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**Effects of clay and organic matter amendments on water and
nutrient retention of sandy soils**

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A thesis submitted to the School of Life Sciences in fulfilment of the
requirements for the degree of Doctor of Philosophy

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List of abbreviations

°C: Degree Celsius

%: Percentage

3D: Three-dimensional

AEC: Anion exchange capacity

Ag: Silver

Al₂O₃: Aluminium oxide

AlOH₆³⁻:

ANOVA: Analysis of variance

B: Bentonite

Ba: Barium

BD: Bulk density

BS: British standard

C: Carbon

C:N: Carbon to nitrogen ratio

Ca: Calcium

Ca²⁺: Calcium ions

CaCO₃: Calcium carbonate

CaO: Calcium oxide

CEC: Cation exchange capacity

CIWMB: California Integrated Waste Management Board

Cmolc: Centimol cations

Co: Cobalt

CO₂: Carbon dioxide

CRD: Completely Randomised Design

Cs: Caesium

CT: Computed tomography

CTAHR: College of Tropical Agriculture and Human Resources

Cu: Copper

EC: Electrical conductivity

FAO: Food and Agricultural Organisation

FC: Field capacity

Fe₂O₃: Iron II oxide
g/g: gram per gram
GE: General Electric
GLM: General Linear Model
GRDC: Grains Research and Development Corporation
GS: Growth stage
GSV: Grey scale value
H⁺: Hydrogen ion
H₂O: Water
IAEA: International Atomic Energy Agency
ISO: International Organization for Standardization
ISRIC: International Soil Reference and Information Centre
JRC: Joint Research Centre
K: Kaolin
K⁺: Potassium ion
K₂O: Potassium oxide
KCl: Potassium chloride
Kg: Kilogram
Kg m⁻³: Kilogram per cubic metre
km²: Kilometre square
kV: Kilovolt
LOI: Loss on ignition
LSD: Least significant difference
Ltd: Limited
MBC: Microbial biomass carbon
MC: Moisture content
Mg: Magnesium
Mg/ha: Megagram per hectare
mg/L: Milligram per litre
Mg²⁺: Magnesium ions
MgO: Magnesium oxide
mL: Millimetre
Mn₃O₄: Manganese oxide
N: Nitrogen

Na₂O: Sodium oxide
ND: No data
NDVI: Normalise difference vegetation index
NH₄-N: Ammonium nitrogen
NH₄⁺: Ammonium ion
Ni: Nickel
NO₃-N: Nitrate nitrogen
NPK: Nitrogen, Phosphorus, potassium
OC: Organic carbon
OM: Organic matter
PAW: Plant available water
Pb: Lead
PCR: Polymerase chain reaction
PS: Pure sand
Pt: Peat
PVC: Polyvinylchloride
PWP: Permanent wilting point
RB: Reference Book
RCOOH: Carboxyl group
RO: Reverse osmotic
ROI: Region of Interest
SE: Standard error
SEM: Scanning electron microscope
Si-O: Silica-Oxygen bond
SiO₂: Silicate
SL: Sandy loam
SOC: Soil organic carbon
SOM: Soil organic matter
t/ha: tonnes per hectare
TCD: Thermal conductivity detector
TGW: Thousand grain weight
TiO₂: Titanium dioxide
UK: United Kingdom
UNESCO: United Nations Educational, Scientific and Cultural Organization

USDA: United States Department of Agriculture

VG: Volume Graphic

WRA: Water retained by amendments

WRB: World Reference Base

Zn: Zinc

μ A: Micron Ampere

μ m: Micron metre

μ S/cm: Micron Siemen per centimetre

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Dedication

This thesis is dedicated to the glory of Almighty God, Jehovah.

Declaration

I declare that the work presented in this thesis was conducted by me under the direct supervision of Robert Lillywhite and Professor Jane Rickson, with the exception of those instances where the contribution of others has been specifically acknowledged. None of the work presented here has previously been submitted for any other degree.

Jumoke Esther Ogunniyi

Abstract

Sandy soils are one of the most widely distributed soils in the world. However, crop production on these soils can be problematic especially in term of water and nutrient retention. In the face of climate change and a projected reduction in water availability, food production is likely to be particularly affected. The aim of this research is to examine if amending soils with clay and organic matter can improve their water and nutrient retention.

The research approach employed laboratory column leaching experiments, rainfall simulation, Computed Tomography (CT) scanning and field trials to investigate the potential of two types of clay, Kaolin (K) and Bentonite (B), and peat (Pt), as well different combinations of clay and peat, to act as effective soil amendments. The influence of amendment materials was assessed by examining water retention, nutrient retention, soil organic carbon and changes in soil properties. Laboratory analysis was supported by field trials to examine the productivity of spring wheat.

The results showed that the amendment materials increased soil water retention and availability, reduced water infiltration, increased nutrient uptake, increased spring wheat growth and yield, and improved soil carbon storage compared to an unamended control.

The findings provide a further understanding of how the addition of clay and OM can affect ecological function of sandy soils and elucidate the mechanisms involved in controlling water retention and availability, as well as nutrient retention in the amended soils.

Chapter 1

Introduction

Soil is an important non-renewable natural resource with many functions that support the existence of plant and animal life. It is a medium for growing crops, a source of nutrients for the plant, essential for water storage, a medium for pollution control and storage of soil carbon. The ability of soils to carry out these roles is controlled by their physical, chemical and biological properties, which vary from soil to soil. Most of these properties are intrinsic, inherited from the original rock parent (e.g. clay minerals), while some are extrinsically acquired over time (e.g. organic matter) from environmental or anthropogenic activities. The ability of a soil to deliver these eco-functions can be greatly influenced by these intrinsic and extrinsic properties.

Soils are formed as a result of interactions among parent materials (rock or its derivatives), climate, living organisms (flora and fauna), relief and time (Hans, 1994; Lal and Shukla, 2004), through a process called weathering. The extent of these interactions plays a key role in the determination of the soil type that will result. The influence of these soil-forming factors on the formation of different types of soil varies from arid to humid regions.

A soil is made up of four elements: (1) mineral matter, (2) organic matter (OM), (3) water and (4) air (Lal and Shukla, 2004). An ideal soil is said to contain 45% mineral matter, 5% organic matter, 25% water and 25% air (Hillel, 1998, Lal and Shukla, 2004). However, the definition of 'ideal' and the proportions of the different elements will depend on the required soil functions, such as crop production, water regulation and/or carbon storage.

Soils are classified on the basis of proportions of sand, silt and clay content. To determine the textural class of a given soil, the proportion of these fractions is first determined using mechanical analysis or particle size analysis. In the presence of water and a deflocculating agent such as sodium hexametaphosphate (Calgon) which complexes and flocculates the soil cations, naturally occurring soil aggregates are separated into the three primary particles by applying mechanical shaking. The method measures the time taken for each fraction to travel (usually) to the bottom of a 1L

measuring cylinder. The last particle to settle out of the soil solution is clay. The hydrometer method is commonly used (Bouyoucos, 1963), which measures the suspension density when sand and silt have settled out of the suspension respectively after a given time interval. The reading is then corrected for the temperature and density of the Calgon used. The proportion of sand, silt and clay is determined using the following formulae:

$$\% \text{ clay} = (\text{sample hydrometer reading} - \text{blank reading}) \text{ at } 412 \text{ minutes} \times 100 / \text{sample wt}$$

$$\% \text{ silt} = (\text{sample hydrometer reading} - \text{blank reading}) \text{ at } 40 \text{ seconds} \times 100 \text{ sample wt} - \% \text{ clay}$$

$$\% \text{ sand} = 100 - \% \text{ silt} - \% \text{ clay}$$

The percentage sand, silt and clay present in the soil sample determines the soil textural class using the textural triangle (Figure 1-1). The classes range from sand to clay.

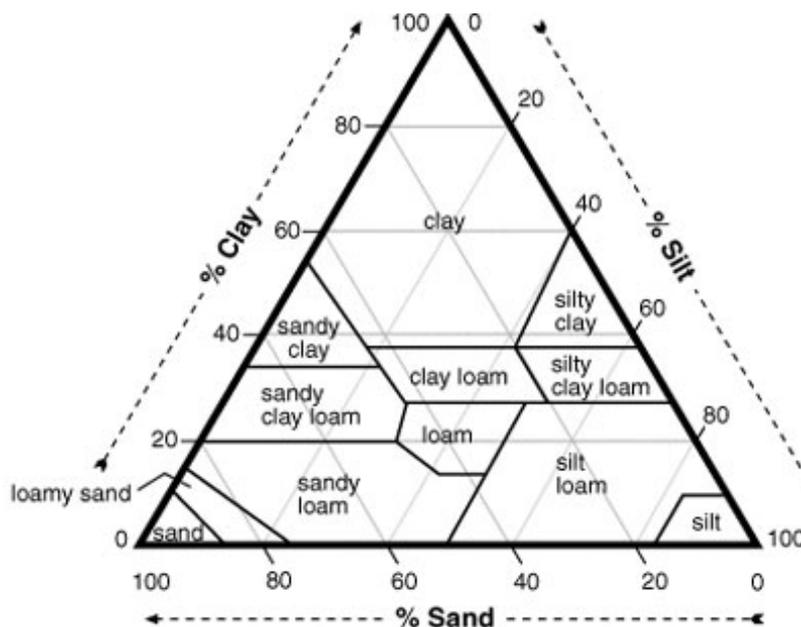


Figure 1-1: Textural triangle and textural classes of soil.

(Source: www.extension.umn.edu/agriculture/soils/soil-properties/soil-management-series/introduction-to-soil-management/; accessed 16/07/2017)

The soil of interest in this project is sandy soil. Sandy soils are found all over the globe from tropical to temperate, and from humid to arid zones. They are significant in terms of global food production and therefore food security due to their wide distribution

(FAO, 1993). In many areas, sandy soils represent a significant proportion of land being cultivated for food (Hartemink and Hunting, 2005).

However, they can be problematic due to their inherent physical, chemical and biological properties, which can result in soil that is low in water and nutrient holding capacity (Eslinger and Pevear, 1988; Dixon, 1991; Reuter, 1994; Franzluebbbers et al., 1996). Sandy soils are also prone to leaching, which can lead to water loss and associated contamination of groundwater (by nutrients or pesticides). Sandy soils have low cation exchange capacity (CEC), poor buffering capacity, high rates of organic matter decomposition and reduced microbial biomass (Kramer, 1983; Bruandi et al., 2005; Blanchart et al., 2007).

The current world water demand, distribution and availability are other reasons why improving water retention of sandy soils should be of global concern. According to Innovation in Business, Energy and Environment (2014)¹, the current water demand has exceeded the supply capacity in some regions of the world such as in Texas (USA), and the trend is likely to increase in the face of desert encroachment and increasing human population of up to 8 billion in 2050 (Tilmer et al., 2011; Alexandratos and Bruinsma, 2012). As shown in Figure 1-2, agriculture is the major user of the water in the world. The large proportion of this water is used in irrigation or produce washing; thus, the water problem is inevitably an agricultural problem. When used for irrigation, the water should be maintained within the root zone to realise its agronomic and economic values. This is a great challenge in sandy soils where excessive infiltration allows water and nutrient movement beyond the crop recovery region (root zone), and farmers usually resort to an increased frequency of irrigation to manage the situation. To mitigate these challenges, management practices that could reduce infiltration and increase water retention in soils are highly essential.

Different approaches have been adopted in managing water and nutrient retention of sandy soils. One way is the use of synthetic hydromorphic polymers (Vroman and Tighzert, 2009; Ekebafé et al., 2011), and it has been reported that these can have positive effects on water retention (Ekebafé et al., 2011). However, their acceptability has been limited by cost and the concern that some of these compounds might not be

¹ <https://innovbusenergyenviro.wordpress.com/2014/10/28/texas-water-supply-and-demand-dynamics/> [accessed 25/03/2015]

biodegradable. Other methods involve using naturally occurring inorganic substances such as clay and organic materials including crop residues, animal waste, sewage sludge, bioethanol wastes, peat, paper mill waste and biosolids (Annabi et al., 2007; Li et al., 2004; Arthur et al., 2010; Yu et al., 2012; Wang et al., 2014). The soil type and the intended crop will influence the choice of material to be used, as well as the rate of application.

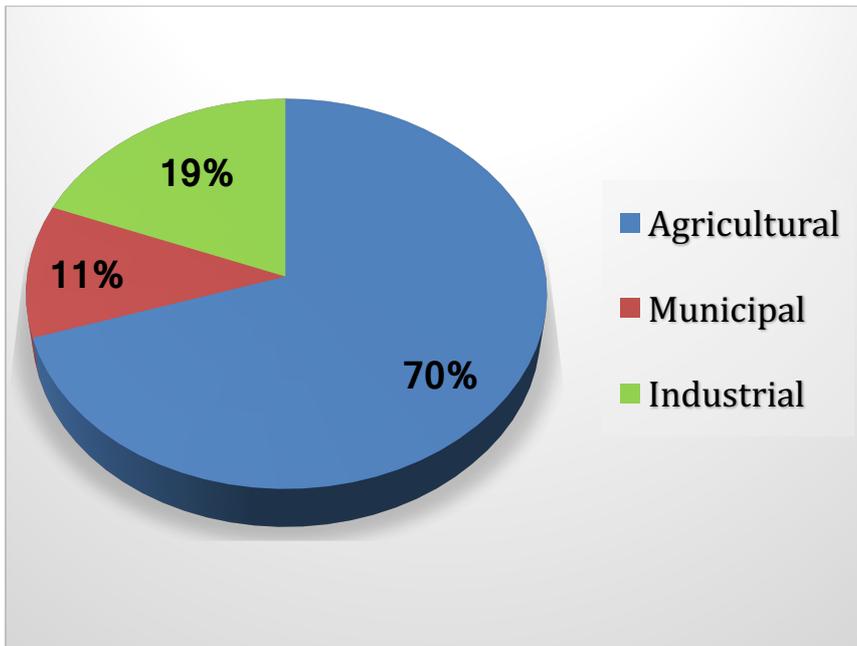


Figure 1-2: Global sum of all water withdrawal
(Source: FAO, 2016)

1.1 Literature review

1.1.1 Pedogenesis of sandy soils

Classification of a sandy soil is based on its proportion of sand compared to clay and silt. Of the three types of particles that form the mineral component of soil, sand has the largest particle size ranges from 0.02 – 2 mm, and is differentiated from silt (0.002-0.02mm) and clay (<0.002mm) on the basis of particle size described by the United States Department of Agriculture (USDA; Lal and Shukla, 2004). Sandy soils can be grouped into textural class ranges including sandy-clay, sandy clay loam, sandy loam, loamy sand and coarse sand. A typical sandy soil originates from aeolian or alluvial material with a deep deposit of sand (Eswaran et al. 2005; WRB, 2006). Sandy soils could be found in different soil orders such as Aridisols (Kadry, 1975), Arenosols, Fluvisols, Regosols, Acrisols and Leptosols (FAO, 2001).

In the World Reference Base (WRB), soils with >70% sand and <15% clay are called Arenosols (FAO, 2001; WRB, 2006, 2014). This Order is equivalent to Sandy Entisols under Soil Taxonomy (Soil Survey Staff, 1999) or Psamment (when it is well drained). Arenosols could be described as the sandy soil representative soil Order. They are soils that have loamy sand or sand within the top 100 cm. They could also have different horizons such as (1) salic horizon which is a surface or subsurface horizon with accumulation of secondary salts that are readily soluble than gypsum; (2) plinthic horizon which is an iron rich and OM poor subsurface horizon that consists of quartz and kaolinitic clay as well as other materials and can harden irreversibly upon exposure to alternating drying and wetting in the presence of enough oxygen; or (3) petroplinthic horizon which has layers of indurated substances that are continuous and cemented mainly by iron with little or no OM around the depth of 50 to 100 cm (WRB, 2006).

Arenosols lack diagnostic horizons except for albic, ochric, or yermic horizons. Albic horizon is a weakly or non-structured subsurface horizon in which clay and oxides have been leached. The colour is usually light due to the removal of clay and oxide, and has a coarse texture compared to horizons above and below it. The ochric horizon is a thin, low organic carbon (OC) surface horizon without fine stratification. Yermic horizon is a surface horizon usually consist of rock fragments accumulation and fixed in a vesicular crust that is loamy, and overlaid with a layer of a dune or aeolian sand, commonly found in the desert area (WRB, 1998). Arenosols are developed from unconsolidated parent materials, including calcareous, residual sandstone, siliceous sedimentary rock, translocated sandy-textured materials or recently deposited sands commonly found in beaches and deserts (FAO, 2001; Seng et al., 2005). Arenosols are also found in association with other soils and when this occurs, such soils are described as “Arenic” (meaning loamy sand or finer textured soil from the surface to the depth of 50 cm; WRB, 1998).

There are clear differences between the Arenosols of dry and wet climatic zones. Soil development in dry areas is associated with sand dunes, with soil forming processes usually proceeding at a very slow pace due to either highly reduced moisture conditions or young parent materials. When the dune is sufficiently covered with vegetation, there will be an accumulation of organic matter in the surface layers as well as the development of an ochric horizon, usually close to the surface. Sand grains

can also get coated with clay, carbonate and/or gypsum, giving them a brown appearance. In the desert, red colouring from goethite is possible. Calcaric, Hypoduric, Hyposalic and Gypsic Arenosols or their combinations can be formed depending on the parent materials and the topography of the area (Kadry, 1975; Soil Survey Staff, 1975; WRB, 2006).

Arenosols of temperate regions are more developed compared to those in arid landscapes (WRB, 2006). The suggested pedogenesis includes the establishment of plant cover after stable geomorphological conditions and decalcification of calcareous sand. This process is followed by the formation of an ochric surface horizon that contains humus (Arwyn et al., 2005). Complexes of iron or aluminium and organic substances (Cheluviation) usually occur as soluble organic substances leached from the previously formed ochric horizon. This marks the beginning of Podzol formation, and a spodic horizon could develop. When this occurs, the soil is classified as a Podzol or an Anthrosol if the intervention of human activities leads to the formation of an anthric horizon typically about 50 cm thick (WRB, 2006). Formation of discontinuous layers of clay lamellae is another feature that signifies periods of stability in Arenosols development (Arwyn et al., 2005).

In the humid tropics, Arenosols are often likely to develop from the intensely weathered quartz-rich rock leading to the transformation of all its primary minerals. Alternatively, they can develop from aeolian, alluvial or lacustrine deposits (WRB, 2006). Figure 1-3 shows examples of different Arenosol soil profiles produced from different parent materials and weathering processes.

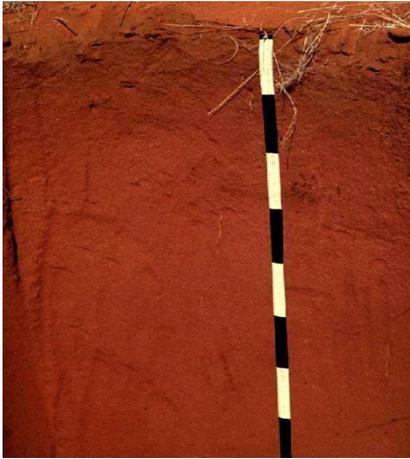
As mentioned earlier, sandy soils are found in other soil Orders such as Aridisols, Fluvisols, Regosols, Acrisols and Leptosols. Aridisols are soils of arid regions characterised by aridic moisture regime. Fluvisols are soils formed from alluvial, lacustrine and/or marine deposits. Regosols are medium textured soils developed from unconsolidated materials, usually not strongly structured. Acrisols are soils commonly found in tropical and subtropical regions, typically a leached acid soil with increasing clay content with depth (argillic horizon). Leptosols are shallow or very gravely soils. However, these soils will not be discussed in detail, rather attention will be focused on Arenosols as being representative of sandy soils.



(a)



(b)



(c)



(d)



(e)



(f)

Figure 1-3: a-e) Typical Arenosols soil profiles with different colours resulting from various soil forming processes f) a sandy soil showing sparse vegetation cover. (Sources²: WRB, 1998, 2006; FAO,2001)

² www.tankonyvtar.hu/en/tartalom/tamop425/0032_talajtan/ch12.html (accessed 12/07/2017)

www.cornandsoybeandigest.com/conservation/adding-topsoil-sandy-soil-increases-crop-yield-south-australia (accessed 29/09/2017).

1.1.2 Global significance of sandy soils and their use

Sandy soils are found all over the world from arid to humid climatic zones. The representative soil Order for sandy soil – Arenosols - has been categorized as one of the main soils of the world (FAO, 1993). Arenosols cover almost a billion hectares of land worldwide, representing 7% of the total soil types in the world (FAO, 1993; WRB, 2006). Half of the world's Arenosols are found in Africa, around 21% in Australasia, 14% in South and Central America, 10% in South and Southeast Asia, and fewer patches in Europe and North America (Hartemink and Huting, 2005). See Table 1-1 and Figure 1-4.

Table 1-1: Arenosols by continents

Country	Arenosols ('000 ha)
North & Central Asia	3,436
Europe	3,806
North America	25,512
South & Southeast Asia	94,530
South & Central America	118,967
Australasia	193,233
Africa	462,401
Total	901,885

(Source: Hartemink and Huting, 2005)

1.1.2.1 Africa

Hartemink and Huting (2005) present information on the extent of Arenosols in nine African countries (see Table 1-2) and showed that the parent materials and the process of soil formation differ from one country to another. For instance, Arenosols are derived from weathering of quartz-rich granite rocks in Zimbabwe. In East Africa, Arenosols are found in coastal regions, while in Botswana and some neighbouring countries, sandy soils were developed from Kalahari sands.

Cultivation of sandy soils was most extensive in Angola, with significant areas in South Africa and Botswana. The reported total area of Arenosols was 176 million ha (Table 1-2), but as sandy soils are present in other soil Orders (Hartemink and Huting, 2005), it can be inferred that they actually cover even larger areas.

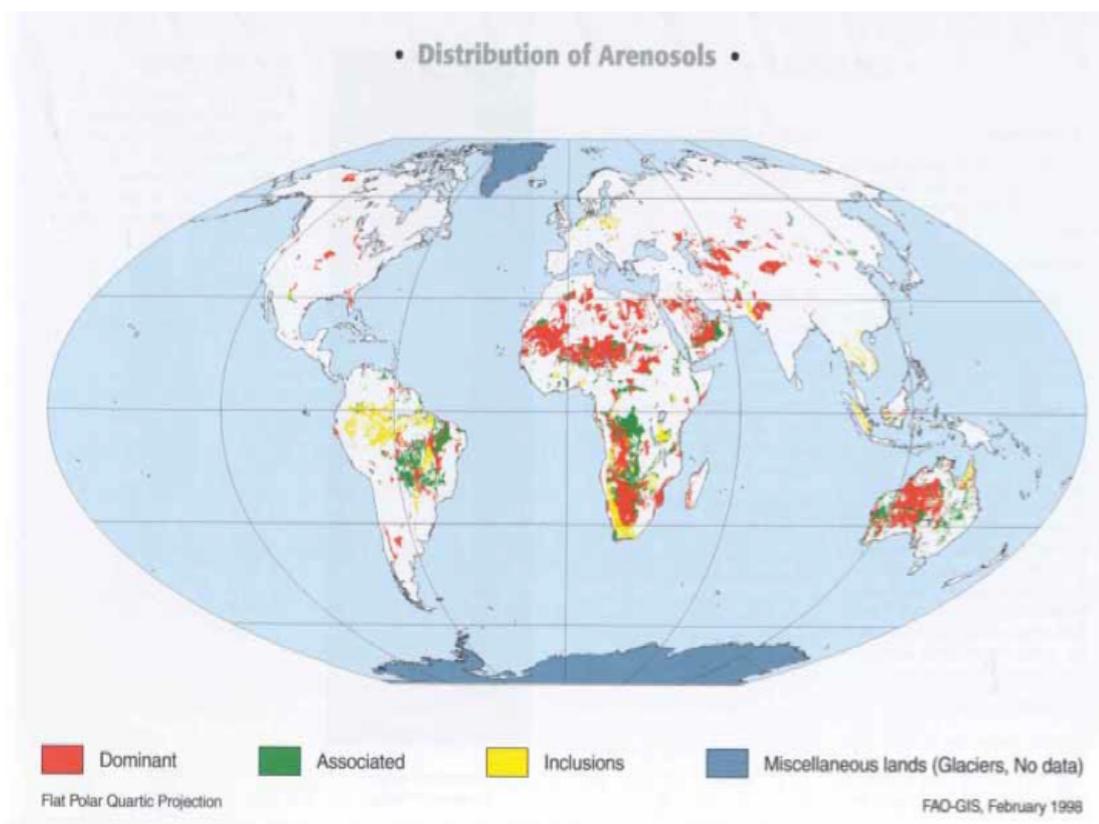


Figure 1-4: Global distribution of Arenosols

(Source: FAO, 1993)

Table 1-2: Total area covered by Arenosols and the percentage cultivated in nine African countries.

Country	Total land area (million ha)	Total Arenosols (million ha)	Cultivated Arenosols (million ha)	% of cultivated Arenosols to the total cultivated area
Angola	125	64	1.9	39
Botswana	58	38	1.1	23
Kenya	59	3	0.1	3
Mozambique	79	17	0.4	5
Namibia	83	26	0	1
Tanzania	95	4	0	0
South Africa	125	18	2.6	10
Swaziland	2	0	0	0
Zimbabwe	39	6	0.9	8
Total	665	176	7.0	

Source: Harmetink and Huting (2005)

1.1.2.2 Asia

Some Asian countries are covered by sandy soils, some of which are subjected to moderate to intensive cultivation (see Table 1-3). In Cambodia, many of the sandy

soils are formed from a siliceous sedimentary material (Workman, 1972 in Seng et al., 2005; Hin et al., 2010) and are used for lowland rice production. According to Seng et al. (2005), only a small portion of the soils that originate from basalt, alluvial or those found along the fringe of Lake Tonle Sap is not sandy in nature. The sandy surface soils of the Acrisols order occupies around 50% of the land, while Arenosols cover about 1.6% (Hin et al., 2010).

In Thailand, sandy soils are dominant in the Northeast where they occupy 80% of the total land area compared to 2%, 9% and 11% in the North, Southern and Central/East regions of the country respectively (Office of Soil Survey and Land Use Planning, 2002 in Caldwell et al., 2005). Because of the undulating nature of the region, the middle / upper slopes are used for commercial cassava and sugarcane plantations, while the lowland is mainly cultivated to paddy rice (Funakawa et al., 2005).

Table 1-3: Land area subjected to low water holding capacity stress associated with a sandy nature in selected countries of Southern Asia

Country	Total land area (km ²)	Arable land (km ²)	Area covered by sandy and skeletal soils (km ²)
Afghanistan	647,500	80,452	9,303
India	2,973,190	1,687,020	6,206
Indonesia	1,826,440	317,294	67,883
Malaysia	328,550	48,387	369
Pakistan	778,720	212,674	48
Philippines	298,170	93,230	2,415
China	9,326,410	972,981	ND
Thailand	511,770	209,130	ND

Source: Eswaran et al., 2005.

ND means no data

As reported by Nguyen (2005), 9 provinces in Vietnam have over 20 million ha of sandy soil. For instance, in Thua Thie Hua province alone, about 66,000 ha out of the 84,000 ha total cultivated area is sandy (Pham et al., 2005). This value represents approximately three-quarters of the cultivated area.

In China, 10% of the total land of Hainan Province is said to be sandy, largely developed from marine sediments and to lesser extent granite material (Zhao et al., 2005).

1.1.2.3 Europe

Arenosols cover 1% of the total land area in Europe (Arwyn et al., 2005; WRB, 2006). According to the FAO, Arenosols include Cambic and Luvic Arenosols. Cambic Arenosols are used for intensive cereal production (especially malting barley) in the United Kingdom, and for valuable arable farmland and forestry in Poland. In Spain, some Arenosols are under forest while some are used for the production of fruit and cereals. Cambic Arenosols are mainly forested in the Czech Republic and Slovakia (formerly Czechoslovakia). Substantial amounts of Luvic Arenosols are found in Hungary, where about 27% of the total land area is either sand or sandy loam, used mostly for fruit, maize, vine and animal production (FAO-Unesco, 1981; Verbal Presentation by the Director of Hungarian Academy of Sciences, 2016).

The information provided for Europe only refers to Arenosols, but sandy soils are found in other soil Orders as well. For instance, Jankowski (2010) shows that in Poland, sandy soils are found in Podzols and Gleysols, which have the regional names: Rusty soil, Mucky soil, Gleyic podzol, Podzolic soil and Ochre soil.

Calcareous and non-calcareous sandy soils cover more than 3.3 million hectares (about 22% of total land area) in England and Wales and belong to the Soil Associations of Sandwich, Methwold, Cuckney (1 and 2), Newport (1 - 4), Kexby and Ollerton (Cranfield University, 2016). Out of these, 55%, 25%, 10% and 10% respectively are Calcaric Arenosols, Dystric Protic Arenosols, Dystric Arenosols and Arenic Eutric Gleysols (WRB, 2006, in Cranfield University, 2014). These soils are used for the production of cereals (mostly barley and wheat), sugar beet, potato, carrot, oilseed rape, brassica, pea, beans, grassland and coniferous woodland. Reflecting the poor water holding capacity of these sandy soils, "Irrigation is needed for the more valuable crops to be profitable" (Cranfield University, 2016).

1.1.2.4 The Americas

Arenosols are virtually absent in North America, although coarse-textured materials exist in association with other soil groups. Most Cambisols in Canada have been said

to develop from parent materials that are coarse-textured. The texture of Dystric Cambisols can be sandy glacial till or sandy loam, and occupy 3% of the land area. Eutric Cambisols have textures ranging from clay to sandy loam, and are the principal soil of almost 6% of the Canadian landscape, with about 780,000 ha used for farming, and 7 million ha for forestry, while large areas of this soil type are unused. Coarse-textured soils are also found in Regosols and Kastanozems in Canada (FAO-Unesco, 1978).

In South America, about 50% of the soil area is characterized by inherent low fertility and is dominated by Feralic Arenosols, Ferrasols, and Orthic Acrisols. Albic Arenosols are found in Bolivian and Atlantic coastal lowlands. Feralic Arenosols are found in Paraguay, and many are found in Brazil where they are used for extensive grazing (FAO-Unesco, 1971). Sandy soils in Mexico and Central America consist of Arenosols and Regosols, although Arenosols are less important in this region because only small areas are found in Cuba and British Honduras (FAO-Unesco, 1975).

1.1.2.5 Australasia

Sandy soils occur extensively in Australasia, with Australia having the highest area. They consist mainly of Arenosols, Acrisols, Podzols and Regosols with Albic, Cambic and Feralic Arenosols. Depending on climatic factors, they are used for forestry, grazing, improved pastures, and cereals or are uncultivated. Calcaric Regosols occur in Australia where they are used for cereals such as barley, cattle grazing or medic pasture. Dystric Regosols are widely found in Australia (where they are used for citrus production and grazing), North Island in New Zealand (for sheep farming) and in a small area in New Caledonia (but not used for agricultural production), with various textures including sand, sandy loam and clayey sand in the subsurface. The Eutric Regosols of Australia have a sandy loam or loamy sand texture. These soil types also occur in New Zealand and the New Hebrides. Land usage differs from one country to another. For instance, Eutric Regosols are used for pasture, cereals and natural grazing in Australia, forestry (*Pinus* spp) and pastoral farming in New Zealand, while left under natural forest in the New Hebrides. Humic Podzols occur in southern and Eastern Australia, with compacted sand or sandy loams in the B-horizon, and are used for farming, pasture and forestry (FAO-UNESCO, 1978).

1.1.3 General characteristics, features and problems of sandy soil

The innate characteristics of sandy soils present a range of challenges for crop production and the environment. Sandy soils generally have poor water and nutrient holding capacity because large pores permit rapid drainage of water, inherent low fertility associated with low cation exchange capacity (CEC), high anion exchange capacity (AEC) in some soils, extremes of pH, low levels of organic matter resulting in poor microbial activity, high vulnerability to erosion and poor aggregate formation which causes poor structural stability (Al-Omran et al., 2005; Blanchart et al., 2007; Sitthaphanit et al., 2010; Wang et al., 2014). In addition, where sandy soils are used for crop production, the problem of insufficient organic matter and hydrophobicity of some sandy soils usually cause uneven germination, resulting in poor weed control, low levels of soil cover and reduced productivity (Department of Agriculture and Food, Western Australia, 2014). The main problems associated with sandy soils are summarized in Figure 1-5 and are discussed in more detail in the following sub-sections.

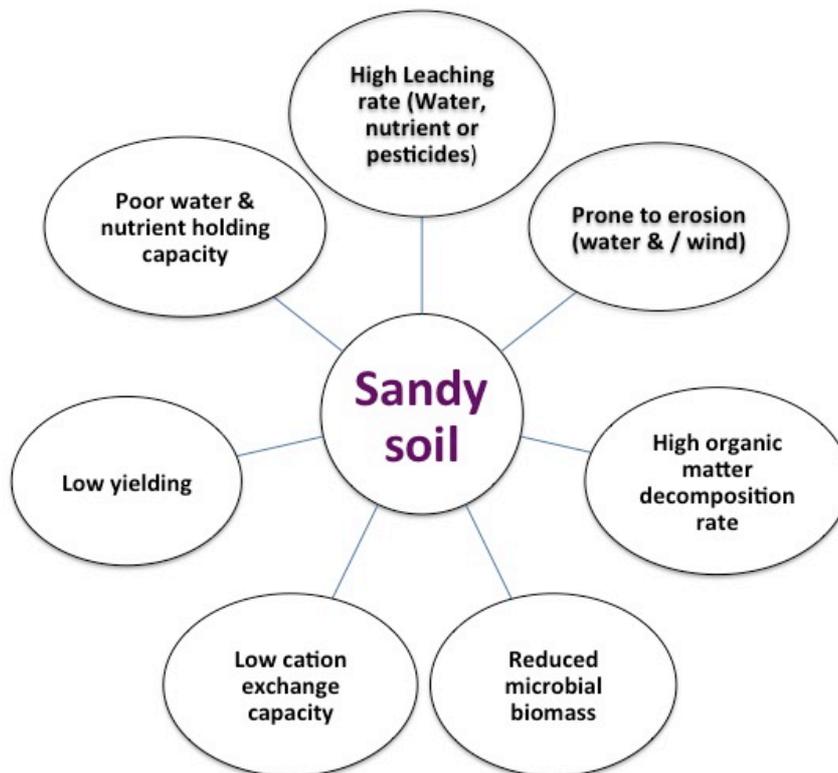


Figure 1-5: Schematic summary of problems of sandy soils

1.1.4 Limitations associated with physical properties of sandy soils

Physical properties of sandy soils such as texture, structure, density, specific gravity, pore distribution, infiltration and drainage are important in elucidating the problems of sandy soils. These properties could inform the degree of cohesion and adhesion forces within soil particles and between soil and other interacting materials such as water and solutes.

1.1.4.1 Texture, Structure and Aggregation

Sandy soils are coarse textured due to their high proportion of sand and minimal silt and clay content. One main benefit of sandy soil is that it warms up quickly in spring because of high porosity and good aeration. This supports easy work in terms of soil preparation and allows for early sowing compared to a clay soil. On the downside, the coarse texture supports high water loss and nutrient leaching due to macroporosity compared to a fine-textured soil, and this reduces nutrient use efficiency of crops (Balba, 1975). Water and nutrient supply has been identified as one of the major ways that soil texture affects plant growth (Tarak and Mukherjee, 1994).

Soil structure is the arrangement of soil particles into aggregates (Hillel, 1998). Soil aggregates are formed by the interaction between soil primary particles and binding agents such as clay, organic matter, plant roots, fungal alphae and microbial exudates. As these factors interact, initial micro-aggregates further combine to form macroaggregates. The spatial arrangement and strength of these aggregates help water infiltration and erosion resistance respectively (Hillel, 1998).

Sandy soils are generally known to be low in clay content, organic matter and microbial activity. Thus, most sandy soils comprise single, unaggregated grains and are structureless (Massoud, 1975; Balba, 1975) which predisposes them to both water and wind erosion.

1.1.4.2 Pore size / Porosity

Pore space refers to the gaps within and between soil aggregates. Porosity is the volume of these pore spaces compared to the total volume of the soil. Sandy soils have fewer but larger pore spaces. The number of large pores in sandy soil is typically high compared to silt and clay soil due to the large grain size of sand particles. The major benefits of large pore sizes in sandy soils are that they promote good aeration and rapid

drainage. However, this property is also responsible for undesirable characteristics such as a high rate of water percolation beyond the root zone, poor water-holding capacity and high organic matter decomposition rate associated with high aeration especially in the presence of aerobic microbes.

The specific surface area is the ratio of the surface area of any given object to its mass. The shape of soil particles plays an important role in determining their surface area. Among the three soil particles, sand has the lowest specific surface area. Sand grains are usually round in shape compared to the thin flaky and elongated shape of clay (Massoud, 1975). The small surface area contributes to low activities of sands, and an inability to bind large amounts of water, nutrients, cations and organic matter.

1.1.4.3 Infiltration and permeation through soil

Infiltration refers to the seepage of water into the soil. The velocity at which this downward movement of water occurs is called the infiltration rate (Hillel, 1998). Particle and pore size affect infiltration rate. Sandy soils with large particle sizes and a preponderance of large pores promote high rates of infiltration (Massoud, 1975). When dry, more water seeps downward from sandy soil surfaces following rainfall or irrigation. However, in agricultural land, the high infiltration rate allows water and nutrients to move quickly beyond the reach of plants roots. In order to combat this, frequent irrigation and heavier applications of fertilizer may become inevitable. This practice has been identified as one that could lead to the accumulation of mineral elements in groundwater resulting in environmental pollution (Reuter, 1994).

In desert regions, the formation of a thin brittle crust on the surface of sandy soils by rainfall events is common. Crust developed by raindrop detachment of unaggregated sand grains on the soil surface, followed by redeposition onto the soil surface, forming a seal that on drying becomes a crust. Crusts can also develop from the accumulation of gypsum or carbonate. Where this occurs, the soil could suffer from erosion by overland flow due to poor water infiltration during rainfall events as a result of a barrier or a restriction created by the crusts (Kadry, 1975).

1.1.4.4 Moisture redistribution and capillarity

Moisture redistribution refers to the movement of water in the soil after infiltration has ceased. Capillarity is the upward movement of water. Moisture distribution occurs

faster in sandy than fine soil. Because of the large pores, the capillary rise in sandy soils is much slower than for clay soils. This can help prevent evaporative water losses, depending on the soil moisture status. In dry conditions, the capability of a sandy soil to supply water to the root zone is hindered by poor capillary movement. In contrast, under wet conditions, sandy soil has a higher hydraulic conductivity that supports rapid upward water movement to the evaporative zone (Massoud, 1975). This process is responsible for salinization in arid and semi-arid regions where salts from the soil solution accumulate on the soil surface following evaporation.

1.1.4.5 Water retention

The amount of water held in the soil at any given time is influenced by the soil texture. Factors such as pore size, type and amount of clay and organic matter in the soil determine soil water retention. Two major ways by which soil retains water are by creating a thin film around the soil matrix and by retaining it in the micropores (Hillel, 1998, Lal and Shukla, 2004). Clay and organic colloids are the active fractions of the soil, so much of the water is held around these colloids. Very active clay (most clay has charge density which serves as a site for most soil chemical reactions including adsorption of nutrients and water) with high CEC holds more water than the less active ones. Since sandy soil is low in clay content and its dominant mineral is the less active type, it will only retain less water.

In addition to the above, the problem of water retention in sandy soils is further compounded by the dominance of macro- over micropores. Water is retained in the soil due to the capillary action of micropores. Because the capillary force is greater than the gravitational force, this ensures that less water drains out of the soil after irrigation or rainfall (Lal and Shukla, 2004). The smaller the soil pore, the greater its affinity for water and more energy is required to drain the water. As the attraction between water molecules and wall of large pores is less, water release in sandy soil occurs rapidly even at a very low pressure (Massoud, 1975; Hillel, 1998; Lal and Shukla, 2004).

1.1.5 Limitations associated with the chemical and biological properties of sandy soils

1.1.5.1 Mineral composition of sandy soils

Quartz is the most common mineral found in sand. It consists of silicate dioxide (SiO_2) and is known to be almost inert due to the strong Si-O bond and its macromolecular structure (Hillel, 1998). This property of the dominant mineral in the sand (especially in humid areas) coupled with their small surface area can contribute to the low chemical / physical activity observed in some sandy soils.

The active fractions of soil are clay and organic matter. These colloidal particles have a large negatively charged surface area that binds and retains water and nutrients. The cations held by these fine soil fractions are the source of nutrients for plants. The fertility or nutrient availability of a given soil is determined by the amount of clay, the type of clay and organic matter present in the soil. Also, soil active fractions play an important role in its ability to act as an absorbent through ionic reaction and, reduce the concentration of heavy metal or pollutants that could reach the groundwater. This explains why sandy soils with low contents of clay and organic matter require attention in order to improve their suitability for cultivation and for the protection of aquifers.

1.1.5.2 Mineralization of organic matter and microbial activity

Rapid decomposition of soil organic matter (SOM) is another problem associated with sandy soils. Higher decomposition rates have been reported in sandy soils (Franzluebbers et al., 1996) and have been attributed to a range of factors including less protection of OM. Clay increases the protection of OM in soil by: (a) its adsorption on clay surfaces, b) its protection within aggregates and c) its reduction in soil enzyme activity by binding to the enzyme and prevent binding to the target substrate. Unlike fine soils, sandy soils with low clay contents have weak aggregates that are not protected against easy decomposition of organic matter by soil microbes (Franzluebbers et al., 1996). In addition, in fine soils, the microbial community found within (stable) aggregates are isolated and do not have access to SOM in other aggregates (i.e. inter aggregate interactions are limited; Franzluebbers et al., 1996). In contrast, in sandy soils, there is little or no aggregate formation, resulting in high microbial mobility and relatively rapid mineralization of SOM. Also, sandy soil is

noted for good aeration; this property supports rapid decomposition of SOM by soil aerobic microorganisms.

1.1.5.3 Cation exchange capacity (CEC)

CEC refers to the estimated amount of exchangeable cation a soil can possibly hold at a given time. It reflects the ability of soil micelles to hold and exchange cations in the double layer region compared to the surrounding soil solution (Hillel, 1998). The CEC of a soil could be used to predict its fertility and its potential to prevent the pollution of groundwater. Ion retention on soil particles is an electrostatic reaction, where negatively charged soil surfaces attract oppositely charged ions (cations). The CEC of sand is very low because sand particles are almost inert due to their small specific surface area and chemical composition. Thus, clay and humus are the only sources of negative charges in the soil matrix. CEC also varies among clay types; clays with high specific surface areas and charge densities will have higher CEC. Generally speaking, the higher the clay and humus fraction of a soil, the higher the CEC. As a result of this, sand dominated soils have low CEC, and associated poor fertility, low water retention and a high potential to allow groundwater contamination, because the higher the CEC the more the capacity of a soil to adsorb cations (Dixon, 1991; Reuter, 1994; Hillel, 1998; Eslinger and Pevear, 1988).

1.1.5.4 Soil pH and buffering capacity

Soil pH is the degree of acidity and alkalinity of a soil, measure as the negative logarithm of hydrogen ion concentration in a soil. It is one of the most important properties of soils, as it can affect soil physical, chemical and biological processes. The pH of a soil can be inherent due to mineralogical composition and climatic condition or induced as a result of human activity. Soil pH affects the potential of clay to hold nutrients as well as the type of charge on clay particles. The latter is more pronounced where the charge is pH dependent, such as for kaolinite. At low pH, there is a high concentration of hydrogen ions (H^+) in the soil solution, which can easily displace cations on the soil exchange sites, leading to the loss of these nutrients. Also, when the soil is acidic, some pH dependent clays can become positively charged and attract anions (Hillel, 1998; Eslinger and Pevear, 1988). Most sandy soils are acidic and could have adverse effects on nutrient solubility and microbial activity.

Buffering capacity, on the other hand, is the ability of a soil to resist changes in its cation exchange capacity or pH. Clays with permanent charges usually have high buffering capacity because their charges are less affected by changes in pH. Soil chemical reactions (including pH and buffering) occur mainly in the presence of clay and organic matter, thus sandy soils with a low level of these components exhibit less chemical reaction. In general, most sandy soils are acidic and are easily subjected to the fluctuation of CEC and pH (CTAHR, 2015).

1.1.6 Soil amendments

Given the problems of sandy soils, organic and inorganic amendments have been used to overcome these challenges for production on sandy soil. Soil amendments refer to organic and or inorganic materials added to soil in order to improve its suitability for a given purpose. Organic materials such as crop residues (Weber et al., 2007); animal wastes, sewage sludge and household wastes (Debosz et al., 2002); bioethanol and paper mill wastes (Wang et al., 2014) and biosolids (Shanmugam and Abbott, 2014; Weber et al., 2007) can be used to improve soil physical, chemical and biological properties. Also, some inorganic materials such as clay and polyacrylamide have been employed as well.

Several attempts have been made to improve the water and nutrient retention of sandy soils using various approaches, including the application of chemically synthesized polymers (Ekebafé et al., 2011). However, widespread adoption of these approaches can be limited by cost, sustainability, biodegradation or compatibility with normal farming activities.

1.1.7. Properties of clay minerals and their role as an amendment

Clays are silicate minerals made up of several layers of silica bound together by Al and other cations. They constitute the smallest particle size in soils ($< 2 \mu\text{m}$) and because of their small size have the largest surface area to volume ratio (specific surface area). They are generally negatively charged and therefore have a high capacity to bind cations (positively charged ions) and other negatively charged molecules via divalent cations such as Ca^{2+} .

1.1.7.1 Origin of charges on clay minerals

The charges on clay minerals originate from two main sources. The first is an ionic isomorphous substitution reaction. This refers to a condition where Si^{4+} in the tetrahedral sheet or Al^{3+} in the octahedral sheet is replaced by a cation of lower valence (e.g. Al^{3+} replaces Si^{4+} or Mg^{2+} replaces Al^{3+}). This reaction usually leads to a net negative charge within the mineral structures and is irreversible, giving rise to permanent charges on clays.

The other type of charge occurs due to the breaking of bonds at the edge and surface of clays and leads to pH-dependent charges. In the presence of water, hydrolysis reactions take place at the edges and /or surfaces of clay mineral leading to cleavage of some of the structural bonds. Following this, the charges on oxygen atoms and hydroxyl groups at the edges of the clays are no longer satisfied, and net negative charges accumulate at the edges or surfaces of the clays. Unlike the isomorphous substitution reaction, the pH-dependent charges are not permanent; rather they vary as the pH of the soil solution changes (Hillel, 1998). The pH-dependent charges can be positive but may become negative; at low pH, the charges are positive (Anion Exchange Capacity, AEC), but negative as the soil solution moves towards alkalinity.

1.1.7.2 Types of clay

Clay minerals differ in their properties. Their main building blocks are silicate tetrahedral (SiO_4^{4-}) and aluminium octahedral ($\text{Al}(\text{OH})_6^{3-}$; Figure 1-6a). Molecules of each building block bond to each other to form a structure called a sheet. It is the arrangement of these two sheets that determines the clay type (Figure 1-6b). Clay with one layer of tetrahedral and one layer of octahedral arrangement are called 1:1 clay mineral (e.g. kaolinites) while minerals with two layers of tetrahedral and one layer of octahedral are called 2:1. The latter group can be further subdivided as non-expanding (e.g. Illites) and expanding (e.g. montmorillonite and vermiculites) 2:1 clay minerals.

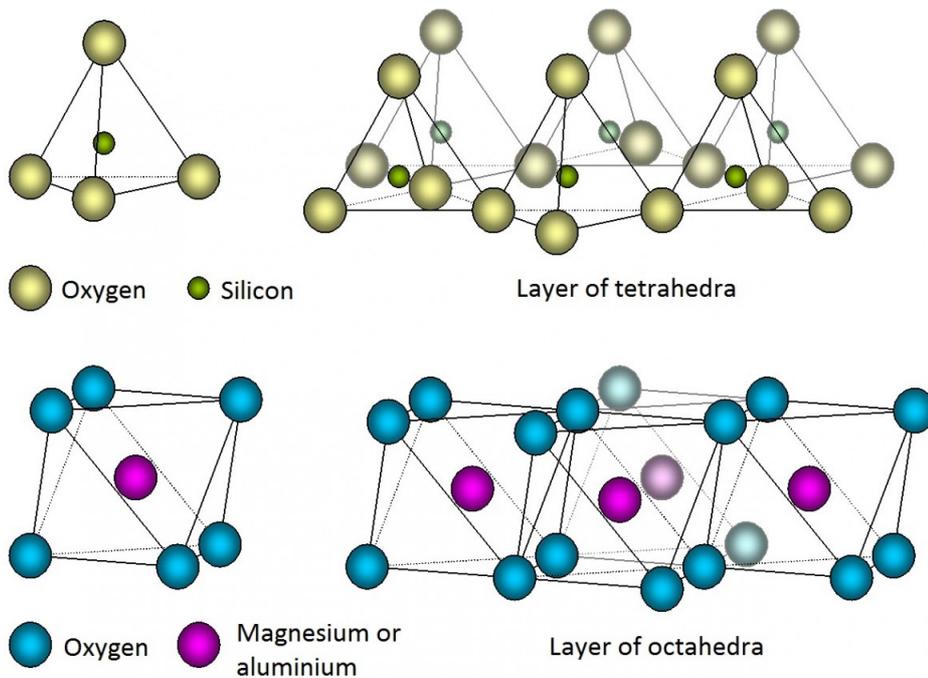


Figure 1-6a: Basic structure of clay minerals

(source: <http://blogs.egu.eu/divisions/sss/tag/soil-genesis/> accessed 08/09/2017)

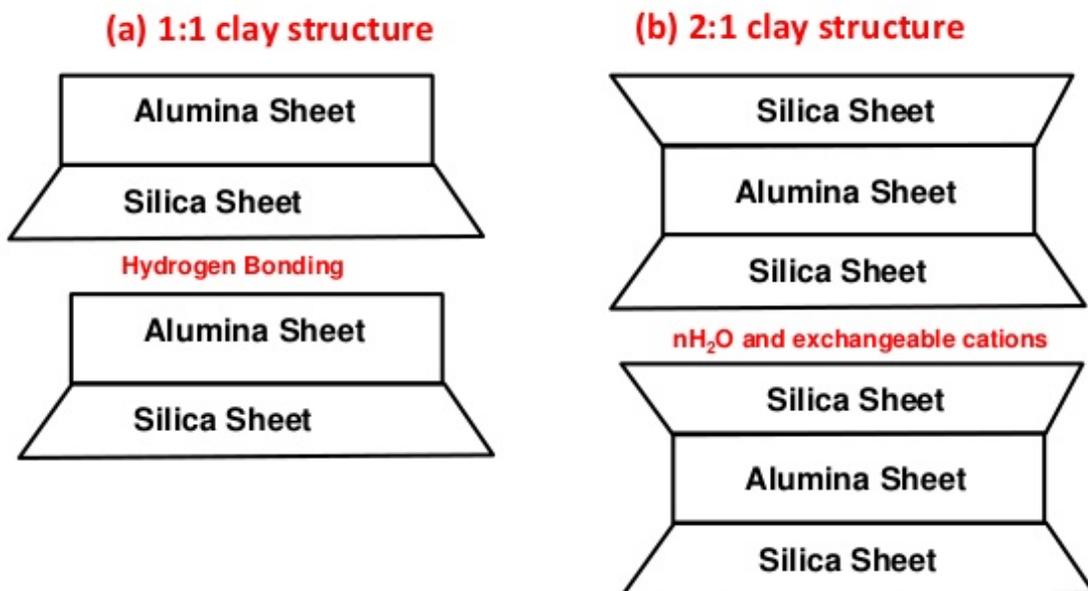


Figure 1-6b: Clay classification (Source: www.slideshare.net/hzharraz/beneficiation-and-mineral-processing-of-clay-minerals accessed 13/12/2017).

a) Kaolinites

Kaolinites are 1:1 clay minerals and the sheets are held together by hydrogen bonds. The group does not undergo an isomorphous substitution reaction and do not have structural charges like other clay minerals. Thus, the charges on this mineral are pH

dependent and can occur on both tetra- and octahedral sheets. Kaolinite is regarded as being electrically neutral because of a lack of permanent charges. The low charge on this mineral reduces its activity and is responsible for its low CEC (1-10 cmol kg⁻¹). It has a large particle size compared to other clays (0.1 - 2 µm). The structure is rigid, non-expanding with little or no swelling. Due to its large size, the surface area is low (10-20 m²g⁻¹) and holds relatively little water (Hillel, 1998). Kaolinites disperse easily in water and do not fix cations. The ease of dispersion makes kaolinites suitable as an amendment for ameliorating water repellency in sandy soils because their particles dissociate and coat sand grains (Eslinger and Pevear, 1988; www.soils.wisc.edu/virtual_museum/).

a) Illites or hydrated mica

Illites are a 2:1 non-expanding clay mineral developed primarily from the mineral mica. Each sheet is made up of two tetrahedral layers, which sandwich an octahedral layer. The sheets layers are then held together by potassium (K) ions called K⁺ bridge. The minerals usually undergo extensive isomorphous substitution reactions in the tetrahedral layer with up to 25% of Si⁴⁺ replaced by Al³⁺. Surface area is fairly large at about 70-150 m²g⁻¹. The charges on the clay originate from both substitution and pH reactions. CEC is low around 10-40 cmol kg⁻¹. The structure is rigid and is non-swelling due to the presence of potassium ion bridges that firmly hold the layers together. The potassium in the structure is fixed and not available as part of exchangeable cations³. The mineral also has a low water holding capacity, which might make it not suitable enough as a sandy soil amendment where attention is on water retention. Because of its high K fixing property, soil amended with illites could suffer from lack of K availability to the crop, and this has to be accounted for while planning fertiliser application.

b) Vermiculites

Vermiculites are expanding 2:1 clay minerals with a structure similar to Illites except that there is no K⁺ bridge, and the sheets are held by electrostatic force of hydrated exchangeable cations. Substitution occurs in both layers with Al³⁺ replacing Si⁴⁺ by up to 10% in tetrahedral layers and Mg²⁺ replacing Al³⁺ (up to 15%) in the octahedral layers and contributes to a high CEC (100-200 cmol kg⁻¹). Vermiculites have an

³ web.utk.edu/~drtd0c/Soil%20Colloids.pdf

extensive surface area that ranges from 600-800 m²g⁻¹. The swelling and water holding capacities are moderate³. Because of their high CEC and large surface area, when used as amendment vermiculites can increase CEC as well as water retention of sandy soils.

c) Smectites

This group of clays are also expanding 2:1 minerals and have montmorillonite as a representative. Sheets are held together by electrostatic forces from hydrated exchangeable cations (Eslinger and Pevear, 1988). Isomorphous substitution reactions in the mineral surface are low, much of which occurs in octahedral layer, giving rise to a moderate CEC ranging from 80-150 cmol kg⁻¹. The surface area is large (600-800 m² g⁻¹). This mineral undergoes extensive swelling and shrinking, and has a high water holding capacity. The presence of cations with varying degrees of hydration is responsible for the swelling and shrinking. When water is added to the mineral, the cations absorb water and increase their radii so the clay swells. When dry, they lose the water and return to their normal size so the clay shrinks (Eslinger and Pevear, 1988). The suitability of smectites as a sandy soil amendment lies in its large specific surface area and high CEC for nutrient and water retention. Smectites relatively hold more water than other clay minerals, assuming other factors remain constant. The cycles of swelling and shrinking can speed up the formation of stable aggregates in amended sandy soils after application (Dixon, 1991).

1.1.7.3 Clay as a sandy soil amendment

According to Reuter (1994), use of clay (especially bentonite) as a sandy soil amendment has been recommended and has been tested by some researchers. Al-Omran et al. (2005) examined the efficacy of three types of unrefined clay from three regions in Saudi Arabia. The clays were applied at the rate of 0, 1 and 2% to the planting furrow. Two types of irrigation method (sub-surface and drip) and four rainfall intensities (60, 80, 100, 120 mm) were simulated. The authors reported an increase in water use efficiency and yield of squash compared to a control treatment (with no clay amendment) for two consecutive years. The ability of the three clays to increase squash yield varied (6.4, 8.35 and 12.8%) compared to unamended soil, depending on their mineral composition. In general, all clay-amended soils showed improved root growth. This report demonstrates that when applied to soil, clay from different sources will behave differently depending on its composition and CEC. As a result, the type of clay chosen will be influenced by what the users want to accomplish.

