil's ability to bioremediate hydrocarbons. It is also expected that with the addition of mineral and organic amendments not only the physical characteristics of the soil change, but the chemical and biological ones as well. To date, the use of both mineral and organic amendments for soil improvement has not been deeply explored by many researchers. The study is composed of two growth trials in which Zimbabwean soil is mixed with either compost, quartzite, water treatment residual (WTR), or a combination of them, two identical sets of amendments were done with the difference that one of the sets contained an addition of nutrients (plant food). The main findings are firstly that for plant health a single compost amendment (10% of compost combined with soil) and a co-amendment of compost and WTR (10% of each material in combination with soil) are both statistically significantly ($P<0.05$) better for plant height and for above ground and below ground biomass. Nutrients addition (plant food), improves the co-amendment's biomass but does not have the same effect in the single compost amendment's biomass. Secondly, it was found that of all soil types the single amendment of compost had the highest CO_2 emissions, after 30 days of oil contamination. This implies that the addition of nutrients (NPK) negatively affected CO_2 emissions rates when soil was contaminated with oil, potentially suggesting that NPK addition has a negative effect in the soil microbiome of this Zimbabwean sandy soil.

Statement of Copyright:

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Dedication

I would like to dedicate this work to my mom and dad, Beatriz and Julio, who shaped me into the person that I am today and made me strong enough to carry out this experience. I would also like to dedicate this to my grandparents Agustin Valdez and Josefina Borboa, and my sisters Mei Ling and An Zhilei, as well as to the rest of my family.

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1. Introduction

1.1 Soil Health

Soil health is defined as the “capacity of soil to function as a vital living system to sustain biological productivity, maintain environment quality and promote plant, animal and human health” [1]. The degradation of soil presents a global problem and sandy soils are arguably of most concern because of their low water holding capacity and low fertility [2]. In Southern Africa, sustainability of maize-based cropping systems is a big challenge, yet the demand for it continues to increase [3].

Approximately 70% of the arable land area in Zimbabwe is covered by granite-derived sandy soils which are known for their low nutrient capital and susceptibility to degradation [4]. These low levels of nutrients, particularly nitrogen, account for continued declines in the production of maize in small holder farms in Zimbabwe [5]. Many African sandy soils, such as Zimbabwean soil, have low organic carbon contents which leads to a vicious cycle of low capacity to accumulate and protect soil organic matter (SOM) [6]. According to Lal (2016) SOM has three main components: plant and animal residues and living microbial biomass, active or labile soil organic matter, and relatively stable soil organic matter. It is largely made up of humic acids which are composed of carbon, nitrogen, hydrogen, oxygen, phosphorus, and sulphur, with Soil Organic Carbon (SOC) being the largest component, and usually around 50% of SOM [11]. SOM both retains and supplies plant nutrients, improves soil aggregation, reduces soil erosion and enhances water holding capacity [7]. Furthermore, SOM increases “structural stability, resistance to rainfall impact, rate of infiltration and faunal activities” [8]. The application of organic matter to soil can potentially increase SOM and it also influences the distribution of SOC and Total Organic Nitrogen (TON) between SOC fractions [9]. SOC improves aggregate stability by providing a food source to microorganisms that can then produce extrapolymeric substances that bind together soil particles creating microaggregates [10].

SOC is at the heart of soil health as it underpins all soil functions, chemical, biological, and physical. It has a strong impact on soil quality (“capacity of the soil to function”, Karlen et al. 1997), functionality and health (“capacity of soil to function as a vital living system to sustain biological productivity, maintain environment quality and promote plant, animal and human health”, Doran and Zeiss 2000) [11]. SOC supplies plant nutrients (chemical attributes), enhances cation exchange capacity, improves soil aggregation and water retention, and supports soil biological activity (biological attributes) [8]. It has been proven that when changes in the organic carbon content of soils occur, there is a correlation with changes in the structural form (physical attributes) and stability of soils, this change can be of great magnitude depending on the soil texture [12].

Inorganic minerals, such as iron and aluminium hydroxides, play an important role in binding soil particles together [13]. This because Fe and Al oxide surfaces are positively charged which helps adsorb negatively charged organic molecules creating strong bonds which allow soil aggregates to form. For this reason, this thesis explores the relatively unexplored topic of soil improvement technologies combining both organic and inorganic mineral amendments.

There are many indicators of soil health and this is still very much a topic of debate in the soil science and agricultural world, with everyone agreeing that it encompasses chemical, biological and physical parameters. Parameters include pH, bulk density and water holding capacity (physical attributes), Soil Organic Carbon (biological attribute) and total nitrogen and total phosphorus (chemical attributes) [11]. In this thesis plant growth, which is dependent on all of these interrelated physical, chemical and biological attributes is used as a soil health indicator. As Lal (2016) stated, “soil health is represented by plant health itself” [11]. In addition, soil’s ability to bioremediate hydrocarbon reflects on a well structured soil, for this can only occur when, amongst other things, a soil presents a well balanced C:N:P ratio, a good structure, and a well preserved microbiome. In order to explore this second hypothesis, that improving soil health improves hydrocarbon remediation, basal respiration was used to monitor hydrocarbon breakdown and microbial activity in our amended soils.

1.2 Effect of amendments on soil physical attributes

“Soil structure refers to the size, shape and arrangement of solids and voids, continuity of pores and voids, their capacity to retain and transmit fluids and organic and inorganic substances, and ability to support vigorous root growth and development” [11]. Physical attributes of soil health are all dependent on soil’s structure which is dependent on soil aggregation and related to soil strength (the ability to withstand erosion). Soil structure affects plant growth by influencing root distribution and the ability to take up water and nutrients, which is important due to the fact that aggregation also tends to increase with increasing root length density [13].

1.2.1 Organic matter amendments on physical attributes

Organic matter amendments can improve soil structure and water holding capacity of soil through increasing aggregation and improving the pore structure. The type and characteristics of the organic matter added to the soil are important, as well as type and characteristics, the amount of organic matter also influences soil aggregation [14]. Leroy et al. (2008), stated that “not only the quantity but also the quality of the organic matter applied has a significant influence” [9]. Furthermore, Abiven et al. (2008) showed that formation of stable aggregates can be modelled in relation to the biochemical nature of the organic matter used [15]. In contrast, Mtangadura et al. (2017) conducted an experiment in which they evaluated the input of organic resources in Southern Africa on maize productivity in a long-term experiment [6]. In said experiment, organic matter of low and high quality was evaluated, and their results suggested that both, high and low quality, organic resources can “practically” increase SOC in the medium to long term. In terms of soil strength, Davies (1985) found a strong increase in soil shear strength due to organic matter, and Spivey et al. (1986) found a strong correlation coefficient of r= 0.88 between shear strength and organic content [45][46].

1.2.2 Inorganic amendments on physical attributes

It has been widely agreed that Fe and Al oxides interact with organic matter in macro-aggregate stability and, therefore, stabilise aggregates [16]. Inorganic minerals, as WTR, have the ability to also change particle size distribution which may allow for more water movement and aeration [17].

Furthermore, WTR has been found to improve soil properties as water retention and pH [18].

1.3 Effect of amendments on soil chemical attributes

Organic matter amendments can increase SOC and carbon storage in soils. This increase takes place via two means: directly (via carbon inputs) and indirectly (by increasing plant production) [7]. However, some researchers still focus the attention on the uncertainty that surrounds the subject. According to Gregorich et al. (2005), organic matter amendments increase carbon and nitrogen pools increasing the potential for carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) emissions, these are greenhouse gasses and they may even alter some environmental conditions of the soil, such as its moisture, temperature and pH [19][47].

1.3.1 Organic amendments on chemical attributes

The addition of organic matter to soils generally increases the nutrient holding capacity by increasing the macronutrient availability (NPK) which is why this is a common practice in cropping systems to enhance net primary productivity [19]. Due to the high cost of chemical NPK fertiliser, smallholder farmers in Africa have used locally available organic nutrient resources, such as, livestock manure, compost, woodland litter, cereal and legume crop residues [6]. Furthermore, organic amendments have been reported to have a high effectiveness in the immobilisation of various types of contaminants [20].

1.3.2 Inorganic amendments on chemical attributes

Due to the high cation exchange capacity generally associated with WTRs, it has been found that these materials have the ability to provide soil with cationic nutrients [18]. However, it has also been found that minerals like Fe and Al oxides, contained in WTR, immobilise elements such as P, Pb and As [20].

1.4 Effect of amendments on soil biological attributes

Microbe-mediated processes are highly sensitive to perturbations in soil, therefore, the capacity of the soil to recover from perturbations can be assessed by monitoring microbial activities [21]. Soil microorganisms have been shown to play critical roles in the regulation of many soil related factors, such as soil fertility, plant health, and the cycling of carbon, nitrogen and other nutrients [22]. More than 90% of the total soil microbial biomass are constituted of bacteria and fungi, which are responsible for the majority of soil organic matter decomposition [23]. Bacterial and fungal communities can be influenced by plants as well as vice versa [24]. Plants have a strong effect on the composition of microbial communities in soil through rhizodeposition and decay of litter and roots [21]. Rhizodeposition is the continuous flow of carbon-containing compounds from roots to soil [25] which then continues to interact with inorganic minerals releasing micronutrients. The environment where complex microbial communities and plant roots interact via nutrients released by the plant is called rhizosphere [26]. This part of the soil is thought to be of great importance to both plant health and soil fertility [19].

1.4.1 Organic amendments on biological attributes

Organic amendments result in an increase in nutrient availability and aside from the remediation of soil fertility, can help in balancing C:N:P ratio in soil for when hydrocarbon contamination occurs this ratio tends to get unbalanced for the increase on carbon, thus increasing nitrogen and phosphorus availability in soil via organic matter inputs has been proven to be an effective tool for biodegradation activity [24]. It is due to the central role of microorganisms in the cycling of N and C, and their sensitivity to change, that microbial and biochemical characteristics are used as soil quality indicators [21]. Therefore, it is of great importance to find eco-friendly amendments such as organic amendments [27].

Soil microbial respiration can be considered as a useful indicator of the total microbial activity since basal respiration is used to measure said activity in soil [21][28]. Soil microbial activities and communities play an important role on petroleum hydrocarbon degradation with bacterial communities being responsible for the degradation of the saturated and partially aromatic hydrocarbons [29]. Even though CO_2 production is not directly related to oil carbon biotransformation, changes in microbial activity indirectly reflect oil microbial breakdown [28]. Furthermore, it has been suggested that CO_2 evolution is considered “vital evidence” linked to transformations of organic carbon and characteristics of soil quality [27].

1.4.2 Inorganic amendments on biological attributes

Most of the research on the biological effects of inorganic amendments focuses on the use of inorganic chemical fertilisers (NPK) to improve either crop productivity or as agents for enhanced bioremediation helping microbes to increase the degrading ability of the indigenous community [29].

1.5 Organic and inorganic amendments combined

The objective of this project is to measure changes in soil health when organic and inorganic amendments are added to Zimbabwean soil. The hypothesis is that organic amendments such as compost and inorganic mineral amendments like water treatment residual will provide organic matter, nutrients and carbon to the soil, therefore having a positive effect on soil health, not only on nutrient holding capacity but also on soil structure. Plant growth (height and biomass) is used a soil health indicator and measured over 10 weeks. The second hypothesis is that the improvement in soil health, the ability of the soil to bioremediate hydrocarbons could be enhanced, and therefore, reflect on the impacts of the soil amendments on soil health once they are put under contamination stress. Hydrocarbon breakdown and microbial respiration were measured through microcosm experiments over the course of 32 days.

2. Materials and Methodology

The following sections include data on the four materials (soil, compost, WTR and quartzite) used to produce different 'soil types'. As well as of other elements, such as lime and two types of nutrients, which were used during the plant growth trials soil preparation. Data on the four main materials was obtained from analyses performed by the Geography Department's laboratories at Durham University and is reported as it was obtained from the spreadsheet sent by them.

In addition, the experimental methodologies which were used to prepare the soil types and to measure improvements on soil health are explained. These methods include two plant growth trials and microcosm experiments, which served as a way to test soils' ability to biodegrade hydrocarbons, and the preparation for them. It should be noted that the first plant growth trial was carried out as part of the method development process, allowing to perfect the methodology for the second trial.

2.1 Materials characterisation

Moisture content was measured for all materials. These calculations were made by oven drying at 105°C for 4 hours. The pH was measured using the pH meter Hanna H18424 in a calibration range between 4.01 and 7.01 units. The extraction was made using 50 ml of deionised water and 20 g of 'as received' soil. The exchangeable bases (extractable Ca, K and Mg) were calculated, for an extract of the soil, using the instrument Agilent 5100 ICP-OES and 5 grams of sample. Total carbon and nitrogen were calculated by combustion method using Flash 2000 Organic elemental Analyser. Extractable phosphorus (plant available) was obtained using the instrument Agilent 5100 ICP-OES with 2.5 g of sample.

2.1.1 Soil

Zimbabwean soil was sourced from Domboshava Training Centre (17°36ˈ S; 31°08ˈ E; 1542 m a.s.l) located 30 km North East of Harare Zimbabwe. The site is characterised by having a sub-humid climate and receiving an annual rainfall of <750 mm [28]. The soil was sampled in October 2018 from a plot measuring approximately 300 m^2 using hand hoes and shovels to a 20 cm depth. Soil was sieved to <2mm and air-dried before transportation and usage. This soil is broadly classified as Paraferallitic 6G soil according to Zimbabwe soil classification or as Lixosoil according to the World Reference Base (2006), it has a concentration of 0 ppm of calcium, 39.1 ppm of potassium and 36.5 ppm of magnesium. It has an Effective Cation Exchange Capacity (ECEC) of 6.5 (meq/100g). It is composed of granitic parent material fused with dolerite intrusions [5]. The soil can be described as a sandy-clay loam with 220 g clay kg^{-1}, 50 g silt kg^{-1} and 730 g sand kg^{-1}. The mean density is 2.6788 (ρ, g/cm^3), a pH of 4.63 units, which makes it an acidic soil, and a total carbon of 0.47% (w/w), a total nitrogen of 0.03% (w/w) and .00039% (w/w) of extractable phosphorus.

2.1.2 Compost

Compost containing 50% peat named "Gro-sure, All-Purpose Compost" was purchased from a local Durham, England store. The moisture content of the compost was found to be 58.2%. The pH was found to be of 4.9 pH units, with 46.90% (w/w) of total carbon and 1.28% (w/w) of total nitrogen. Its density was of 1.56 (ρ, g/cm^3). The compost was sieved to <2mm. Compost was gently compacted using hands while filling up the pots.

2.1.3 Water Treatment Residual (WTR)

WTR is the final product of water purification, the WTR used for this project was obtained from Mosswood Water Treatment Works in Durham and was stored already sieved to <2mm. This material contains iron and manganese oxides, which are expected to increase aggregate stability. It has a moisture content of 38.1% (w/w), a pH of 4.2 units, a concentration of 2.7 (meq/100g) of Ca, 0.1 (meq/100g) of K and 0.6 (meq/100g) of Mg. A total carbon of 19.98% (w/w) and total nitrogen of 5.06% (w/w).

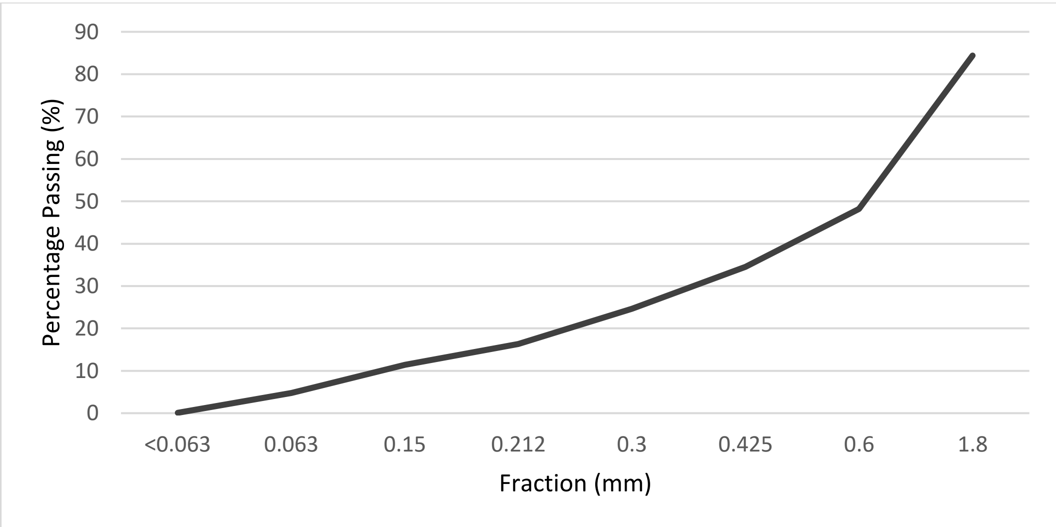


Figure 1. Particle size distribution curve for dry WTR after sieving <2mm.

2.1.4 Quartzite

The material was purchased as Natural White Aquarium Gravel from a local Durham, England pet store with the purpose of it being chemically inert and pure. Quartzite was ground to replicate the particle size distribution (PSD) of the WTR (Fig. 1) by two means, through a mechanical grinder and manually using a mortar and pestle, the latter to try to obtain more material from the particle sizes 0.425-0.6 mm, 0.3-0.425 mm, 0.212-0.3 mm and 0.15-0.212 mm.

The purpose of the use of quartzite on the amendments is to highlight the differences between the chemical and physical influences of WTR on soil as an amendment, this under the speculation that quartzite may provide a control for the physical attributes of WTR but with no chemical influence. Calculations were made with the same volume of quartzite as WTR, and although the particle size distribution was controlled, it was not possible to control for pore size distribution or microbiome. Therefore, variations between soil types might not reflect only chemical differences.

2.1.5 Maize

Seeds of maize from Zimbabwe were used as a way of measuring the soil's ability to grow plants. The seeds were purchased and imported to England in a sealed bag. Previous to planting, the seeds were germinated for 3 days, the processes of planting and germination in more detail are explained in the methodologies section 2.2.2.

2.1.6 Nutrients

During the plant growth trials and due to the soil's specifications, the addition of two types of fertilisers was thought to be the best approach to ensure that nutrient limitation (chemical characteristic) was not a factor for maize growth, thus giving the possibility to assess the impact of the different amendments on soil with respect to biological and physical characteristics.

One of these was an All-purpose Liquid Plant Food purchased from a local (Durham, England) shop. It is an NPK Fertiliser solution 6-3-6 with macro and micro-nutrients such as, nitrogen, phosphorus, potassium, copper, and iron (Table 1). This fertiliser was added in the middle of the first trial at week 5, and in the middle of the second one, at day 33 (Table 2). The calculation followed the recommendations on the container using one cap (50 ml) diluted into 4.5 L of water. In the first trial, the liquid plant food was distributed across the amendments with a double dosage to the ones that lacked organic matter input, such as soil and soil and quartzite. However, during the second trial the dosage was one litre of diluted plant food per tray containing 20 pots, without distinction among the NPK amended soil types.

The second fertiliser used, was added at the beginning of the second trial (Table 2), it was a compound D exported from Zimbabwe, it was purchased from a company called Zimbabwe Fertiliser Company (ZFC) and its contents can be seen on Table 1. The calculations of the amount of compound D that was to be added to each individual pot were made by targeting 26 kg P ha^{-1} for soil types containing non-organic materials or base soil, and targeting 14 kg P ha^{-1} for those soil types containing organic materials. This was done under the assumption that the organic materials would already provide an input of nutrients to the soil type.

The calculation then was made by using the relation of 26 kg of fertiliser to 10 000 m^2 (1 ha) of soil or soil type, therefore the surface area of the pot was multiplied by 26 kg and then divided by 10 000 m^2. The result being the kilograms of fertiliser would then be converted into grams and used in each of the pots. The same process was done to calculate the amount of fertiliser for organic materials containing pots only changing the relation to 14 kg of fertiliser for 10 000 m^2.

Table 1. Table showing the composition of All-purpose Liquid Plant Food and Compound D in percentages, fertiliser called All-purpose Liquid Plant Food was used for the two plant growth trials, whereas compound D was only used for the plant growth second trial see Table 2 for further information on this.

Component	Quantity (%)	Compound d (%)
NITROGEN (TOTAL)	6.00	7.00
Urea Nitrogen	3.30	
Nitric Nitrogen	1.70	
Ammoniacal Nitrogen	1.00	
Phosphorus Pentoxide	3.00	14.00
Potassium Oxide	6.00	7.00
Copper	0.002	
Iron	0.01	
Molybdenum	0.001	
Zinc	0.002	

Table 2. Fertiliser addition showed for both trials. For the first growth trial (12 weeks duration), plant food was added on week 5 to all soil types with second dose only given to those lacking organic matter (soil, soil-quartzite). For the second trial (7 weeks duration), compound D fertiliser was added on the day of planting with a double dosage to those amendments lacking organic matter (soil, soil-quartzite) and plant food was added to NPK amended soil types on week 5, same dose.

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
First Growth Trial					Plant Food							
Second Growth Trial	Compound D Fertiliser				Plant Food							

2.1.7 Lime

The lime used was purchased from a local (Durham, England) shop and contained 50% calcium carbonate ($CaCO_3$) and 50% dolomite ($CaMg(CO_3)_2$). The calculations for the amount of lime needed were done by targeting a pH of 5.5 units. Sandy soils require 600 kg ha^{-1} of lime to raise the pH by 0.1 unit.