The report also showed that there might be a need to modify the amount of clay to be applied in order to reach a specific yield target.

Houcine et al. (2007) demonstrated the ability of bentonite to improve the physical and chemical properties of a sandy soil in Algeria. In a pot experiment, 5 kg leached seaside sand was thoroughly mixed with bentonite at the rate of 2.5, 7, 10 and 15% (w/w). One tomato seedling was planted per pot and grown for 3 months. Soil water was maintained at 30% of field capacity and NPK fertilizer was applied as necessary. The result showed there was an increase in soil electrical conductivity, sodium and calcium with the increase in the dose of bentonite. Bentonite increased total CaCO_3 but decreased active CaCO_3 and K. There was no effect on total phosphorus at 10 and 15% bentonite, but the latter rate reduced organic carbon and magnesium. The report indicates that low application rates of bentonite may be enough to bring desirable, significant changes in sandy soil properties.

The effects of bentonite and clay soil were also investigated in a glasshouse experiment using a soil column to study leaching of nitrogen (N) forms in a sandy soil in Thailand. The soil column was filled with 10kg unamended sandy soil, or soil amended with 50 Mg/ha of either clay soil or bentonite, and NPK fertilizer was applied at 3 levels. Deionized water was added every four days to simulate a rainfall intensity of 50 mm/hr. The result showed that bentonite delayed leaching of $\text{NH}_4\text{-N}$ until the 15th day after fertilizer application with total $\text{NH}_4\text{-N}$ leaching decreased by 38 – 43% in the amended soil, but the bentonite had no effect on the mobility of $\text{NO}_3\text{-N}$ (Sitthaphanit et al., 2010). Houcine and Belkhodja (2007) reported similar observation that addition of bentonite up to 10% of the soil weight reduced nitrate and total phosphorus retention in a clay amended sandy soil in Algeria. On the other hand, other researchers have reported an increase in nitrate retention in sandy soils amended with kaolin (Nguyen and Marschner, 2013; Tahir and Marschner, 2016). These reports emphasise the need for a proper understanding of the performance of different clays, and how their mineralogical composition could affect soil functions. This understanding will inform sound recommendations for the use of clays as sandy soil amendments.

Hall et al. (2010) examined the effect of incorporating clay to the surface 5 and 10 cm of topsoil, as well as deep ripping to 50 cm, and measured the effects on water

repellency in Dalyup, Western Australia. The ability of claying to increase soil organic carbon after cropping was also investigated. The research found that increasing the clay content of a sandy soil from 0.5 to 6% increased soil organic carbon by 0.2%. This value is equivalent to an additional 3 tonnes of carbon within the top 10 cm assuming all of the increase in soil C occurs in this layer. The report also emphasized the role of the resulting increased crop biomass in increasing soil organic carbon (SOC). This would be of great importance in sandy soils where low organic matter content is associated with low biomass yield and high rates of OM decomposition are common.

1.1.7.4 Potential benefits of clay amendments on sandy soil properties

Clay particles have a large specific surface area that makes them active both chemically and physically. Clay minerals naturally have CEC which supports water adsorption, cations and organic matter. These features enable them to contribute to soil fertility and pollution control (Dixon, 1991; Reuter, 1994).

Clay has positive effects on the water retention properties of sandy soils. Reuter (1994) reported improved volumetric moisture content of clay-amended sandy soil at field capacity and at the permanent wilting point. This can be explained as a function of several mechanisms. One mechanism relates to the effects of the small size of the clay particles which when mixed with sands reduces the average pore size from macropores to mesopores (Dixon, 1991; Reuter, 1994). This reduces percolation rate and increases the amount of water that can be held in these soils at a given time. Clay can also achieve this by hydration of cations adsorbed on clay surfaces. Reuter (1994) attributes a further mechanism to the clay's ability to enrich the soil with humus via organic matter protection and the associated formation of stable aggregates.

The swelling of clay when wet and shrinking when dry helps in aggregate formation. According to Dixon (1991), the cracks made by the clays when shrinking serve as the basis for the development of soil structure and aggregation. Clays as well function as a coating for sand particles to form aggregates (Dixon, 1991). Some 2:1 clay minerals are rich in K and can serve as a source of the nutrient to plants. In Australia, Hall et al. (2010) account for the increase in yield in field soils amended with bentonite to the generous supply of K by the clay. Clays also have the capacity to improve the physical properties of soil such as its porosity and density (Reuter, 1994). Active clays form

organo-mineral complexes with organic colloids and prevent oxidation of organic matter (Dixon, 1991; Reuter, 1994), thereby helping with carbon sequestration. In addition, effects of clay on sandy soil could stay active for a long time after amelioration. Reports have shown that a single application of clay remained effective and produced significant increases in crop production over a period of 8 years (Hall et al., 2010) and 15 years (Department of Agriculture and Food, Western Australia, 2014).

1.1.7.5 Potential negative effects of clay amendments on sandy soil properties

Clays have also been reported as possessing some properties that may be detrimental to sandy soils. Some clay has selective adsorption for certain ions. For instance, Fe rich clay fixes phosphates (Dixon, 1991), manganese oxides immobilize some micronutrients such as Cu, Ni, Ba, Zn, Pb and Co (McKenzie, 1989 in Dixon, 1991), while vermiculite clay can fix potassium, NH_4^+ , Cs and Pb. This characteristic of vermiculite can have either positive or negative effect; it will be a desirable quality when used for controlling heavy metals in a polluted soil but will create a problem in agricultural soils where K and NH_4^+ are required (Dixon, 1991).

Clay particles usually repel each other due to the presence of like charges on the clay surfaces, resulting in flocculation. Calcium ion (Ca^{2+}) functions as a cementing agent that helps to hold clay particles together through electrostatic force (Dixon, 1991). At low concentrations of Ca^{2+} , clays are not bound to each other or to organic matter, which causes aggregates to break down, and the clays to disperse. Dispersed clay can enter and clog soil pores, creating anaerobic and hard-set soils where root growth is inhibited. To prevent this, some have recommended avoiding the use of sodium-rich clay as a sandy soil amendment and suggest the use of Ca^{2+} and Mg^{2+} rich clay (Reuter, 1994).

Aside from the properties of clay, other factors that could reduce its usage are its availability and cost. In order to minimize cost, clay pits should be as close to the field to be amended as possible. Although pure clay deposits are limited around the world, research has also shown that crude clay from the field can be an effective alternative. In Australia, fields with clay deposits in deeper soil layers have been used to improve the topsoil by bringing the subsoil clay to the surface (GRDC, 2011; Hall et al., 2010). Furthermore, the initial cost of claying can be offset by its ability to remain effective

for many years following application without any need to repeat the treatment (Hall et al., 2010).

1.1.8 Properties of organic matter and its role as a soil amendment

1.1.8.1 Role of organic matter in soil

Soil organic materials refer to both living and non-living biological entities of plant and animal origins in the soil. The living soil organic materials are microorganisms (bacteria, fungi, nematodes, actinomycetes, algae), macro-organisms (termites, earthworms, insects) and plant roots while the non-living OM includes all dead plants and animals at various decomposition stages in soils. The constituents of SOM are shown in Figure 1-7.

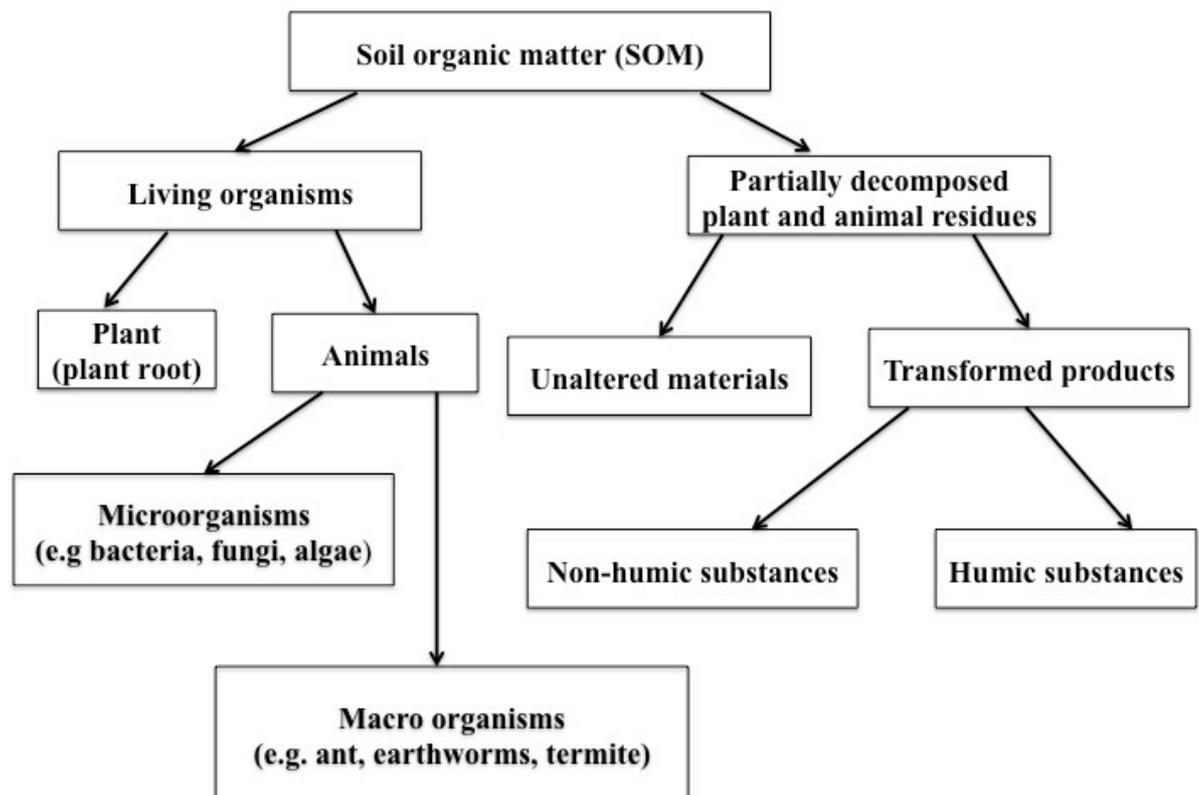


Figure 1-7: Different forms of organic matter in the soil (adapted from Bot and Benites, 2005)

Bot and Benites (2005) classified OM as above ground and within soil. Above ground, OM is planted residue on the soil surface, which protects the soil against erosion,

rainfall and desiccation. ‘Within soil’ OM are living organisms, partially decomposed and transformed plants, as well as animal materials in the soil.

The major role of soil living organisms is the decomposition of complex organic molecules through various enzymatic reactions. This includes the physical breakdown and biochemical transformation of naturally occurring, large biological molecules (e.g. long chain polysaccharides such as carbohydrate, protein and lignin) to simple organic (e.g. amino acids, short chain polysaccharides) and inorganic compounds (e.g. H₂O, CO₂). The continuous addition and decomposition of OM are responsible for maintenance of the carbon cycle (Figure 1-8; FAO, 2005) and nutrient cycling in soils.

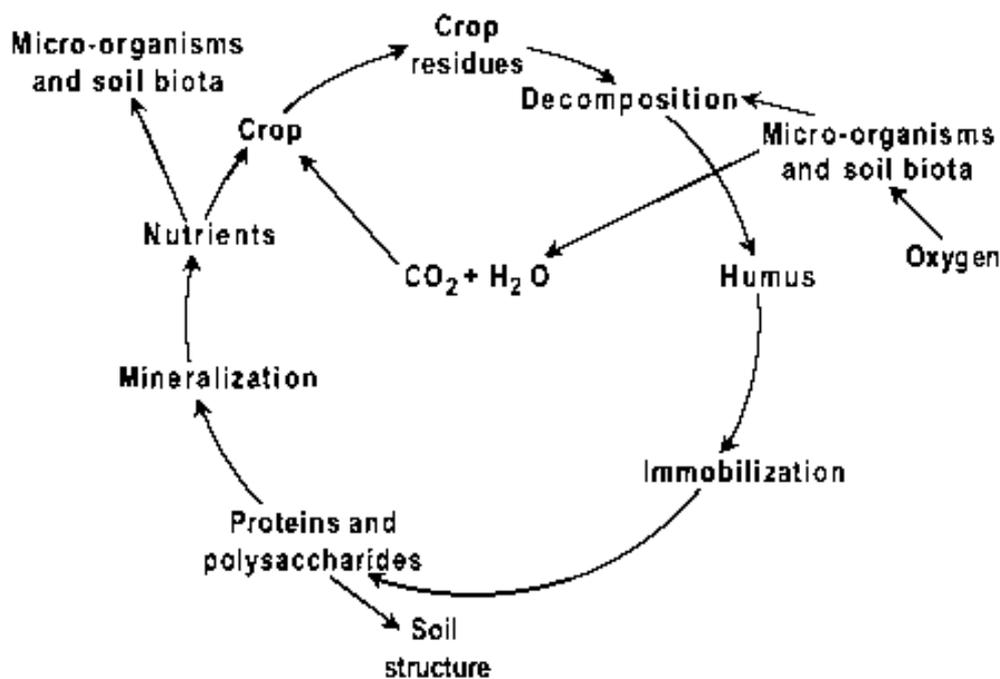


Figure 1-8: Carbon cycle in soil (FAO, 2005)

Improvement of soil by adding organic matter is well known in the farming community. Organic materials such as manures, composts, biochar, biosolids and biological industrial wastes have been added to soil to improve its chemical, physical and biological properties. The major functions of OM include 1) nutrient (re)cycling 2) improvement of soil structure and 3) providing an energy source for soil microfauna. Carbon derived from decomposing OM is the major source of energy for soil microorganisms, so maintaining adequate OM in the soil is vital for good soil health.

Like clay, OM improves soil chemical properties such as CEC, electrical conductivity and soil available phosphorus (Duong et al., 2012). The part of SOM related to CEC and soil colour is the humic fraction (Bot and Benites, 2005). Also, OM is high in plant nutrients and has been identified as a major source of phosphorus (P), nitrogen (N) and sulphur (S). Upon mineralization, these nutrients are released and increase the nutrient-supplying capability of soils (Bot and Benites, 2005). However, the ability of OM to increase plant nutrients in the soil will be more obvious in soils that have low nutrient concentration, than in already nutrient-rich soil (Duong et al., 2012). The effects of OM increase in alkaline soil conditions compared to those in acidic soil because of increasing negative charges on humus surface, which improve its ability to bind more cations. This also explains why soil amended with organic materials could reduce leaching of nutrients and toxic substances.

Organic residues serve as a basis for aggregate formation by binding soil particles together. This is accomplished by the presence of the large specific surface area of the organic materials. OM can increase aggregate stability principally in two ways: 1) by binding to soil clay fractions and 2) by stimulating growth and activity of soil organisms, increasing the production of exudates and fungi hyphae which are important binding agents for soil aggregation (Duong et al., 2012). Increases in soil aggregate stability in sandy soils following the application of compost were observed in both the laboratory (Annabi et al., 2007) and in the field (Arthur et al., 2010; Yu et al., 2012).

As an active component of soil, OM can hold large amounts of water because of the presence of humic acids. Some reports have shown that addition of compost can improve soil water holding capacity and water availability to plants (CIWMB, 2004), while others have reported nil effects (Duong et al., 2012). The ability of OM to hold water is associated with water adsorption by ionic interaction between water molecules and organic colloids, as well as cations adsorbed on the humic acids.

1.1.8.2 Potential benefits of organic matter as a sandy soil amendment

Application of organic matter is reported to have generally positive effects on aggregate stability, water retention, CEC, soil organic matter accumulation, soil micro- and macrofauna, and nutrient availability in sandy soils.

In Florida, Wang et al. (2014) reported that addition of residues from bioethanol production and paper mill waste increased the soil water retention in a sandy soil by 150% and 300% respectively. These authors also documented a 99% reduction in the ammonia and phosphate concentrations in the leachate, compared to the control. This work demonstrated the ability of materials of organic origin to improve water and nutrient retention. However, this was a laboratory experiment carried out in a controlled environment so the effects of climatic factors on the amendments and plant uptake were not studied. Factors such as evaporation, soil water redistribution, nutrient mineralisation and immobilisation as well as gaseous losses of soil nutrient could make a difference between laboratory and field experiments.

Arthur et al. (2011) compared the effects of three types of compost (vegetable, fruit and yard waste compost, garden waste compost, and spent mushroom compost) applied for 10 years on the erodibility of loamy sand in Belgium. They reported that only garden waste compost was able to increase soil aggregate stability significantly (45%), and none of the three composts appreciatively improved the soil's ability to resist erosion by water.

The efficacy of composted leaf litter, termite mound material and bentonite on water retention and structural stability of a light sandy soil was monitored in northeast Thailand for two years (Suzuki et al., 2007). The results indicated that the amendments were able to increase the water-holding capacity of the soil compared to the control. The treatments were able to modify soil porosity and pore size distribution, but only bentonite increased the soil structural stability (Suzuki et al., 2007). This research compared organic material to clay, but did not investigate the combined application of the two. Also, the work was carried out in hot and humid weather, so the result might have been different in a contrasting climatic condition because factors such as the amount of rainfall, soil temperature and evapotranspiration could affect soil water retention.

1.1.8.3 Negative effects of organic matter as a sandy soil amendment

Although there is much evidence that organic matter can improve soil properties, negative effects of using them also exist. Certain organic substances such as (1) waxy organic compounds that may be long chain alkane or fatty acids; (2) exudates and hyphae of certain fungi; (3) hydrophobic substances released by some plants (e.g.

lucerne, lupins and clovers) to compete in their environment and (4) vegetation burning (DeBano, 1981; Jex et al., 1985; Department of Agriculture and Food, Western Australia, 1996; York and Canaway, 2000; Franco et al., 2000; Hallett et al., 2007) can cause water repellence. According to DeBano (1981), decomposing organic matter can release hydrophobic substances, capable of inducing non-wettable conditions in the soil. He also wrote that merely mixing soil and organic matter together could confer hydrophobicity on some soils. Thus, it is imperative that both short- and long-term effects of adding organic matter to sandy soils are further studied.

The addition of some organic materials such as sewage sludge to soil can lead to accumulation of toxic substances such as Cu and Pb (Gliotti et al., 1997 in Bastida et al., 2008; Guerra et al., 2007). If this is not properly monitored and managed, it can lead to serious environmental pollution and health issues, especially if these substances find their way to human diets through crops grown on contaminated soil or with irrigation from contaminated water bodies.

Human and animal wastes, used as soil amendments, if not properly managed can also cause disease and pest infestation. Uncomposted biosolids can transfer pathogenic organisms (Zaleski et al., 2005; Reilly, 2001) or cause nutrient leaching because of a high mineralisation rate due to low C: N ratio (Joshua et al., 1998). Some weed seeds may escape digestion by animals, get egested in animal waste, and establish themselves when animal manure is applied to the soil. This is one of the ways new weeds are distributed into new environments. Composting can provide a solution to this problem, as most pathogens and weed seeds do not survive this process (Bernal et al., 2009). Composting is a biological mineralisation of organic materials by microorganisms and is an exothermic reaction. Thus, the end products include ammonia and heat, which helps to destroy pathogens and weed seeds.

Another limitation of OM as a soil amendment is that its effects do not persist because unlike clay, OM is decomposed by soil microbes. Therefore, farmers will need the repeated application of OM amendments, based on estimation or actual monitoring of the level of soil OC. Other factors limiting the popularity of organic matter additions among farmers include their often bulky nature and availability. High water content of some forms of OM (e.g. manure) can make it expensive to handle. Costs associated with the application of compost (including its transportation) may not bring immediate

economic returns. However, proper education on both the short and long-term benefits of OM application on the soil and environment could motivate some farmers.

1.1.9 Interactions between clay and organic matter

Research reports have shown that interactions between clay and OM exist in the soil. Clay and silt are involved in the formation of organo-mineral complexes and adsorb a large amount of OM and nitrogen in the soil. The report of Reuter (1994) shows that in one of their experiments, a soil made up of 6% silt and clay, and 94% sand held 66% of its organic matter and 70% nitrogen in the smaller silt and clay fractions.

1.1.9.1 Protection of organic matter by clay

Clay interacts with and bonds to organic matter via different mechanisms. In the presence of polyvalent cations such as Ca and Mg, clay particles can bind organic matter on its surface with the cation acting as a bridge holding the two together to form a micro-aggregate (Bonneau and Souchier, 1982 in Theng et al., 1986; Römken and Dolfing, 1998). The reaction can be represented as:



The micro-aggregates can then combine to form macroaggregates (Don and Schulze, 2008; Kaiser and Zech, 2000; Leinweber et al., 1993; Reuter, 1994).

Clay could also form complexes with organic matter by absorbing the latter into its crystal layer. Theng et al. (1986) proved that smectitic clay under acidic soil conditions has the capacity to intercalate compounds of organic carbon in this way. Their report showed that polymethylene humic substances tended to accumulate within the clay interlayer crystals of two low pH soils in New Zealand, that were rich in smectites and OM, resulting in an increase in the thickness of the clay layer.

The texture of a soil determines its ability to protect soil organic carbon. A soil with 40% clay has been shown to have higher soil organic carbon and soil microbial biomass carbon than a sandy soil with 15% clay (Franzluebbers et al., 1996), attributed the differences to the increase in input of carbon from biomass in the fine-textured soil as a result of its high fertility compared to sandy soils. Alternatively, this could also result from the ability of clay to protect organic matter against microbial

mineralization (Hassink et al., 1993 in Franzluebbbers et al., 1996). The binding of organic matter to clay interlayer surfaces and within aggregates protects the organic matter from decomposition and thereby enhances C sequestration (Fujii et al., 2011; Lutzow et al., 2006; Neff and Asner, 2001; Dixon, 1991).

It has also been observed that soil microbial carbon constitutes a larger fraction of soil organic carbon found in clay, and that the proportion of soil microbial carbon in soil organic carbon increases with the increase in clay content of the soil. Availability of soil water in the well-aggregated soil, as well as the ability of clay to prevent soil fauna from feeding on soil microbes also supports their proliferation in fine-textured soils (Franzluebbbers et al., 1996).

One major difference between refined clay mineral and crude clay found in the soil is their CEC. The CEC of clay fractions found in the soil are usually higher compared to corresponding clay from clay deposit, and this has been attributed to the formation of organo-mineral complexes. When clay interacts with organic matter, the properties of the two fractions could combine, producing an additive or synergic effect. That is, the inherent high CEC of the clay together with the high CEC of OM produces the higher CEC (Leinweber et al., 1993).

1.1.9.2 Benefit of co-application of compost and clay on sandy soil

Evidence from research has shown that both clay and OM have the capacity to improve properties and suitability of sandy soils for crop production. However, depending on the type of sandy soil, the climate and the amendment application method, there are negative effects associated with each of the amendments. One of the major benefits of applying the two together is their ability to mitigate the limitations of each other. Clay is expected to offset the non-wetting property of some humic substances, whereas OM should be able to prevent crusting or hard setting of clay, a feature commonly found in sandy soils ameliorated with clay (Djajadi et al., 2012).

The other expected benefit of co-application of clay and OM is that they should have a synergistic effect on sandy soil properties. Kramer (1983) reported that the benefits of amending sandy soils with organic matter alone do not persist for as long in the absence of enough soil clay. Having established that both clay and OM properties (high water holding capacity, high CEC, increase in and protection of soil organic

matter) can improve physical and chemical properties of a sandy soil, it is therefore hypothesized (Djajadi et al., 2012) that their combined effects would be significant in reducing water percolation and nutrient leaching, and in improving crop yield.

The combination of clay and OM additions may increase the acceptability of using amendments by the farmers. A clay-OM mixture may reduce the amount of OM farmers require to ameliorate the fertility of sandy soil if it was used alone. The bulky nature of most OM has served as a barrier for its use in agriculture, but when combined with clay, smaller amounts of OM would be required.

Investigating the effect of combined clay and OM on properties of sandy soils has been attempted by some researchers. Djajadi et al., (2012) reported increased aggregate stability, reduced soil respiration, but decreased soil strength when a sandy soil in Australia was amended with lucerne hay applied at 0, 0.4 and 0.8% and kaolinite at 0, 2, 5, and 10% (w/w) in an incubation experiment for 42 days. Others have also reported a reduction in soil respiration when kaolinitic clay and OM is co-applied (Nguyen and Marschner, 2013; Shanmugam et al., 2014; Shanmugam & Abbott, 2014). The combined application of clay and OM can also reduce leaching. Nguyen and Marschner (2013) reported reduction in N and P concentration when a sandy soil amended with compost (27.3 g/kg) and fine subsoil (34% clay) at 5 and 20% (w/w) was leached with reversed osmotic (RO) water 23 days after incubation, but the amendments have no effect on N and P availability in the amended soil. The findings of Shanmugam et al. (2014) further show a reduction in the rate of N released when a kaolin amended biosolids was added to a sandy soil up to 2 weeks at 50 t/ha and up to 4 weeks at higher rates. Mekuria et al. (2014) demonstrated the effectiveness of bentonite (10 t/ha), composted manure and clay (10 t/ha), compost (4 t/ha), rice husk biochar (10 t/ha), biochar compost and combinations of these to increase maize yield in a two-year field experiment. in the Laos Peoples Democratic Republic. The composted manure/clay mixture was made from local clay obtained from pond dredge and cow manure and tested at two sites. Amendments were incorporated to the depth of 15 cm, 15 days before planting maize in the first year and any residual effect was examined in the second year. The result showed that amendments were able to increase maize yield in the two years compared to the control, with the yield of the first year being higher than the second year. The treatments improved soil chemical conditions as well (Mekuria et al., 2014).

The above review shows that few experiments carried out on the use of combined clay and OM as sandy soil amendment are short-term laboratory or glasshouse investigations involving only one type of clay (Djajadi et al., 2012; Nguyen and Marschner, 2013; Shanmugam et al., 2014; Shanmugam & Abbott, 2014). Since the properties of clay and OM differ from one type to another, different responses are expected, depending on the choice of OM and clay type and application rate. Duration of interaction between the two amendments and the introduction of plants could also make significant changes to the observed results. Any benefits achieved in short-term experiments could differ where more time is allowed for interactions between the amendments. Thus, long-term investigation under field conditions would be necessary to validate these observations.

Mekuria et al. (2014) aimed at deriving locally available material for improving soil fertility in their experiment and did not use sandy soil *per se*. However, one of the soils used in their experiment had 67.7% sand, the other soil 47.7% sand with a clay content of the two soils at 27 and 25%, respectively. These clay contents are high to consider them problematic within the context of the definition of problematic sandy soil (Hartemink and Hunting, 2005; WRB, 2006). The work was conducted in a tropical monsoon climatic region in Asia, where alternating wet and dry seasons mean moisture deficient and excess are limiting factors to crop growth. This is not the case in the United Kingdom (location of the present study), where rainfall is fairly equally distributed all year round. Thus, one could expect differences in responses of plant and soil properties to soil amendments in the two regions. It is also noteworthy that Mekuria et al. (2014) do not report on soil physical and biological properties.

1.2 Gap Analyses and Summary

The above review has demonstrated that clay and / or OM when used as soil amendments can improve soil structure, increase aggregate stability, overcome water repellence (depending on the clay type), increase CEC to a varying degree as conditioned by the inherent CEC of the clay and organic matter, as well as reduce the rate of CO₂ release from soil.

The available evidence on clay-OM mixtures as amendments in sandy soils showed that this is a relatively new and under-researched field of study. The few available publications relating to clay-OM amendments on sandy soils consist mainly of short-

term, laboratory incubation or glasshouse experiments. Most previous work used only one type of clay, and none of the currently reported experiments focused directly on how the constituents of the mixture mediate nutrient retention from added fertilizer, or affect soil hydrology (namely soil erosion and water leaching) of sandy soils. Since clays vary in their properties, we would expect different results from different clay and OM mixes. Moreover, most of the data reports only the effects of the amendments on either crop yield or a limited number of soil properties; none of them attempts to explain the underpinning mechanistic processes responsible for the observed results. In addition, only a few previous studies were carried out under field conditions, and information on the interaction between the amendment and natural climatic conditions are sparse. Climatic and environmental effects are usually responsible for many of the differences in crop and amendment performance in glasshouse and field studies. Therefore, investigating these interactions in the presence of plants under field conditions would test their effectiveness in a more realistic situation.

1.3 Background, Impact and aim of the proposed study

Given the vast area covered by sandy soils worldwide ((FAO, 1993; WRB, 2006), there is no doubt that amelioration of these often-problematic soils will be of great importance in achieving world food security. Food production can be increased either by increasing the area cultivated or increasing production per unit of cultivated land area. However, there are only finite land resources suitable for food production: further deforestation to increase food production will be detrimental, as this will contribute to increasing levels of atmospheric CO₂ and associated global warming and climate change (Hartemink and Hunting, 2005; Rojanasoonthon, 2005). As a result, this change in land use could infringe on the right of future generations for the provision of a safe environment and sustainable food production. An alternative method would be to maximize and improve the capability of existing farmland. This would include various strategies such as the addition of organic and inorganic materials for optimal water and nutrient retention, improved microbial activity, better soil structure and strengthening soil resilience to the ecosystem and anthropogenic disturbances (Hartemink and Hunting, 2005; Rojanasoonthon, 2005).

In addition, because of the multiple uses of soil for important non-agricultural purposes such as water regulation and conservation of biodiversity, the amount of land that could be further cultivated is limited in many places (Eswaran et al., 1999; Young,

1999). The current land use conflicts between farming, industry, urbanization and wildlife refuges call for the development of a robust research agenda that would support sustainable management of existing farmland.

According to Hartemink (2005) and Rojanasoonthon (2005), there is a direct link between poor soil and human poverty. This is especially true in developing countries where large proportions of the population live by subsistence farming. In order to alleviate poverty in the world, the potential of sandy soils to produce food, fibre, fodder and fuel must be improved.

This condition of low water retention could possibly be responsible for the low yield per hectare of some crops. Reuters (1994) confirmed that in a given landscape, patches of sandy soil could be found amidst a soil that is primarily loam. This is typical of soil formed from fluvio-glacial deposits. These patches are responsible for reduced yield and economic loss either through crop loss or wasted irrigation water. With the aid of precision agriculture, farmers could identify these areas and formulate appropriate management strategies.

Amelioration of sandy soils could also help in the improvement of the environment. Currently, practices to maintain yields in cultivated sandy soils involve an increase in inorganic fertilizer rate and frequency of irrigation to mask the low levels of production. Both have been associated with the acidification of soil and pollution of the environment via groundwater contamination (Reuter, 1994). Nutrient loss from agricultural fields is known as a major cause of water pollution and eutrophication. Although not directly focused in this project, it is expected that addition of amendments to sandy soils would mediate transport of some of these pollutants to groundwater, because a) they can replace inorganic sources of fertiliser and b) they retain nutrients within the soil profile, rather than being lost through percolation to groundwater. Soil degradation and loss associated with high erosion could also be reduced in land amended with clay and organic matter (and their combinations).

The proposed research has potential to offset virtually all the problems of sandy soils. In addition, the potential of clayey soil in protecting soil organic matter decomposition has been demonstrated (Leinweber et al., 1993; Nguyen and Marschner, 2013). This implies that significant amounts of carbon could be sequestered in the amended sandy soil, thereby contributing to a reduction in the greenhouse effect.

1.4 Objectives and hypotheses

The current research aims to examine the effect of two clays, OM and OM-clay mixtures on water and nutrient retention of sandy soils. Although some limited attempts have been made to investigate the potential of OM and clay as sandy soil amendments, there is no record that this has been done in the United Kingdom. Also, despite the theoretical potential of combining clay and OM applications, there is little or no extensive work done yet to investigate this, nor on the effects of these amendments on soil biological properties under field conditions.

The objectives of this study are to:

1. Determine the optimal concentration of a clay and /or organic material to enhance water and nutrient retention in a sandy soil, as well as the quantity of nutrient and water that can be held within the amended layer and how this varies with clay properties (i.e. chemical composition and particle sizes).
2. Determine how the clay and organic material influence the interactions in a sandy soil between soil physical (i.e. pore size characteristics, water retention characteristics, soil bulk density, hydrology and water availability), biological (SOC, microbial biomass and respiration) and chemical properties (changes in total and available NPK concentrations, CEC, pH and electrical conductivity).
3. Determine the benefits of the treatments in terms of crop growth, nutrient uptake and crop yield using a field experiment, with the aim of devising practical and economical treatments for using OM, clay and OM-clay mixtures for the improvement of sandy soils.
4. Quantify the ability of the clay and organic matter to reduce the erodibility (susceptibility to erosion) of the amended sandy soil by measuring run-off, sediment and infiltration.

Hypotheses:

On the basis of the above reviews, the overarching hypotheses of this research are:

- 1) That combined application of clay and OM will improve physical, chemical and biological properties of sandy soil. The ability of the amendments to improve the soil properties is associated with their effect on soil aggregation and particle distribution, soil CEC, pH, electrical conductivity (by clay and OM); increase SOC (by OM); improved microbial activity and biomass as

controlled by soil water retention, pH and availability of carbon (by clay and OM).

- 2) That combined clay and OM will increase water and nutrient retention of the amended sandy soil. The water retention is expected to occur via two mechanisms: i) modification of soil pores which will result in reduced infiltration rate and; ii) increased water absorption by the clay and OM (Hillel, 1998; Lambooy, 2013). Added clay and fine particles of OM are expected to fill the large pore sizes between sand particles, and reduce some to mesopores and micropores. The reduction in pore size will reduce water infiltration rate, hence increase absorption by the surface soil. In addition, water absorption by clay and OM will reduce the rate at which soil water could travel to deeper horizons, which in turn will increase interaction between the soil matrix and water in the upper soil layer, resulting in an increase in water retention within the root zone.

For soil nutrients, firstly, nutrient retention is expected to occur as a direct effect of water retention since soil nutrients are normally present in the soil solution. Secondly, the addition of clay and OM would increase CEC, resulting in an increase in nutrient retention. Nutrient retention will be higher in soil amended with 2:1 clay mineral compared to soil receiving 1:1 clay mineral because of a higher CEC.

- 3) It is hypothesised that the improved soil condition will increase growth and yield of a crop in amended soil, compared to the control plots. It is expected that the reduction in leaching and increase in water retention as a result of the addition of clay and OM will increase nutrient and water availability within the root zone, thereby supporting an improved yield.

The research objectives would be examined by using two types of clay, Kaolin (K) and Bentonite (B). The two clays were selected based on differences in their mineralogical composition. K is a 1:1 kaolinitic clay mineral while B is 2:1 clay from smectites clay group. This will enable comparisons of their performance under the same experimental conditions.

The OM used in the project is peat. Although there is controversy over the sustainable use of peat deposits, this material was used because of its uniformity. Other sources of OM normally have wide variability in nutrient composition and physical properties,

but peat compost is uniform and could be stored over a long period. The peat used was sourced from the same batch and used over a period of three years.

Chapter 2

Laboratory column leaching experiment

2.1 Introduction

The importance, global distribution and the limitations of sandy soils have been discussed in chapter one. Sandy soils are by definition low in clay content, which is the origin of fundamental problems associated with this soil group. Clay and organic matter (OM) are the most active and reactive part of a soil (Kramer, 1983; Hillel, 1998). These colloidal particles have relatively large, negatively charged specific surface areas that bind together and retain water and mineral nutrients (Yong et al., 2001). The cations held by these small soil fractions are the source of some of the key nutrients for plants. The potential fertility of a given soil is determined by the amount and type of clay particles, and the organic matter present in the soil.

Laboratory column leaching experiments have been identified as one way to simulate water and solute movements in soils and mimic processes that occur under natural conditions (Yong et al., 2001). This method allows study and monitoring of complex soil processes and provides an insight into processes occurring under field conditions (Zachara and Streile, 1990). Column leaching experiments have been used to study heavy metal retention in soils (Yong et al., 2001); nutrient release from compressed fertilizers (Fernández-Sanjurjo et al., 2014); monitoring water pollution from cattle slurry (Nuñez-Delgado et al., 2002); investigation of nitrogen leaching in the plant root zone (Nakamura et al., 2004); and the effects of localized soil heterogeneity on solute transport in soils (Stagnitti et al., 2001).

Previous work has focused on amending sandy soil with either clay or organic matter. However, recently, the use of combined applications of these two materials has been suggested (Djajadi et al., 2012; Nguyen and Marschner, 2013). One of the major benefits of combining clay and organic matter is the synergy/interactions that overcome the limitations of the individual materials when used separately. It has been reported that the benefits of amending sandy soils with organic matter alone do not persist in the absence of enough clay particles (Kramer 1983). Clay additions are expected to offset the non-wetting properties that some humic substances can confer

on sand grains. On the other hand, OM can prevent crusting or hard setting of clays; a feature commonly found in sandy soil ameliorated with clay (Djajadi et al., 2012).

2.1.1 Objective and Hypotheses

The objective of this experiment is to examine the optimal combination of clay and organic matter that will enhance water and nutrient retention of the test sandy soil in the presence or absence of inherent soil clay using free-draining soil columns. Also, the study will quantify the amount of water and nutrients that can be held within the amended soil and how this varies with the different clay, and the combination of the clay and organic matter amendment.

The experiments are designed to test the following hypotheses:

- 1) That the application of clay or OM will increase water retention and reduce nutrient leaching in sandy soils, and that the combined application of clay and OM (i.e. peat) will have a synergistic effect. We also expect the effects of clay and OM amendments on nutrient leaching and water retention to increase with the ratio of clay and organic matter content used.
- 2) That the amount of clay originally present in the soil would influence the response of sandy soils to the amendments. Also, there will be a threshold in the original soil clay content above which the response to additions of clay would not be significant. Thus, it is hypothesized that the response of sandy soils to clay and OM amendments will reduce as the initial clay content of the soil increases.
- 3) Clay minerals are different in their physical and chemical properties. Thus, it is expected that ability of different clay minerals (i.e. kaolinite (K) and bentonite (B)) to retain water and nutrient in sandy soils would be different under similar experimental conditions.

2.2 Material and Methods

2.2.1 Soils

The study was conducted at the University of Warwick, Wellesbourne Campus, UK. Two soils and three amendment materials were used to explore the relationships between soils and their water retention/leaching potential. The soils were a pure sand (PS) and a sandy loam (SL). The PS was horticultural grit sand (supplied by William

Sinclair Horticulture Ltd), which is predominantly quartz (>98%), with particle sizes of ≤ 5 mm. The grain density is 2 g cm^{-3} and pH is 7.9. The SL was from the Wick series, a typical brown earth developed from Triassic rocks (Whitfield, 1973). The SL's properties are shown in Table 2-1.

The SL soil sample was excavated from the 0-20cm topsoil layer from the Warwick Crop Centre Experimental field (Latitude 52 12 18 N; Longitude 1 36 00 W), Wellesbourne, United Kingdom. The sample was air dried and then sieved (10mm) to remove stones. Both the PS and the SL were oven dried at 80°C for 24 hours before the start of the experiment, to ensure the uniform initial moisture content of the soils and to standardise the measurement of water retention capacity of the amendments. Fernández-Sanjurjo et al. (2014) adopted a similar method in a column experiment to study nutrients released from compressed fertilizers.

Table 2-1: Physical and chemical properties of the field soil (SL)

Property	Sandy loam (SL)
Sand	65 (%)
Silt	17 (%)
Clay	18 (%)
Total carbon	1.10 (%)
Total N	0.12 (%)
Total P	119.30 (mg kg^{-1})
Total K	2819.98 (mg kg^{-1})
C:N	9.17
Available P	44.48 (mg kg^{-1})
Available K	91.97 (mg kg^{-1})
CEC	21.2 (cmol kg^{-1} soil)
Organic carbon (OC)	2.5%
pH in water	6.1
Electrical conductivity (EC)	233.1 ($\mu\text{S cm}^{-1}$)

2.2.2 Amendments

The two types of clay used as amendments were calcium bentonite (B) and kaolin (K). The typical mineralogy of the bentonite is 88% montmorillonite, 5% mica and 5% feldspar. The kaolin is a medium sized china clay, consisting of 47% silica and 37% aluminium oxide by mass. Other properties of the two clay amendments are shown in Table 2-2.

Table 2-2: Typical properties of the bentonite (B) and kaolin (K) used

Property	Bentonite	Kaolin
SiO ₂	60.7%	49.8%
Al ₂ O ₃	18.31%	35.1%
Fe ₂ O ₃	3.95%	0.93%
MgO	3.32%	0.27%
K ₂ O	3.14%	2.7%
CaO	2.85%	0.03%
Na ₂ O	1.56%	0.11%
TiO ₂	0.49%	0.07%
Mn ₃ O ₄	0.08%	-
LOI	6.05%	10.9%
Bulk density	0.85 Mg m ⁻³	0.75 Mg m ⁻³
CEC	76 meq/100g	10 meq/100g
pH	9.5	5.1

LOI means loss on ignition

The organic matter (OM) amendment (Pt) was a medium grade, pure sphagnum peat, sourced from Klasmann-Deilmann Ireland Ltd. Its physical and chemical properties are shown in Table 2-3.

Table 2-3: Physical and chemical properties of the OM (Pt) used

Property	Peat (Pt)
Organic matter	>90 (%)
Density	290 kg m ⁻³
Water capacity	3.5 – 5.0 (g m ⁻¹)
Particle size range	0-14 mm
Air-filled porosity	10 %
pH (in water)	4.2
EC	< 23 (μS/cm)
Nitrogen (NH ₄ , NO ₃)	40 mg kg ⁻¹
P (P ₂ O ₅)	30 mg kg ⁻¹
K (K ₂ O)	130 mg kg ⁻¹
MgO	70 mg kg ⁻¹

2.2.3 Leaching experiment

There are various leaching methods employed to study solute sorption and desorption. The method selected will depend on the objective of the study and the type of data required. The leaching method can involve static flow (one-time application), batch flow (multiple applications) or dynamic flow (continuous application), with the studies conducted using either undisturbed soil in the field or some form of soil column or lysimeter. Column experiments can be conducted under either saturated or unsaturated soil conditions. Intermittent application of solution is commonly used for unsaturated

conditions, while continuous application up to ponding of the column surface with solution is employed in saturated conditions (Wilson, 1995; Kim, 2003, 2005).

Column experiments can involve the use of sieved soil (with or without amendments) or soil monoliths taken directly from the field, with the columns arranged in a vertical or horizontal orientation, see Figure 2-1. In the vertical column method, the leaching solution flows can be gravitational (percolation of solution from the surface of the column down to the bottom) or capillary flow (upward movement of sub-surface soil solution or solution from a reservoir below). In the horizontal column layout, solution moves from one end of the column to the other through the packed porous material (Figure 2-1). Whatever the method employed, the common mechanism is that a solution is allowed to pass through a porous solid material at a rate that allows enough time for interaction between the solid and liquid phases, allowing the sorption or desorption of solutes, before the leachates are collected and analysed (Kim, 2005).

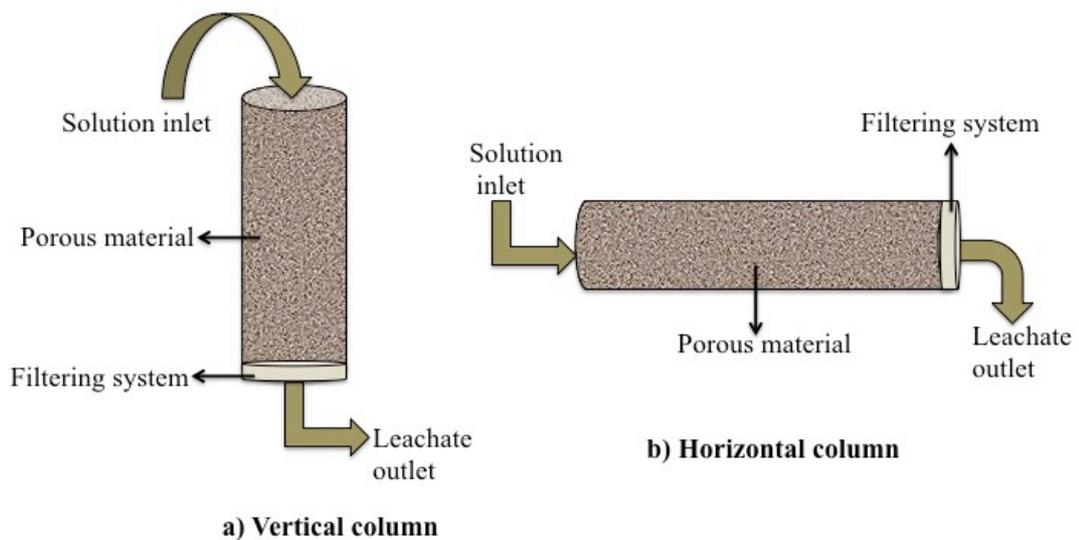


Figure 2-1: Schematic representation of vertical and horizontal column orientation

2.2.3.1 Column flow method

The method employed in this project is the vertical column method using sieved soil to keep the soil column as homogeneous as possible, so treatment effects were easier to observe. Leaching was conducted under unsaturated conditions using static, intermittent applications of nutrient solution (400 ml increments), which were allowed to flow through the column. Zachara and Sterile (1990) and Kim (2005) have

suggested this as a suitable way of mimicking vadose zone hydrology and found it to be effective in achieving uniform fluid distribution.

The experiment was based on the following three assumptions:

- That the flow of the leaching solution is evenly distributed in the column.
- That there is equal exposure of all particulate material in the column to the solution.
- That flow rate is slow enough to allow interaction between the solution and particulate material in the column.

The PS and SL were amended separately. The treatments were three rates of K and B (0, 2.5% and 5% w/w), 4 Pt rates (0, 10%, 20%, and 30% v/v) and combinations of both clay types with Pt at all rates. This adds up to 20 treatments for each soil, as described in Table 2-4. In addition to this, another 16 control treatments (PS alone, SL alone; PS+10Pt, PS+20Pt, PS+30%Pt, SL+10Pt, SL+20Pt, and SL+30%Pt; PS+2.5, PS+5%, SL+2.5 and SL+5% of each clay) were also set up. The experimental design was completely randomized with three replicates, giving a total of 168 experimental units.

Table 2-4: Treatment table

	Treatment name	Treatment description
1	Soil only	Soil only
2	10%Pt	Soil + 10% peat
3	20%Pt	Soil + 20% peat
4	30%Pt	Soil + 30% peat
5	2.5%K	Soil + 2.5% kaolin
6	2.5%K+10%Pt	Soil + 2.5% kaolin + 10% peat
7	2.5%K+20%Pt	Soil + 2.5% kaolin + 20% peat
8	2.5%K+30%Pt	Soil + 2.5% kaolin + 30% peat
9	5%K	Soil + 5% kaolin
10	5%K+10%Pt	Soil + 5% kaolin + 10% peat
11	5%K+20%Pt	Soil + 5% kaolin + 20% peat
12	5%K+30%Pt	Soil + 5% kaolin + 30% peat
13	2.5%B	Soil + 2.5% bentonite
14	2.5%B+10%Pt	Soil + 2.5% bentonite + 10% peat
15	2.5%B+20%Pt	Soil + 2.5% bentonite + 20% peat
16	2.5%B+30%Pt	Soil + 2.5% bentonite + 30% peat
17	5%B	Soil + 5% bentonite
18	5%B+10%Pt	Soil + 5% bentonite + 10% peat
19	5%B+20%Pt	Soil + 5% bentonite + 20% peat
20	5%B+30%Pt	Soil + 5% bentonite + 30% peat

The soil columns used were acrylic tubes of 50 cm high and 11.7 cm diameter. The bottom part of the column was filled with the dried PS or SL to a depth of 10 cm to encourage proper drainage, while the top 20 cm was filled with either PS or SL manually mixed with the appropriate amendment treatment. The whole column was then vibrated gently to allow natural and uniform settlement of all material, and left to equilibrate for 24 hrs before the leaching process was simulated (Figure 2-2).



Figure 2-2: Soil column showing the arrangement of soil layers in the tube

Each column received a solution of ammonium nitrate at the rate equivalent to 150 kg N /ha (15 g m^{-2}) in 2L of reversed osmotic (RO) water. Available nitrogen in soil occurs as nitrate or ammonium ions. The fertilizer chosen yields nitrate and ammonium ions in solution, and allows to measure the leaching rate of these two components in the test soils that could be related to the field condition. The solution was applied by slowly pouring in 400ml at a time; then the whole column was allowed to drain for 24 hrs. The amount of solution leached through each column passed through a filtering system consisting of a stainless-steel metal mesh and fine cloth mesh and was collected in a polyvinylchloride (PVC) cylinders, then measured. Furthermore, the 16 control treatments were also leached with 2L RO water without ammonium nitrate to correct for nitrate and ammonium present in the used soil and amendments. Water retention was calculated as the difference between total water added and total water leached after 24 hrs. A 20 ml subsample of the leachate was filtered using 150 mm Whatman filter paper and analysed for nitrate N and ammonium N concentrations using the FIASTER 5000 Analyser (FOSS Company), and N loads in the leachate were calculated. Ammonium and nitrate from the control treatments were

subtracted from the equivalent treatments that received ammonium nitrate solution before analysis.

Percentage water retained due to the amendment treatment (WRA) was calculated as:

$$\% WRA = \left(\frac{\text{water retained in amended soil} - \text{water retained in unamended soil}}{\text{water retained in amended soil}} \right) * 100$$

2.2.4 Statistical analyses

Significant differences among the means of the treatments were determined at $p \leq 0.05$ using ANOVA. Means of data with homogeneous variances were separated using Least Significant Differences (LSD), using SPSS v.24. Main effects of clay and OM and their interactions were measured using the General Linear Model (GLM). The relationship between soil water and nutrient leachate was measured using the Pearson correlation test ($p \leq 0.01$).

2.3 Results

2.3.1 Effect of amendment on water retention

The volume of water leached from SL and PS was measured and used to calculate the amount of water retained, by calculating the differences between the volume of water added and volume of water leached.

In the SL, the addition of amendments increased water retention in all treatments compared to soil alone (except for 2.5%K), and the differences were significant at $p < 0.05$. For the PS, the treatment with 10%Pt retained the least volume of water. The 30%Pt+5%B treatment retained the highest for both SL and PS (Table 2-5).

The water retention of the SL increased with increasing Pt rate, both in Pt alone and in Pt-clay amendment combinations (Table 2-5), indicating that more water would be retained as the OM content of the soil increases. The main effect of Pt and Pt rate on water retention was significant (Figure 2-5). The order of effectiveness of the Pt rate was $30\% > 20\% > 10\% > 0\%$.

Table 2-5: Water retention capacity of amended sandy loam (SL) and pure sand (PS)

	Treatment Name	SL (ml)		PS (ml)		WRA (%)	
		Mean	Mean difference	Mean	Mean difference	SL	PS
1	Soil only	1,247	-	674	-	0.0	0.0
2	10%Pt	1,292*	44.7	678	4	3.5	0.6
3	20%Pt	1,362*	114.7	688	14	8.4	2.0
4	30%Pt	1,380*	133.0	753*	79.3	9.6	10.5
5	2.5%K	1,217*	-29.7	719*	45.3	-2.4	6.3
6	2.5%K+10%Pt	1,279*	31.7	817*	143.0	2.5	17.5
7	2.5%K+20%Pt	1,363*	115.7	835*	160.7	8.5	19.2
8	2.5%K+30%Pt	1,385*	138.0	894*	219.7	10.0	24.6
9	5%K	1,280*	33.0	828*	154.3	2.6	18.6
10	5%K+10%Pt	1,371*	124.3	895*	221.3	9.1	24.7
11	5%K+20%Pt	1,421*	174.0	921*	246.7	12.2	26.8
12	5%K+30%Pt	1,468*	221.0	981*	307.3	15.1	31.3
13	2.5%B	1,271*	23.7	870*	196.0	1.9	22.5
14	2.5%B+10%Pt	1,347*	100.3	833*	159.0	7.4	19.1
15	2.5%B+20%Pt	1,482*	235.3	856*	182.0	15.9	21.3
16	2.5%B+30%Pt	1,550*	303.0	928*	253.7	19.5	27.3
17	5%B	1,365*	118.0	944*	270.0	8.6	28.6
18	5%B+10%Pt	1,455*	208.3	1,060*	386.0	14.3	36.4
19	5%B+20%Pt	1,545*	298.3	1,071*	397.0	19.3	37.1
20	5%B+30%Pt	1,594*	346.7	1,131*	456.7	21.8	40.4
	LSD	19.52		29.86			
	SE	7.23		11.06			

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error

Also, in the SL, the addition of clay increased water retention, except for 2.5%K, and the effect was again significant (Table 2-5). The reason for the lower volume of water retention for 2.5%K in SL is not clear but could be associated with the larger particle size of K which might have increased pore sizes of the amended SL. Water retention increased with clay rate (Figure 2-4). Comparing the main effect of the two clay amendments, clay B was more effective than clay K in terms of water retention when applied alone or in combination with Pt. The higher water retention of clay B is likely to be associated with its large surface area and higher CEC.

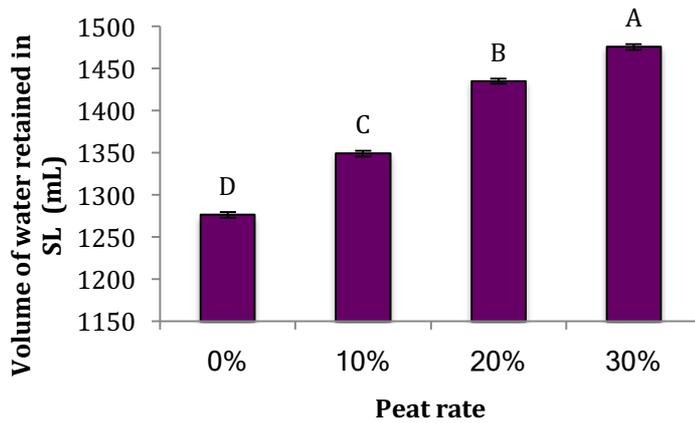


Figure 2-3: Main treatment effects of Pt rate on water retention of SL. Bars with different letters are significantly different at $p < 0.05$; Error bar is \pm standard error of the means (s.e.m).

In the amended SL, for both clays, application of Pt-clay in combination was more effective than peat or clay alone at the same application rate. An exception to this was the 2.5%K treatment when Pt application was below 20%; possibly due to the inability of 2.5%K to offset the low water retention capability of 10 and 20%Pt rates in SL. The interaction between Pt and clay was significant ($p < 0.001$), indicating that there was a change in response from the combined application of Pt and clay on water retention. On a weight for weight of clay basis, the water retention potential of K in the SL soil was less effective than that of B in any Pt-clay combination.

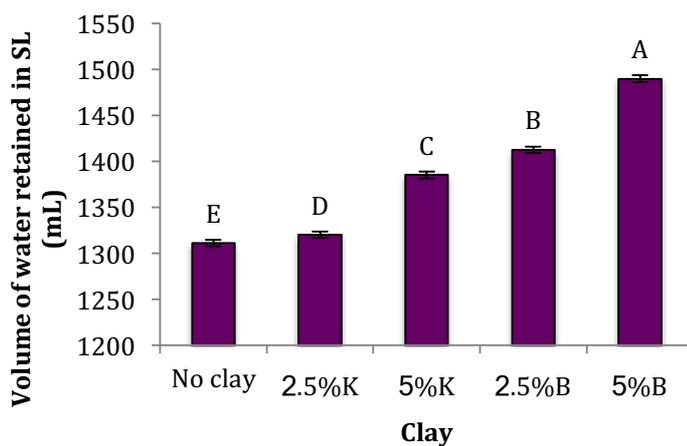


Figure 2-4: Main treatment effects of different clay type and rate on water retention in SL. Bars with a different letter are significantly different at $p < 0.05$; Error bar is \pm s.e.m.

In the PS, all treatments increased water retention, and the difference between amended PS and PS alone was significant, except for PS amended with 10 and 20%Pt. Like SL, PS amended with 10%Pt retained the least amount of water, while 5%B+30%Pt had the highest retention (Table 2-5).

For the PS amended with Pt only, the treatment effect showed that only 30%Pt was able to increase water retention significantly over the unamended PS ($p < 0.001$), suggesting that significant amounts of water would only be retained in soil with little or no inherent clay, if OM application is above 20% (Table 2-5).

On the other hand, the main treatment effect of Pt application (with and without clay additions) showed that Pt application increased water retention over PS without Pt (PS only and PS with clay only) and that the effect increased as the Pt rate increased (Figure 2-5). This observation was similar in SL and PS, supporting the hypothesis that water retention would increase with increasing OM rate.