The pH of the soil needed to be risen by 0.9 units this number was divided by a constant 0.3 and then multiplied by 600 (kg of lime required per ha). The final number was the amount of kg required per ha of soil which was then just calculated considering the surface area of each pot in grams.

2.2 Experimental methods

2.2.1 Soil preparation

Soil preparation presents a difference from the first growth trial to the second one, said difference is further explained in the following sections where the adjustments made to the methodology under which the plant growth trials developed are supported by literature found on similar projects.

2.2.1.1 Plant growth trial 1

Fifteen different combinations across all the materials previously described were put together with seven replicates (n=7) per soil type. The effect of the amendments was evaluated through a period of time of 12 weeks.

The soil type ratios were calculated by taking into consideration the dry mass of each material and the pot size (9 x 9 x 9.5 cm). However, the ratios were created with field moist materials, meaning that no drying was done prior to the mixing of the materials. In order to calculate the amount of dry mass needed of each material, the water content of all materials was calculated by the standard method for soil and rock by mass [30].

Table 3. Soil types and composition of materials for plant growth trial 1, the letters on the name code state the following, S= Soil, C= Compost, Q= Quartzite and WTR= Water treatment residual. The numbers correspond to the percentage of each material in the mixture. ***Highlighted soil types represent those that received a double dosage of nutrients****. Quartzite by mass refers to the one that was applied as it was purchased. While, for quartzite addition by volume, quartzite that was grounded to the same PSD as in WTR was added.*

	Materials			
Soil type	Soil (%)	Compost (%)	WTR (%)	Quartzite (%)
1 S100	100			
2 SC 9010	90	10		
3 SC 8020	80	20		
4 SWTR 9010	90		10	
5 SWTR 8020	80		20	
6 SQ 9010 (mass)	90			10
7 SQ 8020 (mass)	80			20
8 SQ 9010 (volume)	90			10
9 SQ 8020 (volume)	80			20
10 SCWTR 801010	80	10	10	
11 SCWTR 602020	60	20	20	
12 SCQ 801010 (mass)	80	10		10
13 SCQ 801010 (volume)	80	10		10
14 SCQ 602020 (mass)	60	20		20
15 SCQ 602020 (volume)	60	20		20

2.2.1.2 Plant growth trial 2

The second growth trial, was run for 7 weeks due to concerns that the pot size was too small to run for 10 weeks. In the first trial, the root system of the plants seemed to have reached a stage of growth at 10 weeks where they filled the pots and could not develop any further because of the limited space. Therefore if shoot and root systems all reached the same stage, comparison amongst soil types would become difficult. For the previously stated reasons it was believed that the biomass data for this first trial was compromised. Thus, the second trial lasted 7 weeks, six soil types were made with combinations of the materials (Table 4), however, this second time there was a control set of amendments which had no added nutrients to them, making up two lots of six soil types each in total, one lot with nutrient addition and one without.

Of the six soil types, three were single amendments (2, 3 and 4 in Table 4), meaning soil and one of the materials combined. Two other combinations were co-amendments (5 and 6 in Table 4), meaning a combination of two materials and soil, and one acted as a control of only soil (1 in Table 4). The other six combinations were the same as the previously described with the difference that once the trial started nutrients were not added to them.

Table 4. Composition, in percentages, of the different soil types for the second growth trial. Highlighted soil types represent the ones that received double dosage of compound D at week 5. Quartzite addition in this second trial was only by volume (with similar PSD of WTR).

	Materials			
Soil type	Soil (%)	Compost (%)	WTR (%)	Quartzite (%)
1 S100	100			
2 SC 9010	90	10		
3 SWTR 9010	90		10	
4 SQ 9010	90			10
5 SCWTR 801010	80	10	10	
6 SCQ 801010	80	10		10

As in the first trial (see section 2.2.1.2) the calculation of materials was done by dry mass.

A further amendment done to the soil preparation for the second trial involved the application of a method of equilibration of materials [31][32]. This method allowed materials to homogenise by settling and interacting before planting. This 'settling' period in open trays in the greenhouse was of four weeks. During these four weeks, the soil types were mixed, wetted and dried twice a week.

2.2.2 Germination and planting

2.2.2.1 Plant Growth Trial 1

Maize seeds were germinated prior to planting. This process was done in a growth room at 30 °C during three days. All pots were labelled and to avoid losing material through the bottom holes of the pots, tissue paper was placed at the bottom of each pot before adding the mixtures. While placing the material into the pots it was important to maintain a similar volume amongst all of them, this with the purpose of all pots having similar volume of material for roots to occupy.

Once all the material was placed in each pot, a hole of approximately 2 cm was made and the seedling was placed inside. Then, it was covered with the topsoil of the pot avoiding covering the growing stem. Pots were arranged inside trays that fitted fourteen pots in each tray, meaning two soil types were placed in each tray. The pots were initially watered from the top until the water reached the top edge of the pots, this was done for the first four weeks, and afterwards, watering was done by adding water to the tray and leaving the roots to take it up from the bottom of the pots. The amount of water added to each tray depended on different factors, these being, the position of the trays in the greenhouse, the soil type and the level of growth of the plants. Thus, the amount of water added to the trays was calculated by taking into consideration their needs and with the purpose of maintaining a healthy environment so that water deficiency was not a factor. Watering was carried out every three days.

Plants were grown for twelve weeks in a greenhouse under controlled temperature of 23°C during the day and 18°C during the night. These changes in temperature were dependent on the lights which were on for 16 hours and off for 8 hours. During week 5 of the trial, it was noted that plants across the soil types that lacked organic matter were starting to die, it was then that the addition of plant food took place. As explained on section 2.1.6, double dosage of the plant food was added to those amendments that lacked organic matter and one dose was applied to the ones that had organic matter input.

2.2.2.2 Plant growth trial 2

During the second growth trial, and due to the ineffectiveness of tissue paper to contain material and roots inside the pots, frost cloth was placed instead, at the bottom of each pot before the addition of the mixtures. Once all the material was placed inside the pots, a hole of approximately 5 cm was made into them and the compound D fertiliser was placed inside and slightly mixed with the topsoil of the pot. For the soil types containing materials that were rich in organic matter (such as compost) 0.89 grams of compound D were added to each pot, whilst, for the pots containing only soil and soil and quartzite, 1.79 grams were added (Table 4). The seed was then placed in the hole and partially covered by the soil without compromising the growing stem.

The pots were arranged on trays that fitted twenty pots and the watering process was the same as the one described for the first growth trial. Similarly to the first trial, plants were grown in the same greenhouse with the difference that this second trial was done for 7 weeks. The second NPK addition was added on week 5, this was the same plant food used for the first trial, however, the same amount of plant food was added to all of the soil types.

2.2.3 Plant height and weight measurements

During the trial, plant height was measured and recorded twice a week as it was used as an indicator to compare the effect of different amendment materials on soil health. The measurements were done with a plastic 30 cm ruler which was placed at the base of the plant, the longest leaf was used as the reference point to measure height. Height measurements were recorded once a week starting at week 3, once the plants had developed leaves.

Once the trial was finished, the plants were harvested. This was done by cutting off the stem of the plant at the point in which it intersected the soil, this was later stored in a paper bag. The root system was removed from the soil and stored in a separate paper bag. The roots of each plant were removed by shaking off the soil attached to them and then washing them with tap water to remove the remaining soil particles, after that the roots were washed with de-ionised water to further eliminate unwanted materials attached to the roots.

All of the bags were taken to be oven-dried for 48 hours at 65°C to remove all moisture, and, once the weigh was constant, they were taken out of the oven and placed on a scale were the weights were recorded to obtain dry biomass of both the plant and its root system.

2.2.4 Hydrocarbon biodegradation microcosm experiment

Soil types which facilitated the most plant growth were selected to undergo a hydrocarbon biodegradation experiment with the purpose of testing their ability to breakdown hydrocarbon pollution. The soils used for this experiment were sampled the day of harvesting. All of the pots of each individual soil type were recombined together into a tray and soil was then homogenised, 100 grams of sample were collected into a plastic sealed bag and labelled with the name of the soil type (Table 5). Quartzite and compost amendments had resulted in high relative plant growth but due to the significant plant die off (n=7 at time zero became n=2 at week 7) this soil type was not selected for microcosm experiments.

Aside from soil types that had gone through the plant growth trial, the original materials were selected to act as controls in the microcosm experiments and are referred to as ‘raw materials’.

Table 5. Soil types and raw materials selected for hydrocarbon biodegradation experiments.

No. of Soil type	*Amendment*
1	100% Zimbabwean Soil (raw material)
2	100% Compost (raw material)
3	100% Water Treatment Residual (raw material)
4	90% Soil – 10% Compost
5	90% Soil – 10% WTR
6	80% Soil – 10% Compost – 10% WTR

The microcosm experiments were carried out at Newcastle University, Newcastle, UK. To set up the microcosms, autoclaved glass serum bottles were filled with 10 grams of raw material or soil type. Two sets of bottles were created, one set was contaminated with 128.2 µl of an un-degraded North Sea crude oil (known as ‘oil contaminated’) and the other one was not (known as ‘uncontaminated’). 100 µl of a mixture of NPK was added to all of the bottles, without any exceptions. The NPK consisted of 2% $NaNO_3$ and 0.1% of KH_2PO_4, so the C:N:P ratio was 100:2:0.1. The addition of nutrients was made to ensure the microorganisms in all of the microcosms had enough essential nutrients to grow. It is important to note that soil types labelled as “+NPK” in the Results and Discussion section refer to the nutrient addition during the plant growth trial (not to the nutrient addition during the microcosm experiment which was applied to all microcosms).

After the set up, they were placed in a cold room with a temperature of 4°C to slow down microbial activity until the first GCMS measurement, which took place the next day.

The gas chromatography-mass spectrometry (GC-MS) method was performed with Fissons Trio 1000 fitted with Pora Plot Q GC column. The calibration of the GCMS had to be done at the beginning of every run and after 30 minutes of injections of microcosms. This calibration started with an injection of air of 100 µl, followed by sequential injections, every minute, of 100, 80, 60, 40 and 20 µl of two gases, one containing 1% CO_2 and the other one containing 10% CO_2 respectively. After the 11 injections of standard gas were made, 100 µL of sample were injected into the septum, this was repeated for every microcosm at intervals of one minute until the CO_2 in all of the bottles was measured.

Peak area measurements were obtained from m/z 44 and m/z 32 mass spectra to determine CO_2 and O_2 concentrations in the microcosms. The CO_2 indicated the extent of oil biodegradation whereas the O_2 served to monitor that the microcosms did not become anoxic. Once the monitored levels of oxygen declined below 75%, air injections were made to the microcosm bottles to replenish them with enough oxygen. This was done by opening the bottle and flushing five times air with the help of a syringe. On the day where there was air flushing, a measurement of CO_2 was done before and after said air flushing and then taken into consideration in the calculation of cumulative CO_2 for the rest of the days of the experiment.