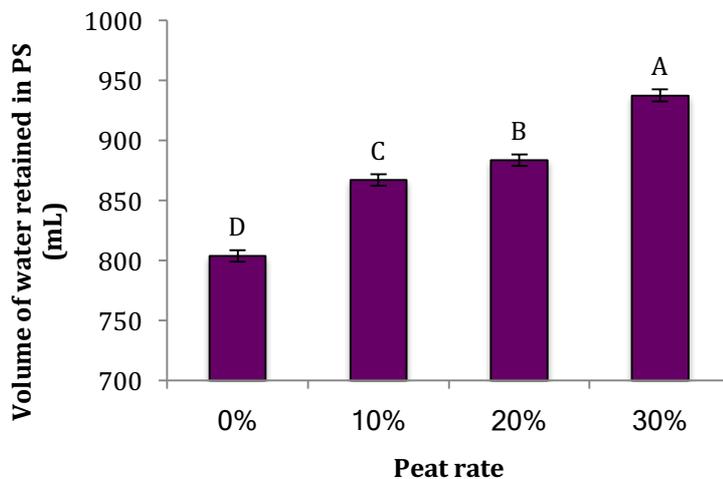


Figure 2-5: Main effects of Pt rate on water retention of PS. Bars with different letters are significantly different at $p < 0.01$; Error bar is \pm s.e.m.

The clay amendments (K and B) increased water retention of the PS: the highest retention was recorded in PS amended with 5%B, while 2.5%K had the lowest retention, although they all significantly increased water retention compared to PS receiving no clay (Table 2-5). The data also show that water retention increased with clay amendment application rate.

The main treatment effect of clay shows that 5%B had the significantly highest effect, followed by 2.5%B and 5%K, while 2.5%K has the least effect on water retention (Figure 2-6), suggesting that under the same conditions, PS amended with 2.5%B and 5%K would hold a similar amount of water. Weight for weight, the clay treatments with B retained more water than K.

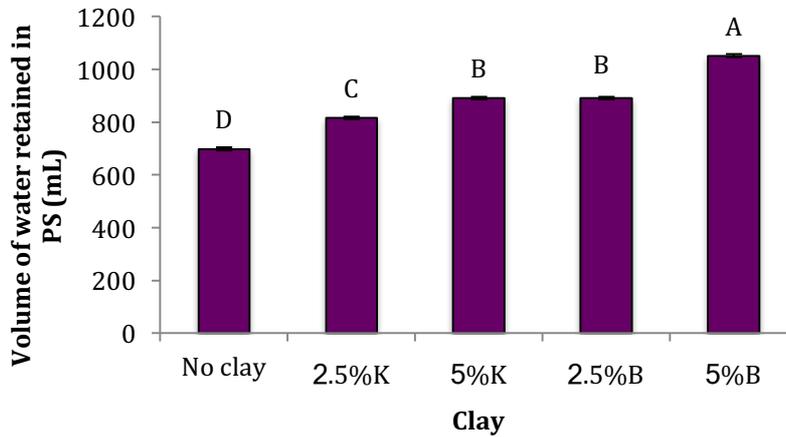


Figure 2-6: Main effects of different clay type and rate on water retention in PS.

Bars with different letters are significantly different at $p < 0.01$; Error bar is \pm s.e.m.

In the PS, the combined application of Pt and clay increased water retention significantly compared to PS, clay and Pt only. Amounts of water retained in combined Pt-clay treatments were higher than the individual effects of Pt and clay at the same application rate (Table 2-5). Interactions between clay and Pt on water retention in PS were also significant ($p < 0.001$), suggesting that the Pt-clay applications have synergistic effects on water retention of PS.

2.3.1.1 Comparison of the effects of the amendments on water retention in the two soils

Water retention of amendments was higher in SL than the corresponding treatments in PS, this difference is possibly due to the presence of inherent clay in SL. However, when the sole effect of amendments (WRA) was compared, amendments increased water retention in PS more than SL, except the soils amended with 10%Pt and 20%Pt (Table 2-5). In the clay-amended treatments, the percentage WRA was up to two-fold higher in PS compared to SL; this was true in the presence or absence of Pt (Table 2-5). This result shows that the inherent clay and OM in the SL reduces the effectiveness

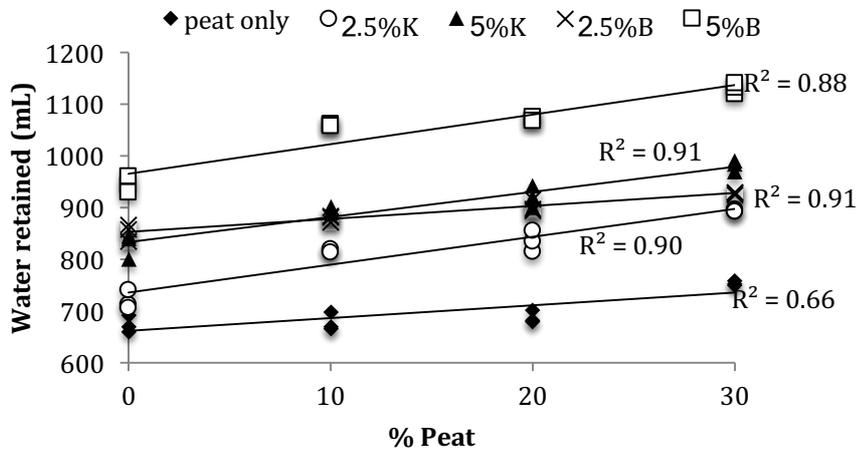
of the added amendments, compared to PS (which had no inherent clay or OM). This result supports the hypothesis that the inherent clay content of an amended soil will affect the effectiveness of the added materials: the higher the inherent clay content, the less the effect. As shown in Table 2-5, at the same clay application rate, water retention was higher in the SL than PS, except for 2.5%K, and the observation was true for both clay types used. For both soils, the least increase in water retention was found in 10%Pt and the highest in 30%P+5%B. In PS, the addition of 10% Pt to 2.5%B reduced water retention compared to 2.5%B alone; this was not observed in the corresponding treatment in SL. In both SL and PS, water retention increased with Pt and clay rate alone; also, the interaction between Pt and clay was significant for both soils ($p < 0.001$), indicating a synergic effect on water control.

The response of water retention to the clay and Pt additions in SL and PS was examined using a simple linear regression. For SL, the result showed that a weak, but significant, positive relationship exists between water retention and peat rate when Pt is added alone, and a stronger one when Pt is used in combination with the different clay types at each application rate (Figure 2-7). For PS, the increase was approximately linear except (possibly) above 2.5% clay in the 30% OM treatment. The application of Pt alone was less effective than either of the Pt-clay treatments on a percentage amendment basis. Peat-clay combinations were more effective than either OM or clay alone at the same rate in improving water retention. This shows that the more organic matter added, the higher the water retention in both SL and PS, irrespective of type and amount of added clay present. The R^2 values were higher in SL than PS in all the corresponding treatments (Figure 2-7). For SL, there was relatively little difference in the R^2 values between treatments (Figure 2-7b), whereas, for PS, the highest R^2 value was found in the 5%K treatment and the lowest for Pt amendment only (Figure 2-7a). In both SL and PS, 5%B significantly held more water than the other treatments, both when applied alone and in combination with Pt, at all rates (Figure 2-7).

For the PS, water retention was higher for B than for K at the same application rate, with 5%K showing only a slightly higher retention than 2.5%B. However, in SL, clay B at 2.5% held more water than 5%K. For Pt application rates higher than 10%, water retention of the Pt-clay mixture is: peat = 2.5%K < 5%K < 2.5%B < 5%B. In both PS

and SL, water retention potential of 2.5%B and 5%K were similar when approximately 8-10% peat is added (Figures 2-7a & b).

a)



b)

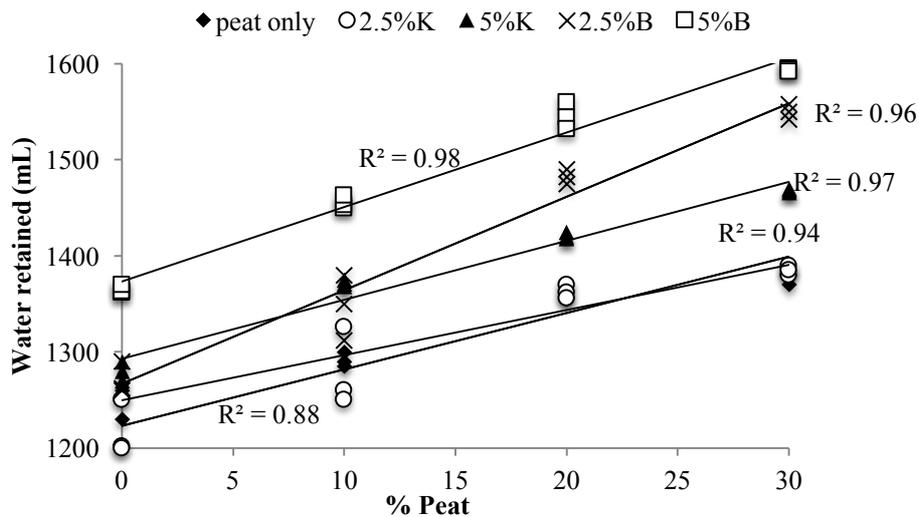


Figure 2-7: Relationship between water retention and peat rate in clay amended (a) PS (Pure sand) and (b) SL (Sandy loam) ($P \leq 0.05$; $n = 3$).

2.3.1.2 Percentage WRA

The percentage WRA was different for both SL and PS at the same amendment application rate (Table 2-5). For SL, the percentage WRA increases with the Pt or clay amendment rate, except where 2.5%K is applied alone. For 5%K, 2.5%B and 5%B, the combined application of Pt and clay increased water retention more than Pt or clay amendment alone. A mixture of 5% B and 30% Pt had the highest WRA value for both soils. For PS, percentage WRA for all the treatments was greater than the soil only.

The pattern of increase was similar to that observed in SL, except for 2.5%K. With the exception of the 10 and 20%Pt amended PS (where the percentage WRA was smaller than for SL), all other treatments had a higher percentage WRA in PS. In the clay-amended treatments, the percentage WRA was up to two-fold higher in PS compared to SL, irrespective of the presence or absence of Pt. This suggests that the potential of the amendment to improve water retention of a sandy soil would be greatly influenced by the percentage inherent clay content of that soil.

2.3.2. Effect of amendment on retention of ammonium nitrogen

Differences in the effects of the two clays, K and B, on ammonium and nitrate retention were expected, because clay B, due to the high negative charges on its surfaces, should attract more positively charged ammonium-N and repel negatively charged nitrate-N compared to clay K, which has pH-dependent charge density. Moreover, higher N retention would be expected where clay (either K or B) and organic matter are co-applied, possibly due to increased water retention and adsorption by soil colloids. The results generally meet these expectations, although some variations were observed in both soils (PS and SL). There was a significant difference between the ammonium N concentrations in the SL and PS leachates.

The addition of both clay (K and B) and Pt to PS reduced ammonium concentration in the leachate compared to the unamended PS, and the reduction was significant, except in 10 and 20% Pt only amended soils. The effect of Pt amendment rate on ammonium N losses was significant at 30%, and the potential of Pt to reduce ammonium N loss increased with Pt rate in SL and PS.

The effect of the addition of clay on ammonium N retention was significant in all clay treatments compared to the unamended PS, and 5%K was the most effective. Also, the ability of the clays to retain ammonium N in the soil increased as the amount of clay applied increased for both K and B. The amount of ammonium N concentration reduced in 5% compared to 2.5% clay amended PS, but it was not significant; the result was the same for both clays. PS amended with clay K and 30%Pt resulted in the lowest ammonium N losses in the leachate. The combinations of 2.5% and 5%B + Pt were significantly higher at reducing ammonium N losses compared to B only (Table 2-6).

Table 2-6: Ammonium concentration in the leachates of amended sandy loam (SL) and pure sand (PS)

	Treatment Name	SL (mgL ⁻¹)		PS (mgL ⁻¹)	
		Mean	Mean difference	Mean	Mean difference
1	Soil only	1.19	-	21.38	-
2	10%Pt	1.06	-0.13	12.56	8.83
3	20%Pt	1.15	-0.04	6.73	-14.65
4	30%Pt	1.08	-0.11	2.27*	-19.12
5	2.5%K	1.18	-0.01	4.80*	-16.58
6	2.5%K+10%Pt	1.27	0.08	4.29*	-17.10
7	2.5%K+20%Pt	1.17	-0.01	2.94*	-18.44
8	2.5%K+30%Pt	1.16	-0.02	0.52*	-20.86
9	5%K	1.04	-0.15	1.14*	-20.24
10	5%K+10%Pt	1.08	-0.11	0.59*	-20.79
11	5%K+20%Pt	1.23	0.04	0.71*	-20.67
12	5%K+30%Pt	1.20	0.01	0.23*	-21.16
13	2.5%B	0.97	-0.22	5.85*	-15.54
14	2.5%B+10%Pt	0.86	-0.33	1.60*	-19.79
15	2.5%B+20%Pt	1.01	-0.18	0.11*	-21.28
16	2.5%B+30%Pt	1.30	0.11	0.14*	-21.25
17	5%B	1.07	-0.12	3.82*	-17.57
18	5%B+10%Pt	0.87	-0.32	0.04*	-21.34
19	5%B+20%Pt	1.04	-0.15	0.05*	-21.34
20	5%B+30%Pt	1.36	0.17	0.11*	-21.28
LSD		0.250		1.696	
SE		0.123		0.839	

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$).

For SL, the ANOVA test showed there were significant differences in the ammonium concentration among the means of the treatments ($p = 0.012$), but none of the treatments was significantly different from the soil only except 2.5%B and 5%B amended with 10%Pt. The ammonium-N concentrations of these two treatments were lower than for the unamended SL. Clay K + Pt reduced ammonium retention suggesting that the increased soil acidity by the added K and Pt, had increased the positive charge on kaolinitic clay and thus repel positively charged ammonium (NH₄⁺). On the other hand, Clay B + Pt reduced ammonium losses. Among the SL treatments amended with the clay B, leachate ammonium-N loss increased with Pt rate (Table 2-6), suggesting possibly an increase in nutrient loss when the sandy soil is amended

with Pt. The efficacy of the Pt to reduce ammonium loss in SL amended with clay B + Pt combined is: 10% > 20% > 30% for the two clay application rates.

Comparing the two clays, clay B reduced ammonium loss compared to K. When applied alone, clay B reduced ammonium loss more than K, except at 5%K in PS. However, when applied with Pt, clay B reduced ammonium losses more effectively than K in both soils (Table 2-6). Comparing both SL and PS, the potential of all the amendments to reduce ammonium loss was more marked in PS than SL (Table 2-6).

2.3.4 Effect of amendment on retention of nitrate nitrogen

Table 2-7 shows the nitrate concentration (mgL^{-1}) leached in PS and SL. The amount by mass (i.e. load; mg) of nitrate leached in each treatment was calculated as a product of the volume of water leached and nitrate concentration and presented in Figure 2-8.

2.3.4.1 Effect of amendments on nitrate concentration

In SL, the amended treatments reduced nitrate leaching compared to the unamended soil, except for 5%K+30%Pt, 2.5%B, 2.5%B+30%Pt, 5%B and 5%B+10%Pt. Pt alone at all rates reduced nitrate leaching compared to the unamended SL. Clay K reduced nitrate leaching on its own and in combination with peat, except when peat rate was 30% in the 5%K amended SL. In clay B treatments, nitrate losses were higher at the two B application rates (2.5% and 5%). The addition of 10 and 20%Pt to 2.5%B reduced nitrate losses compared to soil amended with 2.5%B and 2.5%B+30%Pt. On the other hand, the addition of Pt to 5%B reduced nitrate losses as the Pt application rate increased. Among the treatments, 5%K+10%Pt has the highest effect on nitrate N retention (Table 2-7).

In PS, all the amendments reduced nitrate concentration compared to PS only, except 10%Pt. Addition of 10%Pt slightly increased nitrate leaching, while 20 and 30%Pt reduced it compared to that of PS only, but none of these differences was significant. The means of the three Pt rates were not significantly different, suggesting that their effects on nitrate leaching were similar. Application of K and B at 2.5% and 5% significantly reduced nitrate leaching, but the difference between the two clay rates was not significant for either K or B.

The application of clay K at 2.5% was more effective than combined Pt and K. Above 10%Pt, 5%K + Pt combined held more nitrate than 5%K only. For clay, B amended PS, only 2.5%B+20%Pt was able to reduce nitrate loss compared with 2.5%B amended soil alone. However, at 5%B rate, Pt addition at 10 and 20% rates reduced nitrate loss in the leachate, compared with 5%B only, but the difference was not statistically significant (Table 2-7). At the same application rate, nitrate retention was lower in PS than SL except for 5%K+30%Pt (Table 2-7), suggesting that more nitrate is leached in PS than SL. The effectiveness of the amendments on nitrate retention in the two soils is possibly due to the effect of the inherent clay in the SL.

Table 2-7: Nitrate concentration in the leachates of amended sandy loam (SL) and pure sand (PS)

	Treatment Name	SL (mg L ⁻¹)		PS (mg L ⁻¹)	
		Mean	Mean difference	Mean	Mean difference
1	Unamended soil	67.9	-	114.3	-
2	10%Pt	44.1*	-23.8	115.1	0.8
3	20%Pt	56.3	-11.6	107.1	-7.2
4	30%Pt	47.9*	-19.9	105.0	-9.2
5	2.5%K	44.6*	-23.3	70.1*	-44.2
6	2.5%K+10%Pt	45.2*	-22.7	82.0*	-32.3
7	2.5%K+20%Pt	25.2*	-42.7	93.1*	-21.2
8	2.5%K+30%Pt	55.9	-12.1	83.7*	-30.6
9	5%K	26.7*	-41.2	79.3*	-35.0
10	5%K+10%Pt	3.8*	-64.1	91.8*	-22.5
11	5%K+20%Pt	69.2	1.3	79.9*	-34.4
12	5%K+30%Pt	137.9*	70.1	60.9*	-53.4
13	2.5%B	81.9*	14.0	82.2*	-32.1
14	2.5%B+10%Pt	68.4	0.5	85.4*	-28.9
15	2.5%B+20%Pt	77.1	9.2	76.8*	-37.5
16	2.5%B+30%Pt	151.3*	83.4	92.1*	-22.2
17	5%B	84.9*	16.9	79.4*	-34.9
18	5%B+10%Pt	103.9*	36.1	76.3*	-37.9
19	5%B+20%Pt	49.4*	-18.5	84.9*	-29.4
20	5%B+30%Pt	70.7	2.8	97.3	-17.0
	LSD	14.20		18.63	
	SE	6.79		8.90	

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error

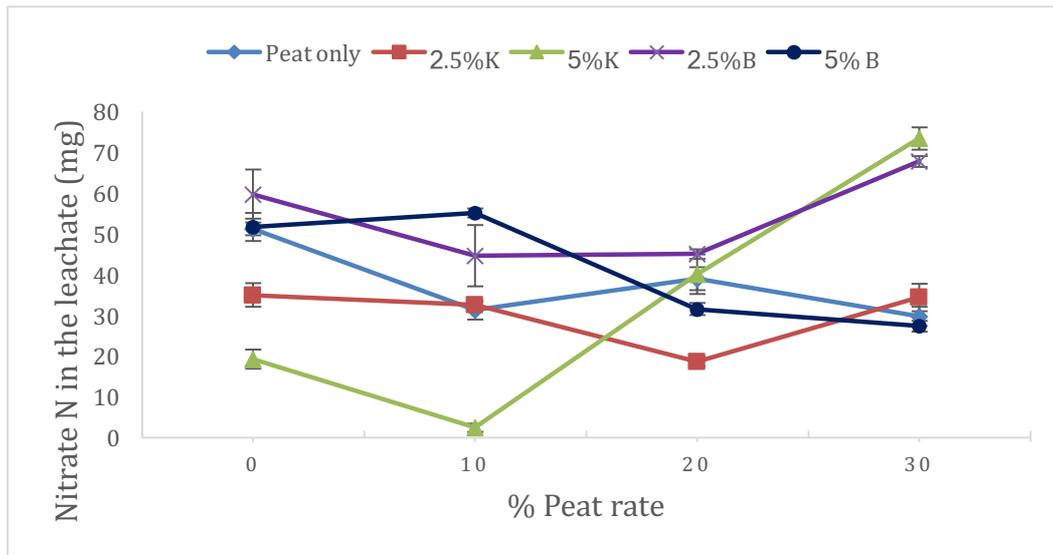
2.3.4.2 Effect of combined clay and peat on nitrate load

Figure 2-8 shows the response of SL and PS to Pt rate with respect to nitrate load in the leachates. In SL, 5%K greatly reduced nitrate load when co-applied with 10%Pt, but nitrate load rapidly increased when Pt was more than 20%. Pt addition up to 20% reduced nitrate leaching in the 2.5%K treatment. Addition of Pt improved nitrate retention of B. At 5%B, a significant increase in nitrate retention was observed when more than 10%Pt was added; while in 2.5%B, Pt addition reduced nitrate retention when application rate was above 20% (Figure 2-8a). Both 2.5%K and 5%K + Pt show that K's ability to increase nitrate retention increased with the Pt rate. Clay B, when applied alone, reduced nitrate retention compared to the unamended SL. However, when mixed with Pt, nitrate-leaching load in the leachate of B amended SL reduced, with the exception of 2.5%B+30%Pt (Figure 2-8a). For the two clay amendments, 2.5%K reduced nitrate leaching more than 2.5%B, both when applied alone and with Pt. 5%K reduced nitrate leaching more than 5%B, but when Pt rate was $\geq 20\%$, nitrate retention potential of 5%B became higher than 5%K (Figure 2-8a).

In PS, 5%B showed the lowest nitrate-leaching load when Pt rate was less than 30%. All clay amended soils significantly increased nitrate retention compared to Pt, except when Pt rate was 30%. When co-applied with Pt, nitrate retention of 5%K was significantly highest at the 10%Pt application rate but reduced as Pt rate increases thereafter. Nitrate retention ability of 2.5%B and 5%K were similar, except when Pt was increased to 30% (Figure 2-8b).

The effect of the two clay amendments on nitrate leaching load in SL and PS was influenced by Pt rate. For instance, at 5% clay rate in SL, nitrate leaching increased with Pt rate in K but reduced in B amended soil. However, in PS, both clay amendments seem to reduce leaching as Pt rate increased, except a slight increase in 5%B + 30%Pt in PS. In all, the effect of clay addition to reduce leaching was more pronounced in PS than SL.

a)



b)

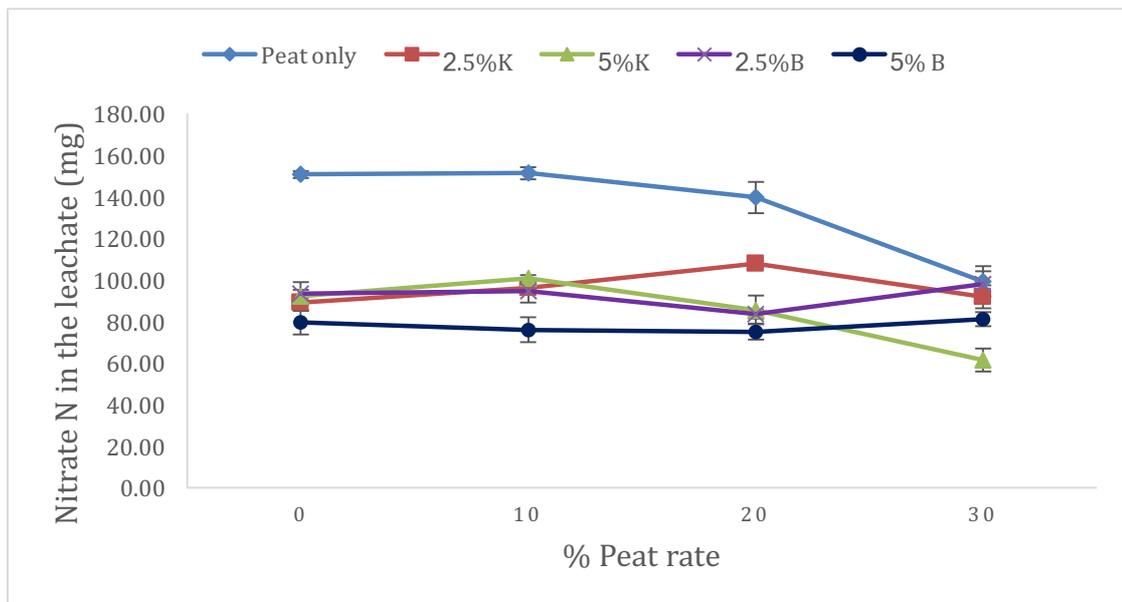


Figure 2-8: Effect of peat rate on nitrate load (a) SL (Sandy loam) and (b) PS (Pure sand) amended with two clays (K: kaolin; B: bentonite) and Pt. Error bar = \pm s.e.m.

2.3.4.3 Main and interaction effects of clay and peat amendments on nitrate load

The main effect of, and interactions between the two soils (PS and SL), the two clays (K and B) and Pt were determined using a general linear model at $p < 0.05$. The main effects in SL are shown in Figure 2-9. Soils amended with 2.5%K significantly leached the smallest amount of nitrate N compared to other clay treatments, but this was not significantly different from 5%K. The reduction in nitrate leaching in 5%B was not

significantly different to the SL receiving no clay; also soils amended with 2.5%B leached significantly highest amounts of nitrate N. Only soil amended with 2.5%K significantly increased nitrate N retention compared to the no clay SL treatments. Comparing the two clays, K significantly increased nitrate N retention compared to B, suggesting K is the better clay amendment when attention is on the reduction of nitrate N leaching in sandy soils. The response of B to nitrate leaching is likely to be associated with its mineralogical properties.

The main effect of applying Pt on nitrate N leaching showed that Pt would reduce leaching when application rates are $\leq 20\%$ in SL. Pt rates of 10% and 20% significantly reduced nitrate leaching compared to 0%Pt and 30%Pt. The difference between 0%Pt and 30%Pt was not significant (Figure 2-10). The result shows that when amending sandy soil with Pt (with the aim of reducing nitrate leaching), application rates of up to 20%Pt (v/v) would be appropriate.

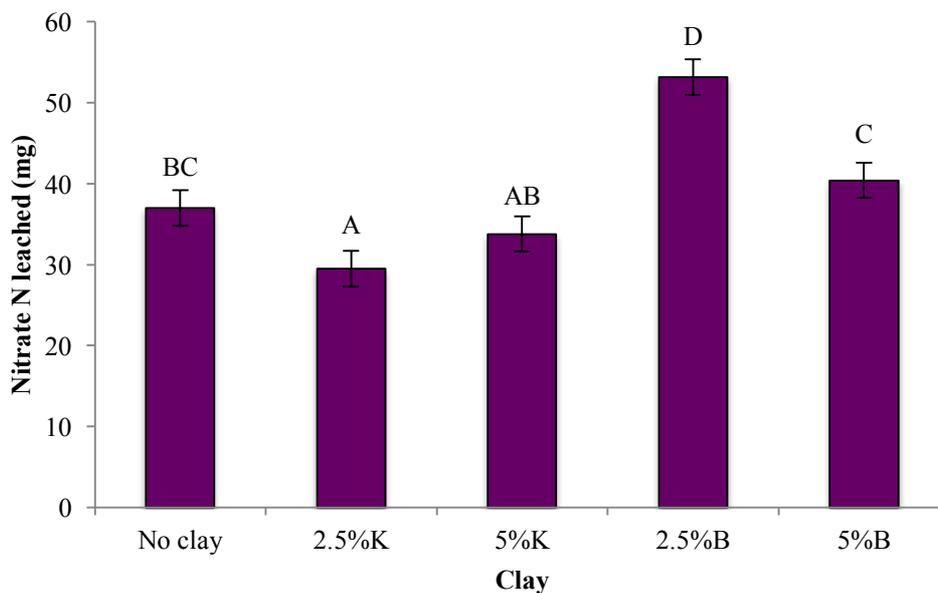


Figure 2-9: Main effect of clay type and application rate on nitrate N in SL. Bars with different letters are significantly different at $p < 0.05$. Error bar = \pm s.e.m.

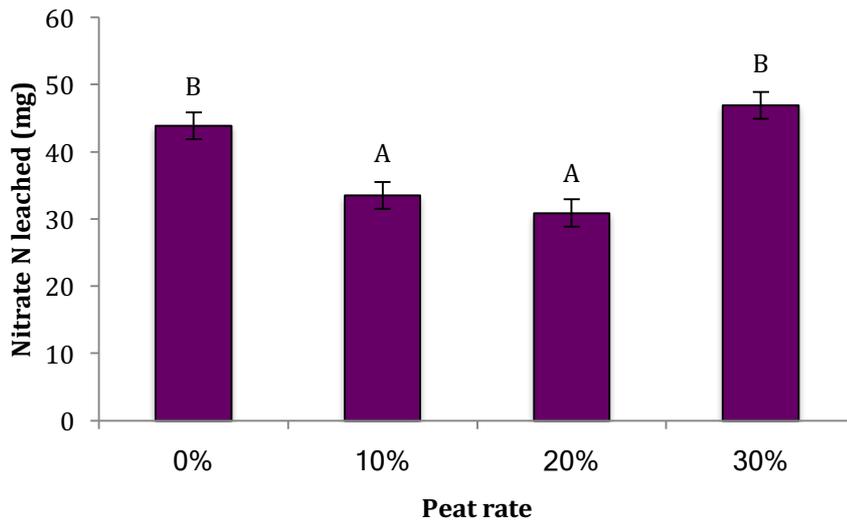


Figure 2-10: Main effect of Pt application on nitrate N in SL. Bars with different letters are significantly different at $p < 0.05$. Error bar = \pm s.e.m.

In PS, the main effect of Pt on nitrate N load was not significant ($p = 0.162$), suggesting that the amount of nitrate N leached in PS is not affected by Pt applied. On the other hand, the main effect of adding clay amendments was significant at $p < 0.05$ (Figure 2-11). The addition of clay significantly reduced nitrate N losses compared to unamended PS. Addition of 5%B significantly reduced nitrate leaching more than 2.5%K, but this effect was similar to 5%K and 2.5%B. The results suggest that in soils with very small quantities of clay (or even none at all), the addition of OM alone would not reduce nitrate leaching.

Comparing the two soils, the result also showed that interactions between Pt and clay amendments were significant for both SL ($p < 0.0005$) and PS ($p = 0.044$), suggesting a positive interaction between clay amendment and OM. However, the interaction effect was more pronounced in SL than PS. In both soils, the effect of amending soils with the clays was significant, however, in SL only 2.5%K significantly reduced nitrate leaching compared to no clay amendment, but in PS, all clay amendments reduced leaching. The results are similar to those of water retention (Table 2-5) suggesting that the inherent clay content of SL might have reduced the effectiveness of any added clay (K or B). This suggests that the beneficial effect of claying in sandy soil will increase with decreasing native clay content. In this experiment, the main effect of OM was not significant in PS but was in SL, suggesting that in terms of reducing nitrate leaching, OM will work only when in combination with clay.

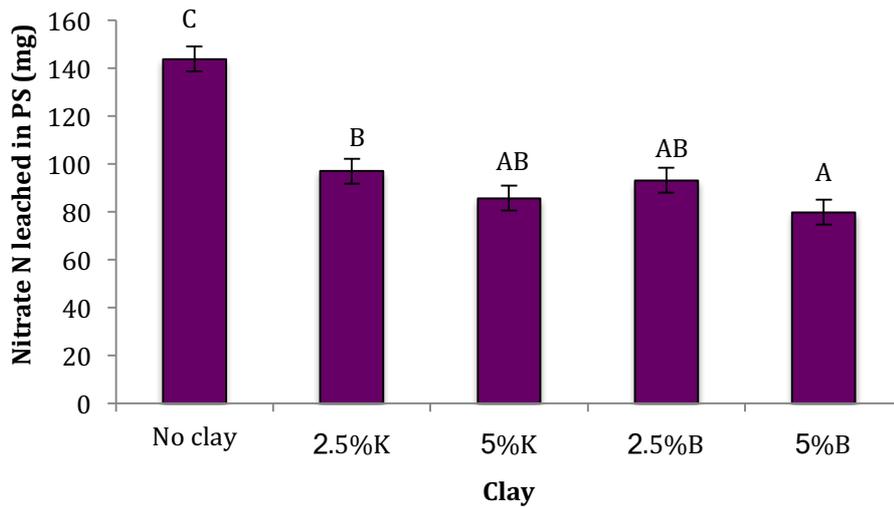


Figure 2-11: Main effect of clay type and application rate on nitrate N leaching in PS. Bars with different letters are significantly different at $p < 0.05$. Error bar = \pm s.e.m.

Deductions from correlation analyses showed that mechanisms responsible for nitrate and ammonium leaching in SL might be different from that of PS. Correlation between volume of leachate and nitrate load in SL was weakly and non-significant ($p < 0.15$; $r = 0.19$); for ammonium, it was weakly negative and non-significant ($p < 0.25$; $r = -0.15$). In PS, this correlation was strongly positive and significant for both nitrate ($p < 0.001$; $r = 0.74$) and ammonium ($p < 0.001$; $r = 0.69$). Thus, it could be inferred that the more the water leached, the higher the load of N losses in PS. This could mean that N retention in PS is largely controlled by water retention while other soil processes control or influence its retention in SL.

2.4 Discussion

2.4.1 Water retention capacity of the amended soil and sand

All amendments and their combinations increased the water-holding capacity of the two soils compared to the unamended controls. The results/outcomes were similar in SL and PS, except for 2.5%K. The inherent clay present in the SL has been identified as bentonite (Whitfield, 1973), which is known to be smaller in particle size than kaolin (Murray, 1999). The water retention in 2.5%K is likely to be partly associated with K particle size, which is possibly larger than the SL inherent clay size, and might have increased the porosity of SL, and partly due to the quantity used which its water retention could not offset the increase in soil pore effect.

The reason for this suggestion is that in PS (with no inherent clay and with particle sizes larger than K), the addition of 2.5%K increased water retention by 6%. Also, in SL, when 2.5%K was mixed with 10% peat, the amended soil's water retention slightly decreased compared to soil amended with 10%Pt alone. However, at 5%K application rate, this was not observed, and the major difference between the two K application rates is the quantity of clay material added. Thus, it can be concluded that at 5%K application rate, the quantity is large enough to offset any increased soil pore sizes resulting from the K amendment.

The percentage increase in water retention as a result of the amendments ranges from 0.6% in the PS amended with 10%Pt, to 40.4% in the PS treatment 30%Pt + 5%B. For the Pt, the amount of water held increases with the percentage of the Pt. Water retention of Pt is largely associated with the dead-end pore spaces found in the cortical layer of plant stems and hyaline cells in the leaves (and stems) which have openings at one end for water storage (Rezanezhad, et al., 2016). A typical peat could hold water up to 18 times of its dry weight (Hobbs, 1986). The water holding capacity of the peat used is 5g/g dry weight, so, in principle the more the quantity of peat added, the more the water that could be retained. The result agrees with the findings of Wang et al. (2014) who reported that in a laboratory experiment in Florida, fermented bioethanol and paper mill wastes at 10% loading increased water retention of a sandy soil by 150 and 300% respectively, compared to the unamended control. Li et al. (2004) showed in a three-year field experiment in Quebec, that amending sandy soil with peat increased water retention and total porosity, especially when the application rate was 48 Mg ha⁻¹. The OM application rate in this experiment at 10, 20 and 30% soil volume were 87, 174 and 261 Mg ha⁻¹, respectively. The application rate used in this experiment were a bit higher, but the results did agree with their findings.

Both bentonite and kaolin increased water retention of SL and PS, but their effect was dependent on the medium being amended. The ability of both clay amendments to increase water retention could be the result of their potential to reduce pore sizes or to their surface charges compared to sand particles (Dixon, 1991; Reuter, 1994; Murray, 1999). A comparison of the two clays showed that B has a higher water holding capacity than K when applied at the same rate. This difference is largely associated with the properties of the clays. Bentonite is a 2:1 clay mineral and the calcium bentonite used in this experiment has 88% montmorillonite, suggesting higher specific

surface area compared to kaolin, whose mineralogical composition is mainly of low activity, 1:1 kaolinitic clay. The water holding action of clay occurs in two ways: (1) bonding of water to clay either through electrostatic forces or reactions between water hydrogen ions and oxygen atoms of clay, and (2) by hydration of cations attached to the clay micelle. Thus, clay minerals with higher CEC and charge densities will hold more water. This phenomenon could explain why B with higher activity holds more water than K. Suzuki et al. (2007) also reported an increase in soil available water when a sandy soil in Northern Thailand was amended with termite mound and bentonite compared to the control and attributed the result to the alteration of pore size distribution by the amendments.

Some synergy was observed for the clay amendments when mixed with peat in that, the percentage water held by each clay-peat combination is higher than the sum of the equivalent clay and peat application rate when applied separately in both SL and PS. It was observed that water retention could be increased at the same clay level with increased Pt rate. The synergistic effect observed in this experiment could be related to the formation of clay-organic matter complexes, which possibly could have stimulated stronger van der Waal forces. Theng et al. (1986) suggested that this kind of interaction is possible between clay and organic polymers.

The observed results in the PS and SL thus confirm the hypotheses that increasing the clay and OM contents of sandy soils will improve water retention, and that the more the clay and OM content, the greater their effect. Also, the significant interactions between clay and OM showed that co-application of clay and OM has positive synergic effects on water retention, thereby supporting the synergistic effect hypothesis.

2.4.2 Nitrogen leaching in amended soils

Overall, the results support the proposed hypothesis that clay and OM would reduce leaching of ammonium and nitrate loads in the soil. This is true for all amended PS treatments. The support is also true for ammonium leaching in the SL soil when amended with B, but not for K. For nitrate in SL, the main effect showed that the hypothesis was only true for soil amended with 2.5%K, 10% and 20%Pt.

The effect of Pt rate on ammonium retention varies with the soil. In PS, ammonium retention follows a pattern similar to water retention, thus it could be concluded that reduction in ammonium losses occurred mainly because it was retained in the soil solution. For SL, ammonium retention appears to result from a porosity effect, as losses increased with an increase in OM (Pt), especially in B amended soils. For the two clay amendments, B reduced ammonium leaching more than K. This is expected, as B has higher CEC than K, and could attract more positively charged ions such as ammonium. Sitthaphanit et al. (2010) also reported higher ammonium retention in soil amended with bentonite, while the clay had no effect on nitrate mobility. The findings from the current investigation agree with their results as B reduced leaching of ammonium in both test soils. However, contrary to their findings, K when applied alone reduced nitrate leaching in SL and both clays in PS. The difference might be due to methods of fertilizer application. Sitthaphanit et al. (2010) mixed the fertilizer with the top 2.5kg soil before leaching, while the current experiment used nutrient solution.

Cation retention in soil follows simple electrostatic force mechanisms. While the quantity of anion retained in soil by clay is small compared to cations, the mechanism is quite complex. Some factors such as (1) charge repulsion (2) water extraction from solution to form double layers by clay (3) clay colloid charge density (4) charge density and concentration of the anion (5) soil pH and (6) specific anion reactions (CTAHR, 2015) have been identified to affect anion retention capacity. In this work, amending sandy soils with K only reduced nitrate loss, compared to B only. This could be a result of several factors, such as charge repulsion and clay colloid charge density (factors 1 and 3 above). Bentonite is a clay with a substitution reaction (exchanging structural cations with others of lower valency, thereby creating a charge deficit), so is expected to have a more negative charge on its surface than K that is less reactive. Coupled with that, nitrate is negatively charged and as like charge repels, B will attract less nitrate. Additional support for less nitrate retention by B is that the clay requires more water to form a double layer (factor 2); this condition will cause an increase in nitrate concentration in the soil solution of soil amended with B. This increase in nitrate (anion) concentration (factor 4 above) in turn increases repulsion, hence more nitrate is leached in B amended soil. Pamukcu and Wittle (1993) showed similar results. Shanmugam et al. (2014), Nguyen and Marschner (2013) and Djajadi et al. (2012), in short-time incubation experiments, also reported a reduction in nutrient losses of sandy soil amended with kaolin and organic matter.

Sivachidambaram and Rao (2012) reported that the iodide retention capacity of bentonite was improved in the presence of silver-kaolin (Ag-kaolin) admixture. The high nitrate retention in K amended soil in current study could also come from the ability of K to modify the anion retention characteristics of the inherent soil clay, which was high in montmorillonite, while addition of B could have stimulated or increased repulsion of nitrate; and this may be responsible for wider variability in nitrate retention in kaolin treated SL compared to PS without inherent clay content.

The impact of adding more than 20% Pt to SL was negative in that the OM did not reduce nitrate leaching. This observation is likely to be associated with increased porosity and permeability in the OM used (peat), as the amount of OM increased, resulting in loss of more nitrate in the leachate. The response of the clay amendments and their application rate to organic matter varies and is complex with respect to N retention in this experiment, especially in the SL.

Reuter et al. (1994) suggested that kaolinites should not be used in amending sandy soil due to their low activity and CEC. In contrast, however, a reduction in water repellency when sandy soil is amended with kaolinite has been reported (Hall et al., 2010; Shanmugam et al., 2014). However, sometimes this involved using large quantities of clay from clay accumulated in the lower soil horizon. Djajadi et al. (2012) have shown that a positive result is also possible when a small amount of kaolinitic soil was used with organic matter. The current study has shown that kaolin has higher potential to reduce nitrate leaching (especially in sandy soil with low inherent clay content) possibly due to less repulsion of this negatively charged molecule compared to bentonite. So, where anion retention is at stake, kaolin may be considered more beneficial.

2.5 Conclusion

The current investigation showed that water retention was enhanced by the addition of clay B; clay K (when application rate is above 2.5%); and clay-peat combinations. In all, the combined application of 5% clay (either K or B) and peat at $\geq 20\%$ Pt rates appear to be most effective in increasing the water retention. The water retention by the added amendments (WRA) was higher in soil with no inherent clay (PS) compared to the sandy loam (SL) that has 18%, thereby confirming the hypothesis that the

effectiveness of the added clay on water retention will reduce as inherent soil clay increases.

The effect of amendments on nutrient retention was more easily elucidated in PS than SL; all amendments reduced nutrient leaching in PS but the response was varied in SL. Bentonite showed higher potential in increasing ammonium N retention, and highest retention was recorded in combined clay and peat soil. Ammonium retention increased with clay rate as a result of higher CEC. Kaolin demonstrated better nitrate retention ability, especially when applied alone or at 2.5% in combination with peat in the sandy loam. The result of nutrient retention agrees with the Third Test Hypothesis that the two clays will have a varying effect on nutrient retention; B showed higher CEC while K demonstrated higher anion exchange capacity.

These results suggest that application of clay and organic materials has the potential to mitigate most of the physical and chemical factors militating against the productivity of sandy soils. The next chapter will examine the influence of the amendments on the properties of sandy loam under field conditions using the treatments that exhibited higher water retention capacity in the laboratory.

Chapter 3

Characterisation of sandy soil amended with clay and organic matter

3.1 Introduction

The ability of soils to carry out ecological functions is controlled by their physical, chemical and biological properties. Some properties such as soil porosity and permeability are important for groundwater management (Bell et al., 1986), however for water and nutrient retention, many if not all of the soil physical, chemical and biological properties are involved. As shown in Chapter Two, under laboratory conditions, up to 20%Pt, 5%K, B (2.5 and 5%) and combined application of these clays and OM increased water retention; and most of the treatments reduced nutrient leaching of the test soils. This chapter examines the potential of the clay and OM amendments to modify properties of sandy loam soil essential for water and nutrient retention under field condition.

3.1.1 Soil biological properties

The section examines soil microorganisms and how their biomass and respiration can be used as indicators of soil quality. Since the discovery of the fumigation-extraction method of determining soil microbial biomass from the soil carbon pool by Brookes et al. (1985) and Vance et al. (1987), soil microbial biomass (MB) has been used extensively to estimate the relative abundance of the living component of soil organic matter (SOM). Microbial biomass carbon (MBC) is the most labile of the soil carbon pool with a turnover of less than a year (Rice et al., 1996), and represents about 1-3% of soil carbon and 5% of soil N (Jenkinson and Ladd, 1981 in Baaru et al., 2007). The non-living fraction of SOM (about 95%) has been reported as having resistance to changes such as oxidation due to the high stability of recalcitrant carbon, hence this property cannot be used to measure any immediate changes due to soil management (Rice et al., 1996). On the other hand, soil microbial biomass is dynamic, and because of the microorganisms' close contact with the soil, they almost immediately respond to the soil changes such as nutrient inputs (including addition of exogenous organic and inorganic materials), physical disturbance (e.g. due to tillage) and climate change (Baaru et al., 2007). Soil microbial biomass is important for soil nutrient storage and

transformation, and Friedel et al. (1996) reported that in the agroecosystem, the nutrient availability and productivity of soils are a function of microbial abundance and activity. The importance of the microbial biomass in nutrient cycling may slightly vary, depending on the nutrient management method adopted. For example, in unfertilised agricultural system, microbial biomass is important for nutrient recycling through the decomposition and the release of organically bound nutrients for plant uptake, while microbial biomass functions as a nitrogen sink in fertilised soil through immobilisation of the soil nutrients (Rice et al., 1996; Baaru et al., 2007).

Another important property of a soil is the organic carbon (SOC) and carbon to nitrogen ratio (C:N ratio). SOC is the fraction of soil carbon that is organic in nature, derived from living and non-living soil flora and fauna. According to McBratney et al. (2014), SOC has recently received international attention due to a) its role in climate change mitigation (by serving as a sink for atmospheric carbon), and b) its function in soil fertility management, and the associated growth and yield of crops, so addressing global food security issues. Andrew et al. (2004, in McBradney et al., 2014) discussed the concept of soil carbon as an important indicator of soil quality. SOC is vital for nutrient cycling, and also serves as the main source of energy for soil microbes. In addition, it also plays a key role in soil aggregation, soil stability, moisture retention and erodibility (McBradney et al., 2014). SOC in the form of humic substances increases soil CEC through adsorption of soil cations by soil humic colloids. SOC can be accumulated in agricultural soil if the appropriate management practices are adopted (Lal, 2008; McBradney et al., 2014).

3.1.2. Soil chemical properties

Important soil chemical properties in all soils include pH, cation exchange capacity (CEC) and electrical conductivity (EC). Soil pH is the soil reactivity measured by the concentration of hydrogen ions in a soil, usually presented as the minus log to base 10 of hydrogen ion concentration. It takes values between 0 and 14, and a typical soil pH ranges from 3.5 to 9.5 (Kalra, 1995), with a value of 6.5 being optimum for many mineral soils (Miller, 2016). Soil pH plays a key role in crop production through its influence on nutrient availability and solubility of aluminium and manganese in the soils (Moore et al., 1998). Low pH induces increased availability of Al^{3+} , which are toxic and can retard root growth (Moore et al., 1998). The increased Al^{3+} can displace

other essential cations (plant nutrients) from the soil' exchange site, leading to their loss through leaching.

Soil CEC is the maximum amount of cations a soil can hold at a given time, and also denotes quantity of cations it could exchange with the soil solution. Cations are held on clay and humic colloids, thus clay mineralogy and the amount of humus in a soil would affect its CEC. Generally, clay soil has higher CEC values than sandy soils, because of high charge density and surface area of clay particles compared to sand (Hillel, 1998). Also, when comparing clay minerals, the lowest CEC values are in the order of kaolinite < muscovite < montmorillonite < vermiculite (Evangelou, 1998). Soil CEC is an important indicator of soil fertility, soil water retention and nutrient retention because it represents the number of cations that could be held in a soil. Soil CEC is determined by using the ammonium ion equivalent adsorbed on a soil, where its cations have previously been leached, or by the sum of all the cations extracted from the soil.

Soil electrical conductivity (EC) measures the soluble salt concentration in soils at a given time. On the basis of this, the soil could be classified as saline or non-saline. Adviento-Borbe et al. (2006) reported that many soils are considered saline if the EC value is above 2 dS/m. The main limitation of EC values is that they cannot provide information about the type of salt present in the soil, but EC has been found to correlate linearly with soil nitrate concentration in non-saline soils (Patriquin et al., 1993; Smith and Doran 1996 in Adviento-Borbe et al., 2006) and microbial respiration (Adviento-Borbe et al., 2006). EC can give an indication of nutrient leaching in the soil when monitored over time. Soil EC can be affected by soil nutrient status: EC is usually higher with increasing soil nutrients, thus EC can be used as an indicator of soil fertility. Also, another factor affecting EC is the soil moisture condition: increased soil moisture dilutes and reduces EC, and vice versa for dry soils.

3.1.3 Soil physical properties

In this project, the soil physical properties considered important for water and nutrient retention as well as crop production are soil bulk density, porosity, pore size distribution, soil pore characteristics, soil moisture content at field capacity (FC), permanent wilting point (PWP), plant available water (PAW) and soil moisture retention characteristics.

Soil bulk density refers to the ratio of soil dry weight to its volume (Hillel, 1998; Lal and Shukla, 2004). For most soils, the value ranges from 1.3 to 1.7 g/cm³ in sandy, 1.1 – 1.6 g/cm³ in clay, and can be as low as 0.5 g/cm³ in peaty soils⁴. Hence, soil texture is an inbuilt factor that affects bulk density. Bulk density also varies among clay minerals; for instance, the density of kaolinite is up to 2.68 g/cm³ while that of montmorillonite is up to 3.0 g/cm³ (Hillel, 1998; Lal and Shukla, 2004). Field soils have lower bulk density than pure clay minerals. In many soils, high bulk density (>1.6 g cm⁻³) could be an indication of soil compaction and hinders plant root growth (McKenzie et al., 2004). Soil bulk density can be used to predict the availability of nutrients to crops, soil porosity, water infiltration, microbial activities and root growth restriction. According to Hillel (1998), soil bulk density will decrease with increasing clay content owing to increase porosity. Also, the addition of OM was identified as one of the management practices that reduce soil bulk density⁵.

Porosity is the proportion of the soil pores to the solid matrix, and it is inversely proportional to the soil bulk density. Porosity takes values between 0 and 1 (or 0 – 100%,) and typically ranges from 0.3 to 0.7 for most soils (Nimmo, 2004). According to Nimmo (2004), soil porosity is controlled mainly by soil intrinsic properties such as:

- a) Soil particle packing density: the more densely packed a soil, the lower its porosity.
- b) The particle shape: soil particles with angular shapes such as sand would have larger spaces between them compared to clay with platy shapes.
- c) Particle size distribution: soils consisting of homogeneous particle size (monodisperse) will have higher porosity while soils with more heterogeneous particle sizes (polydisperse) would have lower porosity.

Extrinsic factors such as the presence of cementing agents could also affect soil porosity. Cementing agents such as clay and microbial exudates increase soil aggregation, which reduces porosity within aggregates as they are bound together, and the cementing agents fill the pore spaces within them (Hillel, 1998; Nimmo, 2004). However, inter-aggregate pore spaces are increased, which overall can result in an increase in total soil porosity (Nimmo, 2004). Other external factors affecting porosity

⁵soilquality.org.au (accessed 05/08/2016).

are compaction, which reduces porosity by closing up pore spaces, while the addition of OM increases porosity as a result of a dilution effect on soil weight and increased pore area.

Methods to measure soil porosity can be direct or indirect. Indirect methods include estimation of porosity by finding the proportion of soil water volume at saturation to the total volume of the soil. This method is based on the assumption that water is held in soil pores, and when a water-saturated soil is oven dried, the weight loss represents the mass of water occupying the pore spaces and can be converted to a water volume using the density of water (Nimmo, 2004; Hillel, 1998). The major limitation of this method is that it can overestimate soil porosity, as water could be held not only in the pores but also adsorbed within the soil matrix. Also, water density varies with temperature, although such errors could be negligible. Another indirect method is the use of an analogous technique, which measures the total volume of gas in the pores of a dry soil, and presents porosity as the fraction of gas from the pore spaces to the volume of the completely dry soil. A major limitation of this method is that the soil is subjected to compression during measurement (Nimmo, 2004), which in turn can destroy the soil structure and alter the initial pore spaces.

A direct method of measuring soil porosity includes the use of imagery photographs from computed tomography or soil thin sections. This gives estimations of total pore spaces in the images, and porosity is calculated as the fraction of total pore areas to the soil solid area of the selected plane (Nimmo, 2004).

Pore spaces are the openings or channels within the soil matrix where fluid or air can flow. The soil pores can be textural, structural or biogenic (Nimmo, 2004). Textural soil pores are the channels created by the arrangement of soil particles, commonly referred to as intergranular pores. Thus, finer textured soils have more of micropores, while sand dominated soils have more macropores as a result of polydispersity as a function of grain sizes and shapes. Structural pores are created by soil aggregation, and these pores are easily subjected to changes due to soil use and management. Biogenic pores are made by the activity of soil biological components such as burrowing animals (e.g. earthworms) and dead plant roots. In reality, soils are made up of heterogeneous pores of various sizes, and the relative abundance of these pores present in a soil is called the pore size distribution.

Pore size distribution can follow a normal distribution or be skewed to the right or left, depending on which pore sizes dominate the soil system. According to Nimmo (2004), a straightforward method for measuring pore sizes is the analysis of images of individual pore geometry from tomographs or microscopy. Computational analysis can then be used to produce the pore size distribution from the individual soil pore data. Other methods include impregnation techniques using a fluid that can solidify on cooling such as resin, which provides a three-dimensional representation of soil pores; and the estimation of soil pores sizes from the water retention curve. Pore size distribution provides a good insight of the relative abundance of different classes of pores in the soil, based on their radii or areas. It could be used to predict soil water retention, the degree of aeration and potential crop root growth. Pore size distribution can also be used for the estimation of soil textural classes. For instance, a pore distribution skewed to the left will reflect more clayey soil, skewed to the right would be sandy soil while normal distribution would represent more loamy soils.

The soil moisture retention curve is the graph that shows the relationships between soil moisture content (usually volumetric moisture content), and the soil water potential. Soil moisture retention curves vary from one soil to another and are typical of a given soil type (Figure 3-1). One of the ways to plot the soil moisture retention curve is the use of the pressure plate method, which measures the amount of water released when a given amount of pressure (or suction) is applied to a saturated soil. The soil moisture retention curve can be used to estimate soil pore distribution, soil textural class and soil moisture content (Loll and Moldrup, 2000). The water released at the upper part of the curve is capillary water, so it is controlled more by soil texture, while the water released under high pressure is more of the adsorbed water and this region of the curve is controlled more by soil structure (Nimmo, 2004; Filipović et al., 2016). Soil use and management can affect the shape of the moisture retention curve; for example, the curve tends to be flat in compacted soils, owing to the reduction in the numbers of macropores (Cary and Hayden, 1973).

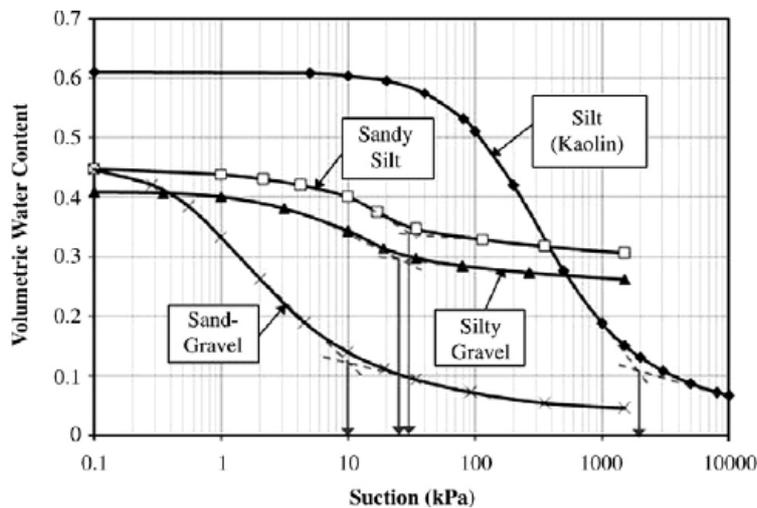


Figure 3-1: Soil moisture retention curves of different soils (Source: Lee et al., 2009).

Other important soil physical properties are soil moisture content at FC, PWP and plant available water (PAW). When saturated, all soil pores are filled with water and are subjected to gravity's pull until an equilibrium is achieved. This equilibrium occurs when all water held in large pores would have drained, so the water left in the soil is mainly held in the micropores (Kramer, 1983). Soil moisture content at this equilibrium is called FC and is the maximum amount of water that a soil can hold against gravitational forces. FC can be measured directly in the field by wetting a selected field area to saturation and covering the area with polyethene for 48 hrs to prevent moisture loss by evaporation. It is expected that the soil would reach FC within 48hrs, after which the field is sampled for volumetric moisture content. In the laboratory, FC is measured by applying 0.05 bar (5.0 kPa) suction to a pre-weighed, saturated soil until equilibrium is reached. Moisture content at FC is calculated as the difference in weight before and after suction was applied.

Permanent wilting point (PWP) is the soil moisture content below which plants can no longer extract water from the soil. Thus, it is considered to be the lower limit of soil water available for the plant. The direct method of measuring PWP involves measuring soil water content of a soil when a crop growing on it can no longer resume turgidity under 100% relative humidity (Kramer, 1983). The laboratory method for measuring PWP is similar to that for FC except that a suction of 15 bars is applied. The selected suction value of 15 bars has been identified as the maximum suction that plant roots can apply to uptake water in soil (Soil Survey Technical Monograph, 1974; British Standard BS 7755,1999). PWP reflects the soil moisture retention capability of a soil

under dry conditions, and management practices that can increase moisture content at this point are considered desirable.

One main usage of FC and PWP is the determination of plant available water (PAW; Hillel, 1998), which is calculated as the difference between FC and PWP. PAW is a better indicator of soil moisture condition than gravimetric moisture content, because it indicates water availability to a crop, while gravimetric moisture value does not. For instance, a clayey soil may have a high water content but this may not be available to the crop, as the water is held tightly, beyond the maximum suction that plant roots can employ. However, PAW represents the amount of water that a soil can release for plant uptake at a given time and therefore can be used for irrigation designing and planning, estimating water budgets, and in the prediction of crop yield and drought.

3.1.4 Objective and hypothesis

The laboratory screening of the water retention of the clay and peat amendments showed that soil water retention was high with increasing clay and organic matter ratio. The soil amended with 2.5%K and 10%Pt had low water retention, demonstrating that the two treatments are not suitable as sandy soil amendments with respect to water retention, therefore they were not used in the subsequent experiment. Although the previous experiment confirmed that the amendments have the capacity to increase water and nutrient retention of sandy soils, there is a need to understand how the amendments interact with underlying soil mechanisms or processes. Therefore, the objective of this chapter is to measure the effect of clay and OM as well as their combination on the physical, chemical and biological properties that govern nutrient retention, water retention and the hydrology of a sandy soil.

3.1.4.1 Hypotheses:

The hypotheses tested in this chapter are as follow:

- 1) Amendments will reduce the number of pores, pore diameter and total porosity of sandy soil, while peat alone and an increase in the peat-clay ratio will reduce bulk density.
- 2) Amending with clay will reduce soil respiration; increase the MBC, SOC and EC. It is also expected that the EC will increase with clay ratio but decrease with increasing peat ratio.

- 3) Soils amended with B will have higher MBC, CEC, water retention at FC, PWP, as well as higher PAW than K amended soils.
- 4) Peat and K will reduce soil pH while B will increase it. This hypothesis is based on the direct effect of the pH of the added materials on the test soil (pH of peat, K and B are 4.2, 5.1 and 9.5, respectively).

3.2 Materials and methods

A microplot field experiment was set up to measure the effects of the amendments on selected soil biological (soil respiration and soil microbial biomass carbon); soil chemical (pH, CEC, EC, SOC and C:N ratio); and soil physical properties (bulk density, porosity, water retention and availability, pore characteristics and soil moisture retention curve).

3.2.1 Soil collection and soil treatments

The soil and amendments used in this experiment were the same as described in the column leaching experiment (Chapter 2), and their properties were reported in sections 2.2.1 and 2.2.2. The sandy loam was excavated from 0-20cm depth from an experimental field at the University of Warwick's Crop Centre in Wellesbourne, United Kingdom (Latitude 52 12 18 N; Longitude 1 36 00 W). The soil was air-dried and sieved to remove stones before being used in the experiment.

Soil treatments were selected from the twenty treatments examined in the column leaching experiment (Chapter 2) based on their water retention capacity. Because the water holding ability of soils treated with 10%Pt was low compared to other Pt rates, and 2.5%K was lower in water retention than the unamended soil, they were not selected for the field trial. The treatments used are shown in Table 3-1; each treatment was replicated 5 times, giving a total of 60 experimental units. The clay application rates were 0, 2.5% and 5% (w/w) for B; 0 and 5% (w/w) for K; while Pt was applied at rates of 0, 20 and 30% (v/v).

Table 3-1: Selected treatments for the field trial

	Treatment name
1	Soil only
2	20%Pt
3	30%Pt
4	5%K
5	5%K+20%Pt
6	5%K+30%Pt
7	2.5%B
8	2.5%B+20%Pt
9	2.5%B+30%Pt
10	5%B
11	5%B+20%Pt
12	5%B+30%Pt

3.2.2 Establishment of the microplot experiment

Experiments were conducted in microplots, which consist of concrete rings sunk into the field soil. The rings are open-ended, 60 cm deep with a diameter of 100 cm and the surface level being the same as the field, and the microplots are 100cm apart. The bottom 20 cm of each microplot was filled with a gravel layer to ensure good drainage. Each microplot was then filled with 300 kg air-dried and homogenized soil and the amendments. The soil/amendment material filled the next 30 cm depth of the microplots. The soil and amendment materials had been homogenised using a mixer before microplot filling. A free area of about 10 cm was left on the surface of each microplot to prevent soil loss through splashing during rainfall. The schematic representation of one microplot is shown in Figure 3-2. Since the filling spanned over a period of 6 weeks (December 2015 to January 2016), polyethene covers were constructed to prevent ingress of water and the initiation of soil reactions before all plots were filled (Figure 3-3).

Treatments were placed in a Completely Randomized Design (CRD); and all plots were opened up on January 19th, 2016 to natural climatic conditions (Figure 3-4).

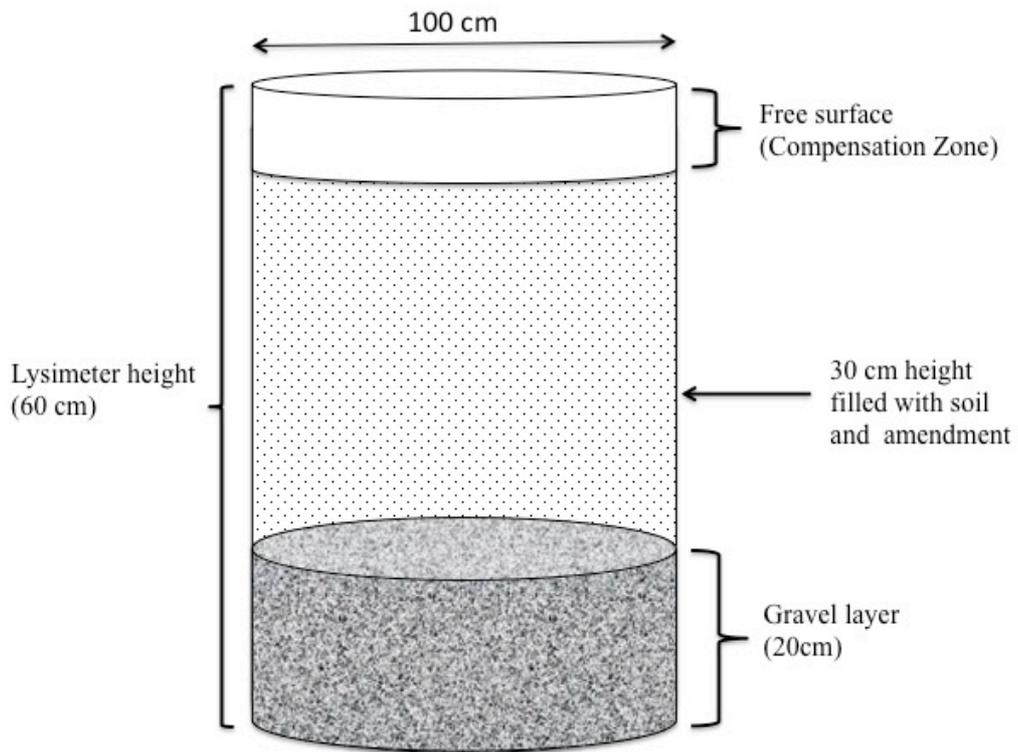


Figure 3-2: Schematic representation of the concrete lysimeter



Figure 3-3: Field trial showing plots covered with polyethene to prevent ingress of water during plot filling.



Figure 3-4: Field plots exposed to environmental conditions

3.2.3 Crop establishment

The crop used in this experiment was spring wheat, variety Mulika. The seed was supplied by Senova Ltd and had been pre-treated with Austral Plus, which is a standard seed treatment. The thousand grain weight (TGW) on this seed lot was 42g and germination was 95%. The seed was first sown on April 5, 2016, with germination and emergence expected to take between 10 and 15 days. However, the seed failed to germinate. Investigations revealed that some seeds had rotted before germination could take place. This is possibly as a result of low soil temperature (average soil temperature in April 2016 was 8.63⁰C) as the winter appeared prolonged. Another potential cause was surface capping following heavy rain, however, it was difficult to pinpoint an exact cause.

Following re-preparation of the soil surface, the trial was re-sown on April 28, 2016. Seeds were drilled in five rows per lysimeter. In an attempt to mitigate any potential problems, the surface of the microplots was covered with polyethene sheeting (Figure 3-5) to prevent the pooling of excess rainfall on the soil surface and to raise the soil temperature. The plots were irrigated both immediately after sowing and at one week after sowing to allow enough water for germination since the plots were protected from rainfall. The target crop population was 450 plants m⁻² to compensate for late drilling as reduced tillering was expected. It has been recommended that an additional

50 plants/m² should be added for every one month delay in sowing for the above reason (Wheat Growth Guide, 2015)⁶.

3.2.4 Agronomic practices

3.2.4.1 Fertilizer application

The plots were fertilized with nitrogen, phosphate and potassium. Phosphorus and potassium were applied at the rate of 70kg and 60 kg ha⁻¹, respectively, before sowing in April. Nitrogen was applied as a surface dressing using ammonium nitrate at the rate of 160 kg N kg ha⁻¹, in two splits. The first dose (100 kg N kg ha⁻¹) was applied on May 11, 2016, after emergence (GS13), and the second (60 kg N kg ha⁻¹) in June at the onset of flowering (GS51). The higher initial dose was applied because spring wheat is known to grow faster than winter wheat, thus have high N fertilizer requirement. The second dose applied at GS51 ensured enough N for ear growth and grain development; these follow the common practice.



Figure 3-5: Field trial showing the polyethene sheeting on the plot surface after re-sowing

⁶ <https://cereals.ahdb.org.uk/media/185687/g66-wheat-growth-guide.pdf> (accessed 10/01/2016)

3.2.4.2 Pesticides

Slug pellets (TDS Major; active ingredient is metaldehyde) were sprinkled on the soil surface to control slugs. Weeds were controlled using a pre-emergence herbicide (Stomp Aqua applied at 2.0L ha⁻¹). Fungicides were applied twice. The first fungicide was Praire applied at 2.0L ha⁻¹ at GS33-35, while Amistar (1L) and Prosaro (0.5L) were applied the second time at GS59.

3.2.4.3 Irrigation

Supplementary irrigation was used to compensate for rainfall shortages especially at critical growth stages such as seedling establishment (from emergence to GS29) and during grain filling (GS71-77). Determination of when to irrigate was based on physical observation of the field condition and interval of rainfall. For instance, irrigation was carried out if it did not rain for 2 consecutive weeks.

3.2.4.4 Harvesting

Matured wheat ears (total ears from each plot) were harvested using scissors on August 29-30, 2016. Ears were retained under controlled temperature conditions for later processing. Data were collected on total ear weight and thousand grain weight. The crop growth parameters and yield results are presented in Chapter 5.

3.2.5 Soil sampling

Soils were assessed for physical, chemical and biological properties. One sample per plot was collected by an auger (1cm diameter) to the depth of 20 cm in a 'W' shape to ensure good sample representation of each plot. Samples were then divided into two. One half was kept in the fridge for available N, microbial biomass and soil respiration analyses, while the other part was air-dried and sieved using a 2mm sieve (or 0.6mm sieve for OC and CEC) before analysis. All soil properties, (except soil physical properties measured by scanning) were measured twice: first sampling was carried out on February 1, 2016, for all the soil chemical properties and on April 1, 2016, for the soil physical properties, respiration and the microbial biomass. The second sampling was on August 31, 2016, after a wheat harvest for all the final chemical and biological soil properties, and on November 17, 2016, for all the final soil physical properties, including the soil scanning and moisture retention characteristics. Soil cores were kept in the fridge (at 3⁰C) until January 2017 when they were analysed. Soils for bulk

density, moisture retention characteristics and soil scanning were sampled using core samplers (5cm x 5cm).

3.2.6 Soil biological properties

3.2.6.1 Soil respiration

Soil respiration was measured using one of the methods described in British Standard BS ISO 16072:2002. The selected method was “measuring of basal CO₂ released from a soil sample following a period of incubation”. The major limitation of this method is that it does not distinguish between the CO₂ released from the biotic and abiotic element of the soil, and could overestimate the biological respiration especially in soil with high OM (BS ISO 16072, 2002). However, the method is still widely used, as it gives a good indication of microbial activity in the soil. The plots were sampled twice (April and August 2016) for soil respiration and microbial biomass carbon.

Briefly, 200g moist, 5mm sieved soil was weighed into an airtight container fitted with a polytetrafluoroethylene (PTFE) tubing of 0.2mm diameter via two bulkhead unions, one on each side. The water content of the soil samples was adjusted to 40% of water holding capacity, and the soil was incubated at 15⁰C for 5 days. The accumulated CO₂ was measured using a gas analyser (Warwick OLFaction Electronic Nose) in the Biosensors Laboratory, School of Engineering, University of Warwick (Figure 3-6).

3.2.6.2 Soil microbial biomass carbon (MBC)

Soil MBC was determined by the fumigation-extraction procedure (Brookes et al., 1985; Vance et al., 1987). The fumigation-extraction principle is based on lysing of intact microbial cells by alcohol-free chloroform. The released microbial carbon and soil carbon is then extracted with an acid extractant usually K₂SO₄. To determine the soil MBC in this experiment, 20g moist 5mm sieved soil was weighed into a glass beaker and fumigated in a desiccator containing 25ml alcohol-free chloroform for two days, after which it was extracted with 0.5 M K₂SO₄. An equivalent amount of non-fumigated soil from each plot was also extracted for soil C as a control. The soil MBC is calculated as the difference in C between the fumigated and non-fumigated soils.

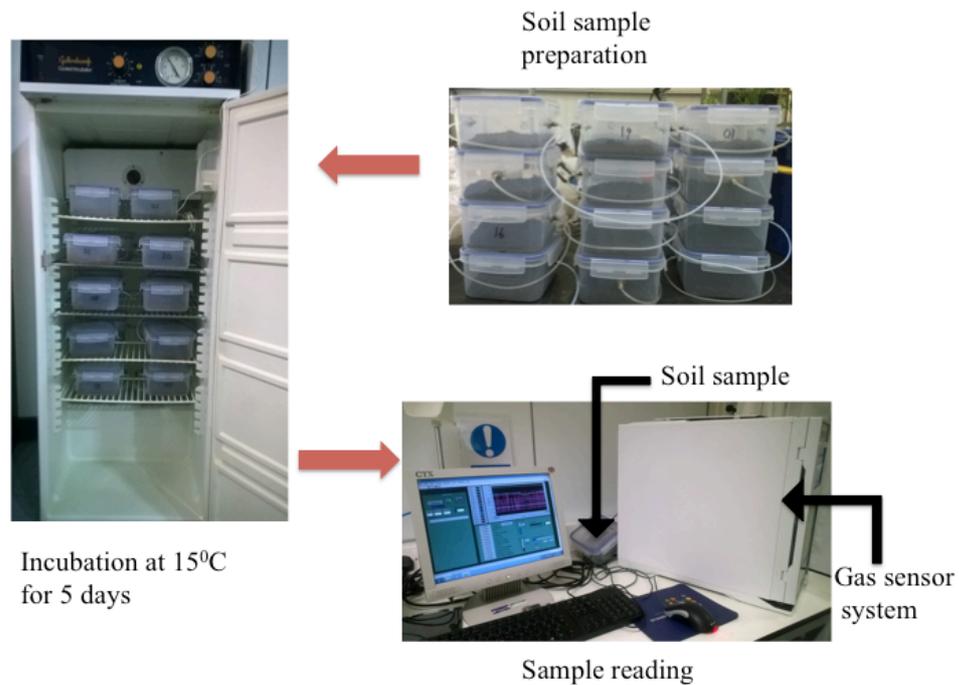


Figure 3-6: Measuring soil microbial respiration

3.2.6.3 Soil organic carbon (OC)

Total organic carbon was determined by the loss on ignition method (LOI; Nelson and Sommers, 1996). This method has been described as cheap, quick and reliable for measuring soil OC (Schulte and Hopkins 1996; Wright et al., 2008). The principle is based on oxidation of soil at very high temperatures up to 200 – 500°C (Chatterjee et al., 2009) or 500 - 575°C (Wright et al., 2008). It is expected that all organic materials in the soil will be oxidised, with only the mineral matter remaining, which is stable at this temperature. The organic carbon present in the sample is determined as the difference between the mass before and after ignition.

To determine soil OC in this experiment, 5g of air-dried, 0.6mm sieved soil were weighed and oven-dried at 105°C for 24hrs. The sample was cooled and weighed to determine its moisture content. The oven-dried samples were then placed in a muffle furnace and heated to 450°C for about 15 hours. Although there has been controversy on the appropriate temperature for the LOI procedure, David (1988; in Chatterjee et al., 2009) showed that in various UK soils, determination of OC at 450°C for 12 hours by LOI has a high recovery of OC ($r = 0.92$) when compared to the wet oxidation method. The oxidised soil samples were allowed to cool, and their final weight was measured. Soil OC was determined as the difference between soil weight after oven-drying and after oxidation and presented as a percentage of the soil weight.

3.2.6.4 Total soil carbon and nitrogen ratio

Total carbon and N in the soil were determined using the Dumas method (British Standard BS EN 13654-2:2001). The process involves thermal oxidation of soil samples (0.500 ± 0.005 mg), tightly packed in a foil, in the presence of excess oxygen at a temperature of 900°C . For the nitrogen, the released nitrogen oxides were first reduced to nitrogen gas by copper in the reduction tube, and the amount of nitrogen released was determined using a thermal conductivity detector (TCD). The CO_2 released from the samples was simultaneously measured for soil total carbon. The carbon to nitrogen ratios of the different treatments was calculated.

3.2.7 Soil chemical properties

3.2.7.1 Soil CEC

Cation exchange capacity (CEC) was determined by the ammonium acetate method as described in “The Analysis of Agricultural Materials” RB427 (1986) and NR-SAS/SOP 7/Version 1 (2012). The main principle involves leaching a small amount of air-dried soil with ammonium acetate. In this reaction, ammonium displaces other cations on the exchangeable sites of the soil colloids. Excess ammonium acetate is washed off with ethanol. The soil is then leached with a potassium chloride (KCl) solution to extract the exchanged ammonium ions, which is equivalent to the cation exchange capacity of the soil, from the exchangeable soil sites. The ammonium N in the extract is then allowed to react with phenol and hypochlorite to develop indophenol blue, and the absorbance of the blue colour is measured at 650nm using an auto-analyser.

In this experiment, 5g of air-dried, 0.6mm (because cations are adsorbed on the fine soil fractions) sieved soil was weighed into a glass beaker and 20ml of one M ammonium acetate (pH 7.0) was added and allowed to stand overnight to allow enough reaction time between the soil and the solution. The following day, the sample was transferred to a funnel fitted with a 125mm Whatman No.1 filter paper, and the leachate was collected in a volumetric flask. The soil then leached with successive 25ml ammonium acetate allowing time for draining between each addition until about 250ml leachate was collected.

The soil samples were then transferred to another flask and washed with 125 ml ethanol by adding 25ml at a time. Following this, the soil samples were transferred to a 100ml volumetric flask and leached with 10% m/v KCl until about 100ml of leachate was collected, and made to 100ml with KCl solution. The KCl leachate samples were analysed for ammonium N concentration, along with blank samples of KCl solution. The CEC from each soil is calculated as shown below:

$$CEC (cmol+/kg) = (N_s - N_b) / 140 * (0.25/m) * 1000$$

where:

N_s is the concentration of the ammonium N in the sample extract (mg/L)

N_b is the concentration of the ammonium N in the blank extract (mg/L)

m is the mass of air-dried soil sample (g)

3.2.7.2 Soil pH

There are various methods used in measuring soil pH. In-situ measurement is taken directly in the field while ex-situ measurement is carried out on soil samples in the laboratory. In this experiment, soil pH in water was determined in the laboratory at 1:2.5 (soil:water) using a pH meter as described in RB 427 (1986). A 10g sample of air-dried, 2mm sieved soil and 25ml of reversed osmotic (RO) water were measured into a glass bottle, capped and shaken on a horizontal shaker for 15 minutes. The pH of the suspension was measured potentiometrically using a calibrated glass electrode pH meter. The pH in water method has been identified as suitable for mineral soils containing up to 17% OC (Kalra, 1995).

3.2.7.3 Soil electrical conductivity (EC)

EC was determined according to the European Standard Working Document (2005). The main principle is the determination of an electrical resistance of a soil suspension in water, usually at 1:5 soil to water ratio. It is expected that the solution of soil containing higher concentrations of soluble salt will have higher electrical conductivity. EC was measured by weighing 20g of 2mm air-dried sieved soil into glass bottles, and 100 ml RO water was added then shaken for 30 minutes. The mixture was allowed to settle, then filtered. The filtrates were then analysed for EC using a conductivity meter (Accumet Research AR50)

3.2.8 Soil physical properties

3.2.8.1 Determination of soil pore characteristics and pore size distribution using Computed Tomography (CT) scanning

Soil sampling: Undisturbed soil cores (5 cm x 5 cm) were taken from each plot 45 weeks after amendment application for the scanning. There were three replicates per treatment, giving a total of 36 samples.

Scanning: A Phoenix VltomelX m240 3D CT scanner (GE measurement and control, Germany) designed for soil and plant analyses located at Sutton Bonington campus, Nottingham University, UK, was used to acquire scanned images. The scanning mechanism is based on a Grey Scale Value (GSV) where individual items in the scanned material will fall into one of the bit different values of the GSV according to their density: the brighter the object, the higher the density. The major limitation of CT is its resolution ($42\mu\text{m}$ in this experiment). Also 8-bit GSV display by the used software (ImageJ) makes it difficult to separate the water filled pores with high accuracy from the soil matrix, therefore the pores presented in the image analysis are all air filled macropores and coarse mesopores (Kumar et al., 2010; Li et al., 2016).

The energy of the scan machine was set to 140kV for voltage; $160\mu\text{A}$ for current and power output was 22.4watt. The voltage is related to how much power that can penetrate through the sample. The denser the sample, the higher the voltage required. The current is related to the contrast of the different substances present in the sample, and is responsible for the spread of the Grey Scale Values (GSV) that could be achieved. The energy required for samples is determined by a preliminary testing using one of the samples to be scanned.

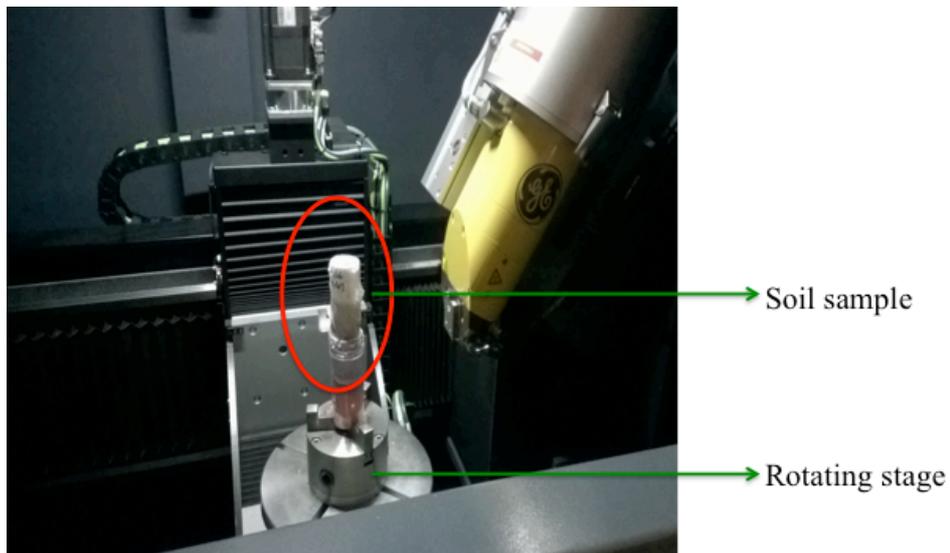


Figure 3-7: A soil sample positioned in the scanner ($42\mu\text{m}$)

The soil samples were scanned in a PVC container because metal containers interfere with the scanning process. One sample at a time was positioned vertically on a rotating stage (Figure 3-6). Unlike a medical CT scanner, the sample was designed to rotate at 360° on a rotation stage while the gun and the detector are fixed. For this work, the image resolution was $42\mu\text{m}$, and the total scanning time was 24 minutes per sample.

Image processing, segmentation and analysis: Raw 16-bits grey-scale images were exported as image stacks and were first processed using Volume Graphic Max (VG Max) software. The thresholding tool was used to separate pores from the surrounding soil matrix, and this was done manually by adjusting the threshold histogram until all air-filled pores were clearly selected, and then the value was applied to all images in the sample. This was repeated for all the 36 samples.

The second stage of image processing and analyses was then carried out in the ImageJ version 1.51f software package⁷, to measure the treatment effect on soil pore characteristics. Uncompleted images from each soil sample were removed before the subsequent analyses. The rest of the images were converted to 8-bits grey-scale value in ImageJ.

⁷ <https://imagej.net> (accessed on January 2017).

Image segmentation: A square area of 550 x 550 x 1255 pixels at the centre of each image was cropped using 'Region of Interest' (ROI) tools. This helps to remove voids near the wall of the cores. Segmentation is the conversion of the images to binary stacks (pore and solid) using Binary tools. Prior to analysis, pores with radius $\leq 0.75\mu\text{m}$ were removed as noise and outliers within a grey-scale threshold value of 50. The 8-bit grey-scale has values ranging from 1-255, and a value below the set threshold is considered to be air-filled pores while values above it are regarded as non-pores. The pore characteristics measured include pore diameter, pore area, total porosity, pore size distribution and total pore count. The statistics of individual pores on each image slide were measured using Analyse Particle Tool.

Slide number standardization: Based on samples with the smallest number of image slides after image editing for disturbance, data from 700 image slides per sample were selected and used to calculate the average values for each sample. Data generated by the ImageJ were exported into Excel and analysed using the 'Analyses Toolpak'.

3.2.8.2 Bulk density

Soil bulk density and soil moisture characteristics were assessed after wheat harvest using undisturbed soil auger cores. Before the cores were taken, the soil surface at the sampling point was cleaned of plants and crop residue. Stainless steel rings (5 cm x 5cm) were placed on the soil surface, covered with a wood block and hammered vertically into the soil gently using a rubber hammer. The rings were then excavated with a trowel, the outer surfaces of the rings carefully cleaned, the soil at the top and bottom of the ring trimmed with a knife and each ring covered with polyethene cling film, to prevent moisture loss and to keep the soil intact. One sample was taken from each lysimeter. A subsample of three replicates per treatment was then selected for determination of the soil moisture retention characteristic curve; this was undertaken at Cranfield University.

To determine the soil bulk density, the undisturbed soil cores were weighed, and oven dried at 105°C to a constant weight. Also, the volume of the ring was calculated and was used as the equivalent volume of the soil. The soil bulk density was calculated as the difference between the weights of the soil before and after oven drying, divided by the soil volume.

3.2.8.3 Soil moisture retention characteristics

The intact core samples described above (section 3.2.5.1) were used to determine soil moisture retention characteristics according to British Standard BS 7755 Section 5.5:1999 and ISO 11274:1998, using the pressure membrane cell method. The resulting data were used to determine plant available water (PAW), field capacity (FC), permanent wilting point (PWP) and the soil moisture retention curve.

3.2.9 Soil cracking

The soil surface in the field was assessed for cracking intensity four weeks after the opening of the microplots. The soil was scored for cracking using visual observations.

The scale was from 0 to 5:

0 – No cracking

1 – very low cracking

2 – low cracking

3 – cracked

4 – moderately cracked

5 – very cracked

Value of zero was not allocated to unamended soil because it was observed that some amendments reduced soil cracking compared to the unamended soil, this prevents generating negative value data which otherwise might be difficult to analyse.

3.2.10 Statistical analyses

Effects of amendments on soil properties were analysed using one-way ANOVA ($p < 0.05$) using SPSS version 24. Means of data with homogeneous variances were separated using Least Significant Differences (LSD), while data with non-homogeneous variances were separated using Dunnett T3. The relationship between initial and final values for the same property was analysed using Pearson correlation ($p < 0.01$) and paired t-test ($p < 0.05$). All soil chemical and biological properties were determined in five replicates, except soil respiration (four replicates), while all physical properties had three replicates.

3.3 Results

3.3.1 Effect of amendments on soil biological properties

In this experiment, soil biological properties were measured at 6 and 33 weeks after amendment application. MBC reflects the abundance of microorganisms in the soil at a given time while respiration provides insight into their activity. Also, soil respiration

can provide information about the rate of carbon mineralisation in each treatment based on the amount of CO₂ emitted.

3.3.1.1 Effects of amendments on MBC

Table 3-2 shows the response of MBC to amendments over time. There was a high variability within the data set at the two measurement times. At six weeks, only plots amended with 5%B increased MBC compared to the unamended soil. The means of 20%Pt, 30%Pt and 2.5%+30%Pt treatments were significantly lower, while that of 5%B+20%Pt and 5%B+30%Pt treatments were higher compared to the unamended soil. Soil amended with the 30%Pt had the smallest MBC value, while 5%B+30%Pt had the highest.

For Pt alone treatments, the difference between 20 and 30%Pt was not significant ($p = 0.45$), indicating that there was no Pt rate effect. For clay alone soils, 5%B increased MBC compared to 5%K and 2.5%B, but the means of 5%K and 2.5%B were not significantly different ($p = 0.212$). When clay was combined with the Pt at 5% application rate, MBC increased compared to the clay alone, but the difference was only significant in 5%B soils (Table 3-2). For 2.5%B rate, the addition of 20%Pt significantly reduced MBC, however, there was a small, non-significant increase at the 30%Pt rate.

At the 33rd week, there was a decrease in soil MBC in all the treatments compared to 6 weeks after amendment, but 20%Pt, 30%Pt and 2.5%B+20%Pt treatments were fairly stable. The reduction in MBC over time is possibly as a result of the reduced soil moisture content at final sampling in August 2016 compared to the initial in February 2016 (Table 5-3). All amendments except 5%K, 5%K+20%Pt, 2.5%B and 5%B increased MBC over the unamended soil, but the increase was only significant at 5%B+20%Pt and 5%B+30%Pt (Table 3-2).

Table 3-2: Effect of the treatments on soil MBC at 6th (initial) and 33rd (final) weeks after amendment application

Treatment	Initial MBC			Final MBC		
	Mean (μ g C/g)	Mean difference	p value	Mean (μ g C/g)	Mean difference	p value
Soil only	78.3	-	-	49.1	-	-
20%Pt	58.6*	-19.70	0.017	57.5	8.36	0.356
30%Pt	52.5*	-25.78	0.002	51.0	1.9	0.833
5%K	65.2	-13.13	0.107	48.1	-1.00	0.912
5%K+20%Pt	76.6	-1.71	0.832	46.3	-2.80	0.587
5%K+30%Pt	68.4	-9.86	0.223	54.9	5.76	0.523
2.5%B	75.3	-3.04	0.705	32.1	-17.04	0.063
2.5%B+20%Pt	56.4*	-21.91	0.009	56.2	7.06	0.435
2.5%B+30%Pt	76.3	-1.97	0.806	59.4	10.28	0.257
5%B	86.3	7.59	0.347	43.3	-5.84	0.518
5%B+20%Pt	113.7*	35.40	0.001	68.8*	19.64	0.033
5%B+30%Pt	123.4*	45.10	<0.001	72.4*	23.26	0.012
LSD		16.05			18.01	
SE		7.98			8.96	

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error of the mean.

In Pt alone treatment, the result of MBC was similar to the initial values where the 20%Pt has a small non-significant ($p = 0.474$) increase over 30%Pt. Also, Pt alone increased MBC compared to the clay alone, but this was only significant ($p = 0.007$ at 20%Pt and $p = 0.04$ at 30%Pt) in the 2.5%B amended soil. All clay alone treatments reduced soil MBC. Among these clay treatments, 5%K had the highest value, followed by the 5%B, while the 2.5%B had the least, but their means were not significantly different. Combined applications of 2.5%B and 5%B with Pt at both rates, significantly increased MBC compared to their corresponding clay only treatments, suggesting that the combined application of B and OM offers more favourable growth conditions for soil microorganisms. For 5%K treatments, only 5%K+30%Pt increased MBC compared to the unamended soil, but this was not significant.

3.3.1.2 Effects of amendments on soil respiration

Soil respiration was measured as the amount of CO₂ released from an incubated soil, and the results were shown in Figure 3-8. At 6 weeks after application, all amendments increased soil respiration over unamended soil except 5%K and 5%K+20%Pt. This increase was significant in all the amendments. In addition, 5%K significantly reduced the soil respiration, while 5%K+20%Pt was similar to the unamended soil treatment.

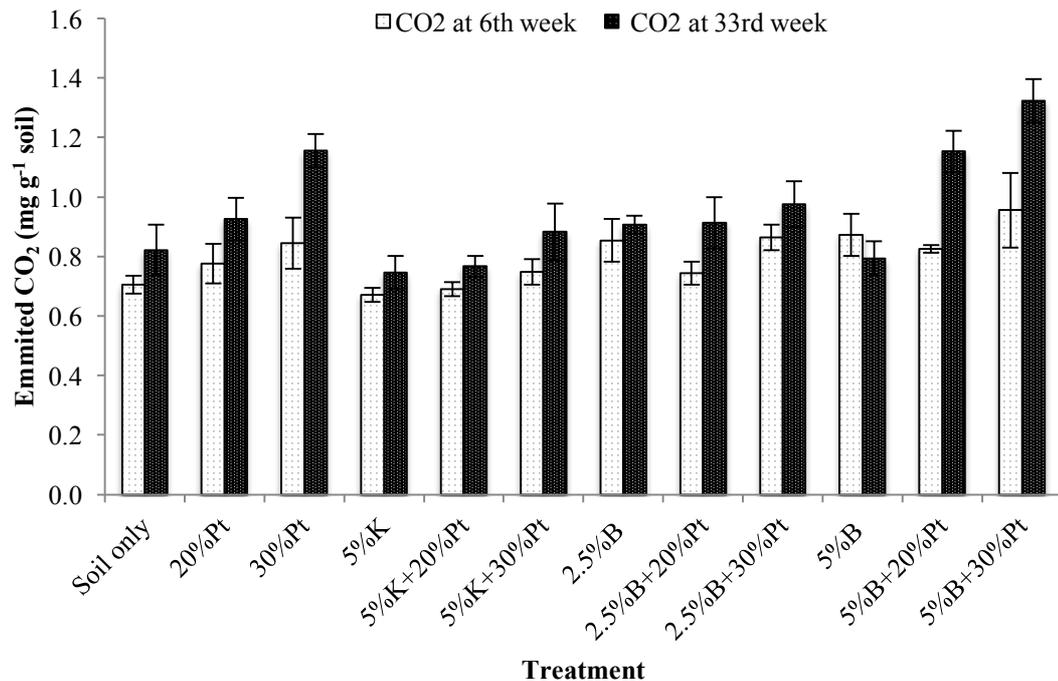


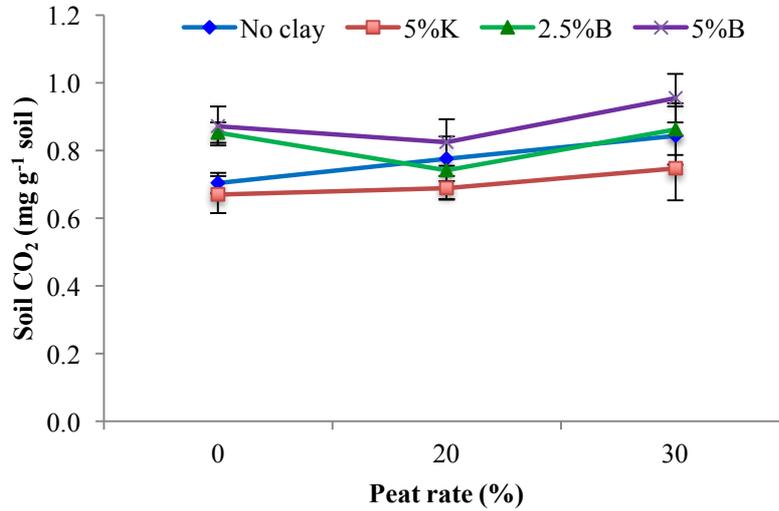
Figure 3-8: Effect of clay (type and application rate) and OM amendment on soil respiration at 6 (initial) and 33 (final) weeks after amendment. Error bar is \pm s.e.m.

For Pt alone treatments, soil amendments significantly increased soil respiration, and the Pt rate effect was significant ($p < 0.001$), suggesting that the soil microbial activity will increase as the amount of soil OM increases. In clay alone treatments, K significantly reduced respiration while B increased it, and there was a small, non-significant increase in respiration as the B rate increased from 2.5% to 5%. The combined clay and Pt treatments increased respiration compared to the clay alone, and the respiration increased with the Pt rate. The respiration in 20 and 30%Pt in combined clay and Pt treatments was significant for 5% clays, but not for 2.5%B.

At the 33rd week, respiration generally increased in all treatments (except 5%B alone) compared to initial values at the 6-week point after amendment. Also, all amendments increased soil respiration compared to the unamended control and the increase was

significant, except for 5%K and 5%K+20%Pt - similar to what was observed at the 6th week. In Pt alone treatments, there was a significant increase in soil respiration as Pt rate became higher. Also, Pt application increased respiration compared to the clays alone. The higher respiration in Pt alone treatments is possibly owing to the availability of carbon from the added Pt.

a)



b)

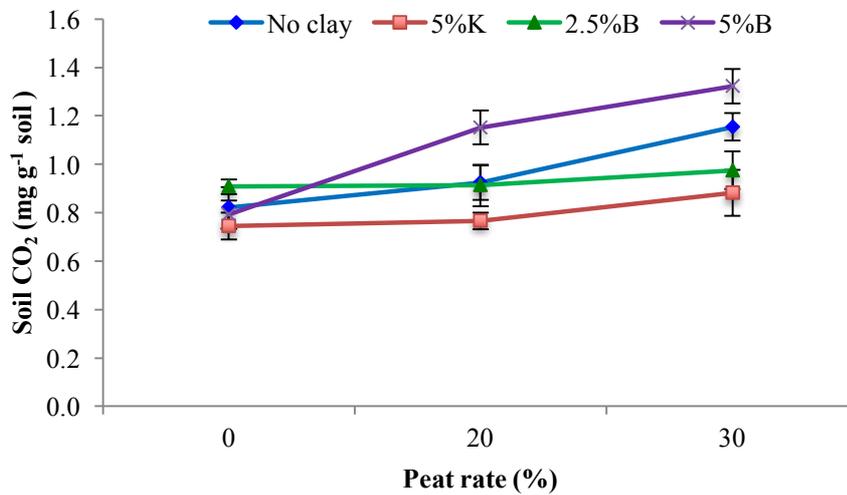


Figure 3-9: Response of soil respiration to peat rate in soils amended with Pt and clay a) 6 weeks and b) 33 weeks after amendments. Error bar = \pm s.e.m.

In clay alone soils, respiration was significantly reduced by 5%K ($p = 0.03$), increased by 2.5%B ($p = 0.02$) while there was a small, non-significant difference at 5%B ($p = 0.74$) compared to the unamended soil. Also, 2.5%B significantly increased soil respiration compared to 5%K and 5%B treatments.

At the 33rd week, the addition of Pt increased respiration in clay and Pt combined treatments compared to clay alone, but the increase was only significant at 30% in 5%K and 2.5%B amended soils and at both Pt rates in 5%B treatments. Comparing the two clays over time, respiration was higher in B amended soil and lower in K amended soil in the presence or absence of Pt (Figure 3-9). The reduced respiration in K amended soil could be associated with low soil pH, which might have hindered the microbial activity. In addition, when combined with Pt, 5%B increased respiration more than 2.5%B at both sampling times, indicating a clay rate effect.

There was a strong and positive correlation ($r = 0.71$; $p < 0.001$) between the soil respiration at 6 and 33 weeks, suggesting that the response of the microbial respiration to the treatments was similar over time.

3.3.1.3 Effects of amendments on SOC

Figure 3-10 shows the effect of amendments on SOC. At 2nd and 33rd weeks after application, all amendments increased SOC except 5%K alone and 2.5%B alone treatments, and the observed results were similar at the two sampling times. The trend also showed that SOC increased as the volume of Pt added increased either when applied alone or with clay, suggesting that increased SOC is possibly a result of the direct increase in soil OM.

Two weeks after application, ANOVA showed that SOC of all treatments was significantly higher than the unamended soil except the 5%K alone and 2.5%B alone treatments. In Pt alone treatments, 30%Pt significantly ($p < 0.001$) increased SOC compared to the 20%Pt treatment, indicating that SOC increased with increasing soil OM. In soils amended with clay alone, only 5%B soil increased SOC possibly as a result of a reduction in microbiological processes compared to the unamended soil. The combined application of clay and OM increased SOC compared to the clay alone in all clay treatments, and the increases were significant ($p < 0.001$) as would be expected.

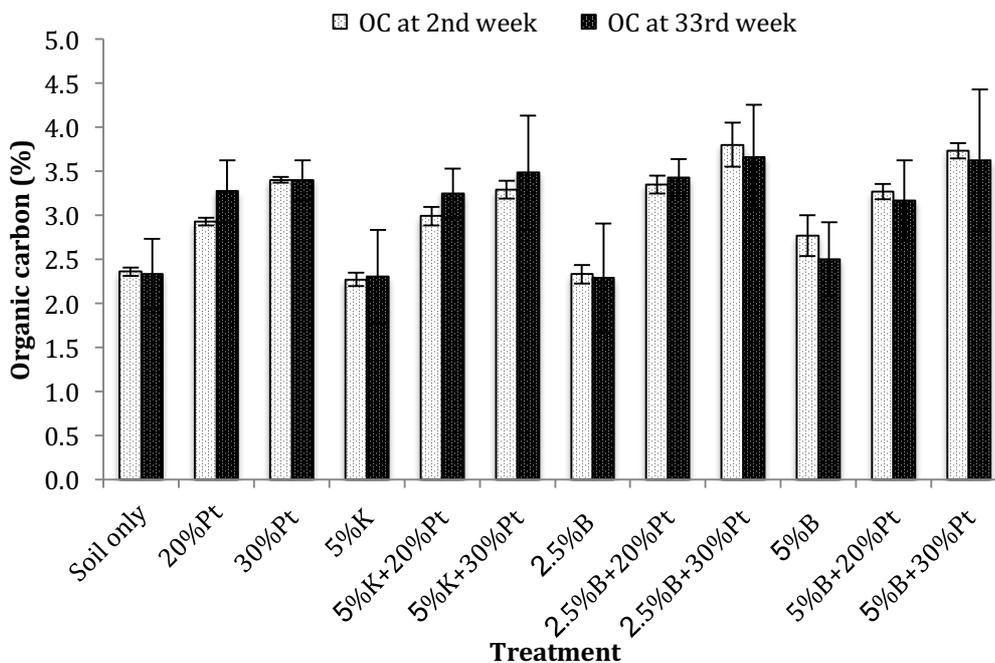


Figure 3-10: Effect of amendments on SOC at 2 weeks (initial) and 33 weeks (final) after application. Error bar = \pm s.e.m.

At 33 weeks after amendment, the observed results were similar to the initial soil samples (a 2nd week after application). Only 5%K alone and 2.5%B alone treatments did not increase SOC compared to the unamended soil (Figure 3-10), but the difference was not significant. In Pt alone treatments, unlike the initial SOC value, the difference between 20 and 30%Pt was not significant, indicating diminishing Pt rate effect over time. In clay alone treatments, only 5%B increased SOC compared to the unamended soil, and the means of 5%K and 2.5%B were not different significantly. The combined application of clay and Pt increased SOC compared to the unamended soil and clay alone, but the differences between 20 and 30%Pt rate were not significant. At both sampling points, combined 2.5%B and Pt had the highest SOC compared to other corresponding combined clay and Pt treatments, possibly owing to the reduced macroporosity (Table 3-5; Figure 3-17), which might have hindered the activity of aerobic microfauna.

One main difference between SOC at the 2nd and 33rd weeks was that there was an increase in all the K amended soils, while the SOC decreased over time in all the B amended soils except in 2.5%B+20%Pt, suggesting higher carbon sequestration in K amended soil than B.

The initial and the final SOC were strongly and positively correlated ($r = 0.89$; $p < 0.001$), and their means were not significantly different ($t_{59} = -0.67$; $p = 0.51$) suggesting that the amount of SOC remains similar over the period of 33 weeks and that SOC is stable over time.

3.3.1.4 Carbon to nitrogen ratio

At 2 weeks after amendment (initial sampling), soil C:N ratio increased in all the treatments compared to the unamended soil. The lowest value was found in soil amended with 5%K and the highest in 5%K+30%Pt treatments. However, only soil amended with Pt with or without clay significantly increased the C:N ratio ($p < 0.01$) compared to the unamended soil, suggesting that Pt is the main factor responsible for the increased C:N. The result also showed that the means of 20% and 30%Pt treatments were not significant in the Pt alone treatments, suggesting that the initial C:N ratio in this experiment is not affected by the Pt rate. Clay alone amendments had no effect on initial soil C:N ratio and the values were similar for all of the clay alone soils (Figure 3-11). The combined application of clay and Pt significantly increased the C:N ratio compared to the unamended soil, and highest values were found in the 5%K and Pt treatments while 5%B+Pt has the lowest at the same Pt application rate, suggesting an increase in C mineralisation for the 5%B+Pt amended soils.

At the 33rd week (final sampling), the effect of the amendments on the C:N ratio was similar to that observed at 2 weeks after amendment (Figure 3-11). All treatments increased C:N ratio compared to the unamended soil, but this was only significant in the presence of Pt. Unlike the initial measurement, however, it was observed that the C:N ratio of 30%Pt was significantly higher than 20%Pt in Pt alone soils, indicating a Pt rate effect over time. Also, while C:N ratio in B alone treatments remained similar over time, there was an increase in the K alone treatment. It is noteworthy here that a reduction in C:N ratio over time was observed only in the unamended soil treatment, suggesting net mineralisation of carbon in the unamended soil and net C immobilisation in amended soils.

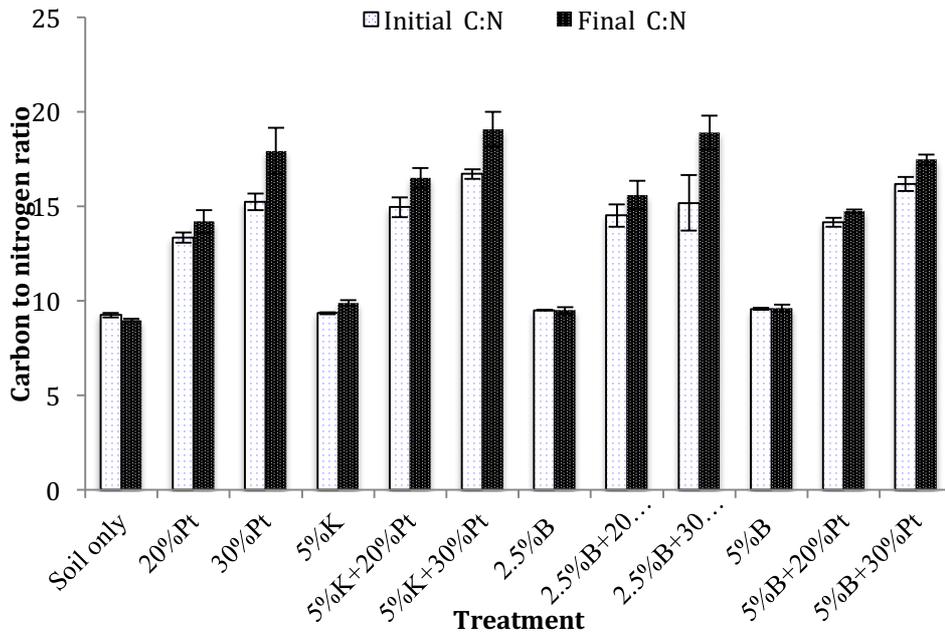


Figure 3-11: Effect of amendments on soil C: N ratio at 2 (initial) and 33 (final) weeks after application. Error bar = \pm s.e.m.

The response of the C:N ratio in different clay types to Pt rate was similar over time (Figure 3-12). At the 2nd week after application, the C:N ratio in the Pt alone at 20% was significantly lower than that of the rest of the treatments at the same application rate, but the C:N ratio at 30% was similar to that of 2.5%B+30%Pt. The combined application of 5% clay and 30%Pt increased the C:N ratio compared to the rest of the treatments, and 5%K had the highest C:N ratio.

Figure 3-12b shows the effect of the combined clay and OM treatments on C:N ratio at 33 weeks after amendment. Pt alone had the lowest C:N ratio when the application rate was ca. 25% (v/v). The C:N ratio of the 5%B soils reduced when compared to the initial values at 2 weeks, and became the lowest when co-applied with 30%Pt. The reduction in C:N ratio of 5%B is possibly associated with increased C mineralisation, as shown by the higher microbial respiration rate in these treatments (Figure 3-8). The result was also similar to what was observed for SOC in 5%B amended soil (Figure 3-10) where SOC decreased over time in all 5%B amended soils, supporting the suggestion of increased C mineralisation as the possible reason for the reduced C:N ratio. The 5%K treatment had the highest C:N ratio at all Pt rates, possibly because of acidic pH in the 5%K amended soil, which resulted in low microbial activity, hence low C mineralisation.

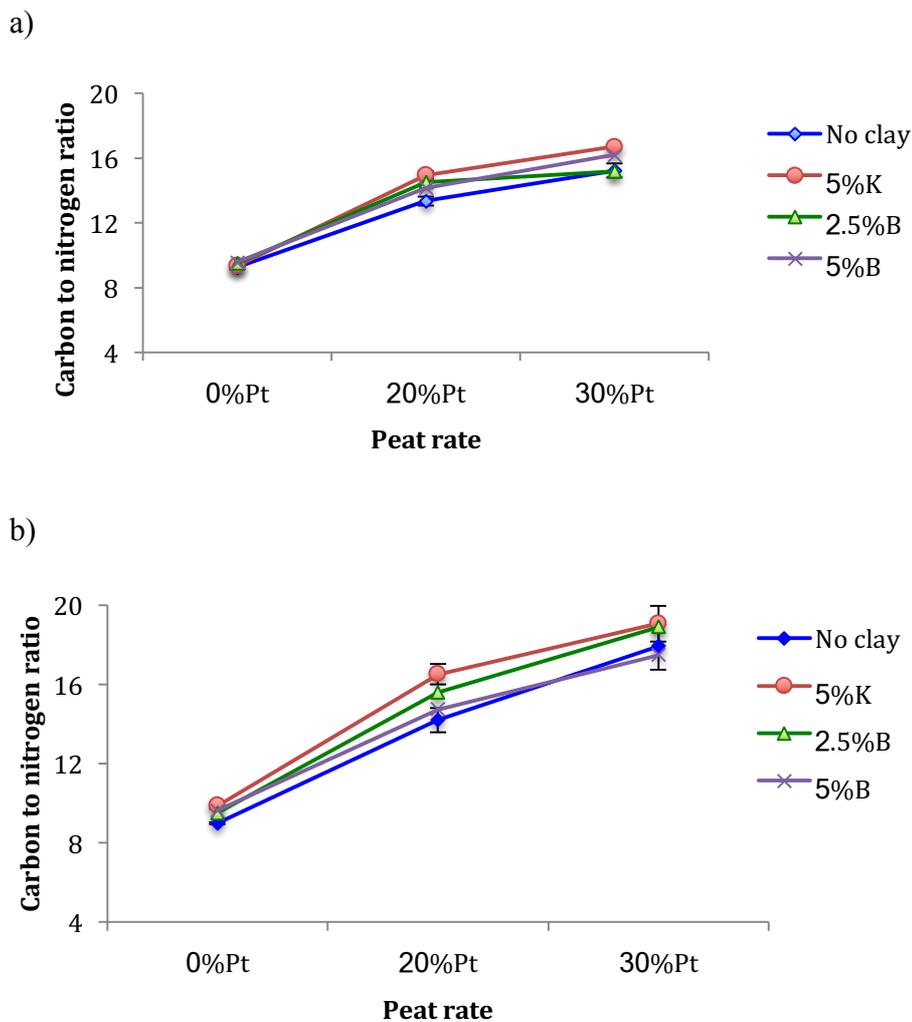


Figure 3-12: Response of soil C:N ratio to Pt rate in soils amended with K and B (a) and (b) 33 weeks after amendments. Error bar = \pm s.e.m.

The initial and final C:N ratio was strongly and positively correlated ($r = 0.96$; $p < 0.001$). Also, the paired t-test showed that there were significant differences between the means of the treatments over time ($t_{59} = -5.23$; $p < 0.001$), suggesting that the C:N ratio of the soils increased over time either as a result of the increase in the soil C or reduction in the soil N.

3.3.2 Effect of amendments on soil chemical properties

The soil chemical properties measured in this project are CEC, electrical conductivity (EC), soil pH, soil OC and total carbon to nitrogen ratio. All measurements were taken at 2 and 33 weeks after amendment.

3.3.2.1 CEC

The effect of clay and OM amendments on the CEC of the sandy soil is shown in Table 3-3. At 2 weeks after application, all amendments significantly increased soil CEC compared to the unamended soil, except for the 20%Pt alone and 5%K+20%Pt.

In soils amended with Pt alone, only 30%Pt significantly increased CEC compared to the unamended soil, and the means of the 20 and 30%Pt were not significant. Also, Pt alone at 30% increased CEC compared to the 5%K while 2.5%B and 5%B increased CEC compared to the both Pt rates. In the clay alone soils, all treatments significantly increased CEC compared to the unamended soil (Table 3-3). The 5%B significantly increased CEC compared to the 2.5%B and 5%K. The order of performances of the clay was 5%B > 2.5%B > 5%K. The higher CEC in B soils than K was not surprising as K naturally has lower CEC than B due to low charge density because of lack of isomorphous substitution reaction in K. All combined clay and Pt treatments increased CEC compared to the unamended soil, and the differences were significant except for 5%K+20%Pt (Table 3-3). At 5% clay rate (for K and B), CEC increased with Pt rate except for 5%K+20%Pt, but at 2.5%B rate, 20%Pt increased CEC compared to the 30%Pt. Furthermore, combined application increased CEC compared to the corresponding clay alone and Pt alone treatments at the same rate, suggesting an improved water and nutrient retention in combined clay and Pt soils owing to the higher CEC.

After 33 weeks, similar to the initial CEC, all the treatments increased CEC compared to the unamended soil except in the 5%K treatment, but the means of unamended soil and 5%K alone were not statistically significant. For Pt alone treatments, only 30%Pt significantly increased CEC over unamended soil, also the differences in the means of 20 and 30%Pt were not significant. For clay alone treatments, only both rates of B significantly increased CEC over unamended soil, and 2.5%B and 5%B increased CEC over 5%K, with the increase for both rates significant. Comparing the two clays, CEC was higher in B than K even at lower B application rate. In combined clay and Pt soils, all treatments significantly increased CEC compared to the unamended soil. CEC decreased as the Pt rate increased between 20 and 30%Pt in 2.5%B and 5%K, but increased with Pt rate in 5%B. Co-application of clay and OM increased CEC compared to the corresponding clay alone and Pt alone, except in 5%K+30%Pt treatment.