2.2.5 Statistical Analyses

Statistics packages Minitab 18 and SPSS 22 were used in order to perform the statistical analyses of height and weight of the plants, and biodegradation rates of CO_2 emissions.

One-way ANOVA tests were performed for both plant growth results, and biodegradation rates of CO_2 results. Tukey tests as post-hoc analysis was performed on Minitab 18 with a p-value of <0.05, in order to determine statistical significance amongst plant growth results. For the biodegradation results, LSD post-hoc analysis was performed on SPSS 22 using a p-value of <0.05 to determine statistical significance amongst the results. Standard error was used for variation of the data.

3. Results and discussion

3.1 Plant Growth Trial 1

As previously stated, the results obtained from the first growth trial were formative and allowed us to perfect the second trial methodology. The biomass data obtained from this trial is believed to be compromised because of the pot size and the duration of the experiment (2.2.1.1), the data is not presented in this section of discussion. However, the measurements of the different soil types plant height, and plant development throughout the weeks, were beneficial to select a smaller number of soil types to run for the second trial.

3.2 Plant Growth Trial 2

During the growing stage of the trial, measuring the height of the plants was considered an acceptable way of knowing which amendment was working best besides looking at different plant factors, such as colour, texture of leaves and stem size.

Plant height developed throughout the weeks differently in each soil type, but said difference was not noticeable until week 5, that is when the plants started to grow at different rates (Fig. 2). Throughout the weeks, some plants behaved differently to the rest of them in the same soil type, which in some cases ended with them dying. Plants that stopped growing and started drying out were kept in the trays so that watering did not differ during the trial. Plants that were growing in soil without any amendments (S100) started off growing similarly to the rest of the soil types. However whilst the amended soil types showed a growth of 3-11 cm every week without NPK addition and 2-19 cm every week with NPK addition, maize growing on unamended soil (S100) presented only 1-3 cm of growth on average between measurements confirming its poor quality.

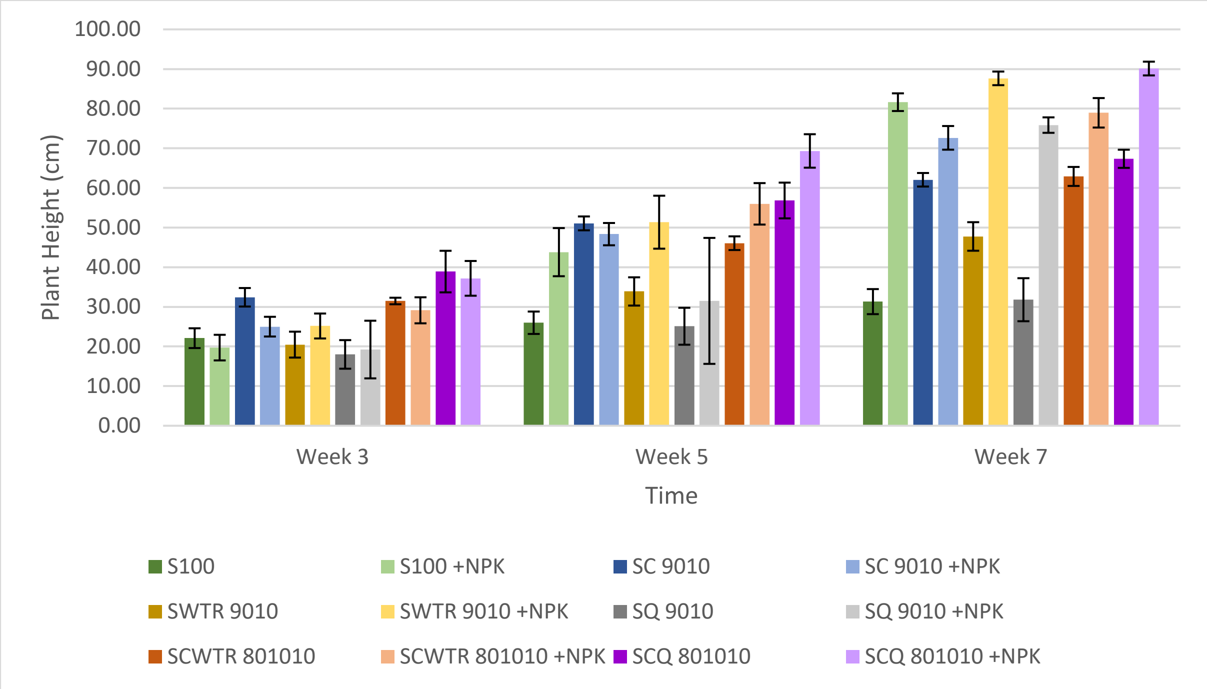


Figure 2. Height progress of all amendments from week 3 to week 7 of the trial. Each bar represents the mean of height measurements of each soil type. Error bars show standard error.

When organic matter or chemical fertiliser was applied to the soil, a difference was visible throughout the trial, this difference also extended to what was able to be seen qualitatively in the colour and apparent strength of the plants (Fig. 3). Furthermore, nutrients in Zimbabwean soil were found to be low in concentration (section 2.1.1), this can also be confirmed by other authors, as an example Mapfumo et al. (2007), and Mtangadura et al. (2017) [6][48].

Plants growing on S100 +NPK started differentiating from the ones growing on soil without NPK amendment (S100) from week 5 of the trial, whereas, plants growing on SC 9010 showed a statistically significant ($p<0.001$) difference from S100 right from week 3 (Fig. 5 and 6). Plant growth mostly depends on the availability of N and P, this availability is influenced by the level of organic matter in soil, compost is known to increase soil's organic matter content [33][34][35]. Therefore, the earlier increase in plant height in compost amended plants could be explained by the availability of its nutrients for plant uptake.

Statistical difference ($P \leq 0.05$) was found on week three (first plant height measurement) between S100 +NPK and SC 9010. S100 +NPK had an average height of 19.71±8.55 cm whereas SC 9010 had an average height of 32.41±6.18 cm. To explain this, it has been found that in soils with low organic matter, applied nutrients are easily lost from the root zone, moreover, crop plants feed on nutrients by root uptake [36][34]. The unavailability of nutrients on NPK amended soils may be a reason to explain their late development.

Figure 3. Plant comparison (week 6) of S100+NPK (three pots on the left) and S100 (three pots on the right). Fertiliser addition to the S100 soil type considerably increased plant height and plant appereance with a better colour and stronger looking stem.

All soils with an organic matter input showed a difference in trend of growth when compared to the base soil (Fig. 4). However, SWTR 9010 did not behave as the rest of the amendments when compared to the soil. This can be easily explained by the characteristics of WTR (see section 2.1.3) and the fact that it has been found to immobilise P, making it unavailable for plant uptake [18].

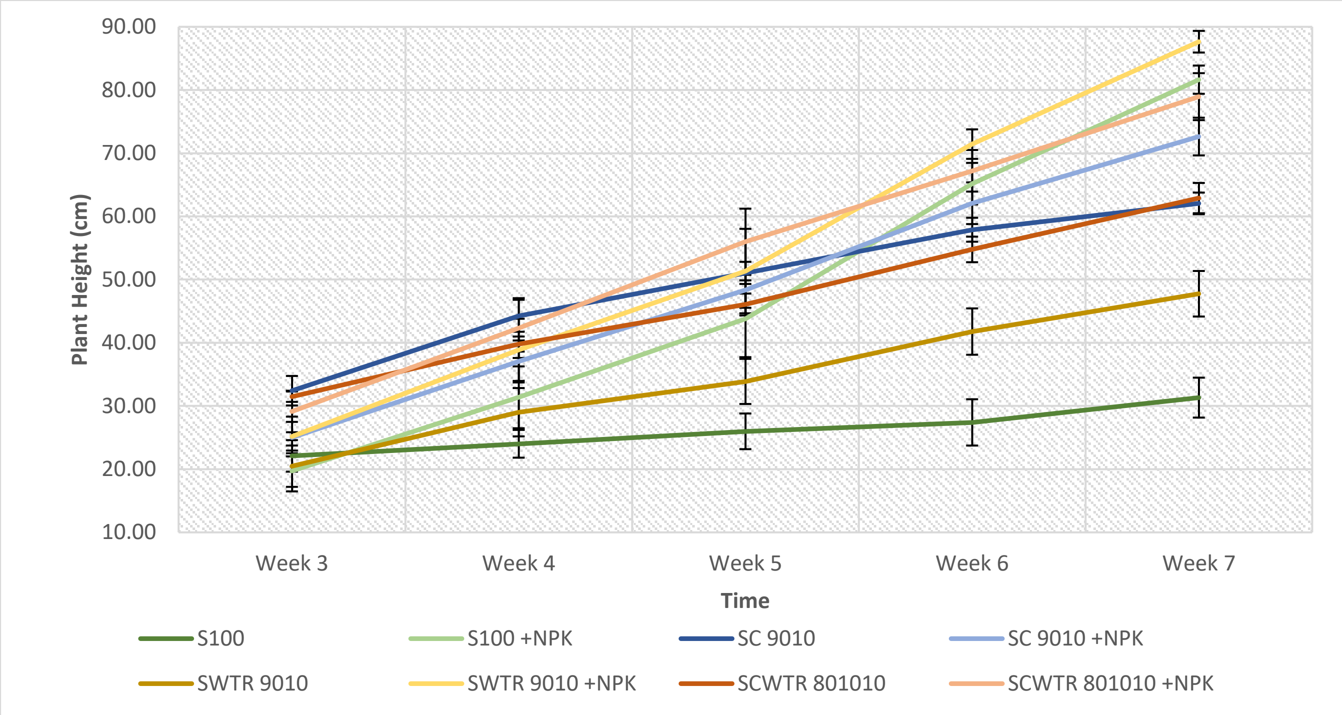


Figure 4. Comparison between soil types with and without nutrients addition throughout the last 5 weeks of the experiment. Note that by the end of the trial (week 7) n=7 for SC 9010, SWTR 9010 and SCWTR 801010, and n=5 for Soil100. And for the soil types with nutrients addition, n=6 for Soil100, SC 9010, SCWTR 801010, and n=5 for SWTR 9010.

The second addition of fertiliser to the NPK amended soil types showed a bigger increase from week 5 to week 6 on the height of plants than the one seen on the weeks prior. This increase is particularly seen on S100 +NPK and SWTR 9010 +NPK. In S100 +NPK, plant height increased an average of 21 cm from week 5 to week 6, if compared to the increase from week 4 to week 5, which was of 12.43 cm on average, almost double. Similarly, on SWTR9010 +NPK, the increase from week 4 to 5 was of 12.47 cm on average whereas the one from week 5 to week 6 was of 20 cm.