Table 3-3: Effect of the treatments on soil CEC at 2nd (initial) and 33rd (final) weeks after amendment

Treatment	Initial CEC			Final CEC		
	Mean (cmol kg ⁻¹)	Mean difference	p value	Mean (cmol kg ⁻¹)	Mean difference	p value
Soil only	20.4	-	-	18.9	-	-
20%Pt	21.8	1.44	0.176	20.6	1.68	0.128
30%Pt	23.0*	2.60	0.017	22.0*	3.04	0.007
5%K	22.5*	2.12	0.049	17.6	-1.28	0.243
5%K+20%Pt	22.0	1.62	0.129	22.3*	3.32	0.004
5%K+30%Pt	24.1*	3.80	0.001	21.8*	2.82	0.012
2.5%B	24.6*	4.22	<0.001	22.1*	3.18	0.005
2.5%B+20%Pt	27.4*	7.06	<0.001	26.9*	7.96	<0.001
2.5%B+30%Pt	26.6*	6.28	<0.001	23.5*	4.56	<0.001
5%B	26.5*	6.16	<0.001	26.1*	7.18	<0.001
5%B+20%Pt	29.0*	8.60	<0.001	27.9*	8.96	<0.001
5%B+30%Pt	31.38	10.90	<0.001	29.5*	10.58	<0.001
LSD	2.11			2.18		
SE	1.05			1.08		

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error of the means

Comparing the CEC of the soils over time, generally, there was a small reduction in all the treatments when the initial values were compared to the final ones, and this might be due to cation mining by crops as the final sampling was done immediately after wheat harvest. Over time, CEC of 5%B, 2.5%B+20%Pt and 5%K+20%Pt remained almost constant, suggesting strong CEC buffering capacity in those treatments. There was a strong and a positive correlation between initial and final CEC ($r = 0.77$; $p < 0.001$), but a paired t-test ($t_{59} = 5.09$; $p < 0.001$) showed that there were significant differences between the two datasets, indicating that the performances of the amendments on CEC changed over time.

3.3.2.2 Soil pH

Table 3-4 shows effects of the amendments on pH of the sandy soil at 2 and 33 weeks after amendment. The addition of Pt and K reduced the soil pH, while B increased it, and the differences were significant at the first sampling. There was a reduction in soil pH in most of the treatments over time, possibly due to ion exchange between the soil and the plant roots or due to the buffering capacity of the soil.

Table 3-4: Effect of amendments on soil pH at 2nd (initial) and 33rd (final) weeks after amendment

Treatment	Initial pH			Final pH		
	Mean	Mean difference	p value	Mean	Mean difference	p value
Soil only	6.36	-	-	6.21	-	-
20%Pt	5.91*	-0.458	<0.001	5.83*	-0.382	<0.001
30%Pt	5.86*	-0.506	<0.001	5.72*	-0.494	<0.001
5%K	6.19*	-0.178	0.002	6.20	-0.006	0.917
5%K+20%Pt	5.75*	-0.612	<0.001	5.68*	-0.528	<0.001
5%K+30%Pt	5.64*	-0.720	<0.001	5.53*	-0.678	<0.001
2.5%B	7.30*	0.940	<0.001	6.97*	0.756	<0.001
2.5%B+20%Pt	6.73*	0.368	<0.001	6.64*	0.426	<0.001
2.5%B+30%Pt	6.48*	0.120	0.033	6.28	0.074	0.202
5%B	7.76*	1.396	<0.001	7.58*	1.370	<0.001
5%B+20%Pt	7.29*	0.924	<0.001	7.12*	0.908	<0.001
5%B+30%Pt	7.00*	0.632	<0.001	6.78*	0.572	<0.001
LSD		0.11			0.11	
SE		0.06			0.06	

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error

At the 2nd week, the pH of Pt alone treatments was similar, indicating that Pt rate has no effect. Addition of Pt reduced soil pH whether applied alone or in combination with clay and was significantly lower than that of clays alone. In clay alone treatments, K had the least pH value, and was significantly lower than 2.5%B and 5%B. The effect of the clays alone on the soil was due to the pH of the clays used (the pH of K was 5.1; B was 9.5). The combined application of B at both rates and Pt increased pH when compared to Pt alone, but all combined clay treatments reduced it when compared to clay alone, suggesting Pt as the main factor responsible for low pH in the clay-Pt system.

At 33 weeks after application, the pH of most treatments reduced compared to the initial sampling; 5%K reduced to about the same value as unamended soil, and was not significantly different, unlike the initial field condition. The effect of the amendments on soil pH was similar over time (Table 3-4).

The pH of the Pt alone treatment was acidic and was significantly lower than for that of unamended soil, however, the Pt rate effect was not significant. In clay alone

treatments, 5%K remained the lowest and most acidic, 2.5%B almost neutral, while 5%B soil was alkaline. The combined application of clay and Pt reduced the pH of all the soils to acidic except 5%B+20%Pt.

There was a very strong and significant positive correlation between the initial and the final soil pH values ($r = 0.97$; $p < 0.001$). The mean pH of the soils significantly varies from initial to final readings ($t_{59} = 7.14$, $p < 0.001$)

3.3.2.3 Soil electrical conductivity (EC)

Figure 3-13 shows the effect of the amendments on EC at 2 and 33 weeks after application. At the 2nd week, B and B+Pt amendments increased the soil EC while Pt, K and combined K and Pt (except 5%K+20%Pt) amendments reduced it compared to the unamended soil. For soil amended with Pt alone, the addition of Pt significantly reduced EC compared to the unamended soil, and the means of the 20 and 30%Pt rate were not significantly different. Among the clay alone treatments, 5%K reduced EC compared to the unamended soil but this was not significant, while 2.5% and 5%B significantly increased EC (Figure 3-13a). When combined with Pt, EC was higher at 20%Pt than at 30%Pt rates, suggesting that leaching of nutrients might be higher as the amount of Pt added to the soil increases.

Comparing figures 3-13 a and b, at 33 weeks after amendment, there was a decrease in soil EC in all the treatments, and this is attributed to nutrient uptake by the crop. The result further showed that all amendments increased the EC compared to the unamended soil, and the increases were significant except in 30%Pt treatment (Figure 3-13b), suggesting that amendments can increase the nutrient retention of sandy soils. In soil amended with Pt alone, only 20%Pt increased EC over unamended soil, and the means of 20%Pt and 30%Pt were significantly different, suggesting that nutrient losses could be higher in soil amended with up to 30% OM compared to a lower OM rate.

Addition of clay increased EC compared to the unamended soil, suggesting improved nutrient retention in clay-amended soil over time compared to the initial soil condition at 2 weeks. Among the clay, only treatments, 2.5%B has the lowest EC, but this was not significantly different from 5%K, while 5%B significantly increased EC over the rest of the clay treatments.

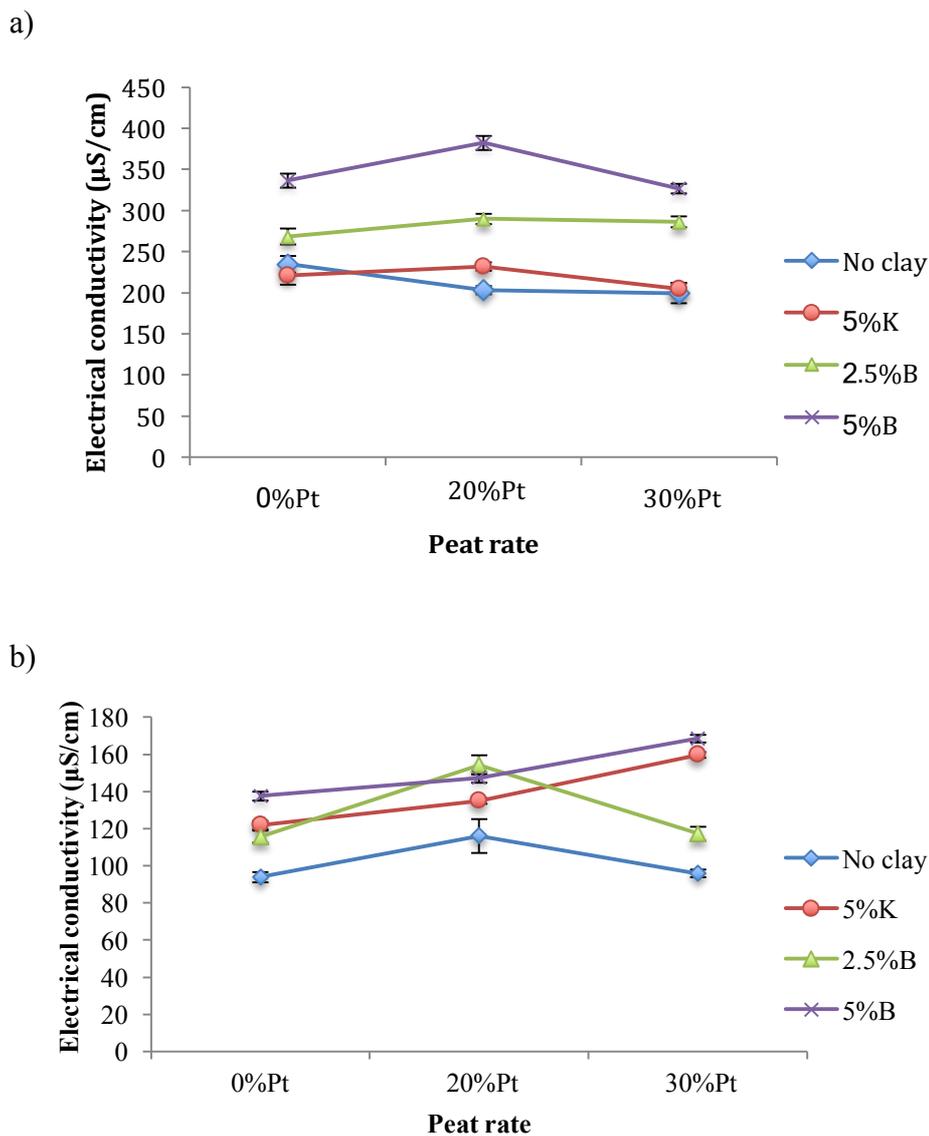


Figure 3-13: Effect of clay (type and application rate) and peat rate on soil electrical conductivity at a) 2 and b) 33 weeks after amendment. Error bar = \pm s.e.m.

Co-application of clay and Pt increased EC significantly compared to the unamended soil. In the 2.5%B treatment, the highest EC was recorded when combined with 20%Pt but decreased significantly as the Pt rate increased to 30%, possibly due to increased permeability as the Pt rate increases, hence higher leaching of the soil solution. However, at 5% clay rate, EC increased with Pt rate, and the values were higher for 5%B than 5%K. The differences in clay response in 5%K and 5%B treatments are possibly due to higher clay in the soil, which enables it to mask the effect of the Pt at 30%.

The observed differences in EC at 2 and 33 weeks after application (Figure 3-13) are likely associated with time effect, which allows interaction between the soil physical,

chemical and biological properties. This inference was supported by the paired t-test, which showed that the initial and final EC were significantly different ($t_{59} = 14.50$; $p < 0.001$). There was a weak, positive correlation between initial and final EC values ($r = 0.46$; $p < 0.001$).

3.3.3 Effect of amendments on soil physical properties

3.3.3.1 Soil pore characteristics

CT scanning was used to measure the effect of amendments on soil pore characteristics, 45 weeks after amendment. Mean data from 3 replicates each consisting of 700 image slides (giving a total of 2,100 image slides per treatment) were analysed. The results below show effects of the amendments on soil pore size distribution, total pore count, amount of large macropores $>1\text{mm}$, minimum pore diameter, and porosity.

Soil pore distribution

The observed air-filled pore area ranged from <0.0032 to 100.00 mm^2 (total selected area $150 \times 150 \text{ mm}$). As shown in Figure 3-14, the addition of Pt greatly increased pores with size ranges ca. 0.1 to 10mm^2 compared to the unamended soil, suggesting that OM amendments will increase macropores and porosity of sandy soils.

All clay amendments reduced the abundance of all pore sizes compared to the unamended soil, except for a few pores that were larger than 36 mm^2 in the 5%K and 2.5%B+30%Pt treatments (Figure 3-14). The abundance of each pore size was smallest in soil amended with 2.5%B and this was surprising, as it was expected that a greater reduction in mean pore size would occur in soil amended with higher application rates of the same clay (5%B). This apparent anomaly is possibly associated with the filling of soil pores by the clay B at the lower rate. When combined with Pt, however, the abundance of each pore size in 2.5%B amended soil increased with Pt rate, suggesting a dilution effect by the Pt or the effect of particle size of the Pt on overall pore size. The abundance of each pore size in the 5%K alone treatment was higher than that of 5%B. The effectiveness of the clay amendments alone on the reduction of abundance in each pore size was $2.5\%B > 5\%B > 5\%K$.

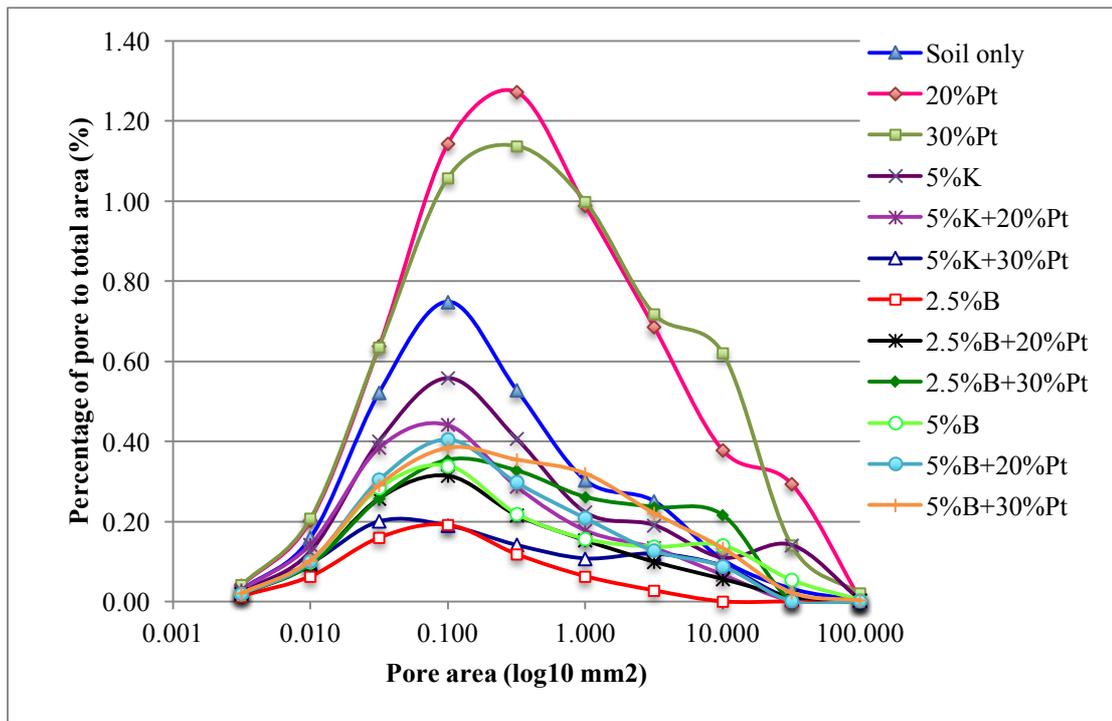


Figure 3-14: Pore size distribution of soil amended with clay and OM

When combined with Pt, the two clays responded differently. For K, the addition of Pt reduced the abundance of each pore size, while they were increased in clay B regardless of the application rate. These observations are largely associated with the pore sizes of the soils amended with clays alone versus the particle size of the OM used. Where soil pore size is predominantly larger than OM particle sizes, there will be a reduction effect and vice versa when soil pore size is smaller than OM particle size when combined. Thus, it could be inferred that soil pore sizes in K soils are mainly larger than Pt particle size while B was smaller, resulting in the observed results.

Total pore count

As shown in Table 3-5, total pore count was increased in the Pt amended soil, but reduced in the clay treatments compared to the unamended soil. The lowest count was found in 2.5%B, while 20%Pt had the highest. Binary images showing pore abundance and sizes (the smallest detectable pores) in each amended treatment are shown in Figure 3-15.

The Pt amendments significantly increased the number of pores compared to the unamended soil, but there was no significant difference between Pt rate at 20 and 30%. All clay alone treatments significantly reduced the number of air-filled pores compared

to the unamended soil. The mean of the 5%K treated soil was significantly higher than that of 2.5%B, but not that of 5%B. Also, the mean of 2.5%B was significantly higher than that of 5%B, showing that a low rate of B is more effective at reducing pore numbers in sandy soils. The reduction in the number of air-filled pores due to the effect of the clays was in the order of 2.5%B > 5%B > 5%K.

In combined clay and Pt treatments, the addition of Pt increased the number of pores compared to the clay alone except in 5% clay + 30%Pt treatments, but reduced pore numbers compared to the Pt alone. In 2.5%B + Pt treatments, there was a non-significant increase in pore number as Pt rate became higher. However, in 5% clay + Pt treatments, pore count was higher in 20%Pt than 30%Pt treatments, but the difference was only significant in 5%K. The observed results showed that Pt generally increased the number of air-filled soil pores, possibly because of its large particle sizes, which can increase the size of the pores.

Minimum pore diameter

High water and nutrient loss in sandy soils are due to a preponderance of macropores compared to fine soils, so amendments that can reduce pore size is expected to have a positive effect on water and nutrient retention.

Data showing the effect of the amendments on minimum pores sizes in each treatment is shown in Table 3-5. Minimum pore size is used as an indicator of the effect of the amendments on the pore size of the test soil. All amendments reduced minimum pore diameter compared to the unamended soil, except soil amended with Pt only, thereby demonstrating the ability of the amendments to reduce pore sizes of sandy soils. Among the treatments, only 5%K+30%Pt, 2.5%B with or without Pt, 5%B and 5%B+30Pt significantly reduced pore sizes compared to the unamended soil and the smallest diameter was found in soil amended with 2.5%B.

Table 3-5: Total number of pores and minimum pore diameter in soil amended with clay and OM

Treatment	Total pore count			Pore diameter (mm)		
	Mean	Mean difference	p value	Mean	Mean difference	p value
Soil only	339,472	-	-	0.104	-	-
20%Pt	462,026*	122554	<0.001	0.109	0.0050	0.402
30%Pt	455,444*	115972	<0.001	0.104	0.0003	0.955
5%K	263,041*	-76431	0.002	0.094	-0.0100	0.101
5%K+20%Pt	274,311*	-65161	0.008	0.093	-0.0117	0.058
5%K+30%Pt	169,945*	-169527	<0.001	0.076*	-0.0283	<0.001
2.5%B	132,844*	-206628	<0.001	0.074*	-0.0303	<0.001
2.5%B+20%Pt	156,495*	-182977	<0.001	0.086*	-0.0187	0.004
2.5%B+30%Pt	186,821*	-152651	<0.001	0.087*	-0.0170	0.008
5%B	226,798*	-112674	<0.001	0.077*	-0.0273	<0.001
5%B+20%Pt	243,163*	-96309	<0.001	0.095	-0.0093	0.125
5%B+30%Pt	224,814*	-114658	<0.001	0.090*	-0.0147	0.020
LSD		46330.50			0.0122	
SE		22491			0.006	

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error

In Pt alone treatments, the effect of the two Pt rates on minimum pore diameter was similar and they were not significantly different from the unamended soil. Among clay alone treatments, the lowest diameter was found in 2.5%B amended soil but was not different from that of 5%B while 5%K had the highest pore diameter and was significantly higher than that of 2.5%B and 5%B, suggesting that the ability of K to modify pore sizes of sandy soil is less than that of B.

The combined application of clay and Pt significantly reduced the soil pore diameter compared to the unamended soil except for the 5%K+20%Pt and 5%B+20%Pt. It is noteworthy that these two treatments (5%K+20%Pt and 5%B+20%Pt) had the higher total larger macropore count (Figure 3-15) among 5% clay + Pt treatments, suggesting that the ability of Pt to increase pore size when co-applied with 5% clay was at its maximum at the 20% application rate. In combined 5%K and Pt treatments, minimum pore diameter was significantly lower only at the 30%Pt rate compared to the 5%K alone. In 2.5%B treatments, 30%Pt significantly increased pore diameter compared to the 2.5%B alone, while in 5%B treatment, both Pt rates significantly increased pore diameter compared to the 5%B alone.

Large macropores

Means of air-filled pores greater than 1mm in each treatment were compared. Due to the high variability among the means of the samples, sample variance was not homogenous, so a Welch F test was used. Comparison of treatment means showed strong significant differences ($p < 0.001$) and data was separated using Dunnett T3. This analysis is considered suitable when a data set does not obey the rule of homogeneity of variance⁸ (Shingala and Rajyaguru, 2015).

Figure 3-15 shows the effect of the amendments on the number of large macropores (>1mm). All clay treatments decreased the number of large macropores while Pt alone increased it compared to the unamended soil. The differences in the number of large macropores in soil amended with Pt only were significantly higher ($p = 0.02$) compared to the unamended soil, and the mean value increased as more Pt was added, but the difference between 20% and 30% Pt was not significant ($p = 0.857$). The results suggest that OM can increase macropores when added to sandy soils, and the outcome might be similar, even when different amounts of OM are added.

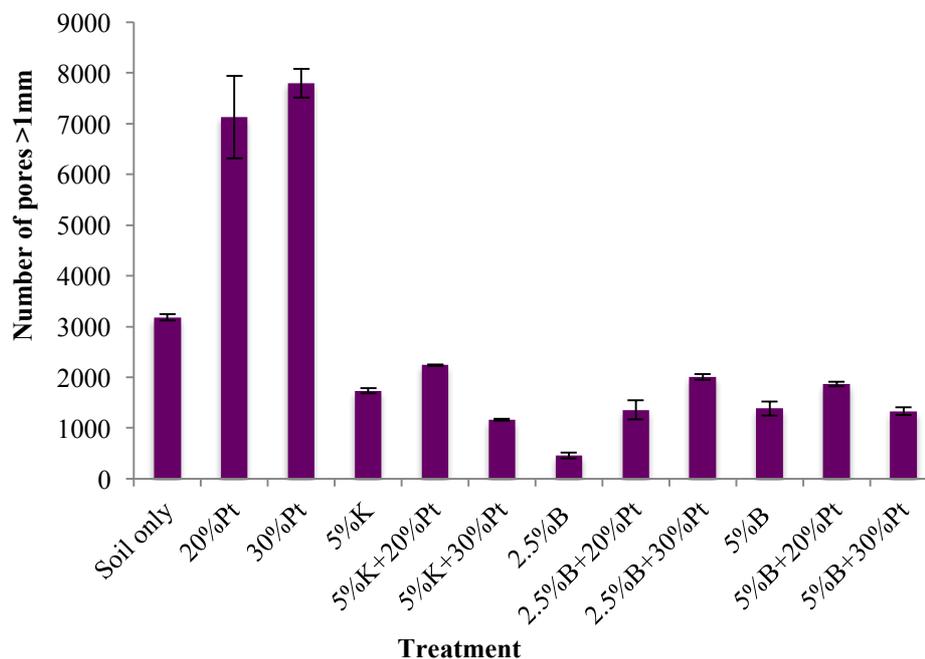


Figure 3-15: Effect of clay and OM amendments on macropores (>1mm). Error bar = \pm s.e.m.

⁸ www.ibm.com/support/knowledgecenter (accessed 01/08/2017)

All clay treatments, whether applied alone or in combination with Pt, significantly reduced the number of large macropores compared to the unamended soil. Among the clay treatments, the number of large macropores in soil amended with 5%K was significantly higher than 2.5%B ($p = 0.001$), but not 5%B ($p = 0.679$). For both B rates, there was no significant difference in the number of large macropores in soil amended with 2.5% and 5%B ($p = 0.11$). Comparing the clay alone treatments, 5%K had the highest number of large macropores, followed, by 5%B while 2.5%B has the least.

In clay and Pt combined treatments, the number of large macropores in 2.5%B treatments increased with Pt rate, possibly as a result of the larger particle size of Pt, but the difference was not significant. However, in 5% clay (both K and B) treatments, a higher total number of pores was recorded for the 20% than 30%Pt rate (Table 3-5; Figure 3-16), and the difference was significant in 5%K ($p < 0.001$), but not in 5%B treatments ($p = 0.064$).

Soil total porosity

Soil porosity was calculated as the ratio of the air-filled soil pore area to the soil solid area and presented as a percentage. The effect of the amendments on soil total porosity is shown in Figure 3-17. Addition of Pt increased soil total porosity compared to the unamended soil but it was reduced in all of the clay treatments. The means of all the treatments are significantly different from those of the unamended soil except 5%K alone and 5%B+30%Pt.

In Pt alone treatments, amending with Pt significantly increased soil porosity, but there were no significant differences between the 20 and 30%Pt rate, suggesting that their effect on soil porosity was similar. Among clay alone treatments, the effect of 5%K was not significantly different from the unamended soil, indicating that K alone had little or no effect on soil properties that influence soil porosity, such as total pore count (Table 3-5). Addition of B significantly reduced soil porosity compared to the unamended soil, and 2.5%B significantly reduced total porosity compared to 5%K and 5%B, possibly due to the reduced pore count and sizes (Table 3-5; Figure 3-16).

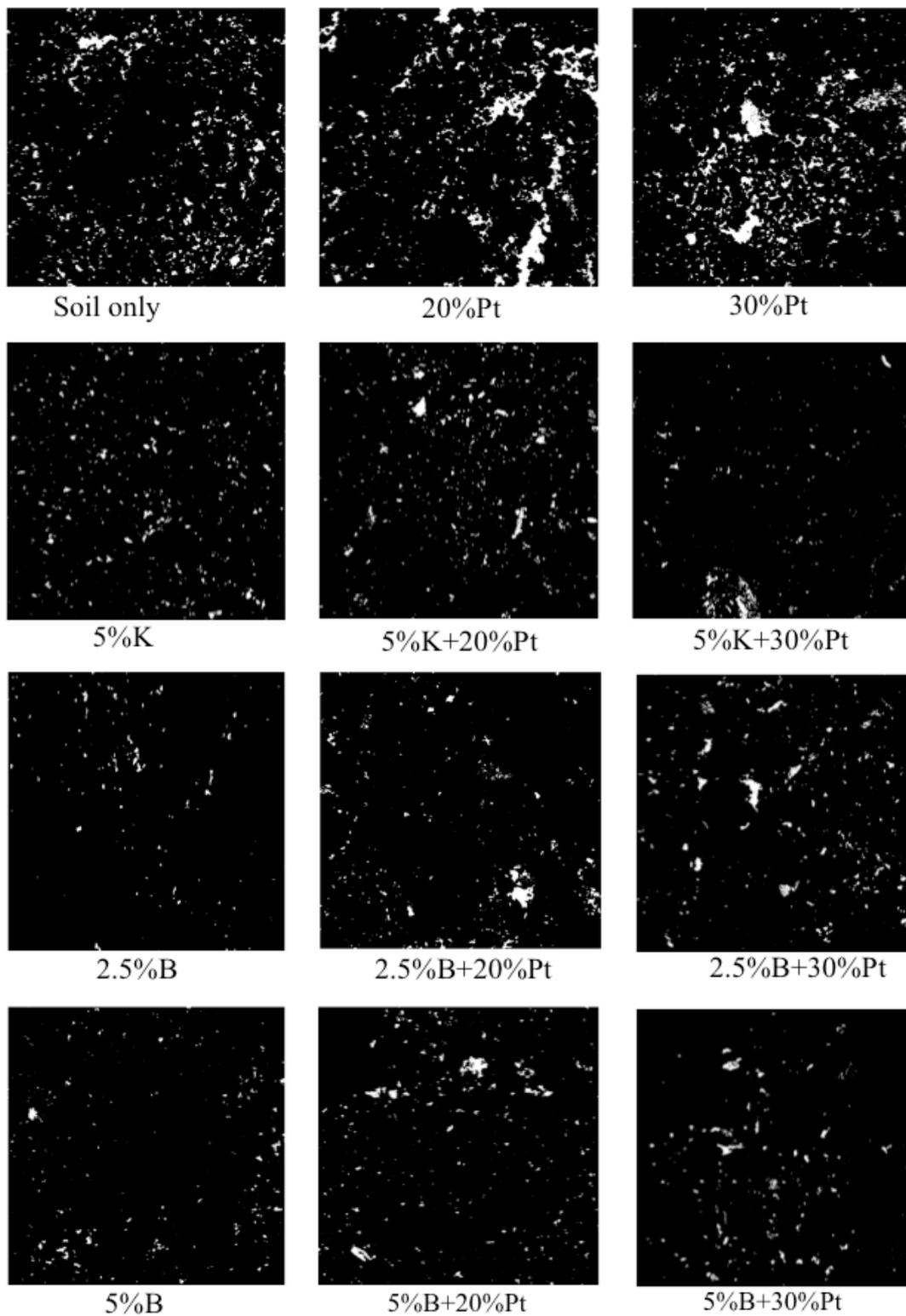


Figure 3-16: Binary images of soil samples showing pore areas (Black = soil matrix and water-filled pores; White = air-filled pores).

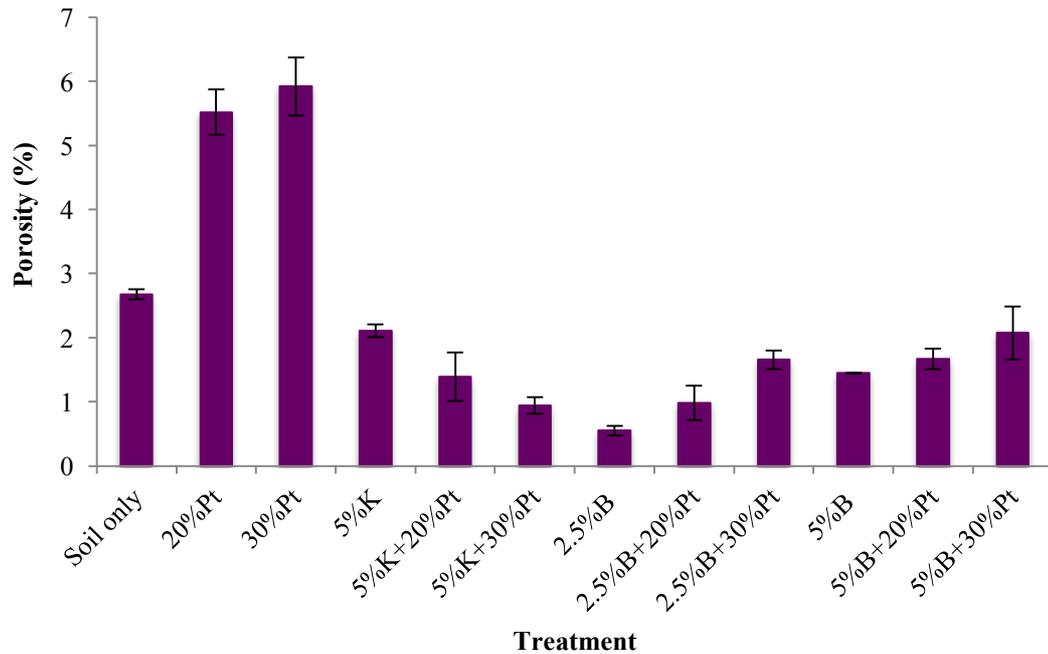


Figure 3-17: Effect of the amendments on soil porosity. Error bar = \pm s.e.m.

All combined clay and Pt treatments significantly reduced soil total porosity except 5%B+30%Pt, possibly due to their ability to reduce total pore count and sizes (Table 3-5). In K amended soil, the difference between 20 and 30%Pt rate was significant, but not in B treatments.

3.3.3.2 Soil bulk density (BD)

The effect of the amendments on soil BD over time is shown in Table 3-6. The initial field condition (6 weeks after application) showed that Pt and K amendment reduced soil BD while B increased it, and the differences were significant in Pt alone, 5%K+Pt, 2.5%B+20%Pt and 5%B treatments.

In Pt alone treatments, there was a significant reduction in BD compared to the unamended soil, and the means of 20 and 30%Pt were not significantly different, suggesting that effect of 20 and 30% Pt is similar on BD. In clay alone treatments, both B rates increased BD while K reduced it compared to the unamended soil. The observed difference between B and K on soil BD is possibly associated with clay particle size and particle density, which are smaller and denser respectively in B than K. There was a small non-significant increase in BD for 2.5%B and a significant increase in BD for 5%B, compared to the 5%K treatment.

Table 3-6: Effect of amendments on soil BD, FC and PWP at 6th (initial) and 45th (final) weeks after application

Treatment	<u>Mean BD (g cm⁻³)</u>		<u>Mean FC (% MC)</u>		<u>Mean PWP (% MC)</u>	
	Initial	Final	Initial	Final	Initial	Final
Soil only	1.45	1.53	20.29	22.78	14.38	15.88
20%Pt	1.25*	1.32*	21.94	23.43	15.75*	14.81
30%Pt	1.29*	1.30*	25.06*	24.84	16.78*	14.90
5%K	1.42	1.53	21.35	25.64	15.03	17.25
5%K+20%Pt	1.25*	1.52	24.72	30.59*	15.94*	19.48*
5%K+30%Pt	1.21*	1.39*	25.47*	27.42*	16.92*	21.71*
2.5%B	1.46	1.61	21.74	24.32	15.65*	16.53
2.5%B+20%Pt	1.54*	1.50	29.89*	29.02*	21.52*	18.38*
2.5%B+30%Pt	1.48	1.52	31.33*	28.53*	24.60*	21.97*
5%B	1.55*	1.52	26.70*	25.80	21.09*	20.92*
5%B+20%Pt	1.46	1.41	26.24*	28.94*	21.94*	20.83*
5%B+30%Pt	1.40	1.36*	33.92*	32.80*	23.41*	25.74*
LSD	0.09	0.12	4.53	3.71	1.19	2.58
SE	0.04	0.06	2.20	1.80	0.58	1.56

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error of the means.

The combined application of clay and Pt reduced BD in 5%K+20%Pt, 5%K+30%Pt and 5%B+30%Pt, but increased it in other combined clay and Pt treatments compared to the unamended soil. In 5%K and 5%B soils, the combined application of clay and Pt significantly reduced BD compared to the clay alone, while in 2.5%B there was a non-significant increase.

At 45 weeks after amendment, BD increased in all treatments compared to the initial field condition, possibly due to dry soil conditions at the point of sampling. All amendments except 2.5%B and 5%K reduced the soil BD compared to the unamended soil, and the reduction was significant in Pt alone, 5%K+30%Pt and 5%B+30%Pt. There was a small non-significant increase in 2.5%B alone treatment.

Similar to the initial conditions, Pt rate where applied alone was not significant. In clay only treatments, there was no significant difference between B amended soils, compared to K. When combined with clay, 5%K+30%Pt and 5%B+30%Pt significantly reduced BD compared to 5%K and 5%B alone, respectively. There was

a small non-significant reduction in 2.5%B+Pt treatments compared to 2.5%B alone. In general, Pt amendment reduced BD in the absence or presence of added clay (Table 3-6), possibly due to the dilution effect of Pt on soil weight or owing to the increased pore number and increased porosity (Table 3-5; Figure 3-17).

The initial and final BD was significant correlated ($r = 0.53$; $p = 0.001$). Also, the paired t-test was significant ($t_{35} = -3.38$; $p = 0.002$), suggesting that the BD changed over time.

3.3.3.3 Soil moisture content at field capacity (FC)

Volumetric soil moisture content at 0.05 bar water tension was measured as a proxy of FC. All the amendments increased soil water at FC compared to the unamended soil at 6 weeks after application, and the increase was significant in 30%Pt, 5%K+30%Pt and in all B amended treatments except 2.5%B alone (Table 3-6).

The effect of Pt rate on water content at FC was not significant when compared with the means of Pt at 20 and 30%. All clay alone treatments increased water content at FC except 5%K and 2.5%B alone compared to the unamended soil, and within the clay alone treatments, 5%B was significantly higher than the rest. The combined application of clay and Pt increased water content at FC compared to their corresponding clay and Pt treatment except for 5%B+20%Pt. The non-significant effect in the 5%B+20%Pt treatment is possibly due to the high variability within the treatment's replicates.

Table 3-6 showed the effect of the amendments on soil water content at FC, 45 weeks after application. The result was similar to initial FC values; all treatments increased moisture content at FC compared to the unamended soil, but this was significant only in combined clay and Pt treatments, suggesting that only combined clay and OM have long-term effects on increasing soil water content of sandy soil at FC. In clay alone treatments, there was no significant difference either within or between clay rate and type.

In 5%K, the combined application with Pt increased FC but this was only significant at 20%Pt rate. In B treatments, combined application with Pt increased moisture content at FC and the increase was significant at both Pt rates in 2.5%B soils, but only at 30%

in 5%B compared to the corresponding clay alone treatments. In 2.5%B and 5%K treatments, highest water content at FC was observed when combined with 20%Pt, but the value reduced as Pt rate increased to 30%, suggesting that more water is retained against gravitational pull at 20%Pt compared to 30% when combined at these clay rates.

There was a significant correlation between initial and final water content at FC ($r = 0.63$; $p < 0.001$). Also, the paired t-test was significant ($t_{35} = -2.12$; $p = 0.041$), suggesting that the water content at FC changed over time owing to the development of soil structure, and formation of humic substances as the added Pt mineralised.

3.3.3.4 Soil moisture content at Permanent Wilting Point (PWP)

Soil moisture content at PWP was recorded as the soil water released at water tension of 15 bars. Effects of the amendments on soil water content at PWP over time are shown in Table3-6. The initial PWP after 6 weeks showed an increase in soil water content in all the amended soils compared to the unamended soil, and the increase was significant except in 5%K only. The difference between 20 and 30%Pt rate was not significant, suggesting that they have a similar effect on water content at PWP. In clay alone treatments, 5%K had the least moisture content at PWP, but this was not significantly lower than 2.5%B but was when compared to 5%B. Also, the mean of 2.5%B was significantly lower than 5%B, thus showing that among the clay alone treatments, 5%B has the highest capability to increase soil moisture content of sandy soil at PWP.

All combined clay and Pt treatments increased water content at PWP significantly compared to the unamended soil. In 5%K, 2.5%B and 5%B soils, the addition of Pt increased water content at PWP but the water content was significantly greater only when clay was combined with 30%Pt.

At the final field condition, water content at PWP after 45 weeks shows a similar trend compared to the initial field condition, but there were variations. Soil moisture content at PWP increased over time in all K amended soil while there were decreases in all Pt and B amended soils, except 5%B+30%Pt compared to the initial field values in the corresponding treatments. The Pt alone reduced PWP while all clay amendments increased it, suggesting that Pt might reduce the amount of water available in sandy

soil under dry condition. All clay alone treatments increased moisture content at PWP, but only 5%B was significant compared to the unamended soil. Also, 5%B increased significantly PWP compared to 2.5%B and 5%K, while the means of 2.5%B and 5%K were not different significantly.

The combined application of clay and Pt significantly increased soil moisture content compared to the unamended soil. In 5%K treatments, combined application with 30% Pt had a significant increase compared to 5%K alone. In B treatments, the combined application also increased soil water at PWP and the increase was only significant at 30% Pt rates in 2.5%B and at 30%Pt in 5%B compared to clay alone. Comparing the two clays, their effect on water content at PWP was similar.

There was a significant correlation between initial and final water content at PWP ($r = 0.66$; $p < 0.001$). However, the paired t-test was not significant ($t_{35} = -0.47$; $p = 0.64$), suggesting that the water content at PWP was similar over time.

3.3.3.5 Plant available water (PAW)

PAW was determined as the difference between soil water content at FC and at PWP, and the observed result over time was shown in Figure 3-18. At 6 weeks after application, the amendments increased PAW compared to the unamended soil, but the increase was only significant in 5%K+20%Pt ($p = 0.041$), 2.5%B+20%Pt ($p = 0.047$) and 5%B+30%Pt ($p = 0.002$). The effects of Pt alone and clay alone on PAW were not significant.

The Pt alone resulted in a non-significant increase in the PAW compared to the unamended soil; also, the means of 20 and 30%Pt were not different significantly ($p = 0.0132$). In clay alone treatments, there was a non-significant increase in PAW in 5%K compared to 2.5 and 5%B. The combined application of clay and Pt increased PAW and was significant at 20% in 5%K and 2.5%B, but at 30% in 5%B soils.

At the 45th week after amendment, PAW responses in different amendments were similar to the initial field condition. Generally, PAW increased in all treatments over time except in 5%B+30%Pt soil. All amendments increased PAW compared to the unamended soil except 5%B, but were only significant in 30%Pt ($p = 0.01$), 5%K+20%Pt ($p = 0.001$) and 2.5%B+20%Pt ($p = 0.013$).

Soil amended with 5%K+20%Pt has the highest PAW, and the increase was significant compared to all other treatments except for 30%Pt and 2.5%B+20%Pt. Application of clay alone had no significant effect on PAW compared to the unamended soil. Also, the effect of 5%K was similar when compared to 2.5%, however, 2.5%B significantly increased PAW compared to 5%B ($p = 0.015$), suggesting less PAW as soil clay content increases. The performance of the clay on PAW is 2.5%B > 5%K > 5%B.

The combined application of clay and Pt increased PAW but only significantly in 5%K+20%Pt and 2.5%B+20%Pt treatments. Also, the effect of the clay and Pt on PAW was significantly higher compared to clay only in clay + 20%Pt for both clay K and B, suggesting that the 20% OM rate might be adequate when combined with clay for optimum water availability to the crop.

There was a weak non-significant correlation between initial and final PAW ($r = 0.24$; $p = 0.16$). The paired t-test showed that the initial and final PAW were significantly different ($t_{35} = -2.58$; $p = 0.02$).

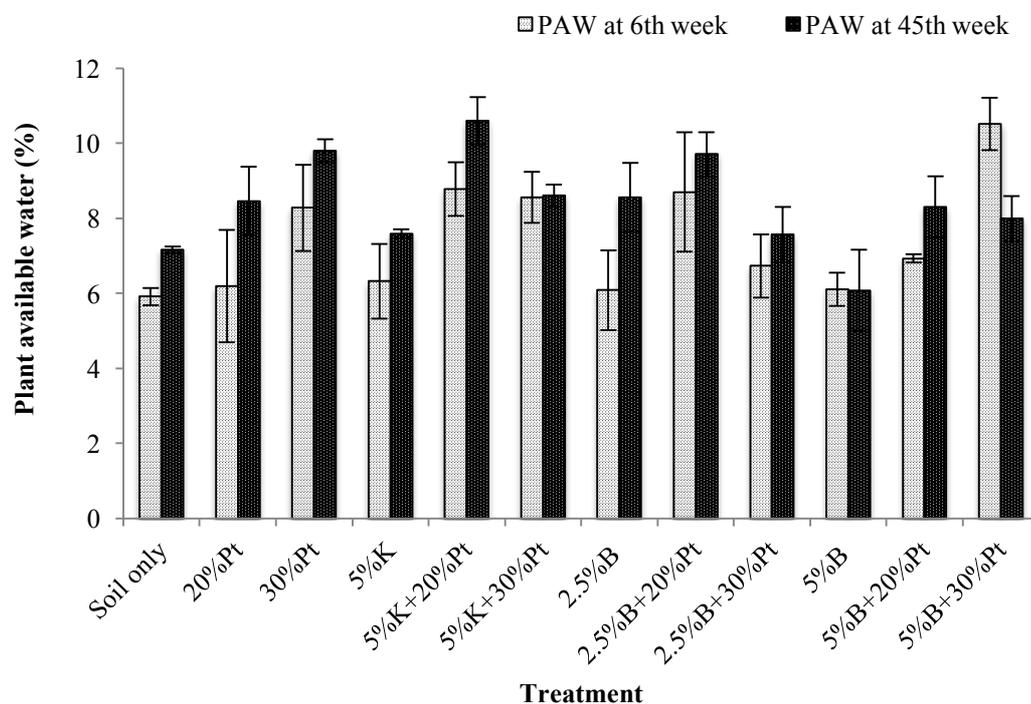


Figure 3-18: Effect of clay and OM amendments on PAW at 6th (initial) and 45th (final) weeks after application. Error bar = \pm s.e.m.

3.3.3.6 Soil moisture retention characteristics

The effects of the amendments on soil moisture retention characteristics over time are presented in Figure 3-19. The curve is drawn based on moisture retention of different treatments at four tensions or suctions (0.001, 0.05, 2 and 15 bars). The soil texture at lower tensions and more by soil structure at higher tensions influence soil moisture retention. So, soil(s) with a preponderance of macropores will drain sharply while a gradual decrease will be displayed by soil with more micropores. Generally, soil moisture retention decreased from the left to right side of the curves in each graph, and the final moisture retention at higher tensions increased compared to the initial values.

At 6 weeks after amendment, the moisture retention of Pt alone treatments was similar to those of the unamended soil at saturation but became higher as tension increased, especially at 0.05 bar. Soil amended with 30%Pt retained more moisture than 20%Pt and unamended soil. Over time, however (45th week), final water retention of the unamended soil at saturation reduced compared to Pt amended soils but no difference was observed as tension increased (Figure 3-19a).

In 5%K soils, the initial soil moisture retained at each tension level by the unamended soil and 5%K alone were similar, while that of 5%K+20%Pt and 5%K+30%Pt were also similar, but higher than 5%K alone. In all 5%K treatments, the response showed an initial sharp decrease at low tension followed by a small gradual decrease which suggests the presence of a high number of macropores, which are known to drain quickly, even at low pressures.

At 45 weeks after amendment, differences in moisture retention were observed in 5%K soils. Moisture retention of the unamended and 5%K soils were similar at saturation, but moisture retention of 5%K was greater as the tension increased, suggesting that more water would be retained in comparison to the unamended soil as the soil becomes drier. Similarly, the combined application of 5%K and Pt increased moisture retention compared to the unamended soil and 5%K alone at the same water tensions (Figure 3-19b).

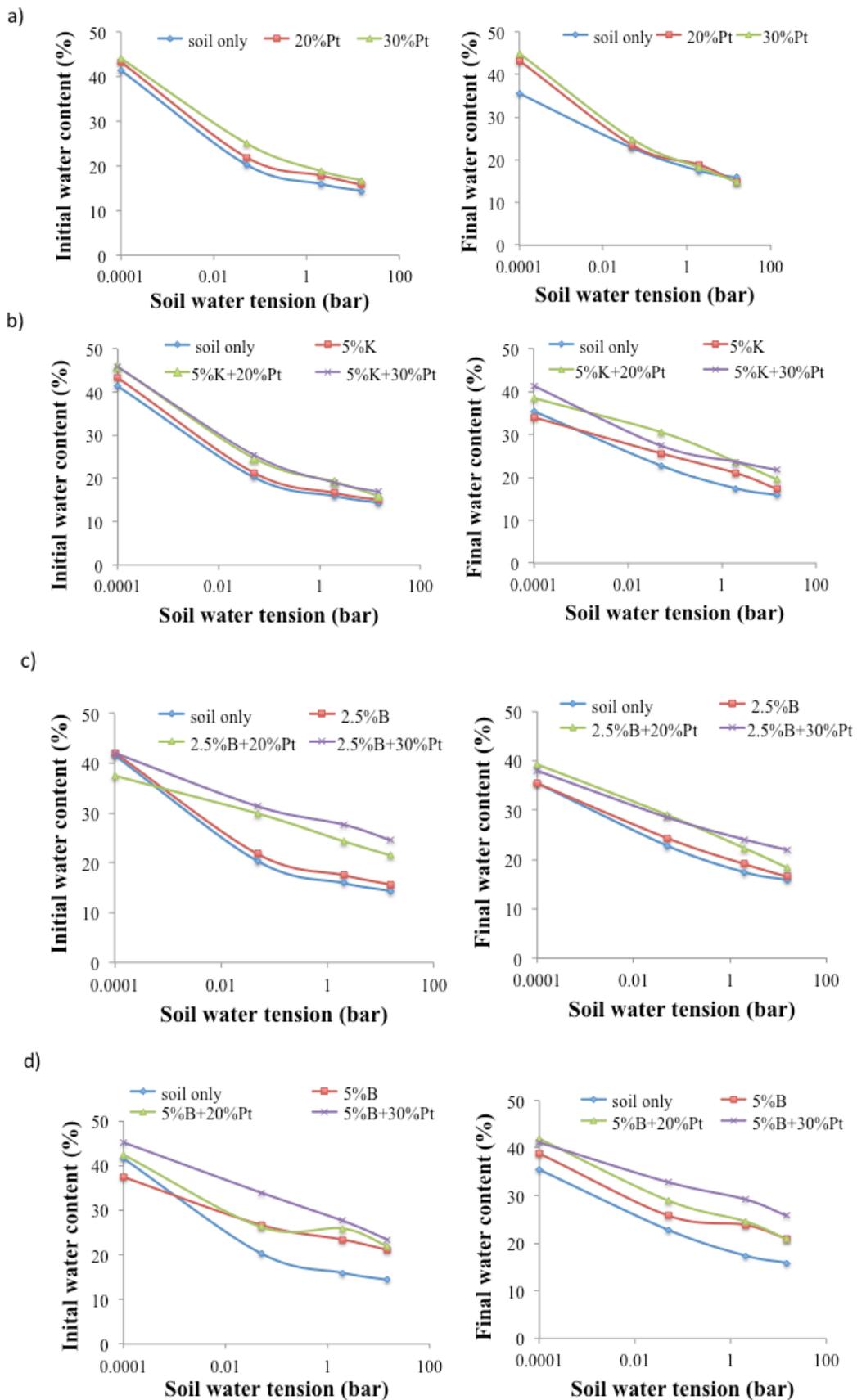


Figure 3-19: Effect of amendments on volumetric soil moisture retention characteristics over time in soil amended with a) Pt alone; b) 5%K; c) 2.5%B; and d) 5%B at 6th (initial) and 45th (final) weeks after application.

Figure 3-19c shows moisture retention curves of 2.5%B amended soils, and the curves indicated faster water release rates in the unamended soil and 2.5%B soils, while the release was gradual in the 2.5%B+Pt amended soils, suggesting higher water retention in the latter than former treatments. At the 45th week after amendments, the observation was similar, but the curvature of the unamended soil and 2.5%B soils reduced at higher tension indicating increased water retention compared to the initial field values.

All 5%B amended soils (with or without Pt) changed the shapes of the water retention curve, and moisture retention increased compared to the unamended soil. The observed results were similar at both sampling times (Figure 3-19d). In all treatments, combined clay and 30%Pt had the highest water retention at all suction levels.

3.3.3.7 Soil cracking

Soil cracking intensity was measured using a relative scale of 0 - 5. Both clay and peat had an effect on soil cracking (Table 3-7). The addition of peat significantly reduced cracking intensity in the no-clay and 5%K treatments. The effect of peat was less obvious where B was added, although there was a significant reduction in cracking at the highest Pt and B rates.

The amendment of soil with clay also had an effect. The addition of K resulted in a small non-significant increase in cracking; however, the addition of B caused a large and significant increase compared with unamended soil, Pt and K. This was unsurprising as K is a 1:1 clay mineral with little or no shrinking and swelling ability. Comparing the clay rates, cracking intensity was similar at 2.5 and 5% B rates in the presence or absence of peat except for 5%B+30%Pt, where Pt addition significantly reduced cracking intensity compared to the soils amended with B alone at the two application rates (Table 3-7).

Table 3-7: Effect of amendments on soil cracking

Soil Parameter	Clay	Peat rate (%)		
		0	20	30
Soil cracking	No clay	1.2ab	0.8ab	0.4a
	5%K	1.6bc	1.0ab	0.6ab
	2.5%B	4.4d	4.8d	4.8d
	5%B	4.8d	4.4d	2.6c

Figures with similar letter in the same column and row are not significantly different ($p \leq 0.05$)

3.4 Discussion

3.4.1 Effect of amendments on soil MBC, soil respiration and SOC

The two biological properties measured in this project were soil MBC and soil respiration in the form of respired CO₂. There was a general reduction in soil MBC between initial and final field values for each treatment. The reduction is largely associated with the soil moisture conditions, which were low in July to August compared to January/February 2016. Soil microorganisms are known to proliferate in the presence of soil water but could suffer moisture stress when the soil is dried or saturated. Also, microbial biomass could decrease as the amount of easily decomposable carbon sources reduce in the soil.

The reason for the initial high MBC values in the unamended soil is unclear, however, when compared to respiration, there was less CO₂ released, suggesting that the organisms are less active or there is less carbon or nitrogen in the system. This suggestion is further strengthened by the soil OC result, where unamended soil had the lowest value (section 3.3.1.3 and Figure 3-10).

The increase in soil MBC and respiration as the rate of soil OM increased is possibly due to the increased availability of carbon. Nguyen and Marschner (2013) reported that in an incubation experiment, the addition of compost at 50 tonnes/ha increased cumulative soil respiration over 23 days compared to an unamended loamy sand in Australia.

Soils amended with combined 5%B and Pt maintained the highest MBC and respiration over time. This is likely to be associated with favourable conditions for microbial growth. Factors such as soil pH, water content, nutrient retention and aeration have been identified as essential for microbial growth and activity (Rousk et al., 2009; NRCS, 2011). As shown in the present study, combined 5%B and Pt plots have near neutral/alkaline pH, highest soil water content, highest CEC (which is a predictor of high soil nutrient and water retention) and low bulk density. These conditions provided an optimum growth medium for the heterotrophic microbes. The above results thus indicate that increased microbial biomass and respiration in 5%B and Pt result from improved soil physical and chemical conditions brought about by the added amendments. Another possible explanation is the increase in soil clay content, which can offer protection to soil microbes from predators, hence support their proliferation (Dixon, 1991; Djajadi et al., 2012; Bronick and Lal, 2005).

Soil microbial biomass and respiration was reduced in 5%K and combined 5%K and Pt soils. The major obvious factor responsible for the decrease is the soil pH. When combined with Pt, 5%K had the lowest pH values. The acidic soil might have altered the microbial community, its growth and activity. When compared to 5%B, the soils amended with 5%K and Pt also had favourable soil physical conditions and enough substrates, but respiration was lowest in these soils, possibly because of lower pH compared to B soils (section 3.3.2.2). The major difference between the two soils aside from their mineralogy is soil pH, which was acidic in 5%K soils. At low pH, there is an increased availability of aluminium, which is toxic to some soil microbes at higher concentrations (Zhou and Gunter, 1992). As reported by Smith and Doran (1996), the optimum pHs for bacteria, fungi, Actinomycetes and protozoans are 7, 5, 8 and >7, respectively, suggesting that 5%K might have been dominated mainly by fungi, while all other microbial groups would have been very active in the B amended soils. Rousk et al. (2009) showed that in the Hoosfield acid strip soil at the Rothamsted Research Station, UK, soil bacteria decreased by fivefold while fungi increased by fivefold when soil pH was decreased across a gradient of 8.3 to 4.0. Therefore, it could be inferred that although most of the soil physical conditions for the 5%K soils were adequate for microbial activity, the soil chemical condition became a barrier to soil microbial functions, showing the interrelationship between different soil properties.

At the final sampling, soil amended with 2.5%B had the lowest MBC. This is possibly due to poor soil condition as this soil had the highest soil bulk density and lowest porosity and number of air-filled pores. It has been reported that poor soil physical conditions such as high bulk density can hinder the activity of soil microfauna (Li et al., 2002; Torbert and Wood, 2008).

3.4.2. Effect of clay and OM amendment on soil reactions

All amendments increased soil CEC both in the initial and final soil samples, possibly because of either an increase in soil clay colloids, humic colloids or both. Cations are adsorbed on clay and humic colloids in soils (Evangelou, 1998; Hillel, 1998), so, management practices that increase the abundance of these colloids can increase soil CEC. In soil amended with Pt only, the increase in CEC can be related to the increase in humic substances, the increase in clay colloid in clay only soil, while an increase in clay and humic colloids would be the main factor in combined clay and Pt soils.

Soil CEC was lower in all treatments when the initial CEC was compared to the final values, and this might be due to cation mining by the crop as the final sampling was done immediately after the wheat harvest. Soil CEC is dynamic and could be affected by the changes in soil use and management as well as climatic conditions.

The CEC of K amended soils were lower than that of B, because of higher negative charge density in B than K (Hillel, 1988). Cation retention in soils is an electrostatic reaction, where negative charges adsorb positively charged cations. B is smectitic clay known for a high density of negatively charged ions on its surface due to isomorphous substitution reactions within the clay lattice, thus allowing the clay to attract and hold cations. The CEC of K is not permanent like that of B. Some researchers have reported that CEC of kaolinite (the mineral that is present in K) is controlled by particle size and pH (Ma and Eggleton, 1999), pH (Zhou and Gunter, 1992) and by type of cation present, solution concentration and solution pH (Ferris and Jepson, 1975 in Zhou and Gunter, 1992). Since K particle sizes were not measured in the current experiment, attention will be on soil pH. Thus CEC of kaolinite has been reported to decrease in acidic soil media (Zhou and Gunter, 1992) because kaolin charges are pH dependent. Being a less reactive clay, chemical reactions occur only along the edges and on the exposed basal hydroxyl group. In acidic soil solution, protonation would occur along the edges of K, and the clay will become positively charged, resulting in a repulsion of cations, hence a low CEC (Zhou and Gunter, 1992; Ma and Eggleton, 1999). The pH of soil amended with kaolin in this project is in the acidic region, and this might have affected the CEC of kaolin. Also, the unstable charge condition of kaolinitic clay mineral might have been responsible for the 21.8% reduction in CEC in kaolin-amended soil compared to 1.5% in B after 33 weeks.