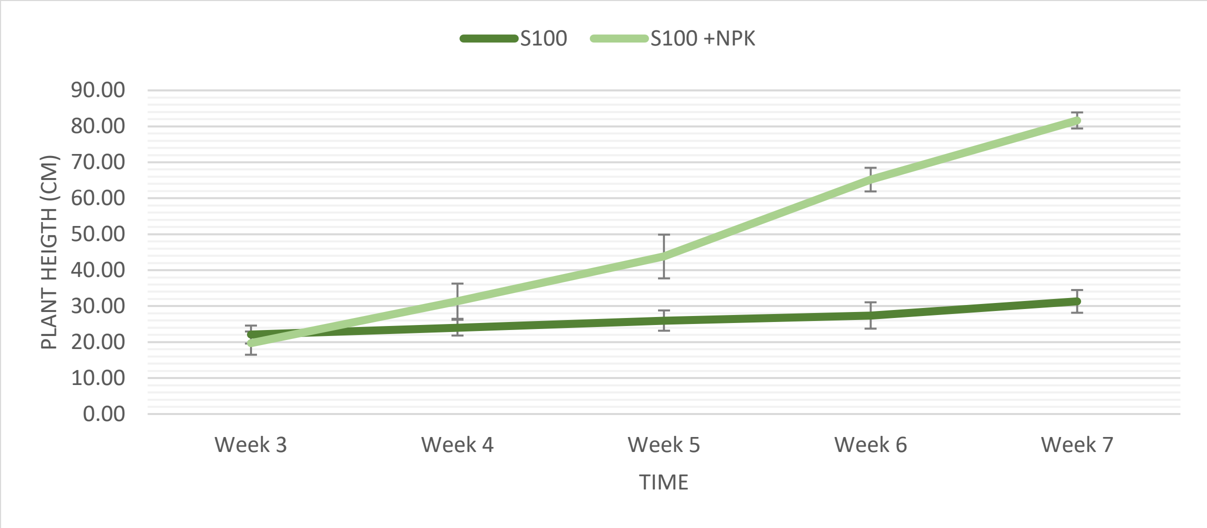


Figure 5. Comparison of plant growth between S100 and S100 +NPK. The data points in each week were taken from the average growth of the n plants in each soil type. Note that n=5 for the last two weeks of S100 and n=6 for the last two weeks of S100 +NPK. Error bars show standard error.

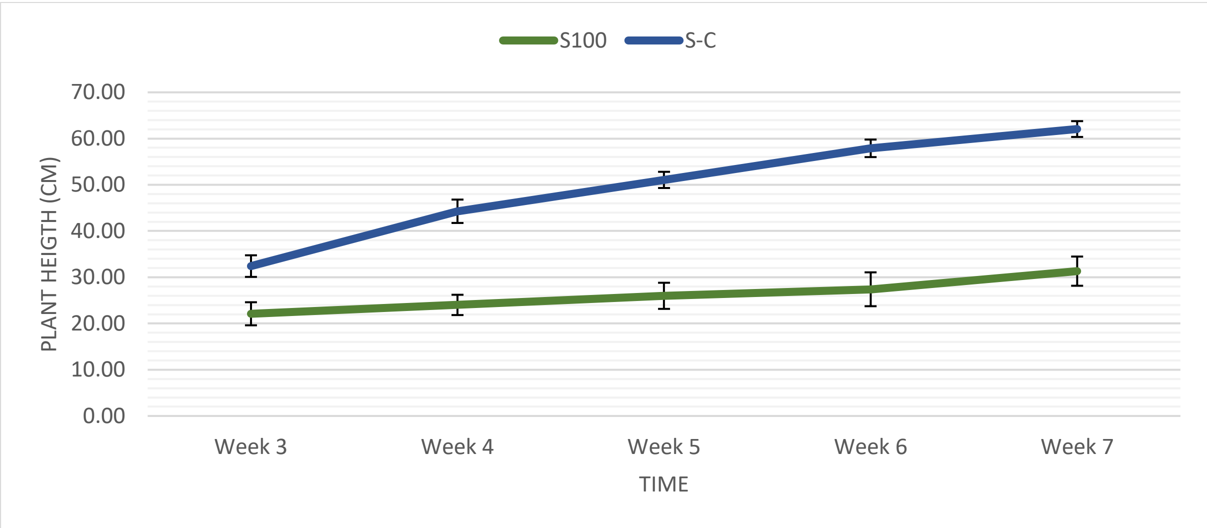


Figure 6. Comparison of plant growth between S100 and SC 9010. The data points in each week were taken from the average growth of the n plants in each soil type. Note that n=5 for the last two weeks of S100 and n=7 for all weeks of SC 9010. Error bars standard error.

Soils that lack nutrients tend to cause a restriction of crop growth which is why the addition of organic matter (Fig. 6) and fertiliser (Fig. 5) to the soil has made a significant difference on growth (height) of these soil amendments compared to the soil by itself (S100) [32]. On granitic sandy soils, as the one used, nitrogen is a limiting nutrient on crop productivity and the addition of it has been proven to boost both above and below ground maize biomass (Fig. 9 a-b) [6].

As previously mentioned, at week three statistical difference ($P<0.05$) was found between S100 +NPK and SC9010. However, no significant difference was found between soil types with and without nutrient addition, which could go on to indicate that either the NPK added at the beginning of the trial did not make any contribution to the soil or that it needed further time to create an impact on plant development.

At week 5, a significant difference was found across all soil types on plant height (P≤0.05). At this stage of the growing period, the base soil did not represent a significant difference against S100 +NPK, this could be due to the reaction time of the compound D or maybe it was washed off due to lack of nutrient holding capacity while watering, since this was done from the bottom of each pot at the beginning of the trial but started to be done from the top of the pots after week 3. However, S100 did present a significant difference when compared against SC 9010 (Fig. 7), which goes further on to explain how organic matter addition had an earlier impact on plant growth than fertiliser addition.

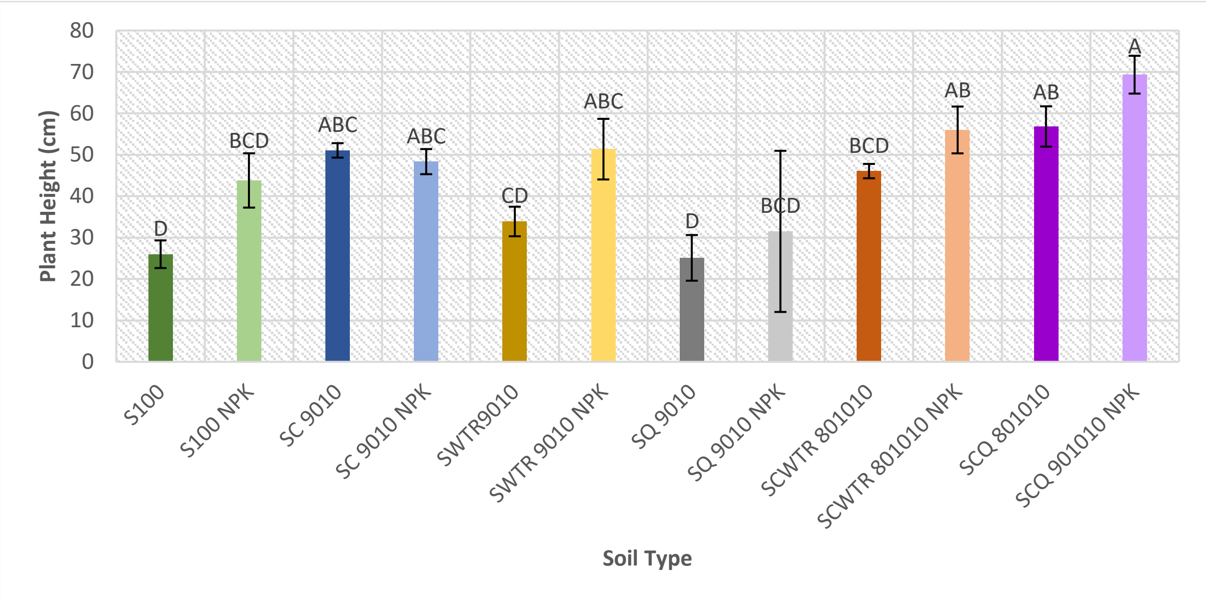


*Figure 7. Week 5 plant height average of growth. Significant difference (P<0.05) was found and is represented with a lettering system. Bars that do not share a letter are significantly different, and error bars show standard error. It is important to note **that n=3 for SQ 9010 NPK,** and one of the plants was starting to dry out thus the error bar being greater than for the rest of the soil types.*

Both SWTR 9010 +NPK and SCWTR 801010 +NPK showed a significant difference (p<0.05) with S100 at week 5 (Fig. 7), the co-amendment had taller plants with an average of 55.99±16.36 cm while the single amendment had an average of 33.89±9.44 cm. Since P available for plants on compost was found to be high (261 mg/kg) and it is known that WTR fixes P, it can be hypothesised that even with the P fixation of WTR, there was enough remaining P available for plant uptake from the further addition of this on the fertiliser [18].

The second addition of nutrients (the All-Purpose Liquid Plant Food) was applied to all NPK soil types on week 5, therefore measurements after this week were affected by this addition. As previously mentioned, a bigger increase on average centimetres of height was seen on some of the soil types after the NPK second addition. This impact can be seen on further significant differences found on week 7, last measurement.

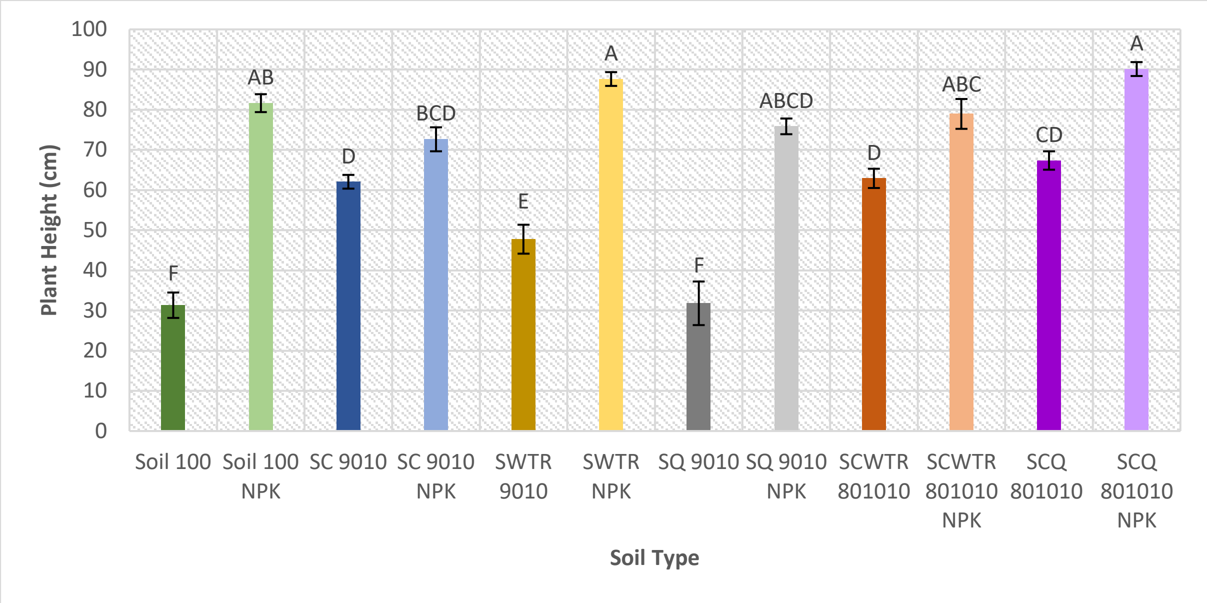


Figure 8. Week 7 plant height average of growth. Statistical difference (p≤0.05) is shown with a lettering system, bars that do not share a letter are significantly different. Error bars show standard error of the measurements. Note that n=2 for SQ 9010 +NPK.