However, when the concentration of cations is very high in the soil, it can displace the protonated hydrogen or prevent the protonation of the hydrogen ion, hence an increase in CEC, despite very low pH (Ma and Eggleton, 1999). This condition could explain why CEC of combined K and Pt amended soils was higher than K alone, despite a much lower pH compared to K alone. Also, the increase in CEC could arise from the presence of humic acid from the added peat compost.

Furthermore, the CEC of kaolin-amended soil was higher compared to pure kaolin (5-10 cmol kg^{-1}). This is likely due to the presence of smectite, the inherent clay in the amended

sandy soil. Ma and Eggleton (1999) reported that presence of smectite impurities on the kaolinite surface increases its CEC.

Combined applications of clay and Pt increased soil CEC compared to clay and Pt when applied separately in most cases. This is possibly associated with increased binding sites arising from increasing humic and clay colloids in the soil system or interaction effects between OM and clay.

The soil pH in all the treatments reduced over time, possibly due to the ion exchange between soil and plant roots or due to the buffering capacity of the soil. The observed variability in pH has basically arisen from the pH of the materials added. Liming of soil to adjust treatments' pH to the same value was avoided to prevent interference with some soil functions whose effects on the actual results will be difficult to separate (Rousk et al., 2009). It is therefore suggested that future investigation should measure the effect of adjusting the pH of the treatments a similar value to provide a further understanding of the amendments.

Reduction in soil EC over a period of time can predict or indicate loss of soil nutrients either through erosion, percolation or crop uptake. A soil is classified as non-saline if its EC value is $\leq 1000 \mu\text{S}/\text{cm}$ or $1\text{dS}/\text{m}$ (European Standard Working Document, 2005); all the EC values measured are below this threshold, thus the soils are considered non-saline.

The observed results showed a decrease in soil EC in all Pt treatments in the soil initial EC, and in Pt alone and 2.5%B combined with Pt in final soil samples. The decrease was linear in Pt only soils, but when applied with clay, reduction compared to clay only occurs at 30%Pt rates. The effect of Pt on soil EC can be influenced by several factors such as an increase in porosity in Pt amended soil, which might have increased infiltration and loss of nutrient through deep percolation. Nguyen and Marschner (2013) reported similar increases in nutrient leaching in a sandy soil amended with compost (50 tonnes/ha) in a laboratory incubation experiment lasting 23 days in Australia.

High carbon to nitrogen ratio of Pt is another possible factor. Addition of Pt might have immobilised N content of the test soil, resulting in low net mineralization, hence lower EC. Other factors include reduced mineralization rates, due to the effect of changes in soil pH on soil microbial activity, since Pt reduced soil pH in this work. West et al. (1985) reported

reduced growth of *Bacillus thuringiensis* and *Bacillus cereus* at pH 5.3 compared to pH 7.3. Also, a direct effect of pH on nutrient availability could be another reason as most soil nutrients can become unavailable as the soil pH becomes lower than 6.5 (Miller, 2016).

Effect of clay type was also observed; the B had higher EC than K, with or without OM at the same application rate. This possibly relates to their CEC values. The higher the CEC, the more reactive the clay, and the more cations a soil can hold. The CEC measured from the soils amended with B (24 - 31 cmol kg⁻¹) in this experiment is higher than that of K (17 - 24 cmol kg⁻¹), suggesting that more salts are held in the B than the K soils; hence the higher EC in the B amended soils.

The final EC showed that at a higher clay amendment rate, EC increased as Pt rate became higher. This change over time is likely to be associated with improved soil structure and aggregation as the soil and the amendments interact over time.

3.4.3. Soil carbon and C:N ratio in sandy soil amended with clay and OM

One major way of increasing soil OC is through the addition of soil OM. Increase in soil OC was expected in Pt amended soils, and that increase would become higher as Pt rate increases. The observed results agreed with the expectation. Several studies have confirmed that addition of fresh organic matter increases soil OC (Li et al., 2004, Shanmugam et al., 2014; Wang et al., 2014).

At final field condition in Pt alone treatments, the difference between 20 and 30%Pt SOC value was not significant, unlike initial values, indicating a diminishing in Pt rate effect over time. One main reason for this observation might be the consumption of easily decomposed carbon fractions such as sugars and carbohydrates by soil microorganisms, and that the number of recalcitrant carbon compounds remaining in the two treatments were similar at 33 weeks after amendment.

The reduced OC in 5%B compared to 2.5%B amended soils could possibly be linked to increased mineralization of OC by soil microbes, as higher microbial biomass and respiration were recorded in soil amended with 5%B than 2.5%B in this work.

One main difference between the initial and final SOC was that there were increases in all K amended soil while the SOC decreased in all B amended soil except in 2.5%B+20%Pt,

suggesting higher carbon sequestration in K amended soil than B. Similar results were observed for C:N ratios. The low C and C:N ratio in combined 5%B and Pt amended soil is a result of the increase in C mineralisation in the soil compared to 5%K. This is evident in the soil respiration result in this project, where there was a significant increase in CO₂ released in B than K soils. This increased mineralisation in 5%B could be attributed to suitable environmental conditions for microbial growth including high pH, higher CEC, higher water content and higher nutrient retention. Other factors could be the protection of soil microbes by clay, which supports their proliferation and increased activity as shown in increased microbial biomass in 5%B than 5%K. Also, an increase in soil carbon owing to an effect of the pH gradient on soil microbial activity (Rousk et al. (2009) could increase SOC more in K than B amended soils.

Comparison of initial and final SOC showed that there was no significant change in SOC value after 33 weeks. Rice et al. (1996) wrote that about 95% of SOC is a non-living fraction and is not subjected to changes over a relatively short time. The result for SOC in this work supports their statement.

On the other hand, the soil C:N ratio significantly increased over time in the amended soils, suggesting net immobilisation of soil carbon, possibly as a result of an increase in over and underground biomass associated with improved crop growth and yield. Also, it is worth mentioning here that soil C:N ratio decrease in only unamended soil, suggesting net mineralisation of soil carbon.

3.4.4 Soil pore characteristics and BD

Soil pore characteristics were measured using CT scanning. Addition of Pt to sandy soil increased total pore count, large macropores and pore diameter while clay reduced them. The observed result is mainly due to the effect of particle size of the Pt (0-14mm) and clay (<2 μ m) used. It is possible that the clay particles (smaller than sand particles) filled up the large pores between sand particles, and reduced some to micropores, while smaller particle sizes in Pt would reduce some pores to mesopores and micropores, larger particles would increase the size of some pores.

Pore sizes are determined by the particle sizes. If particles were large, the resulting pore spaces would be large; if small, pore spaces would be small. This principle governs pore sizes in sand and clay. However, soils are made up of heterogeneous materials with a wide

range of particle sizes where clay and humus are the smallest particle sizes. Thus, the large particle size of OM and the small particle size of clay as well as their abundance would have been responsible for the higher and lower distribution curves in Pt alone and the clay as well as in clay+Pt amended soils respectively, compared to that of the particle sizes of the unamended soil.

Factors affecting soil porosity include packing density, particle shapes and the dispersity (Nimmo, 2004). Smaller and homogeneous particles would have high packing density, allowing more particles per area, hence low porosity. This factor explained while porosity was lower in B amended soils compared to K. Although they are both clays, B has a larger packing density than K because the latter particles are coarse compared to the very fine particles of B.

Soil amended with 2.5%B had the lowest value for porosity, pore area, pore count and large macropores as well as the lowest percentage pore spaces over the whole pore size distribution graph. All these data show that air-filled pores reduced significantly in this treatment. The observed result can be explained in term of dispersity, which simply implies that if all other factors remain constant, porosity will increase as the particle becomes monodisperse (uniform particles) compared to a polydisperse medium. In a polydisperse medium, smaller particles would fill the spaces between the large particles and reduce porosity (Nimmo, 2004). In 2.5%B soil, low porosity is possibly due to polydispersity, where small and uniform sized B particles filled the pore spaces between sand grains. However, as the B content of the soil increased by 100% (in 5%B), the soil tends to be monodisperse due to an increase in the distribution of particles that are uniform in shape, thus porosity increases.

The BD of B amended soils was higher than that of K. The observed difference between B and K on soil BD is possibly associated with clay particle size and particle density, which are smaller and denser respectively in B than K. Also, application of OM reduced soil BD, and this is possibly due to a dilution effect. Wang et al. (2014) also reported a decrease in soil BD when a sandy soil was amended with peat in a field experiment in Canada and attributed the reduction to a dilution effect of peat on the soil weight. Peat has been described as having large inter-particle pores arising from the remains of the plant cells (Rezanezhad et al., 2016). These large pore areas would have been responsible for the low BD, as the area occupied by pores is relatively large.

Comparing the result of final BD and total porosity, it could be inferred that mechanisms responsible for reducing BD in K and B amended soils are different. Porosity is inversely proportional to soil BD (Hillel, 1998), and this was true for the Pt alone and B amended soils, however, in K amended soils, BD increased with increased porosity, suggesting that the reduced BD in B is more of increased pore area in the presence of OM, while it is more of dilution effect in K amended soils. It is also noteworthy, that 2.5%B with the lowest porosity has the highest final BD confirming the reliability of the scanning method as the field was sampled for both final BD and total porosity at the same time.

3.4.5 Soil moisture retention

Soil moisture at FC increased over time in combined clay and Pt treatments, suggesting that only combined clay and OM had a long-term effect on increasing soil moisture content of sandy soil at FC. The major reason for this is possibly associated with the increase of OM in these soils which would have stimulated microbial activity essential for soil aggregate formation and stability, hence improved water retention.

Higher water content at FC was observed in 2.5%B and 5%K treatments when Pt rate was 20% than at 30%, possibly as a result of increased permeability as the amount of Pt increased in these soils. This effect was completely masked by the higher content of clay B at 5%. Comparing the two clays, weight for weight, moisture content at FC was similar. This was unexpected as B had higher water retention capacity than K. It is thus suggested that the observed result is possibly because the force of attraction between B and water molecules is stronger than that of K under the same tension. Also, a higher number of micropores are expected in B than K soils due to their particle sizes, and the smaller the size of micropores and the larger their number, the less the ease of water release due to capillary forces.

The application of Pt alone reduced water content at PWP while all clay amendments increased it, possibly because Pt is highly porous and is dominated by a large number of macropores, thus most of its water has been released at low tension. Also, since water retention of Pt is mainly as a result of water held within the Pt itself, less water will be available as the soil dries out whereas where water is held due to capillary action, retention would be higher at high tension.

PAW increased over time. The increase in PAW compared to the initial field values is possibly associated with increased microbial activities, which might have improved soil structure and soil aggregation over time. At the initial condition, PAW is possibly associated with water retention capability of the added material, while final PAW is possibly due to soil function such as aggregation, porosity and soil structure. None of the clay alone significantly increased PAW over the unamended soil, and that is expected, as clay does not easily release its water compared to sand due to the stronger force of attraction between clay colloids and water molecules. This could also imply that Pt is the main factor responsible for the increased PAW. The combined application of clay with 20%Pt had the highest PAW, suggesting that 20% OM rate might be adequate when combined with clay for optimum water availability to plants in amended sandy soils.

3.4.6 Effect of amendments on soil moisture release characteristics

Generally, water retention increased over time in all the treatments, showing the effect of time on soil development. At the initial stage, the soil mixtures were more or less homogenous and unconsolidated, however, the interaction between soil biological and chemical properties over time might have improved the soil physical condition such as soil structure, aggregate formation and porosity, which might have resulted in the improved water retention.

Moisture retention of Pt alone was higher than that of the unamended soil at low tension but became similar as the tension increased, suggesting that under dry conditions, the moisture retention of unamended sandy soil would be similar to that of the soils amended with Pt only. This finding did not agree with the hypothesis that peat will increase water retention at PWP. The observed result suggests that similar to the sandy soil, the Pt amended soil is dominated by macropores, and this conclusion is evident in soil pore characteristics measured in this work. This shows that amending sandy soil with OM only might not be enough to increase its resilience to drought.

The soil moisture retention characteristics of soil amended with clay or combined clay and OM agreed with the test Hypothesis 3 that clay and combined clay and OM will increase soil moisture content at FC and PWP. This increase in soil moisture content at FC and PWP occurred because of modification of the soil pores by clays (as shown by soil pore characteristics) which might have resulted in an increase in soil microporosity in soils amended with clay compared to the unamended plot, and soils amended with OM alone.

3.4.7 Effect of the amendments on soil cracking

Soil cracking intensity was measured using a relative scale of 0 - 5. Addition of peat significantly reduced soil-cracking intensity. The order of the reduction was Pt > K > B. Cracking occur in smectitic clay as a result of alternating wetting and drying. When wet, the clay absorbs water molecules into its inter-structural space causing expansion; but the soil tends not to contract during drying resulting in cracks. It has been reported that cracking in clay occurs when tensile stress associated with the soil matric potential overpowers the tensile strength of the soil. This process arises when there is a condition preventing the soil from shrinking following an expansion (Kodikara et al., 2000). Thus, any process that could reduce the tensile stress will inevitably reduce soil cracking. Kodikara et al. (2000) wrote that the development of tensile stress is controlled by factors such as a rough layer interface (external influence) or failure of the soil to dry uniformly (internal factor). In this experiment, OM was the main factor that reduced cracking, and the reduction increased with the Pt rate. Since the soil in each plot is homogenous, we could conclude that interlayer restriction is not applicable. On the other hand, OM through increased porosity and macropores could stimulate uniform drying of the soil, thus prevent or reduce the development of tensile stress, which in turn reduced cracking intensity.

Another possible process is the interaction between clay and organic matter. Smectitic clay has been reported to adsorb OM into its inter-structural spaces (Page, 1952; Theng et al., 1986). Therefore, if there is preferential adsorption for OM rather than water, the presence of OM would reduce the amount of water that could be absorbed in Pt amended soils, resulting in less expansion during wetting and less cracking on drying. McCalla (1947; in Page, 1952) reported that adsorption of certain polar organic molecules or large organic compound by hydrophilic clay reduced adsorption of water.

Russel (1929; in Brown, 1964) reported that incorporation of 40 tons/acre (99 tonnes/ha) of rotten manure into the surface of a clay loam soil in the UK reduced soil cracking during dry weather. While this may be an advantage in clayey soils, the extent to which reduced cracking can affect sandy soils requires further examination.

3.5 Conclusion

The results show that combined application of clay and peat improved all the measured soil physical, chemical and biological properties compared to unamended soil, clay alone and

peat alone. Quantitative analysis of the soil pore characteristics using CT scanning showed that incorporation of coarse peat (0-14mm) to sandy soil increased soil porosity, total pore count, number of large pores and pore diameter but were reduced by clay. Soil pH and EC also reduced with increasing peat ratio, while clay at 5% increased EC 11 months after application. Plots amended with B had higher CEC values, and 5%B increased soil MBC and respiration compared to the other treatments; increased soil C:N ratio, but SOC reduced over time. Addition of K reduced microbial respiration and MBC; increased C:N ratio and SOC over time. Comparison of soil water retention characteristics of soil amended with the treatments showed that soil water retention increased in all the treatments within 11 months, but only soil amended with clay increased soil water at PWP over the unamended soil. Soil amended with 5%K+20%Pt had the highest PAW, followed by 5%B+30%Pt.

On the basis of the above result, it could be inferred that clay and OM has a varying effect on soil pore and water characteristics as well as the CEC. Therefore, the next chapter will investigate how these observed variabilities will affect the hydrology of sandy soil, and a possible trade-off between infiltration optimisation and runoff.

Chapter 4

Effectiveness of combined applications of clay and organic matter on the hydrological functions of a sandy soil using rainfall simulation.

4.1 Introduction

The relatively large particle sizes of sandy soils (0.06 – 2.0 mm) create macro- and mesopores, which generate high rates of infiltration following rainfall or irrigation (Massoud, 1975). On agricultural lands, high infiltration rates can cause loss of water and nutrients from the soil profile, which may adversely affect root uptake and subsequent crop growth. To mitigate these stresses on crops, irrigation and/or fertiliser applications may need to be increased in both frequency and magnitude to produce a viable crop. However, these costly practices can lead to the leaching of excessive nutrients into groundwater, leading to environmental pollution (Reuter, 1994) and significant water treatment costs.

One alternative practice is to alter soil properties to increase soil water holding capacity and optimise infiltration rates. The previous investigation of soil pore characteristics using a CT scanning method (Chapter 3) had shown that incorporation of peat alone increased macroporosity of the test soil, which may imply a negative effect on infiltration reduction. On the other hand, clay amendments reduced macroporosity and increased soil CEC with the highest effect found in combined clay and peat plots, suggesting that these amendments would have a greater effect on the optimisation of infiltration rate. Therefore, this chapter seeks to measure the effect of additions of these clay and OM, both separately and in combination, on the hydrological properties of a sandy soil using laboratory-based rainfall simulation techniques.

4.1.1 Water infiltration

Infiltration is the downward movement of water into the soil surface after rainfall or irrigation, and percolation is subsequent movement through the profile. Soil water movement can be explained using Darcy's law (Haghnazari et al., 2015). The law states that the discharge flux is proportional to the hydraulic conductivity and hydraulic gradient or head. Hydraulic conductivity refers to the ease of water movement in the soil and is

particularly influenced by soil pore sizes, particle size and degree of soil wetness, so its value varies for different soils (Haghnazari et al., 2015), while hydraulic head refers to water height within the soil matrix. Water infiltration increases when hydraulic conductivity is large and the hydraulic gradient is small. However, it has also been proposed that other conditions occur when water infiltration would not obey Darcy's law such as discussed below.

Water flow in soils after irrigation or rainfall follows three stages according to Beven and Germann (1982). At stage one, volume fluxes of water from rainfall are less than the water absorption capacity of soil micropores that extend to the soil surface, thus all the water that reaches the soil surface is absorbed by the soil. This can be represented mathematically as:

$$P(t) < I_i(t)$$

Where

P = precipitation

I_i = micropores infiltration

t - time

At stage two, there is simultaneous water intake by both macropores and micropores that are extended to the soil surface. At this point, the rate of water intake by micropores is less than the flux of water supply by the precipitation, but precipitation flux is still smaller than the water absorption capacity of both the micro- and macropores. As macropore flow progresses significantly, water will flow through pore walls, followed by the initiation of lateral flow of water into the soil matrix. Also, small-scale runoff of surface water may develop. This could be represented as:

$$I_i(t) < P(t) < (I_i(t) + S_i(t))$$

Where

P = precipitation

I_i = micropores infiltration

S_i = macropore infiltration

t = time

The lateral flow, in turn, would result in a reduction in water flow through macropores and their walls, hence water movement further down the profile will reduce temporarily.

At stage three, precipitation flux becomes higher than the water infiltration in the micropores and macropores. At this point, the soil would have stored significant amounts of water in the surface layers, and large-scale overland flow will develop. This is represented as:

$$P(t) > (I_i(t) + S_i(t))$$

According to Beven and Germann (1982), beyond stage one, Darcy's law becomes invalid, as the assumption that soil hydraulic properties are homogeneous over a given cross-sectional area of a soil surface would be violated. Several gradients of water fluxes may develop even within a short distance, making the idea of the hydraulic gradient used in Darcy's law difficult to establish. However, under laboratory experimental conditions, the factor of wide variability in the hydraulic gradient can be controlled.

Other factors affecting infiltration include soil porosity and permeability. Porosity is the proportion of soil that is pore, compared to solid. On the other hand, permeability refers to the property of a material that gives the least resistance to diffusion of water through it, without being hindered physically or chemically. However, some substances (such as clay), which are highly porous, may not be permeable because pore spaces are too small for free flow, thus, attention should be on permeability rather than porosity, so the more permeable a soil is, the more the water infiltration.

Infiltration capacities of soils vary and are affected by initial soil moisture content, soil texture, amount of OM, and clay type and quantity. Soil texture and structure mostly control soil moisture content, hydraulic conductivity, hydraulic head and the rate at which water travels through the soil. Infiltration would proceed fairly rapidly in a well-structured soil compared to massive, compacted or unconsolidated soils. The higher infiltration in the former is associated with high soil aggregation. Soils belonging to sandy textural classes are known to have high infiltration rates compared to fine-textured soils (see section 1.1.4.3 for more information). While this may be desirable in controlling surface runoff, when the infiltration rate is too rapid, negative effects can develop in agricultural soils as water flows beyond the reach of plant roots and there can be leaching of agrochemical to groundwater.

It has been established that clay mineralogy and OM composition would affect clay and OM properties (Lambooy, 2013). Water retention in clay soil is usually determined by the soil's CEC, type of cation, surface area, aggregate stability, chemical composition and charge density (Lambooy, 2013; refer to section 1.1.7 on properties of clay minerals and their role as soil amendments for more information). Thus, the higher these properties in a clay, the more the clay's influence on infiltration.

One major factor responsible for high infiltration rates in sandy soils is the preponderance of mesopores (30 μm –75 μm) and macropores (>75 μm ; Soil Science Glossary Terms Committee, 2008). The large particle sizes of sandy soils are associated with large pore sizes, and with low resistance to gravitational movement of water. This is compounded by low clay and often limited OM contents of sandy soils. It is expected that the infiltration rate of a sandy soil will reduce as the OM and clay content of the soil increase.

In finer soils, water absorption by clay and OM reduces the rate at which soil water could travel to deeper horizons. Water retention by clay is controlled by two mechanisms. The first is the effect of the clay particle. Clay particles are known to have flaky shapes (compare to rotund shapes of sand particles) and very small particle sizes (<0.002mm; Hillel, 1998). Because of the shape and size, clay particles are densely packed together resulting in the formation of micropores (pores <30 μm). The size of pores affects the operation of gravitational and capillary forces that control water movement in soil. These forces operate in opposite directions. Gravitational force is a vertical moving force that pushes water downwards, while capillary force draws water into micropores and can cause upward movement of pore water towards the soil surface in response to an evaporative demand. The effect of gravitational force diminishes as soil pore size becomes smaller, and water is retained in the soil where capillary force is larger than gravitational forces (Hillel, 1998; Lal and Shukla, 2004). Thus, the presence of large numbers of micropores in finer soils helps retain water against gravitational forces, unlike sandy soils with larger pore sizes.

The second mechanism is water adsorption by cations attracted by clay and humic micelles. Figure 4-1 illustrates water adsorption by a cation. When in contact with water, these positively charged cations attract water either by electrostatic forces, hydrogen bonding or Van der Waals forces. The adsorption of water through these mechanisms reduces the amount of water that travels to the lower soil horizons over time. The combined effect of

both capillary action and water adsorption would increase the degree of surface soil wetness as rainfall or irrigation progresses.

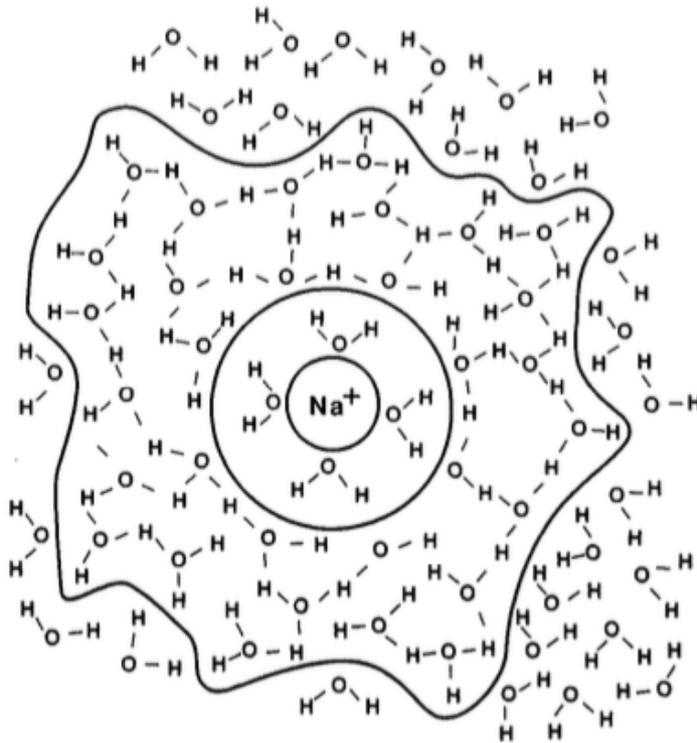


Figure 4-1: A model of the hydration atmosphere of a sodium ion (this is similar for all cations) showing layers of water through hydrogen bonding to a central cation (*Source: Hillel, 1998*).

The wetter a soil is, the less the ease of water movement through it. The mechanisms responsible for the reduced water movement in wet soils could be direct or indirect. The direct effects arise from reduced hydraulic conductivity and increased water head. During rainfall or irrigation, following an initial high infiltration rate, water movement into the soil will decrease as the water head of the soil matrix increases because of the reduction in the forces of attraction between soil particles and water, hence a reduction in soil water movement (Hillel, 1998). An indirect effect is the modification of soil pore sizes and morphology by swelling and expansion of clay, especially montmorillonites (Figure 4-2). When incorporated into the soil, the smaller particle sizes of clay (relative to sand) would increase the number of smaller pore sizes in the amended sandy soil, by filling the void spaces between the sand particles. This would reduce infiltration rate, hence allow time for water absorption by clay and OM. Also, when in contact with water, cations present in the interlayer structure of clay particles can absorb water and increase their radii. As the volume of these cations increases, the clay would expand. The swelling, in turn, can result in further

reduction in soil pore sizes, causing changes in pore geometry, and slower movement of water.

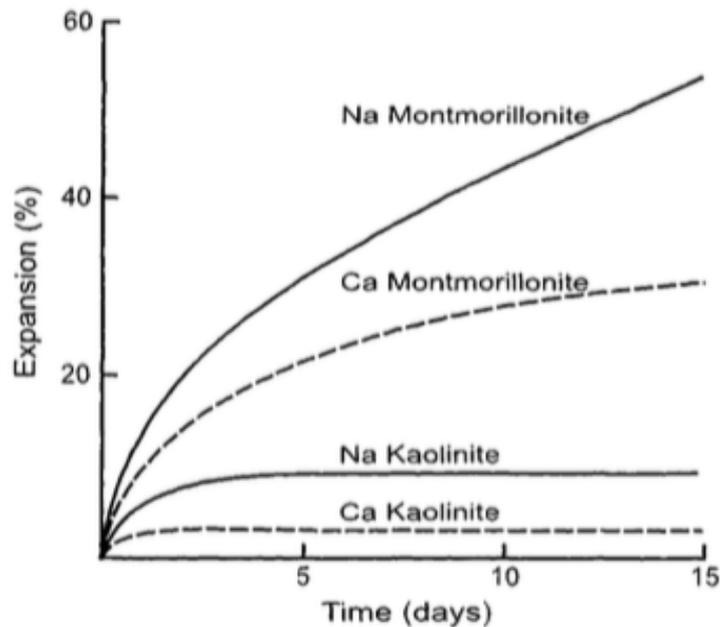


Figure 4-2: Volume changes of montmorillonite and kaolinite clay during hydration (Source: Hillel, 1998)

Clay mineralogy also plays an important role in water retention mainly through the amount and type of cations adsorbed onto the clay colloids. CEC represents the maximum amount of cations that a soil colloid could hold for exchange with the soil solution through cation displacement. As described above, water retention by cations adsorbed onto clay and OM surfaces plays a key role in soil water retention. Clay and OM holding large amounts of cations would retain more water against infiltration losses. On the basis of the amount of CEC and the relatively large specific surface area of clay particles, Lambooy (2013) suggested that water retention by clay minerals would follow the order of smectites > mica = illites > kaolinites.

Water retention of soil OM is controlled by adsorption and absorption mechanisms. Cabrera et al. (2008) reported that solute retention by soil OM occurs mainly by adsorption. The water adsorption mechanism of soil OM occurs as a result of (1) adsorption in the micropores of organic materials and (2) water adsorption by humic substances. OM is usually made up of micro and macropores, and water could be stored in the micropores against gravity. Water adsorption by humus mainly occurs as a result of the reaction between the deprotonated end of a carboxyl group (RCOOH) on or of humic acids and dipolar ends of water molecules. When deprotonated, the loss of the hydrogen ion (H^+) from

the carboxyl group will result in a net negative charge on the oxygen atom (RCOO^-), and the charged compound can adsorb water molecules via its positively charged dipolar end. Water retention by OM could also occur indirectly through the hydration of cations adsorbed on organic molecules in the soils. Therefore, soils with large amounts of humus can hold more water against infiltration losses.

The water absorption mechanisms of OM occur due to the ability of some organic materials to store water in their structural layers. For example, peat is known to hold water up to 18 times its dry weight (Hobbs, 1986). This is due to its porous nature, which is made up of millions of tiny voids in its cells (both dead and living cells) that could absorb and store water. A micrograph of peat morphology from an electron microscope (SEM) at 10kV revealed that peat has three types of pores: (i) macropores that are open and connected, (ii) partially closed or closed pores and (iii) isolated dead-end pore spaces (Rezanezhad, et al., 2016). The ability of peat to retain water is associated with the dead-end pore spaces found in the cortical layer of plant stems and hyaline cells in the leaves which have openings at one end for water storage.

For OM, the degree of decomposition and amount of humus present would also be of importance. Organic matter could have pore size ranges from 0-5mm (can be up to 14mm in peat). Larger pores are found in partially decomposed OM while highly decomposed OM has more micropores (Sposito, 2008). So, well-decomposed OM would hold more water than partially decomposed OM. Also, because of the wide particle size range, the addition of OM will simultaneously increase and decrease the original, unamended soil pore sizes, so overall, it is difficult to assume that OM will reduce soil pore sizes.

In the current experiment, only one type of OM at the same level of decomposition will be used, thus the effect of decomposition rate and humus content will not be considered. The choice of OM used in this project was peat (Pt), which is known to be homogeneous because it was formed from the similar organic material. All Pt amendments used are from the same batch and at the same decomposition stage.

4.1.2 Interactive effect of clay and OM on water infiltration

Reports have shown that clay and OM interact in the soil (see section 1.1.9.1 on the protection of OM by clay for further details). The main mechanism for clay and OM synergy on infiltration reduction could be associated with the increased CEC. Leinweber et

al. (1993) wrote that soil clay always has higher CEC than refined clay, and attributed that to the intercalation or adsorption of OM by soil clay minerals. As mentioned earlier, CEC plays a key role in soil water retention, and if other factors remain constant, soil water retention would increase with soil CEC. When co-applied, clay and OM can form organo-mineral complexes with higher charge density fluxes, due to higher CEC and thus adsorb more water. In soil, water attraction to cations usually occurs in layers (Figure 4-1). The first layer is attracted to the cation by electrostatic force, while the rest of the water molecules are attracted to the next layer of water molecules due to cohesion forces and hydrogen bonding with the cation at the centre. Because of strong cohesion forces within water molecules, several layers of water can be formed around the cation as more water molecules are attracted. In the presence of large amounts of cations, stronger forces of attraction emanating from overlapping electrical charged fields (or fluxes) can develop due to the interaction among neighbouring cations, leading to increases in water retention compared to when clay or OM is singly applied.

The suggested mechanisms (reduction in pore space, water absorption and increase in soil wetness) responsible for infiltration reduction were similar for both clay and OM. Hobbs (1986) wrote that in the context of water retention, there is little difference between the properties of peat and clay. So when co-applied, their effect is expected to combine on the infiltration dynamics of sandy soils and reduce the amount of water that could percolate through the soil profile at a given time. This effect is expected to be higher as the quantity of clay and OM added increases.

4.1.3 Surface runoff and soil loss

Surface runoff is water that accumulates and travels on the soil surface following irrigation, rainfall or snowmelt. In theory, runoff is expected to begin when rainfall or water volume exceeds infiltration rate (Beven and Germann, 1982; Lal and Shukla, 2004). Some researchers have argued that this assumption might not hold under certain circumstances (Miller and Gardner, 1962; Bedaiwy and Rolston, 1993; Hillel, 1998) such as high rainfall intensity, soil compaction or the sealing action of dislodged soil particles. In principle, it is expected that significant runoff would begin when the soil has been fully saturated or has reached its maximum water holding capacity (Beven and Germann, 1982; see section 4.1.1 for more information on how runoff develops during precipitation events). Excess water then ponds on the soil surface and flows over the land until it gets absorbed by the soil, infiltrated or runs into water bodies. In another word, the volume of runoff is inversely

proportional to infiltration volume and directly proportional to rainfall duration (Hillel, 1998).

The inverse relationship between infiltration and runoff thus indicates that soil management strategies that reduce infiltration could increase runoff. Horton (1940) and Shukla et al. (2003) wrote that as rainfall progresses, soil compaction by raindrop impacts, sealing of soil pores by slaking and clay swelling (and its associated reduction in pore sizes and geometry) would increase runoff. So, the addition of clay, especially swelling and shrinking clay, such as bentonite can stimulate generation of runoff. Also, poorly structured soil and soil with easily dispersed clay such as kaolinite could cause clogging of soil pores by erosional deposition, and reduced infiltration, so increasing runoff. Thus, it is imperative to understand how amending sandy soil with clays would influence both infiltration and surface runoff.

The effect of several types of OM such as crop residue mulch (Dickey et al., 1985), leaf litter (Li et al., 2014) and grasses (Adekalu et al., 2007; Pan 2010) on runoff generation in agricultural soils has been measured. The main effect of OM on runoff generation is likely to be related to increased surface roughness and reduction in surface soil compaction due to raindrop impact. Also, due to the high water retention capacity but large hydraulic conductivity associated with OM permeability, OM might reduce water infiltration without any significant effect on the increase in runoff volume.

Soil loss/erosion during precipitation occurs in two stages. First, raindrops impacting on the soil surface dislodge soil particles and small aggregates. Then, the dislodged particles are carried away / transported by surface water. Also, under high-intensity events, runoff travelling at high velocity could also detach and carry away weakly aggregated soils. The ability of rainfall to cause soil loss is related to runoff volume and velocity, the erodibility of the soil and the erosivity of the rainfall (Hillel, 1998). On the basis of these, understanding relationships between soil loss and runoff in an amended sandy soil would provide a better understanding of the short and long-term effect of the amendments, and formulation of possible management strategies that control runoff and soil loss.

4.1.4 Rainfall simulation

Rainfall simulation is a technique used experimentally to understand some of the processes controlling water infiltration, runoff and soil loss. Rainfall simulation could be conducted in

the field or in the laboratory. Rainfall simulators are valuable research tools to study soil hydrology and erosion processes as they reduce the variability and uncertainty of natural rainfall. Vadas et al. (2007) reported similarity between rainfall studies conducted in the laboratory and the field to justify the use of this technique in predicting real-life conditions.

Different simulators are employed in rainfall study, but they could be grouped into two viz: pressure dropper and non-pressure dropper. The pressure dropper involves the use of pressurized hosepipes, while the principle employed in the non-pressure system is forming and dropping of water drops from a defined height using hoses made of glass, metal or plastic, or the use of hypodermic needle drop formers (Hudson, 1993). The method used in this experiment is a non-pressure dropper with hypodermic needles. The main benefits of this method are that it allows constant drop size, uniform rainfall distribution, constant fall velocity and can be used with low water pressure. The main disadvantage includes dropping of raindrops at lower velocity, but that can be managed by raising the height of the device (Hudson, 1993).

4.1.5 Objectives and hypotheses

Clay and OM soil amendments have the ability to modify the two major factors responsible for high infiltration rates in sandy soils. The desirable effects of OM on soils have been demonstrated (section 1.1.8.2). Amending soils with exogenous OM has a good effect on soil physical condition by improving resistance to compaction, reducing surface sealing, and improving soil saturated hydraulic conductivity and water retention (Grosbellet et al., 2011; Li et al., 2004). The beneficial effects of exogenous clay include good soil aggregate formation and maintenance, good soil structure, protection of organic matter and soil nutrients, and water retention (Dixon, 1991; Reuter, 1994; Houcine et al., 2007; Sposito, 2008). However, little is known of the threshold of clay content in sandy soil that would optimise infiltration without significantly increasing surface runoff (due to reduced infiltration). None of the currently reported research on the effect of claying on sandy soil (and its hydrological properties) has investigated the effect of the clay amendment on surface runoff and soil loss. Therefore, the objective of this chapter is to measure the effect of clay, OM and their combination on infiltration, runoff and soil loss in an amended sandy soil.

Based on all the aforementioned evidence, the following hypotheses will be tested:

- 1) Peat will reduce infiltration by increasing water retention, and its effect will increase with increasing peat dose. Addition of clay will reduce infiltration in sandy soil due to their ability to modify soil pore sizes and morphology as well as their higher water retention capacity. Also, smectitic (B) clay will reduce infiltration volume more than kaolinitic clay, because of its high swelling capacity when wet, higher CEC and high surface area (refer to section 1.1.7 on the properties of clay minerals and their role as soil amendments). It is predicted that 5%B+30%Pt will have the lowest infiltration.
- 2) There will be interaction effects for the combined application of clay and OM on the reduction of infiltration in sandy soils.
- 3) Runoff volume will increase as the potential of the clays to reduce infiltration becomes higher.
- 4) Soil loss will increase as the amount of runoff generated increases.

4.2 Materials and method

4.2.1 Soil collection and preparation

The surface horizon of a sandy loam soil was collected (0-20cm deep) from the University of Warwick, Wellesbourne experimental field, Warwickshire, United Kingdom (Latitude 52 12 18 N; Longitude 1 36 00 W). The soil was air dried, mixed thoroughly and sieved through a 10mm screen. The soil was identified as a typical brown earth, belonging to the Wick series (Whitfield, 1973). The soil used was a sandy loam containing 65% sand, 18% clay and 17% silt. Its pH was 6.1 and organic matter content was 2.5%.

4.2.2 Soil amendments

The soil was amended with two types of clay and an organic material. The amendments used were the same as those in Chapter 2, and their properties can be found in section 2.2.2. The clays were kaolin (K) and bentonite (B) representing 1:1 and 2:1 clay minerals respectively. The organic material used was a medium grade (particles range from 0-14mm) pure sphagnum peat (Pt), with a pH of 4.2, sourced from Klasmann-Deilmann Ireland Ltd. The treatment combinations consisted of three clay rates (0, 2.5% and 5% w/w) and three Pt rates (0, 20% and 30% v/v), and the combination of clay and OM at all rates.

4.2.3 Soil packing

Soil erosion trays (20cm x 11cm x 6cm) were used. Each tray was lined with a perforated metal mesh, covered with a layer of fine cloth to prevent soil from washing out, whilst providing free drainage. Each tray was fitted with a funnel at its downslope edge, which collected surface runoff that then discharged into a plastic container via a 30mm diameter pipe. Any infiltrate was collected in a sump underneath each erosion tray and it was discharged into collection bottles via a 10mm diameter pipe at the bottom of the tray. All treatments were packed to the same volume, which was 1,100 cm³. For the clay treatments (K and B) and clay+Pt treatments, replicates with the same application rate were packed to the same density. All samples were saturated by capillary action (Figure 4-3). The time required for complete saturation varies from one treatment combination to another. So this preparation stage was not timed. Thereafter, trays were arranged in a slating position vertically and allowed to drain for two hours. Earlier experiments to determine a suitable draining period showed that after 30 minutes all soil water held under gravity was drained. The trays were placed on a sloping table (15%) and placed under a laboratory-based, gravity-fed, rainfall simulator.



Figure 4-3: Saturated soil samples prior to rainfall simulation

4.2.4 Rainfall simulation technique

4.2.4.1 Rainfall simulation

The gravity-fed rainfall tower at the Soil and Water Management Facility, Cranfield University, UK was used. Raindrops were generated by ponding a constant head of water

above an array of hypodermic needles inserted into the bottom of a water tank measuring 100cm x 45cm x 8cm. Raindrop size was then randomised by letting the drops fall through a metal mesh (10 mm) located 1 m below the hypodermic needles (Figure 4-4). Total drop fall height was c. 8.8 m, ensuring over 95% of drops reached their terminal velocity (Gunn and Kinzer, 1949).

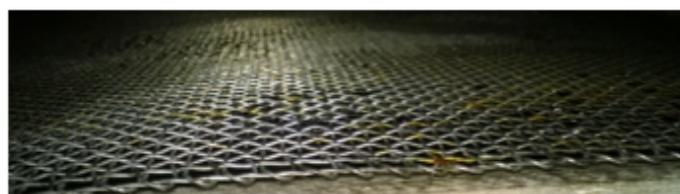
4.2.4.2 Rainfall calibration and simulation of soil samples

The intensity of rainfall from the rainfall tower was calibrated by placing cups of known diameter on a table on a similar slope gradient to the one to be used in the main experiment. The cups were arranged uniformly on a grid. Rainfall was collected for 15 minutes, and the amount of rainfall in each cup was measured. Rainfall intensity across the grid was calculated and used to identify rainfall spatial distribution. The mean rainfall intensity was 65 mm/hr (SE = 0.22).

The packed soil trays were placed under the simulator in positions that had similar rainfall intensity (Figure 4-5). Two storm durations used were 15 and 30 minutes. After each storm event (i.e. 15 minutes and 30 minutes), infiltration and runoff volume (which contained any eroded soil) were measured. The 2 storm events used are typical of storms in the UK with a return period of c. 5 years for 15 mins and c. 20 years for 30 mins (assuming central UK conditions).



Needle bed (drop formers)



Metal mesh to randomize raindrop distribution

Figure 4-4: Rainfall simulator

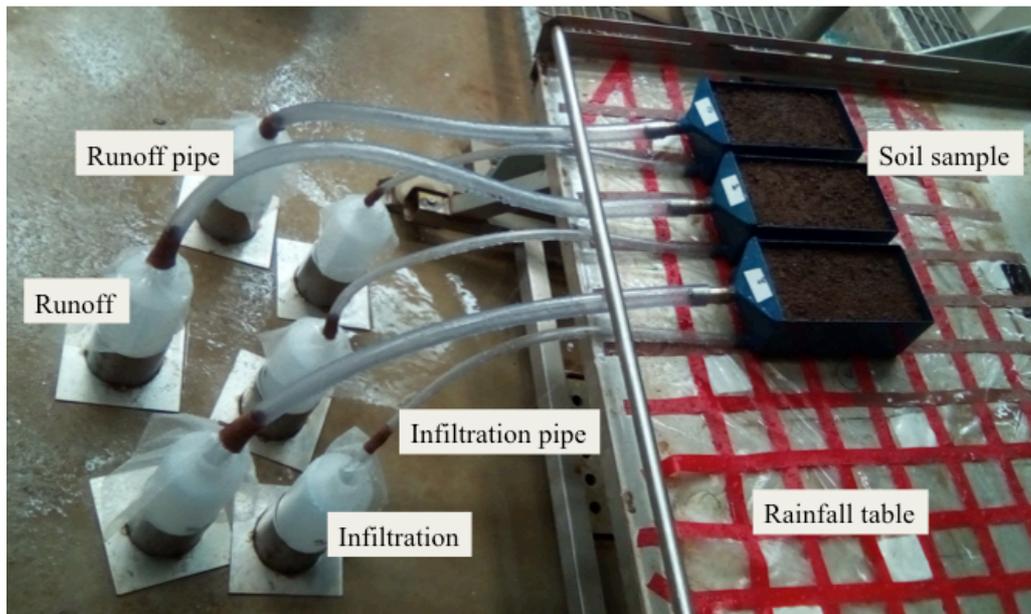


Figure 4-5: Rainfall simulation experiment showing the arrangement of the soil samples and the infiltration and runoff collection

4.2.5 Statistical analyses

The effects of clay and OM amendments on infiltration, runoff and soil loss were analysed using one-way ANOVA ($p < 0.05$) in SPSS version 24. Means of data with homogeneous variances were separated using Least Significant Differences (LSD), while data with non-homogeneous variances (runoff and soil loss) were separated using Dunnett T3. Interactions between clay and OM amendments were measured using GLM. The effect of storm duration was measured using a paired t-test at $p < 0.05$. The relationships between infiltration and runoff as well as runoff and soil loss were measured using correlation and regression analyses ($p < 0.01$). All the means were presented as a mean of four replicates after outliers have been removed. Percentage reduction in infiltration volume was calculated using the mean of infiltration volume in each treatment compared to that of the unamended soil.

4.3 Results

4.3.1 Infiltration

Infiltration was measured at 15 and 30 minutes after storm events, and the result is presented as a stacked bar chart (Figure 4-6). Generally, Pt only and low rate of K had no

effect on infiltration reduction, while higher rates of K, B (low and high rate) and their combination with Pt reduced infiltration.

4.3.1.1 Infiltration after 15 minutes storm duration

For the initial 15 minutes, the results show that the amendments reduced infiltration volume compared to the unamended soil. Also, the means of all the treatments were significantly lower than that of unamended soil, except in soil amended with 20%Pt and 2.5%K only (Figure 4-6).

In soils amended with Pt only, infiltration reduced as Pt rate increased. Within this group of treatments, infiltrated water from the unamended soil and 20%Pt was significantly higher than that of 30%Pt, while means of 20%Pt and unamended soil were not significantly different (Figure 4-6). The reason for the observed reduction in infiltration at higher Pt rates is possibly associated with the ability of Pt to absorb more of the rainfall, thus reducing the amount that finally percolated through the soil.

Application of clay alone also reduced water infiltration of the sandy soil. The mean differences of the soil amended with clays and unamended soil were significant ($P < 0.05$) except 2.5%K. The ranking of the ability of the clays alone to reduce infiltration was shown as $2.5\%K < 2.5\%B < 5\%B < 5\%K$. Statistically significant differences were also observed within the treatments of soil amended with clay alone (Figure 4-6).

The responses of infiltration volume to the two clay types were similar. For both clays, infiltration reduced as the quantity of clay applied increased. The differences in infiltration volume for both clays as a function of the rate of clay applied were significant ($p < 0.05$; Figure 4-6). The ability of 2.5%B to reduce infiltration was higher than that of 2.5%K, but vice versa at 5% clay rate, suggesting that effect of some properties of K such as dispersion must have been greater at the higher application rate.

The combined application of clay and Pt significantly reduced infiltration compared to that of the unamended soil. The reduction ranges from 16 percent in 2.5%K+20%Pt to 73 percent in 5%B+20%Pt. Among this treatment group, 5%B+20%Pt was the most effective at reducing infiltration, but this was not significantly higher than 5%B+30%Pt. The effect of clay application rate showed that for the two clay types used, infiltration reduced as clay content of the amendments increased, but there was no significant difference between the

2.5% and 5% clay rate within each clay type. This was similar to what was observed in the clay only soils. Comparing the Pt rate effect in the combined amendments, infiltration reduced as peat rate increased except in 5%K where infiltration was similar at the 20 and 30% Pt rate (Figure 4-6).

4.3.1.2 Infiltration after 30 minutes storm duration

Infiltration of the unamended and amended soils was also compared after 30 minutes storm duration. All amendments reduced infiltration volume compared to the unamended soil (Figure 4-6), and they were significantly lower ($p < 0.05$) except for the soil amended with Pt only at 20 and 30%. The observed performance of 20 and 30% Pt on infiltration volume at 30 minutes was slightly different from what was observed after 15 minutes storm duration, where infiltration at 30%Pt was significantly lower compared to that of the unamended control and 20%Pt level. This could mean that the potential of OM to reduce infiltration would only be pronounced at the beginning of a rainfall event. Thereafter, as the OM reaches its maximum water holding capacity, more water would infiltrate.

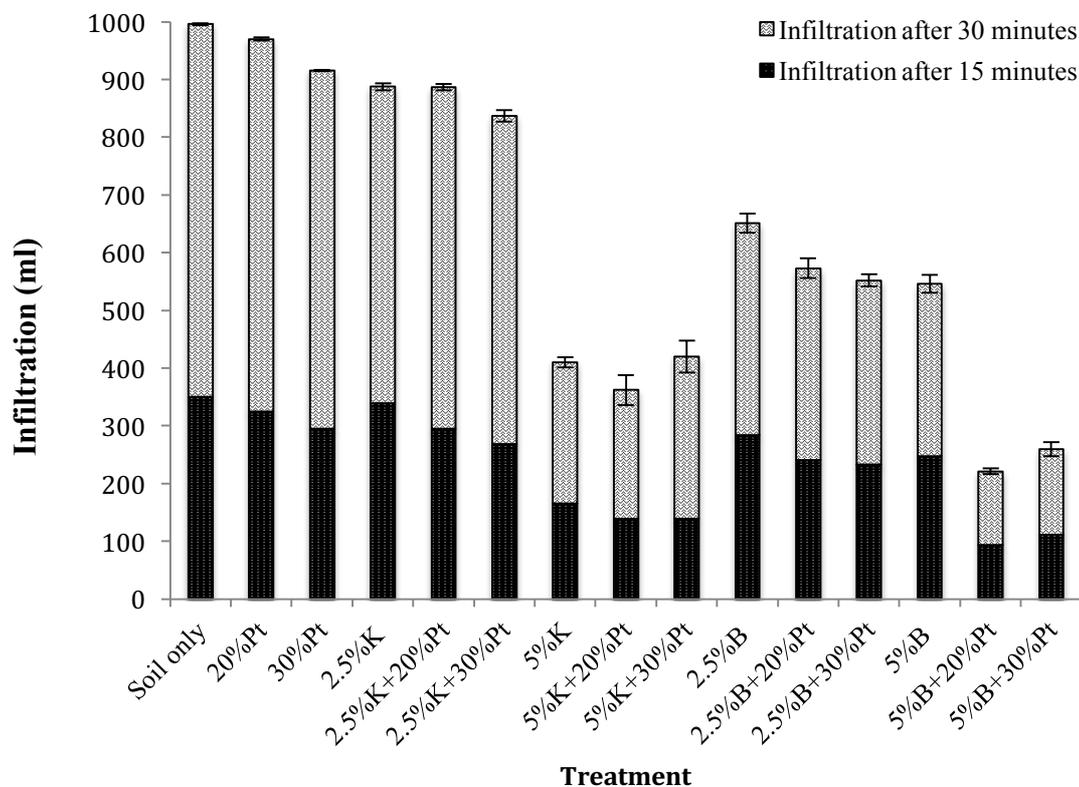


Figure 4-6: Infiltration volume as affected by clay type and application rate, and organic matter amendments at 15 and 30 minutes storm duration. Error bar = \pm s.e.m.

In soil amended with clay only, infiltration reduced significantly compared to the unamended soil except for 2.5%K. The ability of soil amended with 2.5%K to reduce infiltration was significantly lower ($p < 0.05$) than the rest of the clay only treatments. This was true at both storm durations, suggesting that at low application rates, K might not be a suitable amendment for infiltration reduction in sandy soils. Clay B was effective even at the low (2.5%) application rate (Table 4-1). However, the data did show that after 15 and 30 minutes, 5%K was most efficient at reducing infiltration, as its infiltration volume was significantly lower than the rest of clay only treatment (Figure 4-6), this does not support the test Hypothesis one that B will reduce infiltration than K. This is unexpected as the water absorption capacity of clay B is naturally higher than that of K (as shown in section 2.3.1.1; Table 3-6). This suggests that there might be other intrinsic or extrinsic factors (such as clay swelling and dispersion) controlling infiltration in soil of different clay types. Weight for weight at 5% rate, K reduced infiltration more than B, and vice versa at the 2.5% rate.

Also, the means of infiltration volume in 2.5%K and 5%K were significantly different, showing quantity effect. The results also showed that the hypothesis that increasing clay content would reduce infiltration in the sandy soil was valid. However, the amount of clay required to significantly reduce infiltration volume would vary, depending on the clay properties.

The combined application of clay and Pt also reduced infiltration of the sandy soil after 30 minutes storm duration, and the differences were significant ($p < 0.05$) compared to the unamended soil except for the 2.5%K + Pt treatments. Infiltration volume was higher at 30%Pt than 20% Pt when applied with 5% K and B. The differences between the two Pt rates at all clay rates for both clays were not statistically different. This suggests that applying higher quantities of Pt up to 30% when co-applied with clay might not be necessary when reducing infiltration in sandy soils. Comparing the two clays used, effectiveness to reduce infiltration volume increased with the clay content of the combined amendments. Also, at both clay application rates, B when co-applied with Pt was more effective than K. The observed results are possibly associated with greater interactions between Pt and B than K.

The observed results after 15 minutes storm duration support the hypothesis that an increase in OM would reduce infiltration of sandy soils. While this did not statistically hold after 30

minutes storm duration, the experimental data did show a reduction in infiltration volume as the Pt level increased. Also, when Pt was co-applied with clay, the hypothesis was only valid at the 2.5% clay level.

Table 4-1: Percentage change in infiltration volume as affected by the amendments

Treatment name	Infiltration volume (%)	
	15 mins	30 mins
Soil only	100.0	100.0
20%Pt	92.8	99.9
30%Pt	84.3	96.1
2.5%K	96.9	84.9
2.5%K+20%Pt	84.0	91.7
2.5%K+30%Pt	76.6	88.1
5%K	47.4	37.8
5%K+20%Pt	39.8	34.5
5%K+30%Pt	39.5	43.7
2.5%B	81.0	56.9
2.5%B+20%Pt	68.7	51.4
2.5%B+30%Pt	66.5	49.4
5%B	70.5	46.3
5%B+20%Pt	26.8	19.7
5%B+30%Pt	31.7	23.1

4.3.2 Effect of amendments on runoff

Similar to infiltration, runoff was measured at 15 and 30 minutes after storm events. Pt only and low clay rate did not increase runoff significantly compared to the unamended soil. Runoff increased in clay-amended soils at a higher rate. Combined clay and Pt increased runoff. The Relationship between runoff and infiltration was linear.

4.3.2.1 Runoff after 15 minutes storm duration

Addition of clay and OM increased runoff compared to the unamended soil. Soil amended with 20%Pt had the lowest runoff volume while 5%B+20%Pt had the highest. Significant differences were observed in the means of the samples ($P = <0.001$). Runoff in the unamended soil was not significantly lower than soils amended with Pt alone, 2.5%K and 2.5%K+Pt, 2.5%B, 2.5%B+Pt and 5%B. Also, no significant difference was observed between the means of Pt at 20 and 30% (Figure 4-7).

The runoff volume of all the soils amended with clay alone was not significantly higher than the unamended soil except for 5%K. Also, in soils amended with clay alone, only

2.5%K significantly reduced runoff. Runoff also increased as the clay rate increased. The difference in runoff between the two clay rates was significantly higher in K but not in B (Figure 4-7).

The combined application of clay and OM significantly increased runoff except in soil amended with 2.5% clay and combined 2.5%B+20%Pt. The highest runoff volume was recorded in soil amended with 5%B+20%Pt. At 2.5% clay rate, runoff increased with Pt volume, suggesting that at low clay rates, OM is the driving factor responsible for runoff control. However, when clay was increased to 5%, clay+20%Pt had higher runoff (Figure 4-7), demonstrating that this treatment combination had the least permeability.