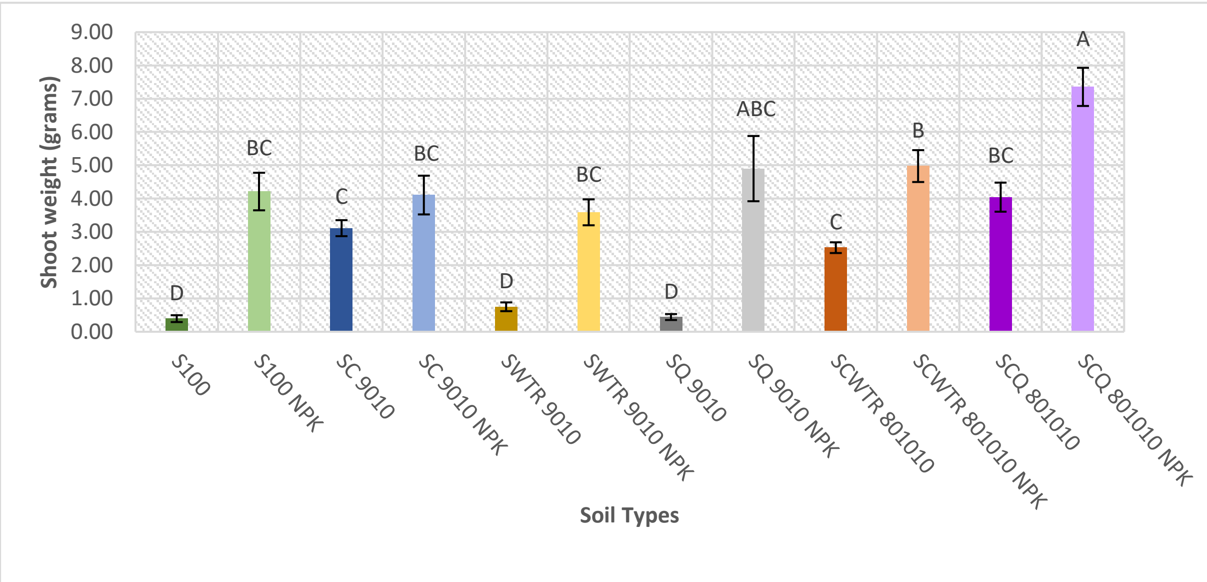
Since nutrients in compost were found to be low in concentrations (1.28% N, 0.026% P), it is believed that this may have caused plants growing with NPK addition (S100 +NPK) to grow significantly higher than the ones with a 10% compost addition (SC 9010) by the end of a seven week trial (Fig. 8). S100 +NPK had an average of 81.63±5.47 cm on height whilst SC 9010 had an average of 62.05±4.52 cm. And, although no significant difference was found between SC 9010 with and without NPK addition, SC9010 +NPK had a higher average of plant height and no significant difference when compared against S100 +NPK. Sikora and Enriki (2001) stated that the combination of compost with a chemical fertiliser is considered as an “appealing alternative” to compensate for the fact of the unavailability of nutrients of compost compared to chemical fertilisers [49]. This coincides with what was found on the growth trial where, although no significant difference was found, SC 9010 +NPK had taller plants on average than the same soil type without fertiliser addition. It is also hypothesised that in a longer trial, statistical difference could be found between these two soil types.

SWTR 9010, 47.75±6.33 cm, was significantly higher than S100, 31.32±7.06 cm, at the end of the trial, whereas SQ 9010, 31.8±12.14 cm, was not significantly higher than S100. This statistical analysis of comparison between WTR and quartzite, could indicate that the addition of WTR to the soil goes further than just a physical contribution, and might be a chemical one. However, since as previously stated (section 2.1.4), quartzite PSD did not fully imitate that of WTR, the physical characteristics of WTR cannot be completely ruled out by these results.

However, no significant difference was found between SCWTR 801010 and SCQ 801010, neither with the same co-amendments and NPK addition. This can also be observed on shoot biomass weight for the non-NPK co-amendments (Fig. 9-a), however when comparing SCWTR +NPK against SCQ +NPK on shoot biomass, significant difference was found with SCQ +NPK having an average weight of 7.36±1.4 grams, and SCWTR +NPK 4.98±1.17 grams. This meaning that even when in height they were similar, on shoot biomass weight a difference was found. Furthermore, the same difference was found on root weight, where SCQ +NPK had an average root weight of 6.8±0.63 grams, and for SCWTR +NPK it was of 4.87±2.07 grams (Fig. 9-b). Meaning that on plant health, SCQ provided a better soil combination for maize growth than the one SCWTR did, with nutrient addition. Further research on the effects of quartzite with NPK addition could be used to explain the effect the mineral has on sandy soil.

It is also important to note that the number of plants on SQ9010 +NPK significantly decreased during the trial with four of them dying during the first couple of weeks and one more drying out by week 4. By the end of the trial, the soil type had only 2 plants, however these two plants presented high levels of height and biomass.

a)



b)

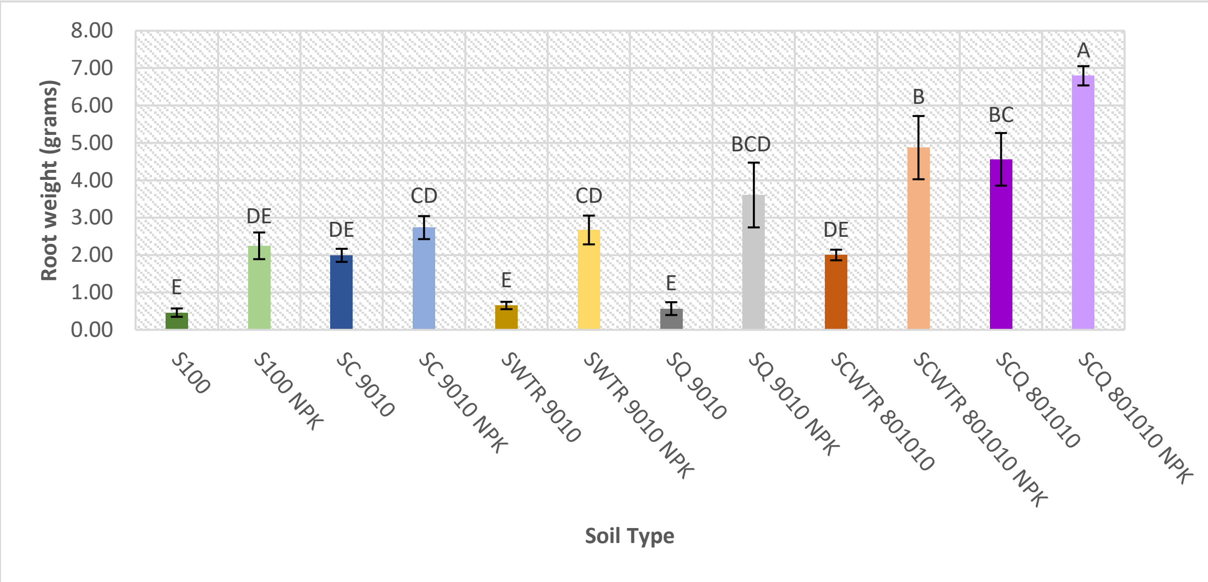


Figure 9. Week 7 measurements of shoot (a) and root (b) biomass weights of all soil types in grams of dry biomass. Labels show statistical difference (p≤0.05), bars that do not share a letter are significantly different. Error bars show standard error of the measurements.

Dry biomass measurements followed a similar trend to that followed by plant height, soil was statistically lower in both shoot and root biomass than the organic amendments. It is important to note that in soils where pH <5.5, root elongation is inhibited [37] but the pH was >5.5 in all cases due to lime addition to the raw Zimbabwean soil at soil type preparation stage. Root and shoot weights on S100 +NPK and SC 9010 had no significant difference, however it is important to note that the correlation (r) of plant height and shoot weight of S100 +NPK was r= -0.02, similarly, the relation between plant height and root mass was r= -0.5. Whereas for SC 9010, for plant height and shoot weight r=0.35, for plant height and root weight r= 0.31. Meaning that, although S100 +NPK had significantly taller plants, they were not as strong-looking as the ones growing on SC9010 which had a consistent co-relation between height and weight of shoot.

Table 6. Average shoot and root biomass (grams) of all amendments. Note that n=2 for SQ 9010 NPK soil type.

n	SOIL TYPE	SHOOT BIOMASS	ROOT BIOMASS
5	Soil 100	0.39	0.46
6	Soil 100 NPK	4.21	2.24
7	SC 9010	3.11	1.99
6	SC 9010 NPK	4.10	2.73
7	SWTR 9010	0.75	0.65
5	SWTR 9010 NPK	3.58	2.67
5	SQ 9010	0.44	0.56
2	SQ 9010 NPK	4.90	3.60
7	SCWTR 801010	2.53	2.00
6	SCWTR 801010 NPK	4.98	4.87
6	SCQ 801010	4.04	4.56
6	SCQ 801010 NPK	7.36	6.80

No significant difference was found on plant height or shoot biomass when comparing SCWTR +NPK against S +NPK, SC +NPK and SWTR +NPK. However, when comparing root biomass, SCWTR +NPK had a significant heavier root system than the rest of the amendments, perhaps this can be explained by drainage of water due to the physical contribution of WTR to the soil in combination with compost.

Further statistical analysis was performed to compare soil types without taking into consideration quartzite soil types. This with the purpose of narrowing down to the hypothesis of organic matter and inorganic mineral amendments addition to the soil having an effect when compared against base soil. This analysis showed a significant difference on plant height when comparing the single amendments of compost and WTR against the base soil where SC 9010 provided the highest average, SWTR 9010 following and S100 with the smallest average of height (Fig. 10), further significant difference was found when comparing S100 against SC 9010 on shoot biomass, but no difference comparing S100 against SWTR 9010 (Fig. 11) (Table 6). In addition, on root biomass, no significant difference was found in any of the soil types.

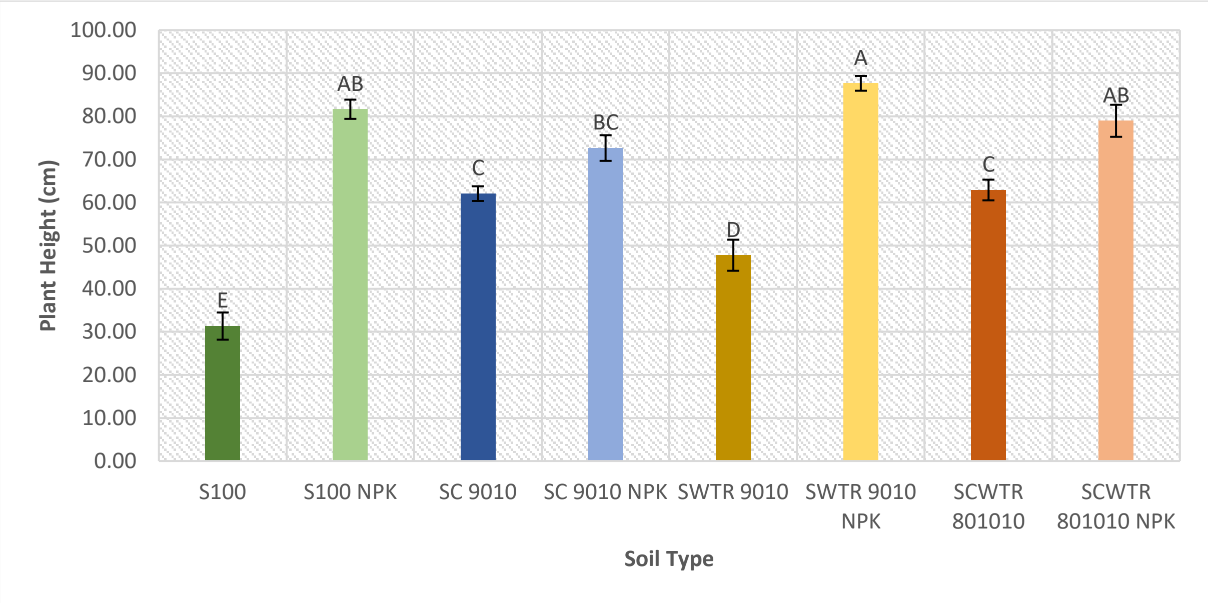


Figure 10. Plant height measurements in centimetres recorded on week 7. Labels show significant differences, bars that do not share a letter are significantly different. Error bars show standard error.

In 2017, Mtangadura et al. experimented with high and low quality organic resources in Zimbabwean soil and found that their results suggested an increase on soil organic carbon in the medium to long term (5-9 years) [6]. Therefore, it is hypothesized that due to the small period of time in which the plant trial was done, and the fact that plant growth does not seem to be slowing down (Fig. 4), longer time is needed to assess the differences between the addition of NPK fertiliser to the soil and the addition of an organic material for it to be able to conclude which one might be more beneficial for Zimbabwean soil. This is further backed up by the fact that no significant difference was found on either shoot or root biomass between S100 +NPK and SC 9010 (Fig. 11).

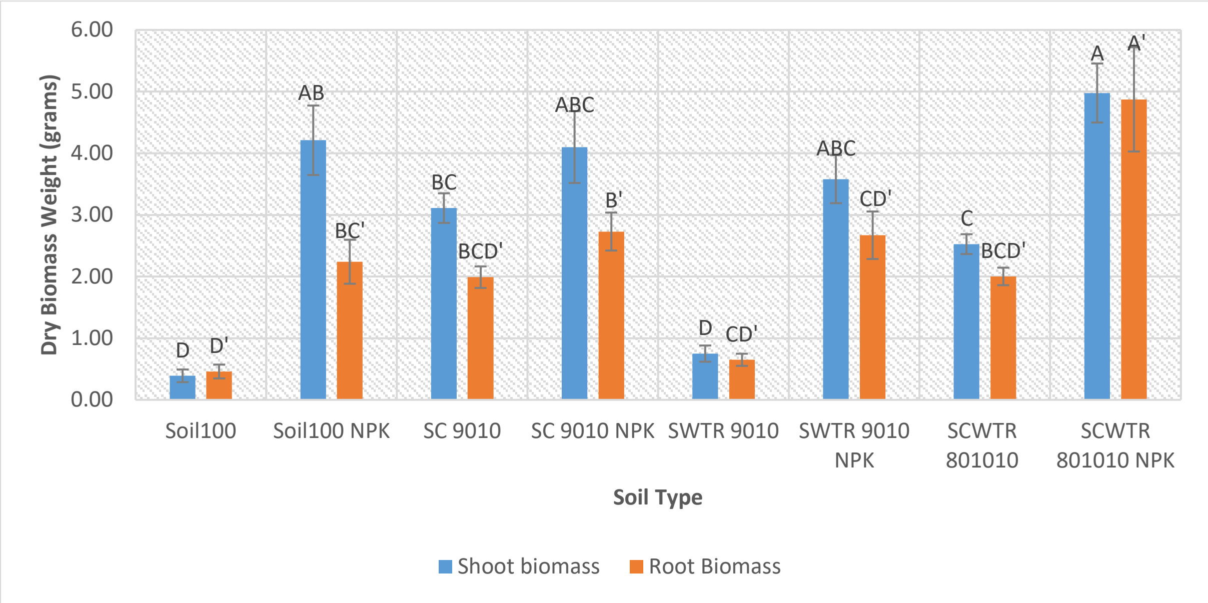


Figure 11. Biomass (shoot and root) dry weights recorded on grams. Labels show significant difference between bars. Bars that do not share a letter are significantly different. Different ANOVA tests were performed, one for shoot biomass ($p<0.05$) and another for root biomass ($p<0.05$).

SWTR 9010 was significantly higher than Soil 100 by the end of the trial. In 1980, Rengasamy et al. found that the addition of WTR to a pot trial of maize increased yield of dry matter of the crop in pots grown with and without a fertiliser addition. However, in this trial, it did not increase shoot biomass significantly (Fig. 11) [50]. Furthermore, on the same experiment it was also found that the P uptake of plants was reduced at the high rate of 10 g of WTR per kg of soil.

According to literature, the optimal rate of WTR addition to improve corn yields is of 0.1 to 10 g of WTR per kg of soil [34]. However, the addition to the single amendment SWTR 9010 was of 300 g of WTR per kg of soil (approximately). Thus, it can be hypothesized that the addition of WTR was too high and, therefore, plants grew in an unsuitable environment. However, when fertiliser was added to the single amendment, P limitations were ‘compensated’ and available for plant uptake.

Although not significantly different, the co-amendment with NPK addition (SCWTR 801010 +NPK) provided with more shoot biomass. In addition, significantly higher root biomass was found in the same co-amendment (SCWTR 801010) than in the rest of the soil types which is showed on figure 10. This could be an indication of the good development of the root system provided by the co-addition of compost and WTR to a sandy soil. The hypothesis being that the addition of WTR could be improving soil properties like soil structure and water holding capacity [34]. Furthermore, in the co-amendment the rate of WTR application lowered to 192 grams of WTR per kg of soil, meaning that the impact of WTR on P was different than the one in the single amendment.

Plant development as well as shoot and root biomass might suggest that the co-amendment compost and WTR could be improving soil properties, as suggested by the literature, and the addition of a fertiliser with targeted nutrients for maize growth might increase crop fertility of Zimbabwean sandy soil.

3.3 CO_2 production as a proxy for hydrocarbon biodegradation

Microbiological parameters measurements, such as soil respiration, provides information on the presence and activity of microorganisms as well as on the intensity, duration, and type of the effects of hydrocarbon pollution. Therefore, CO_2 emissions serve as a good index of the impact of soil pollution [38].

During the preparation of the soil types for the plant growth trial, as previously described in the methodology section, lime was added to the soils to raise the pH. The application of lime to soils has been shown to enhance soil carbon loss by increasing C solubility, microbial activity, and thus the rates of C decomposition [39]. Because all soils had lime in them, the CO_2 emissions represented in the graphs, might show C loses or increased microbial activity when comparing against the raw material Zimbabwean Soil, for this 'raw material' represents soil as it was imported from Africa, with no lime addition.

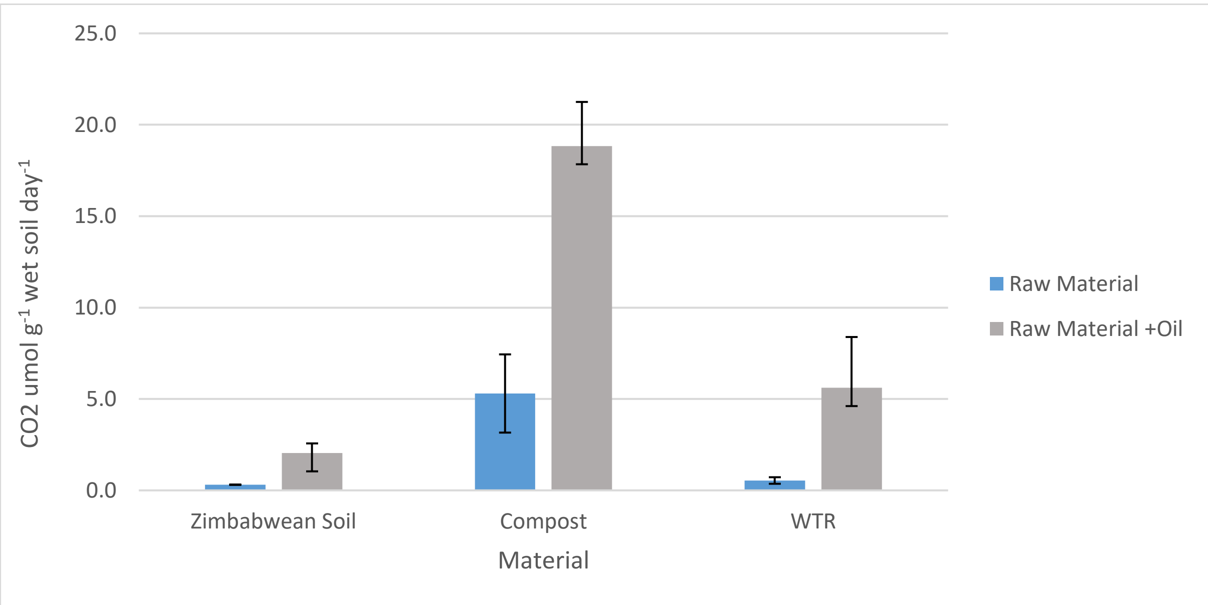


Figure 12. Rate of raw materials CO_2 emissions. Error bars show standard error. Important to note that these materials categorized as raw still have had a nutrient addition during the set-up of the experiments.