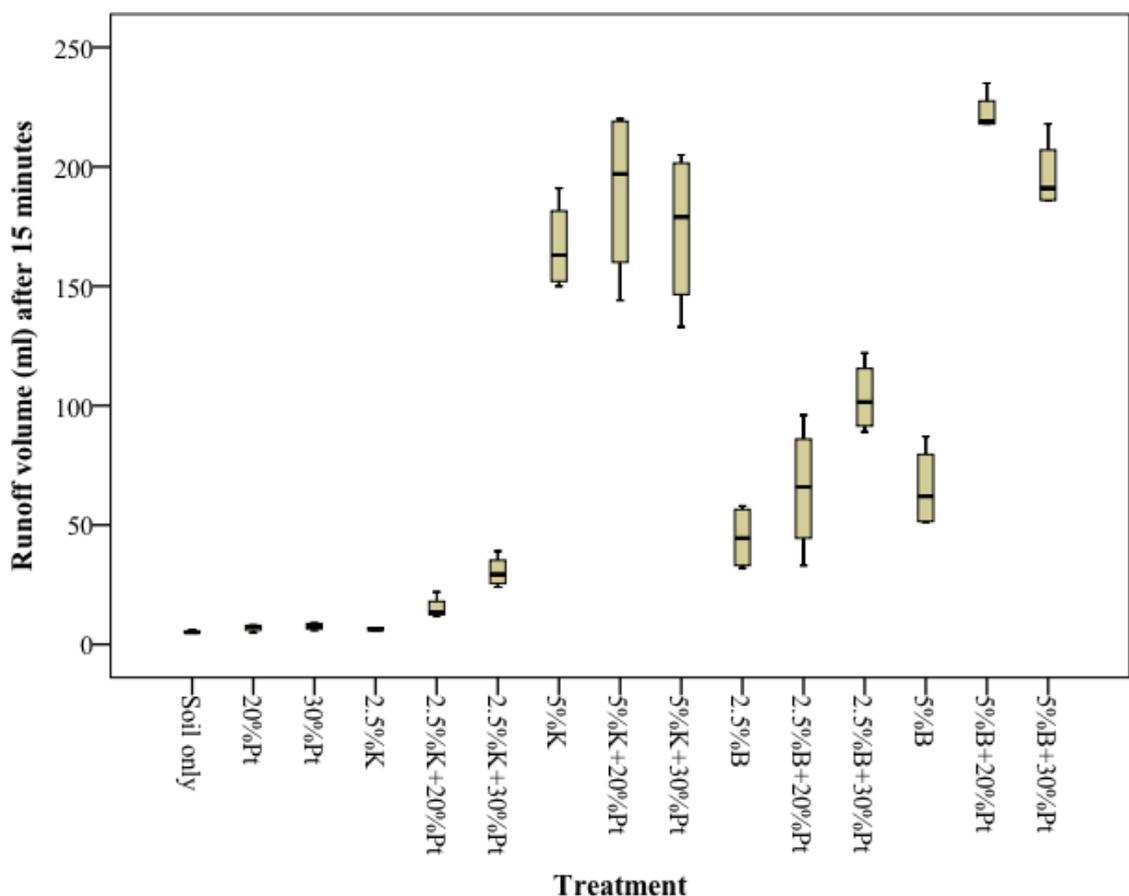


Figure 4–7: Runoff response to clay and OM amendment in sandy soils⁹.

⁹ The bottom and top of the rectangle of the box plot shows interquartile range; the middle line is the median; the whiskers are minimum and maximum values.

4.3.2.2 Runoff after 30 minutes storm duration

Runoff increased in all the treatments when storm duration was increased from 15 to 30 minutes. After 30 minutes storm duration, the response of the runoff to amendments varied. For instance, runoff from soil amended with Pt alone was statistically lower than that of the unamended soil. This suggests that increasing OM content of sandy soil could reduce runoff. Runoff from the soil amended with 2.5%K+Pt was not significantly different from the unamended soil, possibly because they had similar erodibility, while the rest of the treatments were significantly higher than unamended soil (Figure 4-8).

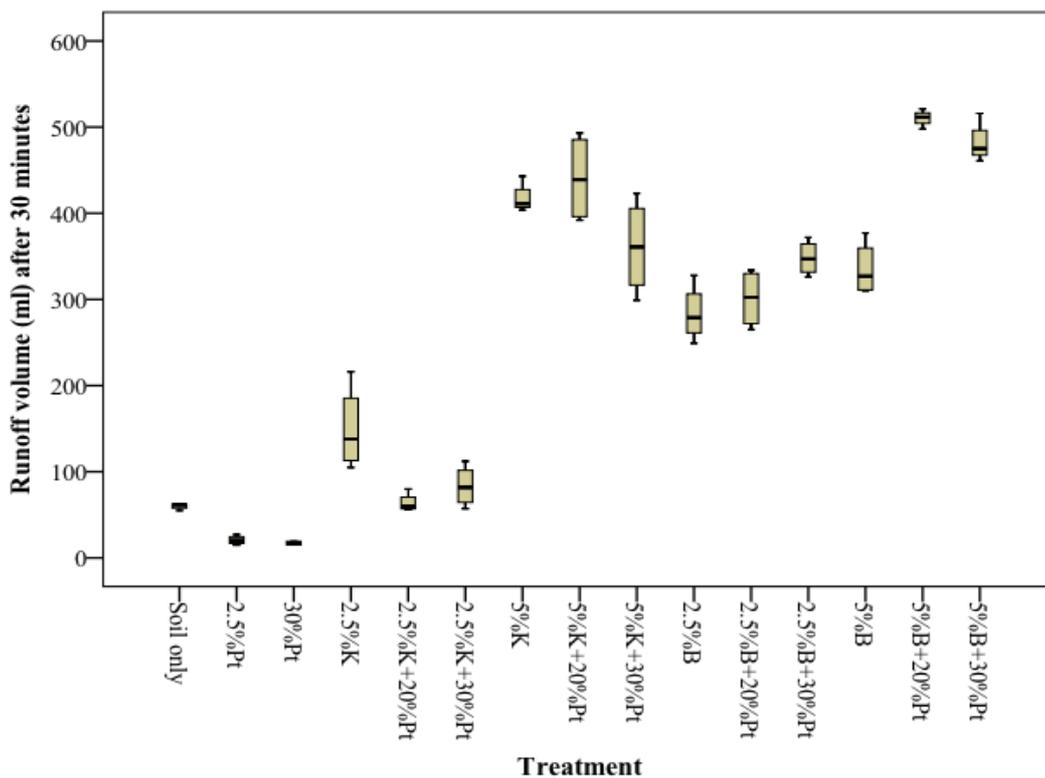


Figure 4–8: Runoff response to clay and OM amendment in sandy soils after 30 mins storm duration.

The runoff from all clay alone soils was significantly higher than that of the unamended soil. Among the clay alone treatments, 2.5%K was significantly lower than the rest. Highest runoff volume was recorded in 5%K amended soil, possibly because kaolin has a high dispersion rate, which might have resulted in the dispersed particles clogging the soil pores, thereby reducing infiltration while increasing surface runoff. Also, clay rate effects were observed because the runoff increased as clay application rate increased. Also, the differences in runoff generated between K and B rates were large and significant (Figure 4-8).

The combined application of clay and Pt increased runoff compared to the unamended soil, and only 2.5%K+Pt was not significantly different. Similar to 15 minutes storm duration, at 2.5% clay rate, runoff increased with Pt rate; however, at 5% clay rate, runoff of soils amended with 20%Pt, was higher than that of the 30%Pt rate. Among the combined clay and Pt treatments, the means of the 20 and 30%Pt treatments were significant in 2.5%B+Pt and 5%K+Pt amended soils.

4.3.2.3 Runoff response to peat rate in clay amended soils

Figure 4-9 shows the response of runoff generation to clay (type and application rate) and Pt additions. The unamended soil had the lowest runoff. Where Pt alone was added, runoff was similar to that of the unamended soil for the first 15 minutes. However, as rainfall duration increased to 30 minutes, the addition of Pt reduced runoff by up to 71%, compared to the unamended soil, showing the potential of Pt at reducing runoff in sandy soils.

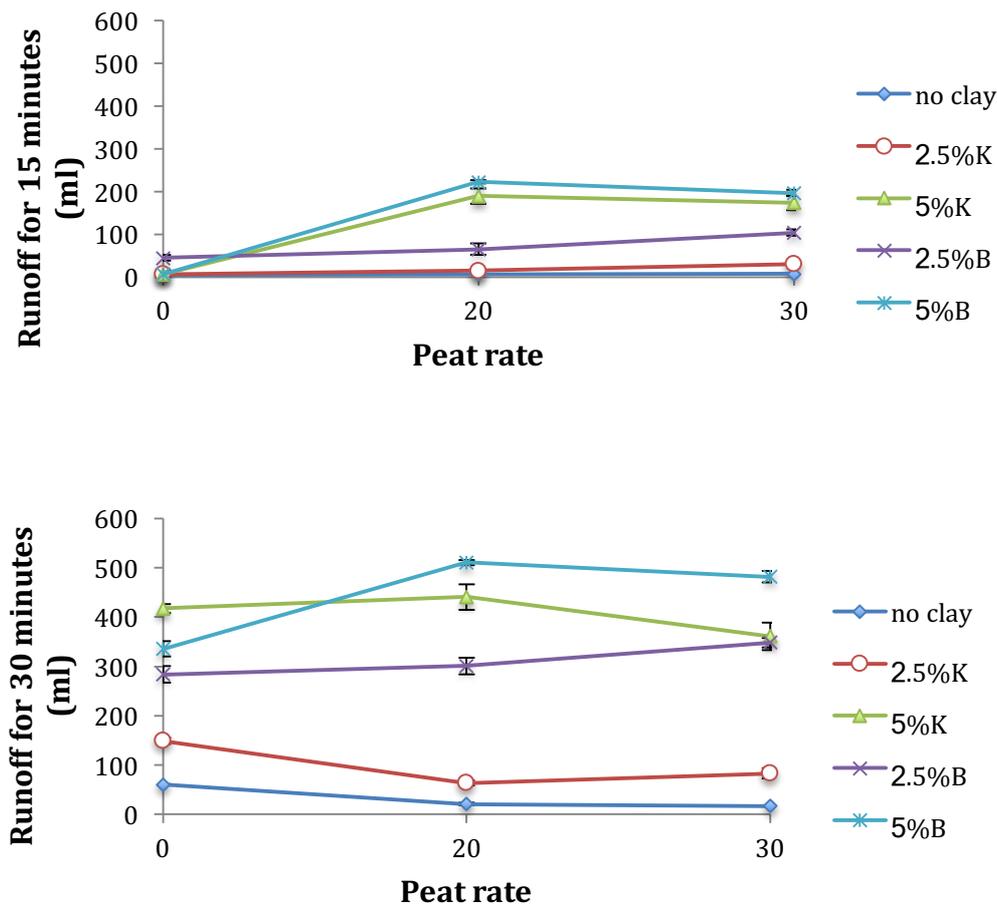


Figure 4-9: Runoff responses to peat rate in soil amended with different clay type and the rate at a) 15 mins and b) 30 mins storm duration. Error bar = ± s.e.m.

For the clay amended soils at the low application rate of 2.5%, the response for K was similar to that of the unamended soil as Pt increased, except for 30%Pt after 30 minutes. For 2.5%B, runoff increased with Pt rate over the two rainfall durations. At the 5% clay rate, within the first 15 minutes, the response of the two clays was similar, having higher runoff at 20%Pt, but reduced as Pt rate increased to 30%. The results after 30 minutes followed similar patterns (Figures 4-9 a & b). When combined with Pt applications, there was more runoff from the soil amended with B than with K at the same application rate. The increased runoff in soil amended with clay is associated mainly with a reduction in infiltration.

4.3.2.4 Interaction between infiltration and runoff

The relationship between infiltration and runoff was measured using the Pearson correlation and a linear regression model was fitted to the data. Figure 4-10 and Figure 4-11 show that there were negative strong significant associations between infiltration and runoff after 15 minutes ($r = -0.97$; $P < 0.01$) and 30 minutes ($r = -0.99$; $P < 0.01$), respectively. The very strong inverse relationship between runoff and infiltration was expected and suggests that soil management techniques that bring about reductions in infiltration would simultaneously increase surface runoff.

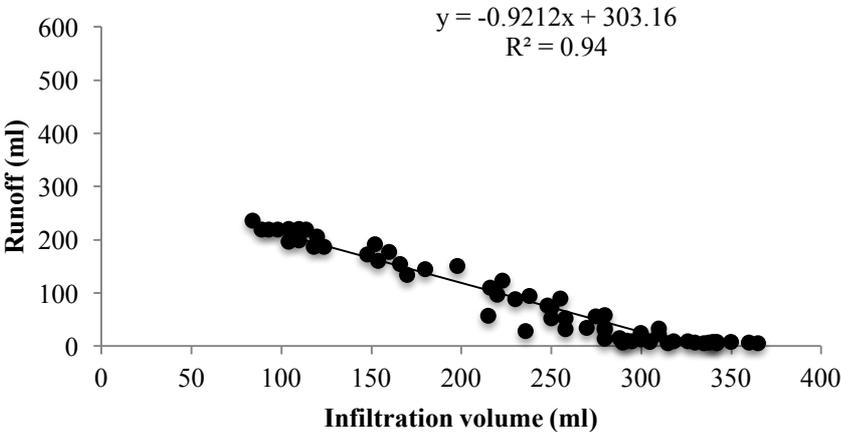


Figure 4-10: Relationship between infiltration and runoff at 15 mins storm duration

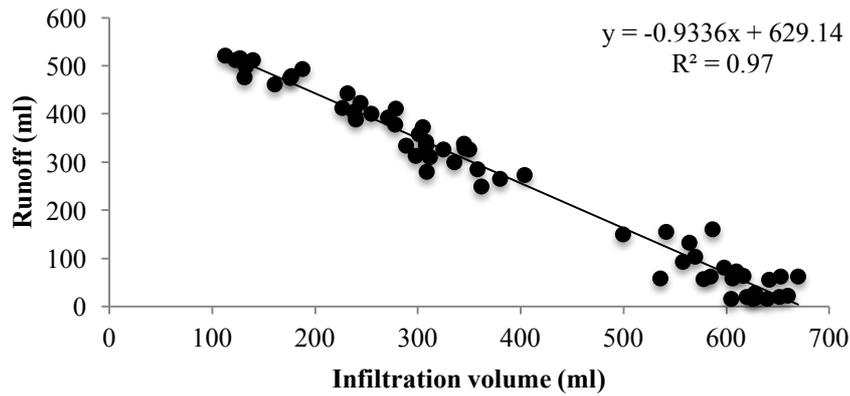


Figure 4-11: Relationship between infiltration and runoff at 30 mins storm duration

4.3.3 Effect of amendments on soil loss

Soil loss during the two rainfall events was measured. Pt only reduced soil loss after 30 minutes compared to the unamended soil. Soil loss was higher in B than K amended soils. Also, the relationship between runoff and soil loss tends to be exponential as rainfall duration increases.

4.3.3.1 Soil loss after 15 minutes storm duration

After 15 minutes storm duration, only soil amended with 20%Pt and 2.5%K+20%Pt reduced soil loss compared to unamended soil, but only soil loss in 2.5%B+30%Pt and 5%B+Pt was significantly higher than the unamended soil. The difference in soil loss between the peat rates was not significant.

Among the soils amended with clay alone, 2.5%K was most effective at reducing soil loss. Soil loss increased with clay rate, and the highest amount of soil loss was observed in 5%B but this was not significantly higher than 5%K. Comparing the two clay types, the soil loss response was similar at the same application rate (Fig 4-12).

The combined application of clay and Pt increased soil loss compared with unamended soil, but only significantly so at the 5% clay rate. For 5%K+Pt, there was no significant difference in soil loss as Pt rate increased. On the other hand, in 5%B amended soils, the soil loss at 20%Pt was significantly higher than at 30%Pt. It is noteworthy here that soil amended with 5%B+20%Pt had the highest runoff volume (Fig 4-7) and soil loss (Fig 4-12), suggesting that when amending soil with up to 5%B and OM combined, OM application rate should be above 20% to avoid an excessive runoff and soil loss.

4.3.3.2 Soil loss after 30 minutes storm duration

After the 30 minutes storm event, all amendments increased soil loss except Pt alone; however, only 2.5%B+Pt and 5%B+Pt were significantly higher than the unamended soil (Figure 4-13). In Pt alone soils, there was a small, non-significant increase in soil loss as Pt rate increased from 20%Pt to 30%Pt.

In soils amended only with clay, soil loss in 2.5%K was significantly lower than the rest. Highest soil loss was observed in 5%B soil, but this was not significantly different from 5%K. Soil loss response was similar in both clay types used because soil loss was not significantly different as clay rate increased from 2.5 to 5% (Figure 4-13).

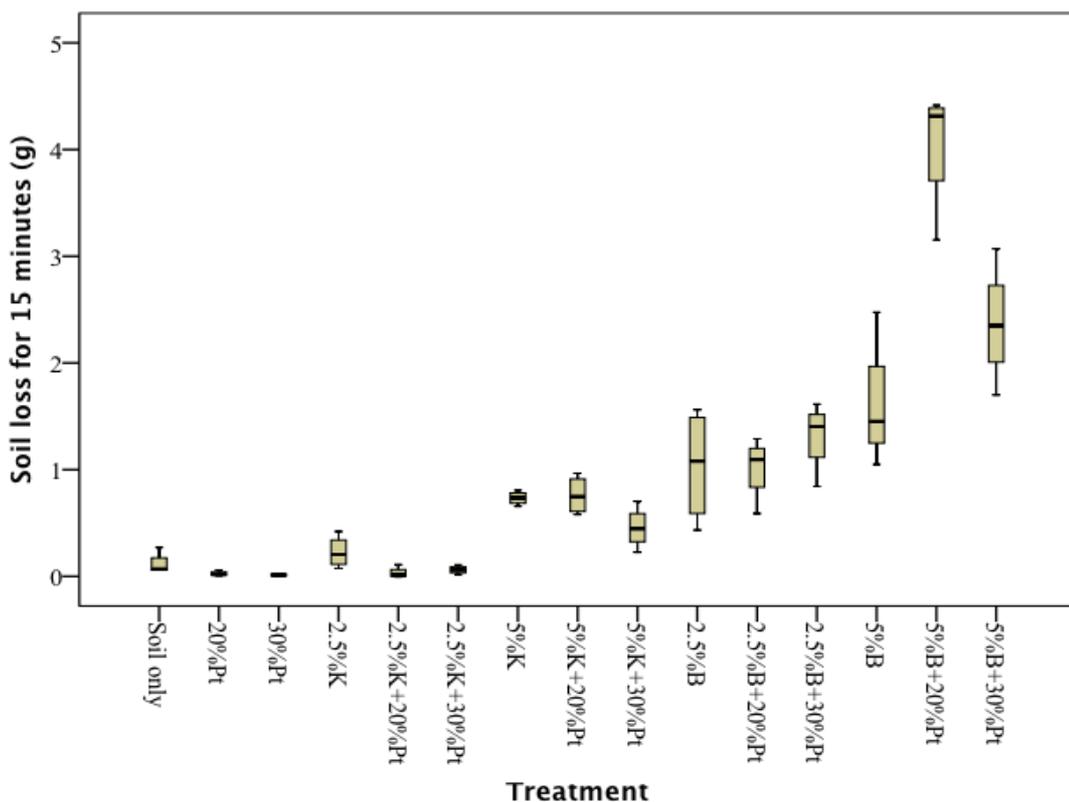


Figure 4–12: Soil loss response to clay and OM amendments in sandy soils after 15 minutes storm duration.

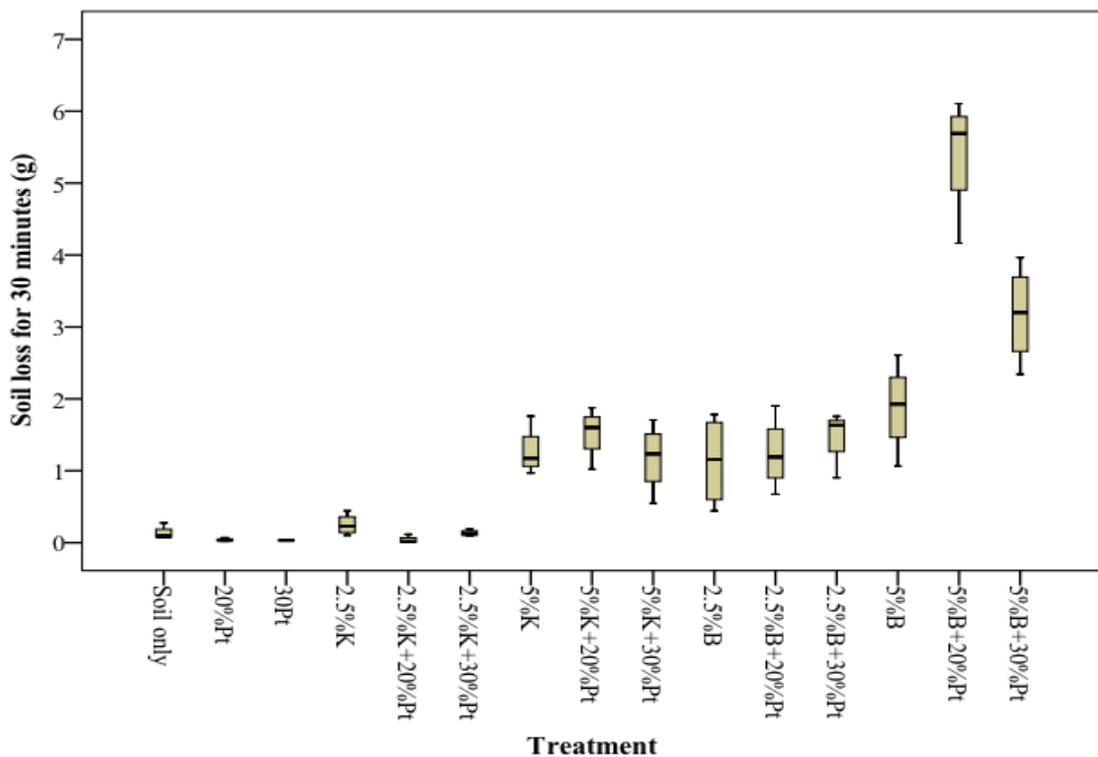


Figure 4–13: Soil loss response to clay and OM amendment in sandy soils after 30 minutes storm duration

Figure 4-14 shows the effect of the combined application of clay and Pt on soil loss after both the 15 and 30 minutes storms. Co-application of clay and Pt increased soil loss compared to the unamended soil. Highest soil loss was observed in soil amended with 5%B+20%Pt irrespective of the storm length. Also, the amount of soil loss was significantly higher in 5% clay and Pt than 2.5% clay and Pt soils. There was no significant difference in soil loss due to Pt rates in combined clay and Pt amended soil except 5%B+Pt, where soil loss was very high at 20% rather than 30%Pt after both storms.

4.3.4 Relationship between runoff and soil loss

To measure the relationship between runoff and soil loss, correlation analysis was used, and the regression line of best fit was fitted. Figure 4-15 shows that there was a positive strong significant association between runoff and soil loss after 15 minutes ($r = 0.89$; $p < 0.01$) and 30 minutes storm duration ($r = 0.79$; $p < 0.01$). This shows that about 89% and 79% of the soil loss in this experiment could be explained by runoff volume after 15 minutes and 30 minutes storm duration, respectively.

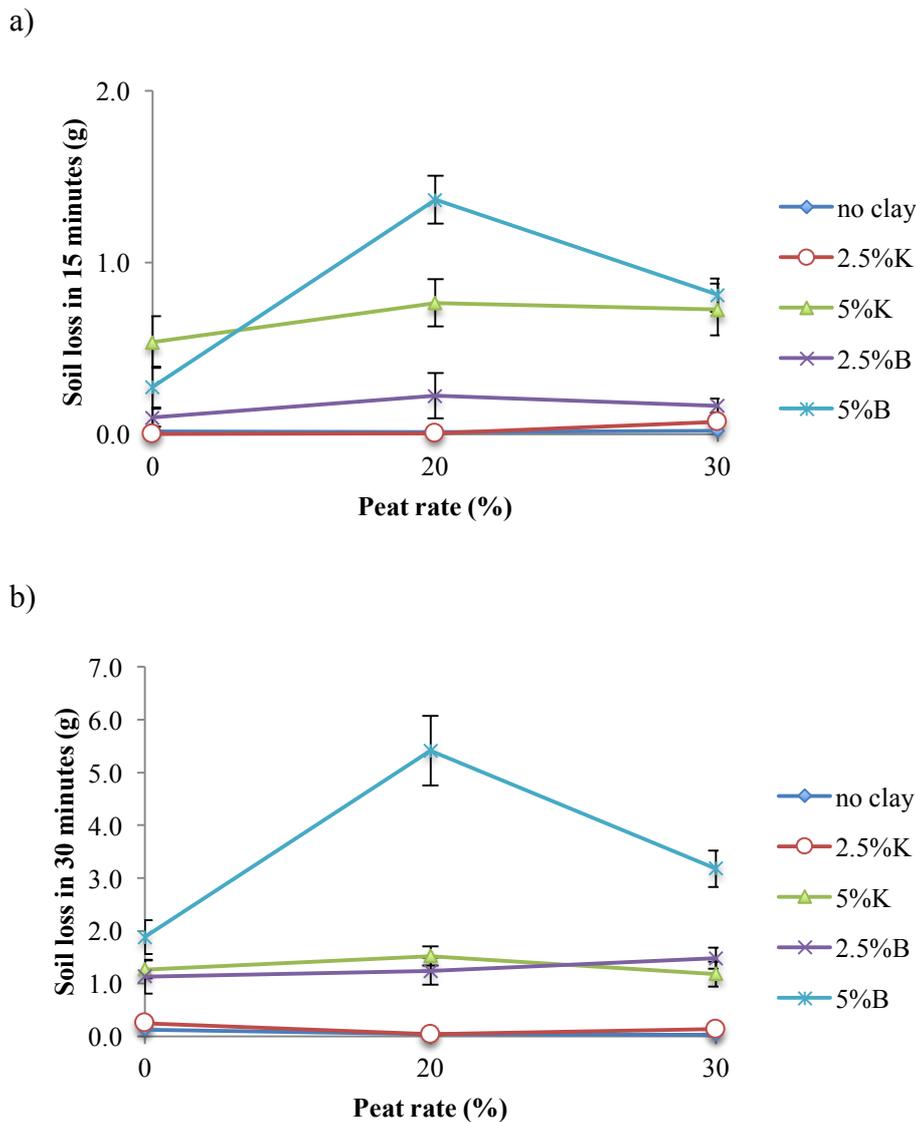


Figure 4-14: Soil loss response to OM application rate in sandy soil amended with clay and OM a)15 minutes and b) 30 minutes after storm duration. Error bar = \pm s.e.m.

Based on the form of the data distribution shown by a scatter plot, the obtained data were fit into linear and exponential models to predict the kind of interaction between the two variables. Runoff was the predictor (independent variable X) while soil loss was the predicted (dependent variable Y). After 15 minutes storm duration, both models showed that 80% of the observed data could be explained by a (positive) linear relationship while 75% could be explained by an exponential relationship (Figure 4-15). However, after 30 minutes storm duration, the linear model could explain only 63% of the data while 86% could be explained by an exponential relationship, suggesting that the relationship between runoff and soil loss tends towards being exponential as rainfall duration increases.

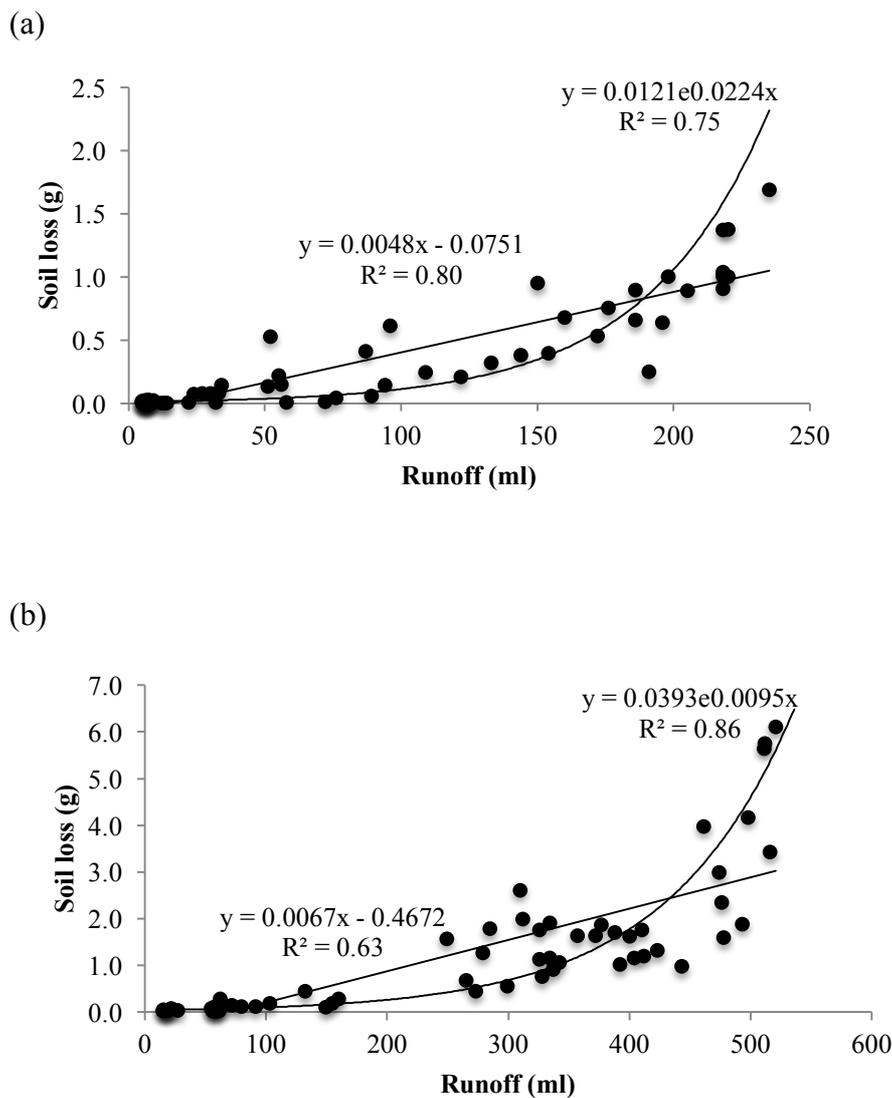


Figure 4-15: Relationship between soil loss and runoff in sandy soils amended with clay and peat at a) 15 minutes and b) 30 minutes after storm duration.

4.3.5 Interaction effects of combined applications of clay and OM

Table 4-2 shows the main and interaction effects of the amendments on infiltration, runoff and soil loss. After 15 minutes storm duration, the main effect of K was significant on infiltration, runoff and soil loss. The main effect of Pt in K amended soil was only significant on infiltration, but not on runoff or soil loss, suggesting that addition of Pt has no effect on soil loss and runoff in K amended soils. Interactions between K and Pt were not significant on infiltration, runoff and soil loss, indicating that the combined application of the clay and Pt had no change in effect on the measured parameters.

Table 4-2: Effect of interaction of clay and Pt on infiltration, runoff and soil loss

	df	Infiltration	Runoff	Soil loss
<i>15 minutes</i>				
K	2	5.08×10^{-18} ***	6.09×10^{-20} ***	1.17×10^{-10} ***
Pt	2	1.1×10^{-4} ***	0.250	0.392
K x Pt	4	0.308	0.490	0.610
<i>30 minutes</i>				
K	2	1.24×10^{-22} ***	1.39×10^{-4} ***	1.89×10^{-13} ***
Pt	2	0.672	2.07×10^{-23} ***	0.543
K x Pt	4	0.028*	0.003**	0.292
B	2	2.51×10^{-27} ***	1.66×10^{-26} ***	1.01×10^{-14} ***
Pt	2	5.11×10^{-9} ***	1.0×10^{-6} ***	3.20×10^{-5} ***
B x Pt	4	2.96×10^{-7} ***	8.33×10^{-10} ***	7.60×10^{-7} ***

* $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$

At 30 minutes storm time, the main effects of K on infiltration, runoff and soil loss were similar to the 15 minutes storm event with a significantly higher K effect. The main effect of Pt in K amended soil was only significant on runoff but not on infiltration or soil loss, suggesting that Pt did not affect how much water was infiltrated or the amount of soil loss compared to the unamended soil. The interaction between K and Pt was significant with respect to infiltration and runoff, but not soil loss, indicating that combined applications of K and Pt have synergistic effects on the amount of infiltration and runoff at the longer storm time, but there was no interaction effect of the two amendments on the amount of soil loss.

In B amended soils, the main effects of Pt and B as well as interactions between them when combined were significant for all the measured parameters for both storms. These results suggest that combined applications of B and Pt change the pattern of response on the amount of infiltration, runoff and soil loss. The main effect of Pt was not significant on most of the measured parameters in K amended soils, but was significant in B amended soils, suggesting that the function of Pt might change depending on the type of clay added to the soil. On the basis of the observed infiltration data, mechanisms responsible for the reduction in water infiltration in soil amended with K, B and OM was proposed (Figure 4-16) to provide a better understanding of how the amendments possibly reduce infiltration and increase water retention in the soil profile.

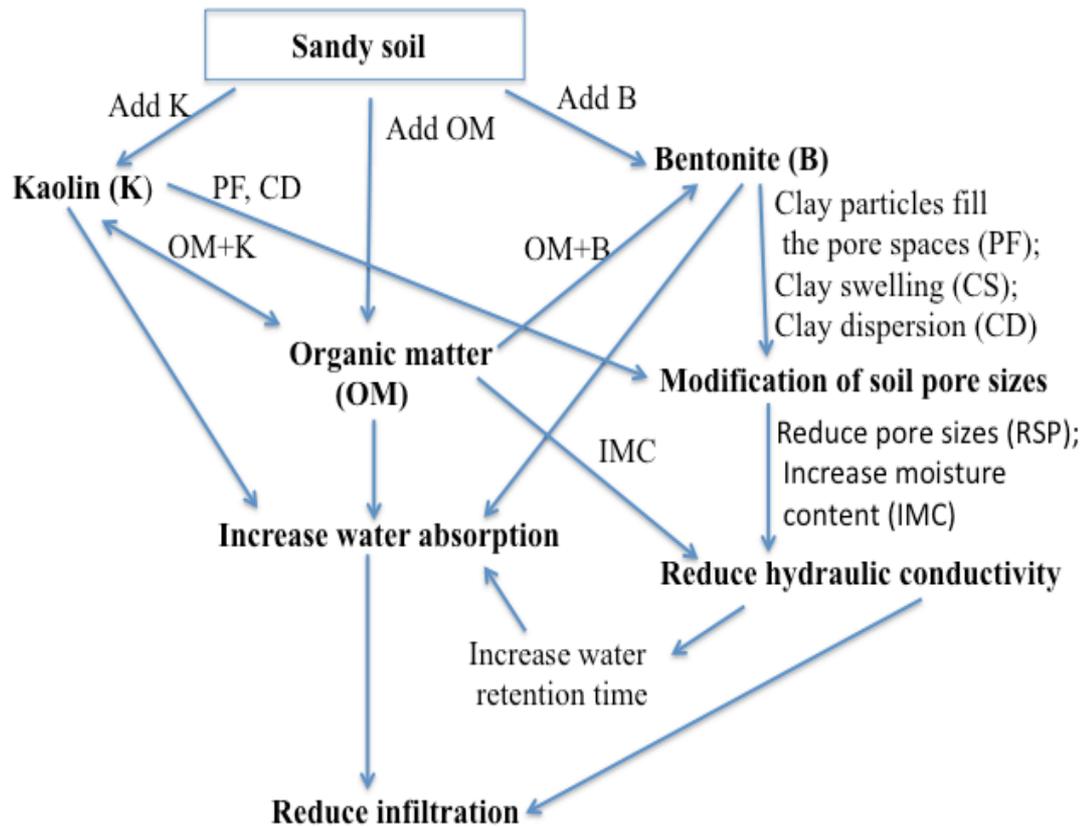


Figure 4-16: Proposed mechanisms for infiltration reduction in sandy soil amended with K, B and OM

The stronger interactions compared with K observed between B and Pt could be largely associated with high reactivity of clay B. This constraint reduces soil hydraulic conductivity of water and increases the time available for interaction between soil water, clay and OM. This, in turn, increases water absorption by clay and OM, hence reduces infiltration volume.

4.4 Discussion

4.4.1 Mechanisms for infiltration reduction in sandy soil amended with clay and OM

Addition of Pt had a small non-significant effect on infiltration reduction, suggesting that addition of OM on its own does not appreciably reduce water infiltration. The ability of Pt alone to reduce infiltration decreases as rainfall progresses, suggesting that over time during rainfall, Pt likely reaches its maximum water holding capacity, allowing more water to infiltrate. Infiltration reduction mechanisms in soil amended with Pt only would occur mainly as water absorption by the Pt and the reduction in soil hydraulic conductivity, which will increase the water retention period, and allow for absorption of more water. Addition of

Pt alone had little or no effect on reduction in overall soil pore size as OM has a wide range of particle sizes (the particle size of Pt used in this experiment ranges from 0-14mm), which could decrease or increase the initial soil pore size. This is evident in the soil characterisation experiment (Chapter three) where the application of Pt alone significantly increased the number of large macropores, total pore count, and soil porosity (see Table 3-5, Figures 3-15, 3-16 and 3-17). From this result, it could be concluded that the hypothesis that OM reduces water infiltration was not supported statistically, although the data did show a small reduction in infiltration as the amount of Pt increased.

Addition of B significantly reduced infiltration when applied alone or with Pt supporting the hypothesis that clay amendment would reduce infiltration. In the presence of the B amendment, reduction in infiltration might have been controlled by several mechanisms. The first mechanism is by pore modification because by having small particle sizes, B can fill the large pore spaces between sand particles and reduce them to either micro or mesopores. Also, when wet, B can swell and expand resulting in a reduction in the initial soil pore sizes and modification of pore geometry. This proposed mechanism is supported by the total pore count result (in Chapter 3) where the addition of 2.5%B and 5%B reduced the initial pore count by 61% and 33%, respectively (Table 3-5). The second mechanism is through water absorption. Due to high charge density and cation adsorption on B surfaces and interlayers, more water can be held against percolation, and this is supported by the result of soil moisture retention curves (Figure 3-18b and c in chapter three) where B showed higher water retention characteristics compared to the unamended soil and K. The third mechanism would be reduction in soil hydraulic conductivity (Frenkel and Levy, 1992; Hillel, 1998) associated with the reduced soil pore size and increased surface wetness. Although hydraulic conductivity was not measured in this experiment, theoretically it could be inferred that as the other two mechanisms above are effective, soil surface wetness will increase as rainfall progresses and soil hydraulic conductivity will reduce, hence, less infiltration. McNeal (1966, in Frenkel and Levy, 1992) reported a linear relationship between macroscopic swelling and reduction in soil hydraulic conductivity in an experiment conducted on an extracted clay from soil.

Addition of K reduced infiltration but this was only significant at the 5%K rate, suggesting that the proposed hypothesis that clay would reduce infiltration holds only at the higher K application rate. In the presence of K, infiltration reduction would be more to do with water absorption and reduced hydraulic conductivity (Frenkel and Levy, 1992) associated with

increased soil wetness, and pore modification possibly through pore filling and dispersion compared to B. The evidence that K has a smaller effect on pore size reduction is supported by the total pore count result in the soil characterisation reported by the previous experiment in this project where K reduced air-filled pores by 23%, that is 10% less than B at the same application rate (Table 3-5) and gave a higher porosity than B (Figure 3-16). The non-significant effect of K on infiltration reduction at the low K rate shows that the above mechanisms would only be effective when large quantities of K are applied. Murray (1999) wrote that some properties of kaolin such as the flow of dispersed particles in water are observed when kaolin is present in large quantities. Kaolin's ability to flow in water is owing to it having no structural charge deficiency and a relatively small specific surface area (Murray, 1999).

Contrary to the tested hypothesis, soil amended with 5%K significantly reduced infiltration more than 5%B after both 15 and 30 minutes storm duration. This higher reduction by K is probably linked to the dispersity of K particles. Kaolin is a highly dispersive clay compared to the calcium-based bentonite used in this experiment. McKenzie et al. (2002) wrote that spontaneous dispersion of clay occurs when interparticle space is increased to $>7\mu\text{m}$, and this hardly occurs in calcium-bentonite except if additional forces (e.g. mechanical dispersion such as shaking) are employed, which was not done in this experiment. This suggests that the B used would be relatively resistant to dispersion from rainstorms compared to K. Researchers have reported that in the presence of molecules that can balance the edge charges, kaolin would disperse readily in water (Frenkel and Levy, 1992; Murray, 1999; McKenzie et al., 2002; Nguyen et al., 2013). In an acidic soil medium, these molecules have been identified as organic and inorganic anions, which present naturally in the soil or through fertiliser application (Oades 1983 in Frenkel and Levy, 1992; Nguyen et al., 2013). The K amended soil has acidic pH, and the sandy soil used on these amendments has a long-term cropping history with fertiliser application, suggesting the presence of these anions which can stimulate K dispersion in the test soil. In the presence of the aforementioned soil conditions, coupled with K natural rheology, K dispersion would occur, and the dispersed K's particles would have flow with infiltrated water, clogged or partially blocked the pore spaces, hence reduced infiltration. Also, since the inherent clay present in the soil is bentonite, the combined effect of swelling of the inherent bentonite and the dispersion effect of K could also be responsible for the highest infiltration reduction observed.

When B is co-applied with Pt, strong positive synergy would develop in B, this is supported by a significant interaction between Pt and B at all application rates, and the infiltration reduction mechanisms in the system would be similar to that of soil amended with B alone. The stronger interaction observed between B and Pt could be largely associated with the high reactivity of clay B and high CEC. The presence of high CEC, the relatively large specific surface area, high charge density on clay and OM colloids, and presence of divalent cations such as calcium will increase water retention of B. The soil characterisation results showed that the CEC of combined K and Pt soils ranged from 22-24 cmol kg^{-1} , while that of B was 28 - 31 cmol kg^{-1} . As a result, if all other factors remained constant, the combined application of B and Pt would hold more water and reduce infiltration compared to combined K and Pt.

When K is co-applied with Pt, it appears there is less interaction, as the Pt x K effects in amended soils were not significant for infiltration, and the interaction effect is only significant at 30 minutes ($p \leq 0.05$), while interaction for B was significant even at $p < 0.001$, suggesting a less strong interaction of K and Pt. The reason for poor interaction between K and Pt might be because K has a low surface area, low surface charge and low CEC, compared to the B (Murray, 1999).

4.4.2 Effect of amendments on runoff

At the two storm durations used, there was a strong negative and significant relationship between runoff and infiltration. The negative relationship showed that one factor will increase as the other decreases, and the very high R^2 values (0.94 and 0.97 for 15 and 30 minutes storm duration respectively) thus suggest that up to 97% of the runoff response could be explained in terms of infiltration volume of the treatments.

Addition of OM reduced runoff as rainfall progressed compared to the unamended soil, and this is attributed to the ability of the OM to increase soil macroporosity, hence reduce the velocity and volume of surface runoff.

All clay amendments increased runoff compared to the unamended soil except 2.5%K after 15 minutes storm duration. The increase in runoff is possibly due to a reduction in pore size, surface sealing and clogging of pores by slaking, dispersion and flocculation of the added clays. Lee et al. (2015) reported similar results from a rainfall simulation experiment in a soil amended with 50kg ha^{-1} of polyacrylamide and attributed the increase in runoff volume

to clogging of soil pores by the added polyacrylamide. In K amended soil, the increase in runoff volume would be more of an effect of clay dispersion clogging the soil pores as clay rate increased, while it would be more of clay swelling in B amended soils.

4.4.3 Effect of amendments on soil loss

While other factors such as soil structure, soil texture, moisture content, erosivity of rainfall and erodibility of the soil play key roles in soil loss processes, the amount of runoff could also determine the quantity of soil loss.

Soil loss increased with storm duration, and this is associated with reduced aggregate stability. As soils become wetter, aggregate strength becomes low due to the weakening of Van der Waals and columbic forces between soil and water, along with simultaneous less cohesion forces between soil particles. This makes aggregates susceptible to dispersion. At this point, the impact of raindrop energy to detach primary soil particles could be significant. This could explain why soil loss increased from 15 to 30 mins storm duration.

Only the OM amendment reduced soil loss in both storms. Lee et al. (2015) observed a reduction in soil loss in soil amended with 10Mg/ha of biochar. Also, Sadeghi et al. (2015) showed that straw mulch and manure at 500g m⁻² and 300g m⁻² respectively reduced soil loss in a sandy loam. The ability of OM to reduce soil loss has been attributed to its capability to decrease rainfall and runoff detachment energy by buffering raindrop energy, resulting in the mitigation of particle detachment and soil pore sealing (Lee et al., 2015; Sadeghi et al., 2015). Also, Gossin et al. (2003) revealed that manuring could decrease total sediment load through a reduction in runoff volume.

Soil amended with 5%B+20%Pt had the significantly lowest infiltration, highest runoff and highest soil loss, suggesting that clay and OM synergistic effects on soil pore morphology were at their highest in this treatment combination. This might have resulted in a marked reduction in permeability, hence reduced infiltration and increased surface runoff generation and soil loss.

The relationship between soil loss and runoff tended toward the exponential rather than linear as rainfall progressed. The stronger R² value for the exponential relationship at 30 minutes could mean that there exists some non-linear relationship between runoff and soil

loss. Thus, this suggests that as rainfall progress, soil loss would increase exponentially after a given threshold of runoff has been reached. According to Hillel (1998), during rainfall, two opposing forces – retarding forces and motive forces - control soil losses. The retarding forces include the gravity force which includes the particle weight, the frictional forces and the cohesion forces between the particles in a soil matrix formed by electrochemical bonding or as a result of cementation by OM or other binding agents. The motive forces include lateral drag that is acting on the surface and vertical force which tends to push the particles off surfaces. During runoff, particles are lifted by hydraulic forces into a “low-pressure flow domain”, and are then carried away by the runoff when the motive forces overcome the retarding forces. This may explain the exponential relationship between runoff and soil loss. The exponential increase in soil loss possibly would begin when the runoff volume and kinetic energy is high enough to significantly increase the motive forces (lateral, vertical and hydraulic lift forces) over retarding forces (gravity, frictional and particle cohesion forces).

4.4.4 Interaction effects

The interaction effect of K and Pt on infiltration and runoff was only significant at 30 minutes, while that of B and Pt was significant for both storms with higher probability ($p < 0.001$). The higher interaction between B and Pt is likely associated with B physicochemical properties. This was true for runoff and soil loss. K and Pt interaction has no effect on soil loss, suggesting that combined application of kaolin and OM does not create a synergistic or antagonistic effect on the amount of soil loss in the soil system.

Generally, all clay amendments increased soil loss, and this is attributed to particle loss from the added clay materials, which are not yet aggregated. It is therefore believed, that this result likely represents a temporary observation of soil condition immediately after clay amendment, and that runoff and soil loss would reduce as soil structure and stable aggregates develop. Future work should focus on monitoring the effects of these amendments over the longer term. The current results thus demonstrate that the addition of amendments especially up to 5%K and $\geq 2.5\%$ B with or without OM have potential to reduce infiltration and percolation in sandy soil and increase water retention for crop uptake if cropped.

4.5 Conclusion

Addition of peat alone had no effect on the infiltration and runoff but reduced soil loss compared to the unamended soil. Clays reduced infiltration volume, and 5%K was the most effective, thus the hypothesis that B will be most effective was not confirmed. Combined application reduced infiltration in the B amended soil compared to the clay alone, but not in K, showing that clay minerals behave differently in the soil. Contrary to the prediction that 5%B+30%Pt will have the lowest infiltration, the soil amended with 5%B+20%Pt was the least permeable with 80% reduction in the infiltration compared to the unamended soil. The relationship between runoff and infiltration was negatively linear, while that of runoff and soil loss tended to be exponential ($R^2 = 86$) after 30 minutes of a rainfall event. Infiltration increased while runoff reduced with increasing clay rate.

The current results showed that amending with clay or combined clay and peat have the potential to reduce water loss through deep percolation, thereby increasing water availability within the upper soil layer. The robustness of this result under field condition will be examined in the next chapter. Also, the ability of the amendments to increase growth and yield of spring wheat will be investigated.

Chapter 5

Effect of amendments on yield of spring wheat and soil nutrients: Field Trial

5.1 Introduction

Field trials provide an opportunity to measure the performance of techniques in an agricultural context and under natural climatic conditions. While controlled environment experiments allow an evaluation of an intervention or treatment, they cannot replicate real-life behaviour, because factors such as rainfall, pests, diseases and temperature, which could introduce significant differences, are excluded. Therefore, field trials provide a validity test for laboratory and glasshouse experiments.

Use of amendments and/or fertilisers to achieve an adequate nutrient supply and optimum crop yield is inevitable (Baligor et al., 2001). The role of OM in soils has been discussed in section 1.1.8.1 (Chapter one), and their benefit as a sandy soil amendment in section 1.1.8.2. Nutrient from inorganic fertiliser and organic amendments applied to soils sometimes are not directly available to crops. Rather, they are subjected to various processes such as solubilisation as a result of soil pH, mineralisation and immobilisation by soil organisms, leaching as well as fixation depending on the soil type and clay minerals (FAO, 2005). Given the complex soil reactions that affect nutrient availability in soils, it is necessary to combine information from soil and plant responses in order to get a better understanding of nutrient retention in soils.

Different approaches used in monitoring added soil nutrients include direct soil sampling following application, use of isotopic labelled organic and mineral fertilisers or elements, remote monitoring, plant analyses and measuring of leaching rate (IAEA, 2001; Kim et al., 2009; Zu et al., 2014). The last two methods are used as proxy measurements of soil nutrient concentration or utilisation by the plant. Direct sampling is a conventional method involving extraction and detection of nutrient concentration from soil samples in laboratories. The main limitation is that it gives mainly information on the soil condition at the time of sampling. Also, it is a destructive method. Nevertheless, it is one of the

commonly used and reliable methods for assessing soil nutrients. Also, it can be used for detecting soil total and available nutrients as well as nutrient deficiencies.

The fate of nutrients applied to the soil can also be monitored using isotopic labels. This is a direct method of determining nutrient uptake from added fertilisers by using stable isotopes or radioactive isotopes. The underlying assumption for using labelled element is that both the label and the carrier would be affected equally by the processes occurring in the soil-plant system (FAO, 2001). This method allows for estimation of the fraction of added fertiliser that is taken up by the plant and can be used for the formulation of fertiliser management. The main limitations are the extra cost of analysis compared to the unlabelled nutrients and the concern for environmental safety when radioactive isotopes are used.

In a review, Kim et al. (2009) grouped remote sensing of soil nutrients into optical sensing and electrochemical sensing methods. Optical sensing detects spectroscopically the energy reflected or absorbed by a nutrient ion and soil particles, while electrochemical sensing measures voltage generated by an ion-selective electrode in response to the activity of the ion of interest (Kim et al., 2009). The limitation of the spectroscopic method is that it is only effective at detecting total soil nutrients but less sensitive to the plant available fractions because it is difficult to calibrate the reflectance sensitivity to accurately detect these concentrations compared to conventional methods (Kim et al., 2009). Also, spectroscopic methods can be affected by different soil conditions and soil types. Limitations associated with electrochemical sensing include a slow and incomplete extraction process, frequent calibration to correct for drift of signals, as well as less durability of electrodes (Kim et al., 2009).

Kaiser et al. (2013) wrote that plant analysis can be used as a monitoring or diagnostic tool to provide information about the relationship between plant nutrient status and the fertiliser used. Plant analysis has been used extensively as a diagnostic tool to monitor soil nutrient condition. In that case, nutrient concentration in a crop is compared to a baseline value to determine if it is optimal and, on the basis of that, a decision to apply fertiliser can be made. In addition, as a monitoring tool, plant nutrient concentrations can be used to calculate nutrient use efficiency or nutrient uptake.

In order to understand the potential of clay and organic matter amendments on soil nutrient retention and crop yield under normal environmental conditions, a field trial was set up to

investigate the performances of some selected treatments. In this experiment, plots were fertilised using non-isotopic fertiliser, and direct soil sampling (twice) was used along with plant nutrient analysis to monitor soil nitrogen, P and potassium retention/utilisation.

5.1.1 Objectives and hypotheses

The main objectives were:

- 1) To understand nutrient retention in a sandy soil amended with clay and OM under field conditions compared with an unamended soil.
- 2) To test the ability of the system to support crop growth, and to evaluate any yield improvement.
- 3) To compare the effectiveness of OM, kaolin (K) and bentonite (B) as well as combinations of the clays and OM at varying rates as sandy soil amendments.

Hypotheses

The following are the test hypotheses:

- 1) That clay and OM would increase water and nutrient retention in a sandy soil.
- 2) That amending sandy soil with OM, clay and clay-OM mixes would increase the yield of spring wheat (the test crop) compared to unamended soil, and that the increase will be greater as OM and clay rates increase. This is based on the assumption that clay and OM will increase the soil CEC, carbon and water retention which are essential for improved crop biomass.
- 3) That the effects of bentonite on water and nutrient retention as well as crop yield would be higher than that of kaolin based on their mineralogical composition.

5.2 Materials and methods

5.2.1 Soil collection and soil treatments

Chapter five was an extension of experiment presented in chapter three. The soil and amendments used in this experiment were the same as described in Chapter 3, and the full description of the field trial is given in section 3.2.1 and 3.2.2. The treatments used are shown in Table 3-1 but repeated in Table 5-1 for convenience. There were 12 treatments, each with five replicates giving a total of 60 experimental units. The B application rates were 0, 2.5% and 5% (w/w), K application rate were 0 and 5% (w/w), while that of Pt were 0, 20 and 30% (v/v). The 2.5%K rate was not used as it was evident it had low water

retention capacity (Chapter two) and had no effect on infiltration optimisation (Chapter 4) compared to the control treatment.

Table 5-1: Selected treatments for field trial

	Treatment name
1	Soil only
2	20%Pt
3	30%Pt
4	5%K
5	5%K+20%Pt
6	5%K+30%Pt
7	2.5%B
8	2.5%B+20%Pt
9	2.5%B+30%Pt
10	5%B
11	5%B+20%Pt
12	5%B+30%Pt

5.2.2 Installation of soil moisture probes

Soil moisture probes (Theta probes and SM 200 manufactured by Delta-T Devices Ltd.) were installed on March 23, 2016. A small section of the soil was cut to a depth of 25 cm using a trowel, and probes that had been connected to a data logger earlier were carefully inserted into the soil mass horizontally and covered firmly with the same soil. Three of each treatment's five replicates were randomly selected for probe installation.



Figure 5-1: Moisture probe inserted into the soil

5.2.3 Data collection on soil

5.2.3.1 Soil moisture

All lysimeter were sampled monthly to determine soil moisture content. Soils were sampled using 2mm diameter soil auger to the depth of 20cm (except during the dry period in July 2016). Subsamples were weighed as fresh weight and then oven dried at 105⁰C overnight. Soil moisture content was determined gravimetrically as the difference between the weight of wet and oven-dried soil. In addition, data from the soil moisture probes were downloaded every two or three weeks.

5.2.3.2 Soil chemical analyses

Total N was determined using the Dumas method modified by Sweeney (1989). Inorganic nitrate and ammonium nitrogen were determined as 2M KCl extractable nitrogen by modifying the method described in RB427 (1985). A sub-sample of 20g of soil and 100ml of KCl were used. Available P was estimated following the method of Olsen et al. (1954). Soil-available K was determined by extracting 10g of 2mm sieved air-dried soil with 50ml 1M ammonium nitrate (RB427, 1985). Total P and potassium were measured by the microwave aqua regia digestion method (British Standard BS 7755: Section 3.13:1998; ISO 11047:1998) with 0.5±0.001g of 0.6mm sieved air-dried soil extracted with a mixture of nitric acid and 30% hydrogen peroxide used for the digestion. The extract was filtered and made up to 100ml using RO water. Total P was measured using a spectrophotometer (880nm) while potassium was measured using atomic emission spectrometry. Soil extracts for the three available macronutrients were frozen on site at the University of Warwick, Wellesbourne campus, and stored until analysis at Cranfield University Analytical Laboratory, UK.

5.2.4 Plant data collection

Detailed information about wheat sowing, agronomic practices and harvesting is presented in chapter 3 (Materials and methods).

5.2.4.1 Plant vigour

Plant vigour was measured twice using a GreenSeeker Handheld sensor (Trimble Navigation Ltd.). This instrument measured normalized difference vegetation index (NDVI) using remote sensing. The sensor measured the ratio of reflectance of light at near-infrared and red region to the incoming radiation from sunlight or a light spectrum and has value

ranges from 0 to 1, with the 0 representing a bare soil (Pietragalla et al., 2012; Li et al., 2014). The vigour and /or greenness of crops is taken as increased with the NDVI value. The measurements were taken at (1) Growth stage 29 (GS29) which marks the end of wheat tillering and the initiation of stem elongation; and at (2) Growth stage 39 (GS39) which is the onset of the reproductive stage marked by a visible flag leaf.

5.2.4.2 Plant height and biomass yield

Plant height and shoot biomass yield were assessed at the onset of ear formation (GS51). This growth stage marks the end of the vegetative growth and the beginning of seed development. Ten plants were harvested from each lysimeter. Plants were grouped into three (long, medium and short) heights and measured with a ruler from the root crown to the base of their flag leaf. Data for each plot was presented as the mean of the three height groups.

For fresh shoot weight, 10 plants were randomly selected per plot. The roots were cut off from the crown, and the shoot weighed. The shoots were then washed in RO water to remove any soil particles and pesticide residues before being oven dried at 70⁰C for 2 days. Dried samples were then weighed to determine shoot dry weight (dry matter yield).