Statistical difference ($P<0.05$) was found between oil-contaminated and uncontaminated raw material in compost and WTR, meaning hydrocarbon mineralization was occurring on those raw materials. However, no significant difference was found between Zimbabwean soil with and without oil added to it. Even though WTR and compost are both mineralising hydrocarbons, compost is significantly better than WTR, meaning that out of the three raw materials used, compost provided the most CO_2 emissions for both uncontaminated and oil-contaminated materials.

It has been found that compost provides a high diversity of microorganisms and that those degrading hydrocarbons can be found amongst them [40]. Furthermore, the organic matter contained in compost influences sorption/desorption processes of hydrophobic organic contaminants [41].

WTR CO_2 emissions compared to Zimbabwean soil emissions did not present a significant difference, however, on contaminated materials the difference was significant. An increase in CO_2 emissions on contaminated raw materials compared against uncontaminated raw materials can be seen (Fig. 12), this rate can also represent microbial activity. Hydrocarbon contaminants serve as organic carbon sources for microorganisms, thus increasing microbial activity, which can also explain why contaminated rates are higher than uncontaminated rates [38].

Although organic amendments have been found to enhance soil respiration rates on different soils, no significant differences were found when comparing basal respiration of S100 against the rest of the soil types (Figure 13) [27]. The low levels of Zimbabwean soil CO_2 emissions could be a consequence of its low organic matter content for it has been suggested that soils with a higher organic matter and clay content are less affected by hydrocarbon contamination [38].

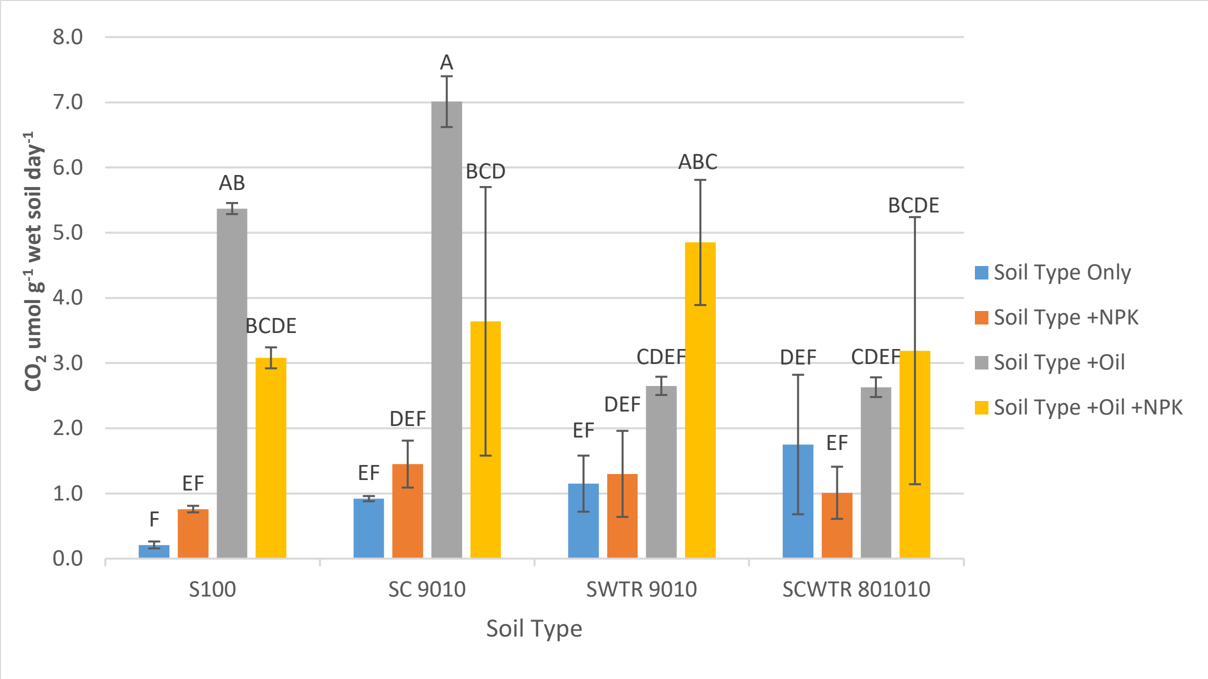


Figure 13. Rate of CO2 emissions on all soil types. Labels show significant difference, bars that do not share a letter are significantly different. Error bars show standard error. Soil types that include "+NPK" refer to the NPK added during the plant growth trial.

Out of the four soil types assessed, S100 and SC 9010 showed significant difference in basal respiration with the addition of oil, whereas SWTR 9010 and SCWTR 801010 did not show a significant difference.

From the results obtained of the 32-day microcosms set up, no significant difference was found between non-NPK amended soil types and NPK amended ones in all but one soil type, this being SC9010. Fertiliser addition to soil type SC 9010 produced less CO_2 emissions. The lack of effectiveness of nutrient addition to the rates of soil types could be explained by the fact that soil types catalogued as "+NPK" received fertiliser during the growth trial and a second addition was made before starting the microcosm experiments. Plants grown in SC9010+NPK had no statistically significant difference in either shoot or root biomass at 7 weeks and so we can assume that root exudates were not different in either soil type. Therefore we might hypothesise that an 'overdose' of nutrients could explain an inhibitory effect on hydrocarbon biodegradation and that by extension possibly NPK has a deleterious effect on the ability of the soil microbiome to degrade hydrocarbons. Furthermore, it has been suggested that organic and inorganic fertilisers are needed to maintain chemical, physical and biological characteristics of soil quality in order to achieve a high removal of hydrocarbon compounds [27]. However, studies have shown that fertiliser amendments produce no increase in biodegradation rates, and this can be attributed to the complex composition of soils and other factors [42].

According to Fig. 14, cumulative CO_2 showed that soil types with oil contamination were not entering into a lag phase by the end of the experiments. It also showed no significant difference when comparing polluted soil types S100 +NPK and SC9010, however SC9010's rate is higher than S100 +NPK (although not significantly), a longer experiment could provide enough time for compost to have a greater effect on soil microorganisms and a greater rate of CO_2 emissions. Rolling et al. (2004), found that polluted soils treated with compost amendments can produce higher bacteria community structures which leads to higher degradation rates when compared to liquid nutrient sources, and that the addition of compost increases microbial diversity and has been found to take less time during bioremediation than a fertile, productive soil [40].

Soil respiration was significantly increased by hydrocarbon pollution, therefore the effect seen in the rate of S100 +NPK might be that of the hydrocarbon introduction to the soil microorganisms rather than the biodegradation of said hydrocarbon. In 2006, Labud et al. reported that the contaminants used increased soil respiration in a clayey and sandy soil but particularly in the latter.

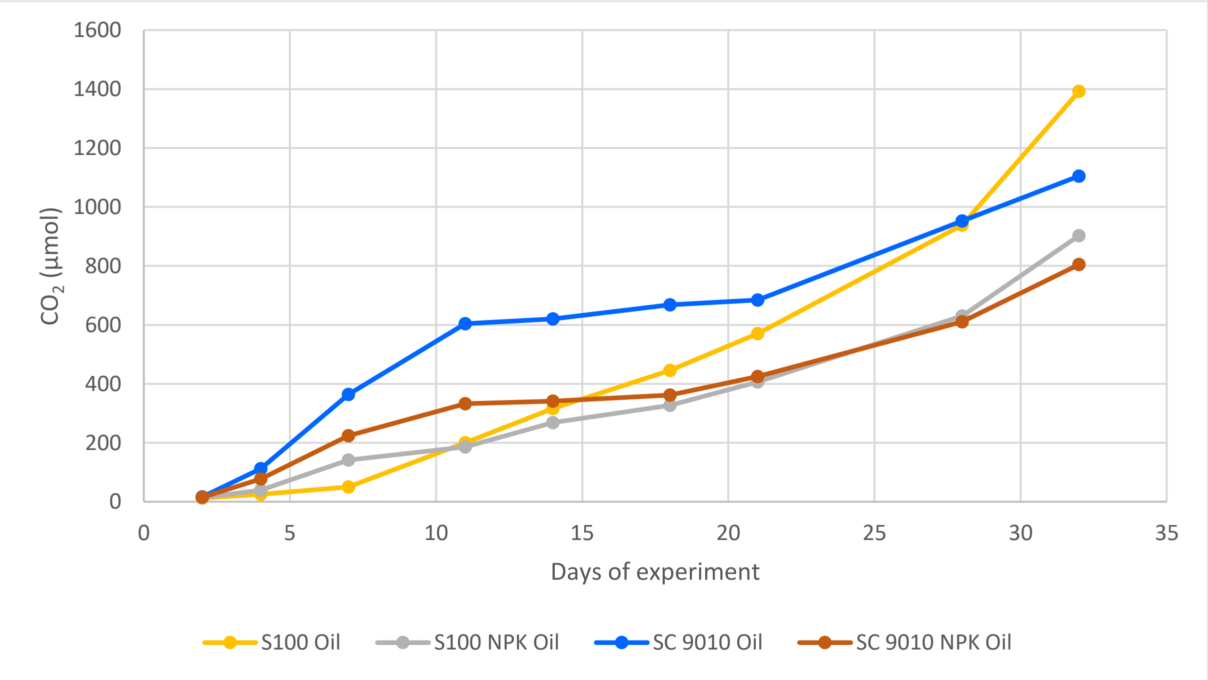


Figure 14. Cumulative CO_2 for selected soil types throughout the 32-day experiments.

As it is observed on figure 14, soil types suffered a lag phase during the first measurements, this is consistent with what was found by Labud et al., 2006. They found an initial lag phase in soil respiration in polluted sandy soils and suggested that this could be due to a period of adaptation needed by microorganisms.

Among many different physical, chemical, and biological factors that can affect microbial community composition and activities, temperature is listed as one [21][39]. The microcosm bottles were not stored under controlled conditions which means they were set at room temperature, on wintertime through the duration of the experiment. As a result, it is hypothesized that further statistical differences could be found in a longer experiment.

4. Conclusions

Zimbabwean soil suffers from poor structure, as expressed by many studies [3][4][5][6]. It can be concluded that organic matter input and nutrient addition to this soil creates a significant increase in plant development, which at the same time, helps improve soil properties, as reflected on plant growth and microbial respiration.

The results show that compost amendment created a fit environment for plant growth and proved to be the best material to promote microbial activity in the soil. However, short-term experiments can only provide with enough data to set up a long-term experiment, and it is for that reason that it is concluded in this work that compost amendment (with NPK making no statistically significant improvement) and compost-WTR co-amendments both provided evidence of soil improvement in terms of plant biomass (with NPK making a statistically significant improvement) and no signs of these improvement to be slowing down. It is believed that in longer experiments these organic and inorganic amendments would show significant differences when compared against fertiliser addition with the last one having a less beneficial effect on soil health (plant development) and hydrocarbon breakdown.

Further analyses to microbial communities are also needed in order to explain hydrocarbon breakdown activity and how each material changed microbial communities and their activities in each soil type.

5. References

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