5.2.4.3 Total ear weight and thousand grain weight (TGW)

At maturity, all the ears from each plot were clipped just below ear stalk and weighed. For TGW, ears were shredded and subsamples were cleaned manually to remove chaff. One hundred clean whole seeds were randomly counted from each plot, and multiplied by 10 to get the thousand-grain weight (RB427, 1985).

5.2.4.4 Plant nutrient uptake

Dried shoots were milled and kept in polyethene bags for analyses of plant nitrogen, phosphorus as well as potassium concentrations, the data were used to calculate nutrient uptake for the three nutrients. Total N was determined using the Dumas method modified by Sweeney (1989). To determine total N, 0.5 ± 0.001 mg milled plant samples were weighed and tightly packed into small square aluminium foil, before total N was measured by thermal oxidation in the presence of copper reductant that converted all nitrogen oxides to elemental nitrogen. The amount of nitrogen is then measured by a thermal conductivity detector (TCD). Total phosphorus and potassium were measured by microwaves aqua regia digestion method (British Standard BS 7755: Section 3.13:1998; ISO 11047:1998) using

0.5±0.001g plant samples extracted with a mixture of hydrochloric and nitric acids before digestion. The extract was filtered and made up to 100ml using RO water. Total phosphorus was measured using a spectrophotometer while potassium was measured using atomic emission spectrometry. All plant analyses were carried out at Cranfield University Analytical Laboratory, UK. Plant uptake was determined as the product of dry matter (in kg) and total nutrient concentration (mg/kg).

5.2.5 Statistical analysis

The values presented in this report are means of five replicates. One-way ANOVA was used to determine significant differences between the treatments, and means were separated using the least significant differences (LSD) at $p \leq 0.05$. The interaction effect of clay and Pt on soil moisture retention was determined using a general linear model ($p < 0.05$). The relationships between initial and final soil nutrient concentrations were determined using a paired t-test.

5.3 Results

5.3.1 Soil moisture content

Soil moisture contents (MC) were determined gravimetrically once a month for 12 months. The average MC for all the treatments from February 2016 to January 2017 is shown in Table 5-2. Amendments increased soil moisture contents in all the treatments compared to the unamended soil, and the increases were significant except in soils amended with 5%K and 2.5%B. The main effect of clay and Pt was significant ($p < 0.001$), and their interaction was also significant ($p = 0.046$), suggesting that there is the synergistic effect of the two combined amendments on soil MC.

The Pt alone amendment increased soil MC compared to the unamended soil, and the mean of 30%Pt was significantly higher than that of 20%Pt, indicating a strong Pt rate effect. Addition of 20%Pt significantly increased soil MC compared to 5%K and 2.5%B while 5%B only produced a non-significant increase compared to 20%Pt. However, 30%Pt significantly increased MC compared to all of the clay alone treatments, indicating that application of 30%Pt alone retained more water than any of the clays alone.

All of the clay-amended soils increased MC over that of unamended soil but it was not significant with 5%K or 2.5%B for which moisture retention was similar, while that of 5%B rate was significantly higher than both of the latter. Comparing the two clays, B retained more water than K, possibly as a result of its high reactivity.

The combined application of clay and Pt increased soil MC in all of the treatments compared to the unamended soil, clay alone as well as Pt alone (at the equivalent rate), and the increase was significant except in 5%K+30%Pt plots which were not significantly higher than 30%Pt. The result thus shows that combined application of clay and Pt is more effective at improving MC of sandy soils compared to the single application except in soil amended with K when OM rate is above 20%.

Table 5-2: Effect of clay and peat amendments on mean gravimetric soil moisture content

Treatment	Mean soil MC in 12 months (%)	Mean difference	% Increase in mean MC due to amendment
Soil only	12.7	0.0	0.0
20%Pt	14.3*	1.60	12.6
30%Pt	15.9*	3.17	24.9
5%K	13.2	0.42	3.3
5%K+20%Pt	15.6*	2.89	22.7
5%K+30%Pt	16.5*	3.78	29.7
2.5%B	13.4	0.67	5.3
2.5%B+20%Pt	16.5*	3.73	29.3
2.5%B+30%Pt	17.3*	4.60	36.1
5%B	14.6*	1.84	14.5
5%B+20%Pt	17.1*	4.34	34.0
5%B+30%Pt	18.9*	6.17	48.4
LSD	0.73		
SE	0.36		

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error of the mean.

5.3.2 Monthly moisture content

Data for monthly MC is presented in Figure 5-2. All data showed seasonal variability in MC with lowest values in summer (June to August 2016). Generally, monthly moisture contents increased in all the amended soil compared to the unamended soil in all the months except occasionally in the 2.5%B alone treatment, and more frequently in the 5%K alone.

Also, amendments increased MC over that of the unamended soil in the driest month, suggesting improvement in soil water storage during dry or drought period.

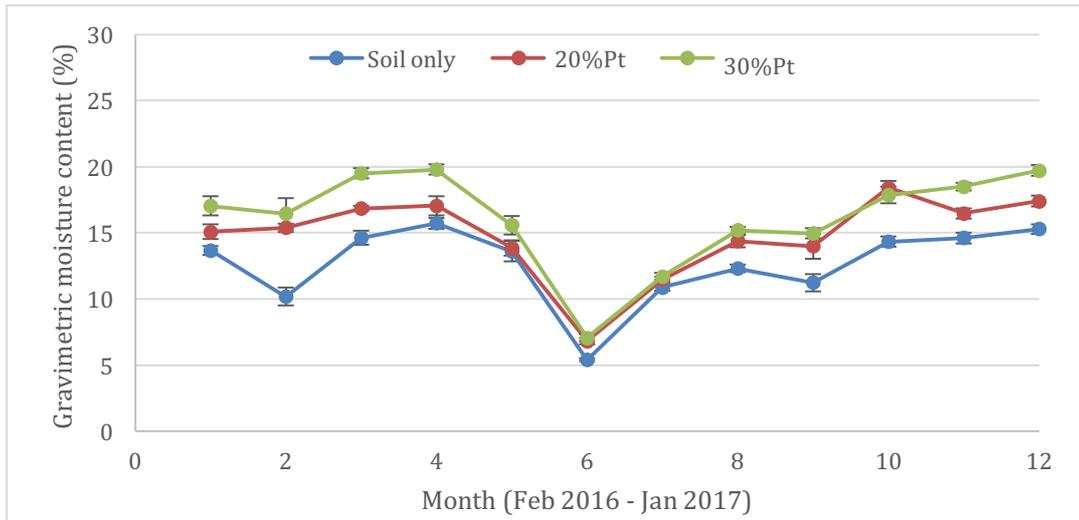
In soil amended with Pt alone, all amendments increased MC compared to the unamended soil. During the dry months, the difference between 20 and 30%Pt was smaller but increased as the soil MC become higher (Figure 5-2a).

In soil amended with 5%K, there was variability in the MC of unamended soil and that of 5%K alone over months. The combined application of K and Pt increased MC compared to K alone and the unamended soil. Soil moisture retention pattern was different in 5%K + Pt treatments compared to Pt alone. Combined additions of 5%K with 30%Pt increased MC compared to 20% from February 2016 to May 2016 (wetter months), but at the onset of summer in June 2016, MC became similar in both treatments. Thereafter 20%Pt increased MC over 30%Pt in these combined treatments as the soils become drier (July to November 2016), but the condition reversed again as the weather become wetter in December (Figure 5-2b). This result suggests that addition of 20%Pt to 5%K might be sufficient to improve MC of sandy soils, especially under dry or droughty weather conditions.

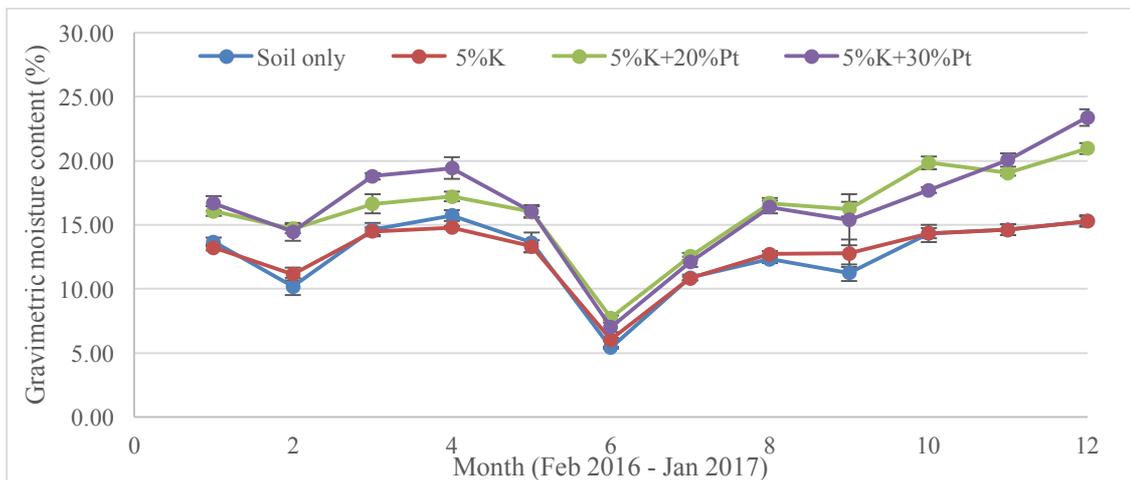
In 2.5%B soils, clay alone increased MC compared to the unamended soil except in February, June and August 2016, whereas combined clay and Pt increased MC compared to the clay alone in all cases. Similar to combined 5%K treatments, soil MC increased in 2.5%B + 20%Pt more than 30%Pt from September to November 2016, while the 30%Pt was higher in the rest of the months (Figure 5-2c). The increase MC observed in September to November might partly be associated with a re-wetting problem of peat after drying, which might have been more pronounced at a higher Pt rate or it may partly be associated with increased porosity.

In 5%B, amendment increased soil MC over the unamended soil in all the treatments for the whole 12 months. Also, the combined application of clay and Pt increased MC compared to clay alone, and 30%Pt had a higher MC over 20%Pt throughout the measuring period (Figure 5-2d), suggesting that the higher B rate overcame any possible rewetting effect of 30% Pt in the combined treatment at the onset of winter.

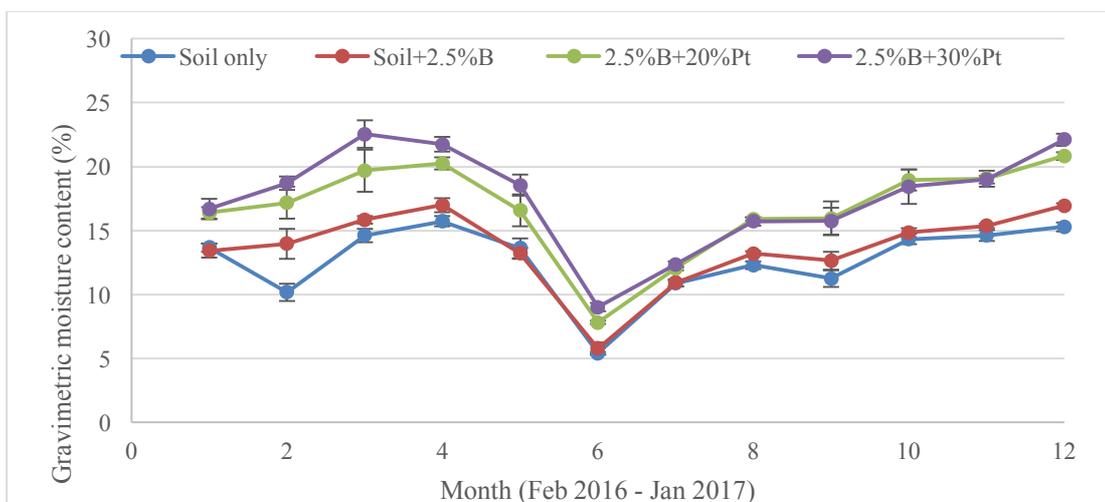
a) Peat alone



b) 5%K and peat



c) 2.5%B and peat



d) 5%B and peat



Figure 5-2: Effect of amendments on monthly soil moisture contents from February 2016 to January 2017 in soil amended with a) peat alone, b) 5%B and peat, c) 2.5%B and peat and d) 5%B and peat. Error bar = \pm s.e.m.

5.3.3 Soil nutrient retention

Change in soil available nutrient status is a function of several factors including plant uptake, leaching, plant and microbial immobilisation as well as mineralisation rate. It is postulated that the amendments would increase nutrient retention either via adsorption of nutrient ions on clay and organic matter colloids or through increased water retention since nutrients are mostly carried in the soil solution.

Plant available and total nitrogen, P and potassium in the soil were determined at 2 (initial field condition/sampling) and 33 (final field condition/sampling) weeks after amendment. The data show that unamended soil generally had a higher nutrient content compared to the amended soils especially for the final field sampling, possibly as a result of poor nutrient utilisation or a higher rate of mineralisation in the unamended soil.

5.3.3.1 Soil phosphorus

Soil available phosphorus

Table 5-3 shows the effect of amendments on soil available phosphorus. The amendments increased the initial soil phosphorus except in 30%Pt, 2.5%B+30%Pt, 5%B+20%Pt and 5%B+30%Pt; all the increases except 2.5%B+20%Pt and 5%B were significant ($p < 0.05$).

In Pt alone treatments, 20%Pt increased available phosphorus, but it was reduced by 30%Pt compared to the unamended soil, suggesting an increased soil phosphorus loss at 30%Pt rates. The available phosphorus at 20%Pt was significantly higher than for 5%B (0.043) but lower than for 5%K (0.007), while 30%Pt was significantly lower than all the clay alone treatments except 5%B.

In clay alone treatments, 5%K had the highest available phosphorus content and was significantly higher than the two B rates. Within B soils, the phosphorus content of 2.5%B was significantly higher than 5%B ($p = 0.007$). The lower available phosphorus in B than K, is possibly associated with the repulsion of negatively charged phosphate by B. Combined clay and Pt increased available phosphorus compared to the unamended soil in all K soils and in 2.5%B+20%Pt, but the increase was only significant in K soils. In B soils, available phosphorus content decreased with increasing Pt rate between 20 and 30% Pt in 2.5%B and 5%B treatments but increased in K soils.

For final field sampling, the unamended soil had the highest available phosphorus, and the increase was significant except in 2.5%B+30%Pt treatment. The high available phosphorus in the unamended soil after harvest might have resulted from poor phosphorus utilisation in the plot. The lower phosphorus content in all other treatments was possibly due to adsorption, fixation or crop uptake compared to that for unamended soil.

In Pt alone soils, 20%Pt increased available phosphorus compared to 30%Pt, and the increase was significant ($p = 0.01$). The two Pt rates had non-significant increases in available phosphorus compared to all the clays alone except 30%Pt vs 2.5%B and 5%B where it was significant.

Among the clay alone treatments, 2.5%B had the highest P and was significantly higher than 5%K but not 5%B. Unlike the initial field value, 5%K had the least available phosphorus content, and this might be due to fixation) as kaolin in acidic soils is known as having high phosphorus fixation) or due to crop uptake.

Table 5-3: Effect of the treatments on plant available phosphorus at 2 (initial) and 33 (final) weeks after amendment application

Treatment	Initial available phosphorus			Final available phosphorus		
	Mean (mg kg ⁻¹)	Mean difference	p value	Mean (mg kg ⁻¹)	Mean difference	p value
Soil only	44.70	-	-	64.06	-	-
20%Pt	52.06*	7.36	0.04	50.40*	-13.66	<0.001
30%Pt	40.98	3.72	0.292	40.60*	-23.46	<0.001
5%K	61.98*	17.28	<0.001	43.72*	-20.34	<0.001
5%K+20%Pt	53.38*	8.68	0.016	48.68*	-15.38	<0.001
5%K+30%Pt	62.08*	17.38	<0.001	55.20*	-8.86	0.019
2.5%B	54.68*	9.98	0.006	54.76*	-9.30	0.014
2.5%B+20%Pt	50.86	6.16	0.084	34.58*	-29.48	<0.001
2.5%B+30%Pt	42.76	-1.94	0.581	60.24	-3.82	0.300
5%B	44.80	0.10	0.977	51.92*	-12.14	0.002
5%B+20%Pt	43.90	-0.80	0.820	52.82*	-11.24	0.003
5%B+30%Pt	40.32	-4.38	0.216	49.32*	-14.74	<0.001
LSD	7.01			7.33		
SE	3.49			3.65		

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error of the means.

Combined clay and Pt had significantly lower available phosphorus compared to the unamended soil, except in 2.5%B+30%Pt. Also, phosphorus content was decreased as a result of Pt addition compared to B alone, possibly due to reduced pH induced by Pt addition, as shown in the soil pH results in Chapter 3 (section 3.3.2.2; Table 3-4). Available phosphorus content increased with Pt ratio between 20 and 30% Pt in 5%K and 2.5%B but decreased in 5%B soils.

A Paired t-test showed that there was no significant difference between the means of the initial and final available phosphorus ($t_{59} = -0.669$; $p = 0.506$), suggesting that the performance of the amendments on the soil available P was similar over time as expected.

Soil total phosphorus

Table 5-4 shows the effect of the amendments on soil total phosphorus at the 2nd and 33rd week after application. At the initial field condition, the total phosphorus in the unamended

soil treatment was higher than in all the amended soils except for 2.5%B. However, the decrease was only significant in 5% clay (K and B) + Pt soils.

Table 5-4: Effect of the treatments on soil total P at 2nd (initial) and 33rd (final) weeks after amendment application

Treatment	Total phosphorus (mg kg ⁻¹)	
	Initial	Final # ns
Soil only	118.42	135.78
20%Pt	114.79	124.40
30%Pt	116.05	127.06
5%K	114.95	133.18
5%K+20%Pt	111.11*	128.64
5%K+30%Pt	108.93*	126.85
2.5%B	121.31	132.17
2.5%B+20%Pt	114.29	133.70
2.5%B+30%Pt	117.66	126.82
5%B	116.31	127.17
5%B+20%Pt	113.88*	126.65
5%B+30%Pt	109.37*	122.69
LSD	4.42	
SE	2.20	

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error of the means. # ns = non significant.

The mean total phosphorus of the Pt alone treatments was lower than that of the unamended soil but was not significant. Also, there was no significant difference in the total phosphorus between the two Pt rates. For clay alone treatments, 2.5%B significantly increased total phosphorus compared to all other treatments except 2.5%+30%Pt. Among the clay alone treatments, 5%K had the least total phosphorus. The combined application of clay and Pt did not increase soil total phosphorus compared to the unamended soils.

The means of soil total phosphorus at the 33 weeks after application was not significantly different between treatments or sampling date ($p = 0.211$), suggesting that the performances of all the amendments with regards to total phosphorus were similar over time or there is a high variability among the treatments.

5.3.3.2 Soil nitrogen (N)

Available nitrate

Table 5-5 shows the effect of the amendments on nitrate at the two sampling times. The result of initial field sampling shows higher nitrate in amended soils except for 30%Pt compared to the unamended soil, but only the clay alone soils were significantly higher, suggesting better nitrate retention in clay only soils. The 5%K amended soil had the highest nitrate value.

Amending with 20% Pt only brought a small non-significant increase compared to the unamended soil. Soil nitrate increase in 20%Pt treatment compared to 30%Pt but this was not significant; the lower nitrate in 30%Pt rate suggests nitrate reduction with increasing Pt rate, possibly due to increased leaching losses or increased porosity at 30%Pt rate or greater immobilisation on N in the high OM treatments. These suggestions were supported by the result of soil characteristics where 30%Pt rate reduced soil EC (Figure 3-13) especially at the 2nd sampling and increased porosity at 30%Pt than 20%Pt (Figure 3-17).

Clay alone significantly increased nitrate compared to the unamended soil and the two Pt rates. Within the clay alone group, 5%K had the highest nitrate but this was not significantly different from the 2.5%B and 5%B treatments. The performances of 2.5%B and 5%B were similar. The combined application of clay and Pt had a small non-significant increase over the unamended soil and also Pt alone except for 2.5%B+30%Pt and 5%B+30%Pt where it was significant. Also, all clay alone treatments had non-significant increased compared to their corresponding combined clay and Pt.

The final field sampling shows nitrate retention was different from the initial field values. The unamended soil had the highest soil nitrate and was significantly higher than all the amended soils except 5%K+30%Pt. In Pt alone soils, nitrate decreased with increasing Pt rate similar to the initial field condition. The 20%Pt alone increased nitrate compared to the clay only and the difference was significant in 2.5%B soil. The nitrate in the 30%Pt plot was lower than that of the clays at the 5% rate but higher than at 2.5%B. In clay alone soils, nitrate retention in 5%K and 5%B was similar, and they were significantly higher than in 2.5%B (Table 5-5).

Table 5-5: Effect of the treatments on soil available nitrate N at 2 (initial) and 33 (final) weeks after amendment application

Treatment	Initial nitrate			Final nitrate		
	Mean (mg kg ⁻¹)	Mean difference	p value	Mean (mg kg ⁻¹)	Mean difference	p value
Soil only	6.3	-	-	17.8	-	-
20%Pt	7.1	0.80	0.571	10.1*	-7.65	<0.001
30%Pt	4.5	-1.80	0.205	8.7*	-9.05	<0.001
5%K	10.3*	4.00	0.006	9.8*	-7.95	<0.001
5%K+20%Pt	8.6	2.30	0.107	10.8*	-6.95	<0.001
5%K+30%Pt	8.0	1.70	0.231	16.6	-1.13	0.38
2.5%B	9.8*	3.50	0.016	6.7*	-11.05	<0.001
2.5%B+20%Pt	8.6	2.30	0.107	4.2*	-13.55	<0.001
2.5%B+30%Pt	7.9	1.60	0.259	8.1*	-9.63	<0.001
5%B	9.7*	3.40	0.019	9.5*	-8.25	<0.001
5%B+20%Pt	8.6	2.30	0.107	8.2*	-9.55	<0.001
5%B+30%Pt	7.0	0.70	0.62	5.0*	-12.75	<0.001
LSD	2.82			2.56		
SE	1.40			1.28		

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error of the means

The combined application of Pt and clay reduced soil nitrate compared to the unamended soil. Co-application of 5%K and Pt increased soil nitrate compared to the K alone, and the increase was higher with more Pt added. The observation was similar for 2.5%B, however, in 5%B, nitrate decreased with Pt rate. The means of the initial and the final nitrate concentrations were significantly different ($t_{59} = -2.39$; $p = 0.020$), suggesting changes in soil nitrate occurred over time.

Ammonium nitrogen

The ammonium nitrogen in the initial field was not significant ($p = 0.323$) possibly due to high variability among the treatments, so posthoc analysis was not conducted. For the final field sampling, the concentrations of ammonium in the soils were below the machine detection level, and this was attributed to a very low ammonium in the soil due to plant uptake, immobilisation or the dry soil condition at sampling.

Total nitrogen (N)

The response of soil total N to the amendments varies widely among the treatments for the two sampling periods. At the initial sampling time, Pt alone increased soil N while other amendments reduced it compared to the unamended soil except for 5%B+30%Pt, but the difference between the means of the unamended soil and the other treatments was only significant in 5%K alone and 5%B (Table 5-6).

In Pt alone soils, there was no significant difference between the two Pt rates. When compared to the clay alone treatment, both 20 and 30%Pt increased total N significantly. The effects of 5%K and 5%B on total N were similar, while 2.5%B was greater. The combined application of clay and Pt increased soil total N compared to clay alone treatments, and the increase was significant at 5% clay rates (K and B). Total N decreased as Pt rate increased in K+Pt soils, while it increased in B+Pt soils. At second sampling, generally, total N decreased over time, with the observation similar to the initial field condition.

Table 5-6: Effect of the treatments on soil total nitrogen (N) at 2nd and 33rd weeks after amendment application

Treatment	Initial total N			Final total N		
	Mean (%)	Mean difference	p value	Mean (%)	Mean difference	p value
Soil only	0.106	-	-	0.091	-	-
20%Pt	0.109	0.003	0.519	0.096	0.006	0.201
30%Pt	0.109	0.003	0.519	0.091	0.000	0.927
5%K	0.093*	-0.013	0.008	0.080*	-0.011	0.016
5%K+20%Pt	0.105	-0.002	0.731	0.084	-0.007	0.133
5%K+30%Pt	0.103	-0.003	0.492	0.090	-0.001	0.854
2.5%B	0.101	-0.005	0.248	0.083	-0.007	0.102
2.5%B+20%Pt	0.103	-0.004	0.440	0.092	0.001	0.783
2.5%B+30%Pt	0.111	-0.005	0.266	0.083	-0.008	0.070
5%B	0.091*	-0.016	0.001	0.078*	-0.012	0.006
5%B+20%Pt	0.101	-0.006	0.232	0.086	-0.004	0.336
5%B+30%Pt	0.108	0.002	0.636	0.084	-0.006	0.145
LSD	0.009			0.009		
SE	0.004			0.004		

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error

5.3.3.3 Soil potassium (K₂O)

Soil available potassium

Effect of amendments on soil available potassium is shown in Table 5-7. At the initial field sampling, the addition of 5%K+Pt (at 20 and 39%) and 5%B significantly increased soil available potassium compared to the unamended soil, while other treatments were lower than the unamended soil.

Application of Pt alone reduced available potassium compared to the unamended soil, and the two Pt rate were not significantly different. Comparing the Pt alone to the clay alone, clay addition at 5% increased soil available potassium but the increase was only significant for the 5%B soil.

Among clay alone treatments, 5%B had the highest amount of available potassium, followed by 5%K while 2.5%B had the least. The combined application of clay and Pt increased soil available potassium in 5%K and 2.5%B amended soils, while it was reduced with 5%B compared to the corresponding clay alone treatment. Also, it was increased with the Pt rate, and combined application of 5%K and Pt had the highest value compared to 2.5%B and 5%B with Pt.

At final sampling, only 5%K, 5%B+20%Pt and 5%B+30%Pt increased available potassium compared to the unamended soil but the increases were not significantly different. The rest of the treatments were lower than for unamended soil but were only significantly lower in 2.5%B and 2.5%B+20%Pt soils. For the Pt alone treatments, there was a reduction in available potassium compared to the unamended soil, and the potassium decreased as the Pt rate increased, unlike the initial field values. The means of the 20% and 30% Pt rates were not significantly different, as were the means of 5%B and 2.5%B compared to the Pt alone, while that of 5%B was significantly differed to 30Pt.

In clay alone soils, 5%K had the highest available potassium at final sampling, followed by 5%B while 2.5%B had the least. The mean of 5%K was significantly higher than that of soil amended with B, suggesting higher potassium availability in K- amended soils possibly owing to low crop uptake compared to B. This suggestion was supported by the estimated potassium uptake data in section 5.3.8.3 (Table 5-13). Within B amended soils, 5%B had a small non-significant increase over 2.5%B.

When applied with Pt, potassium decreased in 5%K, increased in 5%B, while the response varied with Pt rate in 2.5%B (Table 5-7) compared to their corresponding clay alone. Combined application increased available potassium compared to Pt alone at 5% clay rate, suggesting improved potassium retention when 5% clay and OM are combined.

The paired t-test showed that the difference between the means of the two data sets (initial and final sampling) was significantly different ($t_{53} = -7.107$; $p = <0.001$), suggesting variability in the initial and final soil available potassium measured in this experiment.

Table 5-7: Effect of the treatments on soil available potassium at 2 (initial) and 33 (final) weeks after amendment application

Treatment	<u>Initial available potassium</u>			<u>Final available potassium</u>		
	Mean (mg kg ⁻¹)	Mean difference	p value	Mean (mg kg ⁻¹)	Mean difference	p value
Soil only	81.2	-	-	122.0	-	-
20%Pt	72.8	-8.40	0.265	117.2	-4.89	0.504
30%Pt	73.2	-8.01	0.288	110.5	-11.50	0.120
5%K	78.9	-2.32	0.757	130.6	8.56	0.244
5%K+20%Pt	98.1*	16.96	0.028	118.5	-3.50	0.632
5%K+30%Pt	162.4*	81.24	<0.001	120.0	-2.05	0.779
2.5%B	71.2	-9.93	0.189	105.9*	-16.18	0.031
2.5%B+20%Pt	73.1	-8.11	0.310	102.3*	-19.71	0.013
2.5%B+30%Pt	76.9	-4.25	0.594	110.0	-12.07	0.103
5%B	103.6*	22.40	0.004	113.1	-8.90	0.227
5%B+20%Pt	71.0	-10.20	0.178	124.9	2.84	0.713
5%B+30%Pt	76.0	-5.21	0.513	133.2	11.20	0.130
LSD	14.97			13.76		
SE	7.45			7.26		

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error

Total soil potassium

Soil total potassium was measured twice (2nd and 33rd weeks) after amendment, and the data are shown in Table 5-8. At initial sampling, the amendments increased soil total potassium compared to the unamended soil, and the increase was significant except in the Pt only treatments and both B + 30%Pt soils. In Pt alone plots, there was a non-significant

increase in total potassium compared to the unamended soil. The amount of total potassium in the 20 and 30%Pt treatments were similar indicating no Pt rate effect.

All clay alone treatments significantly increased total potassium compared to 20% Pt, and 5%K significantly increased potassium over 30%Pt while the rest were not significant. All clays alone significantly increased total potassium compared to the unamended soil. Among the clay alone treatments, 5%K had the highest, while the value was the same in 2.5% and 5%B, but the difference was not significant.

Combined clay and Pt significantly increased total potassium compared to the unamended soil except for 2.5%B+30%Pt. In 5%K, the addition of Pt increased soil total potassium compared to clay alone, with the value similar to the combined 20% and 30%Pt rate. In 2.5%B soils, the addition of Pt reduced total potassium compared to 2.5%B only, and the more the Pt, the less the total potassium. In 5%B soils, 20%Pt increased soil total potassium while it was reduced at the 30%Pt rate compared to the 5%B alone treatment.

At final field sampling, only 5%K and 5%K+20%Pt significantly increased soil total potassium compared to unamended soil. Also, 5%K+30%Pt and 2.5%B+20%Pt had a small non-significant increase compared to the unamended soil, while other treatments were lower but only significantly so for 30%Pt.

The Pt alone could not increase total potassium compared to unamended soil, and 30%Pt was significantly lower than the 20%Pt rate, possibly due to increased leaching at the 30% rate. Total potassium in clay alone treatments at 5% was significantly higher than that of Pt alone at the two application rates, while 2.5% clay was significantly higher than 30%Pt alone. Among the clay treatments, 5%K had the highest total potassium and was significantly higher than B at both rates. When combined with Pt, 20%Pt increased soil total potassium while 30%Pt reduced it in all clays, suggesting an increased loss as more Pt is added.

There was a weak and positive significant correlation between initial and final total potassium ($r = 0.32$; $p = 0.014$). Also, the paired t-test showed that there was a significant difference between the initial and final total soil potassium ($t_{59} = 3.439$; $p = 0.001$), suggesting that the total potassium concentration in the soil were different over time.

Table 5-8: Effect of the treatments on soil total potassium at 2nd (initial) and 33rd (final) weeks after amendment application

Treatment	<u>Initial total potassium</u>			<u>Final total potassium</u>		
	Mean (g kg ⁻¹)	Mean difference	p value	Mean (g kg ⁻¹)	Mean difference	p value
Soil only	2.74	-	-	3.07	-	-
20%Pt	2.80	0.06	0.502	2.98	-0.09	0.476
30%Pt	2.84	0.10	0.265	2.69*	-0.38	0.003
5%K	3.07*	0.33	0.001	3.34*	0.27	0.027
5%K+20%Pt	3.23*	0.49	<0.001	3.42*	0.35	0.005
5%K+30%Pt	3.24*	0.49	<0.001	3.31	0.24	0.051
2.5%B	2.99*	0.24	0.009	2.99	-0.08	0.507
2.5%B+20%Pt	2.96*	0.22	0.017	3.16	0.09	0.436
2.5%B+30%Pt	2.75	0.01	0.929	2.94	-0.13	0.283
5%B	2.99*	0.25	0.007	3.05	-0.01	0.907
5%B+20%Pt	3.04*	0.30	0.001	3.04	-0.02	0.842
5%B+30%Pt	2.90	0.15	0.089	3.03	-0.04	0.752
LSD	0.180			0.241		
SE	0.089			0.120		

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error of the means.

5.3.4 Effect of amendments on seed emergence

The effect of amendments on spring wheat emergence is shown in Figure 5-3. The visual observation of the plots shows that amendments had effects on the emergence of the seedlings. Soil amended with Pt produced uniform seedling emergence with or without clay compared to the unamended soil and clays alone. Generally, emergence was poor and irregular in clay alone compared to the Pt alone or clay and Pt combined. Plots amended with 5%K+20%Pt had the most vigorous seedling emergence followed by 5%B+30%Pt and the Pt alone plots.



Soil only



20%Pt



30%Pt



5%K



5%K+20%Pt



5%K+30%Pt



2.5%B



2.5%B+20%Pt



2.5%+30%Pt



5%B



5%B+20%Pt



5%B+30%Pt

Figure 5-3: Seedling emergence as influenced by the clay and Pt amendments (The figure is showing two replicates per treatment)

5.3.5 Wheat yield parameters

5.3.5.1 Plant vigour

The plant vigour presented is the normalized difference vegetation index (NDVI) values. Plant vigour was measured twice at GS29 and GS39 during the growing season, and the result is shown in Table 5-9. At GS29, all amended plots increased plant vigour compared to the unamended soil except 5%K alone and 2.5%B, and the increase was significant in all plots treated with Pt, possibly because of good seedling emergence. The Pt alone increased the green area cover compared to the unamended soil and clays alone. Within the Pt alone treatments, there was a non-significant increase in plant vigour with Pt rate, suggesting that performance of the two Pt rates were similar.

Plant vigour in soils amended with clay only was not statistically different from the unamended soil, indicating that claying has no effect on green area cover (a proxy of green area index) of the wheat. Although plant vigour was higher in B than K at 5% clay rate, it was not significant, also there was a non-significant increase in the means of 2.5%B and 5%B, suggesting similar effects of the two B rates. The combined application of clay and Pt significantly increased plant vigour compared to the unamended soil. For 5%K and 2.5%B, the increases were significant at the 20% and 30%Pt rates while it was only significant at the 30%Pt rate for 5%B compared to the corresponding clay alone treatments.

The second measurement of plant vigour at GS39 showed no significant differences between treatments. This could mean that at GS39, the green area covered was identical in all the plots, suggesting that tillering might have compensated for poor emergence in some treatments.

5.3.5.2 Plant height

Amendments are expected to increase plant height compared to unamended soil mainly owing to their ability to increase soil water retention (Figure 5-3) and soil CEC (Table 3-3), which are an indicator of soil nutrient retention.

Table 5-10 shows the effect of clay and Pt amendments on plant height at GS51. All amendments increased plant height, but only 5%K, 2.5%B and 5%B were not significantly higher than the unamended soil. Effect of the Pt alone on plant height was significant at

both 20 and 30%Pt rates. Plant height increased with Pt rate whether applied alone or with clay, but the Pt rate effect was not significant.

Table 5-9: Wheat yield vigour in sandy soil amended with clay and peat

Treatment	Plant vigour at GS29			Plant vigour at GS39		
	Mean	Mean difference	p value	Mean	Mean difference	p value
Soil only	0.61	-	-	0.80	-	-
20%Pt	0.75*	0.14	<0.001	0.84	0.04	ns
30%Pt	0.78*	0.16	<0.001	0.85	0.04	ns
5%K	0.60	-0.01	0.657	0.80	0.00	ns
5%K+20%Pt	0.71*	0.10	0.010	0.84	0.03	ns
5%K+30%Pt	0.77*	0.16	<0.001	0.85	0.05	ns
2.5%B	0.61	0.00	0.956	0.82	0.02	ns
2.5%B+20%Pt	0.70*	0.09	0.013	0.81	0.01	ns
2.5%B+30%Pt	0.75*	0.14	<0.001	0.82	0.02	ns
5%B	0.68	0.07	0.072	0.80	0.00	ns
5%B+20%Pt	0.74*	0.12	0.001	0.84	0.03	ns
5%B+30%Pt	0.78*	0.17	<0.001	0.82	0.01	ns
LSD	0.069					
SE	0.036					

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error

Effect of clay alone on plant height was not significant compared to the unamended soil, and the means of the three clay alone treatments were similar. The combined application of clay and Pt increased plant height. Plots amended with 5%K+30%Pt had the highest but was not significantly greater than any of the rest of the clay + Pt plots. These results suggest that addition of clay to this soil type under similar conditions may not bring any improvement in plant height.

5.3.6 Plant Biomass

The parameters measured were fresh shoot and fresh root weight at GS51 to determine the effects of the amendments on the vegetative growth of the test crop. Grain yield was monitored by measuring both total ear weight and thousand grain weight at harvest.

5.3.6.1 Fresh shoot weight

The effect of the amendments on fresh shoot weight of spring wheat is presented in Figure 5-4 as a percentage of the unamended soil treatment, and significance difference was

determined using one-way ANOVA ($p < 0.05$). All amendments significantly increased fresh shoot weight compared to the unamended soil. The increase ranged from 21% in 5%K to 91% in 5%K+30%Pt.

Table 5-10: Effect of amendments on plant height at GS51

Treatment	Plant height (cm)		
	Mean	Mean difference	p value
Soil only	41.0	-	-
20%Pt	47.2*	6.20	0.014
30%Pt	51.0*	9.96	<0.001
5%K	43.7	2.64	0.285
5%K+20%Pt	49.5*	8.46	0.001
5%K+30%Pt	53.5*	12.44	<0.001
2.5%B	43.5	2.50	0.311
2.5%B+20%Pt	48.7*	7.70	0.003
2.5%B+30%Pt	50.6*	9.54	<0.001
5%B	44.8	3.80	0.127
5%B+20%Pt	51.1*	10.08	<0.001
5%B+30%Pt	51.9*	10.84	<0.001
LSD	4.91		
SE	2.44		

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error

Higher fresh shoot weight was observed in Pt-amended soils whether clay was present or not compared to the unamended soil and clay alone. The Pt rate effect was not significant as the means of the 20 and 30%Pt were not statistically different.

The effects of amending with clay alone were also significant compared to the unamended soil, and B performed better than K. There was non-significant increase in fresh shoot weight of 5%K treatment compared to 2.5%B, while 5%B significantly increased compared to 5%K, but not 2.5%B, suggesting that there was no B rate effect.

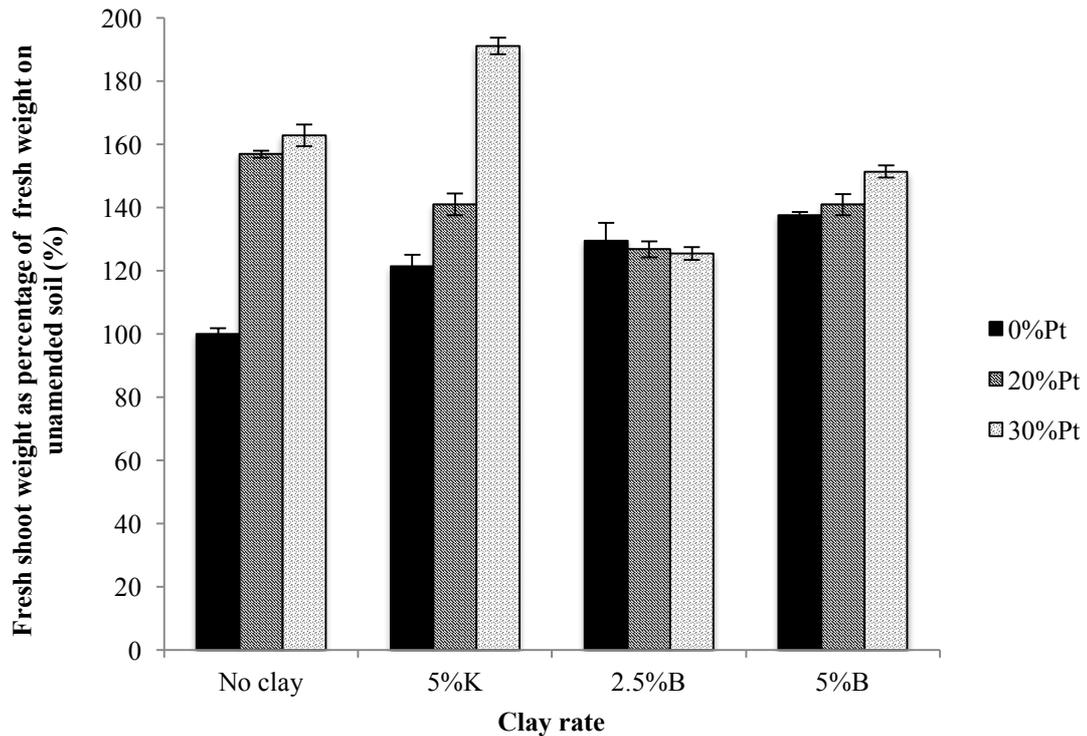


Figure 5-4: Fresh shoot weight in different clay amended soils at GS51 in response to Pt rate presented as a percentage of the yield in unamended soil. Error bar = \pm s.e.m.

The combined application of Pt and clay increased fresh shoot weight compared to the unamended soil. In 5%K amended soils, Pt addition significantly increased fresh shoot compared to 5%K alone, and the increase becomes higher with Pt rate. The effect of clay+Pt was greater at the 5%K rate, with K+30% significantly highest, suggesting that combined K and Pt may have a better immediate effect on crop growth. In 5%B soil, the effect of Pt was smaller and it was not significantly higher than 5%B alone. In 2.5%B soils, the addition of Pt reduced fresh shoot weight, and the reduction tended to increase when more Pt was added, which might indicate an antagonism relationship on fresh shoot in this clay rate. Generally, the addition of clays suppressed yield when compared to Pt alone at 20 and 30%Pt rates, but increased yield when compared to clay only. The reduction could possibly be associated with reduced mineralization of Pt in combined clay and Pt amended soils.

5.3.6.2 Fresh root weight

Plant roots weight (g) was measured at GS51, and the results are presented in Table 5-11. The main effect of fresh root weight was significant ($p = 0.005$) but only a pair of means, 30%Pt and 2.5%B+30%Pt was significantly different, while all other treatments were

statistically similar. Despite the small differences, the fresh root result was higher for all amendments than the unamended soil except for the combined 2.5%B and Pt treatments. Soil amended with 5%B+30%Pt had the largest fresh root weight, but it was similar to the Pt alone and the 5%K+Pt treatments.

Among the clay alone treatments, 5%B had the highest root fresh weight followed by 2.5%B and 5%K which were similar. In the 5%K treatments, fresh root weight increased with Pt rate, and the addition of Pt increased root growth compared to 5%K alone. In soils amended with 5%B, fresh root weight increased with Pt rate, and addition of Pt at 30% increased fresh root weight compared to 5%B. In 2.5%B treatments, addition of Pt reduced root weight with the more Pt added the less the root weight.

Table 5-11: Effect of amendments on spring wheat root biomass at GS51

Treatment	Fresh root (g)*
Soil only	3.04
20%Pt	4.66
30%Pt	4.76
5%K	3.28
5%K+20%Pt	4.14
5%K+30%Pt	4.38
2.5%B	3.32
2.5%B+20%Pt	2.88
2.5%B+30%Pt	2.36
5%B	4.02
5%B+20%Pt	3.28
5%B+30%Pt	4.78

* None of the means is significantly different from the unamended soil ($p < 0.05$).

5.3.6.3 Total ear weight at harvest

The crop was harvested at maturity and the total ear weight from each plot was measured, see Figure 5-5. All the treatments increased total ear weight and the increase was significant compared to the unamended soil, except for 5%B alone. Addition of Pt alone increased yield compared to the unamended soil and clays alone. Also, 30%Pt increased ear weight significantly compared to 20%Pt indicating positive Pt rate effects. Application of clay alone increased ear weight compared to the unamended soil, but was not significant for 5%B. Among this treatment group, 5%K had the highest ear weight but was not significantly different from 2.5%B and 5%B.

Combined clay and Pt treatments increased wheat ear yield compared to the unamended soil, and clay alone. For 5%K and 2.5%B, the addition of 20% Pt significantly increased wheat ear yield while in 5%B it was significant only at the 30% Pt rate compared to their corresponding clays alone. Similar to biomass yield, the combined application of clay and Pt resulted in yield depression compared to the Pt alone except for 5%K+20%Pt. At 20%Pt, the reduction was significant only in 5%B while at 30%Pt rate it was significant for all the clay treatments.

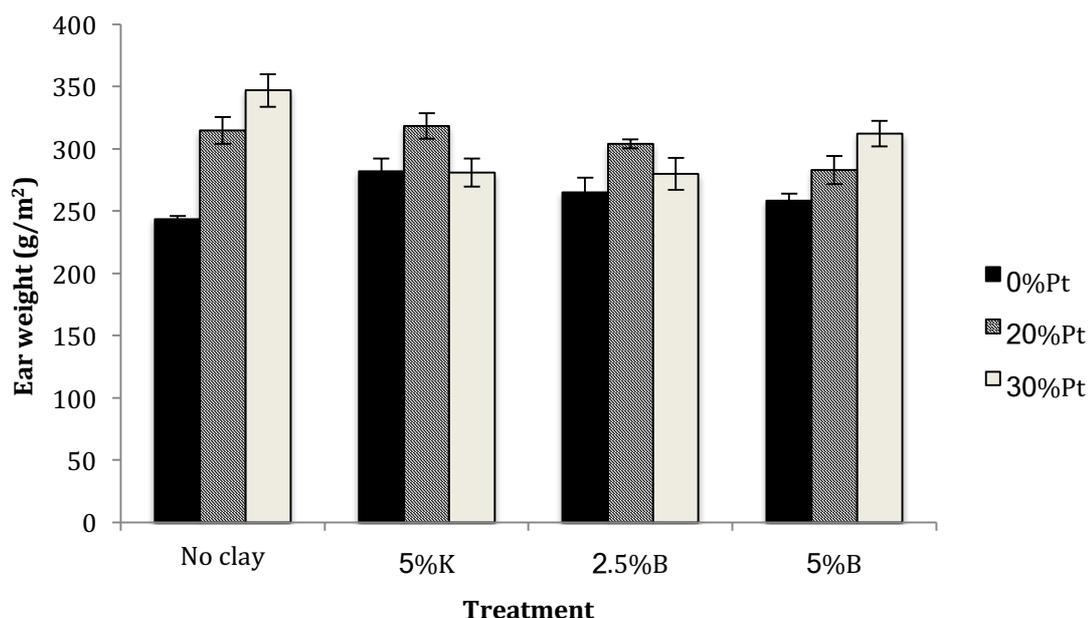


Figure 5-5: Effects of clay and peat on total ear weight at harvest. Error bar = \pm s.e.m.

5.3.6.4 Thousand grain weight

The thousand grain weight (TGW) of the treatments was determined after harvest and the result is presented in Table 5-12. All treatments increased TGW but the increase was not significant for 5%K+30%Pt and 2.5%B. The Pt alone amendments increased TGW significantly compared to the unamended soil. At the 30%Pt rate, there was a small non-significant increase in TGW compared to the 5% alone, while both 20 and 30%Pt significantly increased TGW compared to 2.5%B alone. The performance of 20 and 30% Pt rate were similar, suggesting no Pt rate effect.

Application of clay alone increased TGW compared to the unamended soil but was not significant in 2.5%B. Among the clay alone treatments, 5%B has the highest TGW but was

not different significantly from 5%K. TGW increased significantly in 5% clays compared to 2.5%B, possibly as a result of the increased clay content.

The combined application of clay and Pt increased TGW significantly compared to unamended soil except in the 5%K+30%Pt treatment. In 5%K soils, co-application of clay and Pt increased TGW significantly at 20%Pt compare to clay alone. In B amended soils, the combined application of 2.5%B increased TGW at both 20 and 30%Pt rate compared to the clay alone while the increase was not significant for co-application with 5%B. Soil amended with 5%K+20%Pt and 2.5%B+20%Pt increased TGW more than the starting seed lot (42g), suggesting that the unit weight of the seed might have contributed to the high yield in this plot. Soils treated with B and 30%Pt have approximately equal TGW as the starting seed lot while the rest were lower, with the unamended soil having the lowest value (Table 5-12).

Table 5-12: Effect of amendments on spring wheat thousand grain weight (g)

Treatment	<u>Thousand grain weight (g)</u>		
	Mean	Mean difference	p value
Soil only	38.16	-	-
20%Pt	41.04*	2.88	0.003
30%Pt	41.18*	3.02	0.002
5%K	40.96*	2.80	0.004
5%K+20%Pt	43.44*	5.28	<0.001
5%K+30%Pt	39.82	1.66	0.082
2.5%B	39.02	0.86	0.362
2.5%B+20%Pt	43.82*	5.66	<0.001
2.5%B+30%Pt	41.74*	3.58	<0.001
5%B	41.08*	2.92	0.003
5%B+20%Pt	41.16*	3.00	0.002
5%B+30%Pt	41.72*	3.56	<0.001
LSD	1.88		
SE	0.94		

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error

5.3.7 Relationship between soil moisture properties and wheat yields

There was a relationship between final plant available water (final PAW; measured as the difference between soil moisture content at 0.05 and 15 bars using pressure plate method)

and total ear weight at harvest. The R^2 value showed that up to 54% of the ear weight can be explained by the final PAW (Figure 5-6).

In order to understand the soil water characteristics that might influence thousand grain weight (TGW), the relationship between final PAW and soil moisture content at the grain filling stage (GS71-77) were measured. Unlike ear weight, there was only a weak relationship ($R^2 = 0.23$) between TGW and PAW, indicating that PAW is not a good predictor of the TGW (Figure 5-7). However, the R^2 value for soil moisture content at grain filling stage (July 2016) showed that up to 58% of the TGW could be explained by the July 2016 soil moisture content (Figure 5-8), suggesting that soil water at this stage is crucial for optimum grain yield. Interestingly, in the UK, this is summer time when soil moisture is likely to be low as evident in soil moisture content from this research (Figure 5-2). So, soil amendments that could increase soil moisture retention at this stage would improve grain yield.

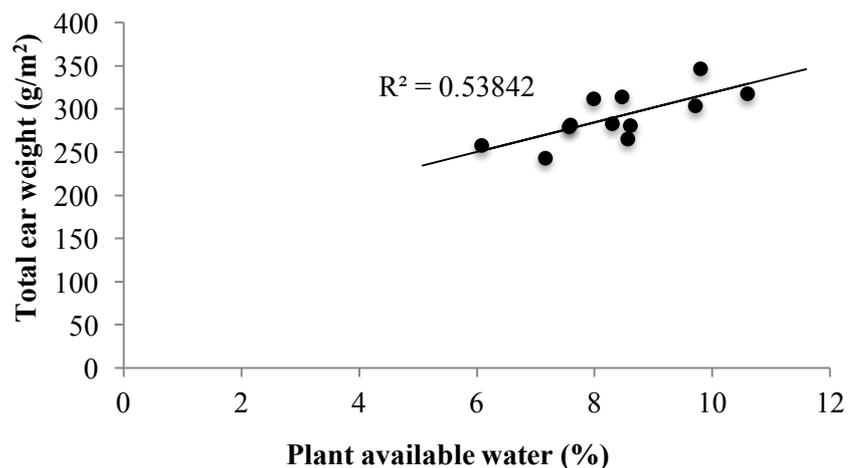


Figure 5-6: Relationship between final plant available water and total ear weight.

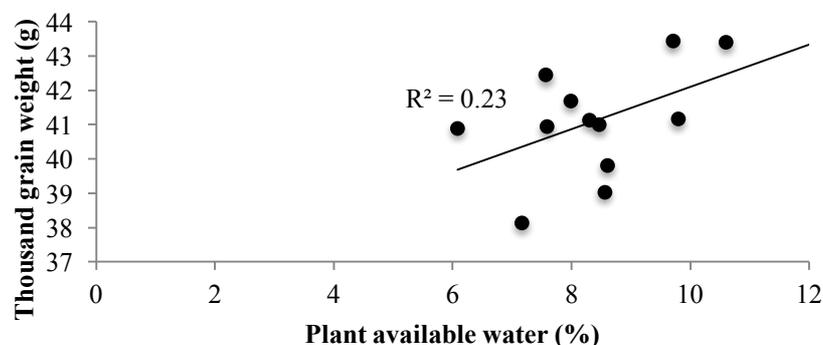


Figure 5-7: Relationship between final plant available water and TGW.

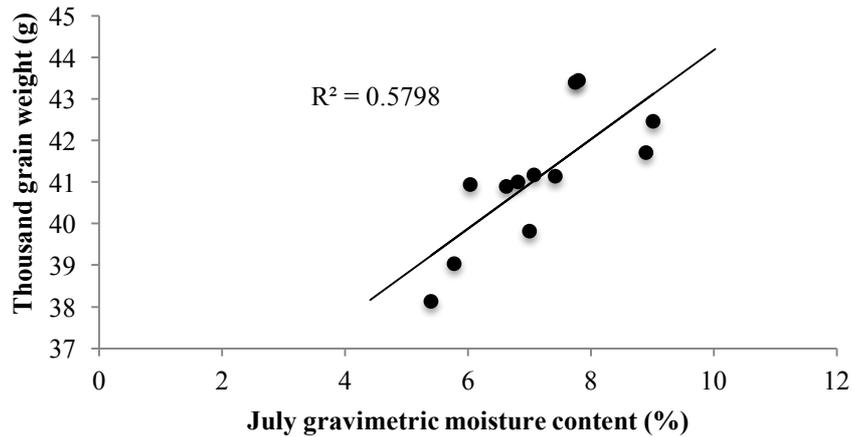


Figure 5-8: Relationship between soil moisture content at the grain filling stage and TGW.

5.3.8 Effect of amendments on nutrient uptake by wheat plants

5.3.8.1 Nitrogen uptake

The product of the nutrient concentration of the plant biomass and the dry shoot weight was used as an indicator of nutrient uptake by the crops during the growing season, and the data are presented in Table 5-13. Amendment increased uptake of nitrogen compared to the unamended soil except for 2.5%B+30%Pt, and the increase was significant for all 5%K and 5%B amended soil treatments. The low uptake in 2.5%B + Pt amended soils is likely to be associated with poor root growth in this treatment (Table 5-11) compared to the other treatments.

Amending with Pt alone significantly increased uptake of nitrogen compared to the unamended soil. Application of 20%Pt alone increased nitrogen uptake significantly compared to 2.5%B alone, but the increase was not significant for the 5% clays, while 30%Pt was significantly higher than all the clay alone treatments.

All clay alone treatments increased nitrogen uptake compared to the unamended soil, but this was not significant for 2.5%B, suggesting there was better nitrogen uptake at higher clay contents. When combined with Pt, nitrogen uptake increased with Pt rate in 5% clay (K and B) but was reduced at 30%Pt in 2.5%B plots compared with the 20% combined treatment.

5.3.8.2 Phosphorus uptake

All amendments increased P uptake compared to the unamended soil treatment, with the increase significant in all Pt amended soils as well as 5%B alone plot compared to the unamended soil (see Table 5-13). The highest P uptake was recorded in 5%K+30%Pt.

Application of Pt alone increased P uptake compared to the unamended soil and clays alone. A Pt rate effect was also observed as 30%Pt significantly increased P uptake over 20%Pt. Amending with 5%K alone and 2.5%B did not significantly increase uptake of P compared to the unamended soil, suggesting similar performance with unamended soil.

The combined application of clay and Pt increased P uptake compared to the unamended soil and clay alone except for 2.5%B+30%Pt treatment. For 5%K, uptake increased with Pt rate and was significantly higher than for 5%K alone. In 2.5%B+Pt soils, the increase in uptake reduced with increasing Pt rate and there was no significant difference compared to the unamended soil or 2.5%B alone treatments. For 5%B, combined application with Pt increased P uptake significantly compared to the unamended soil but not 5%B alone treatment. The combined application also reduced P uptake compared to the Pt alone treatment. Soil amended with 2.5%B had the smallest effect possibly because of lower dry matter yield.

5.3.8.3 Potassium uptake

All amendments significantly increased potassium uptake compared to the unamended soil (Table 5-13). The highest value was found for 5%K+30%Pt and was significantly greater than all other treatments.

The Pt alone increased potassium uptake compared to the unamended soil, but the difference between the two Pt rates was not significant. The 20%Pt alone also increased potassium uptake more than for the clays alone but the increase was only significant in 5%K only treatments, while the increase in 30%Pt was significant compared to 5%K alone and 2.5%B but not for 5%B.

Uptake of potassium increased in clay alone soils significantly compared to the unamended soil. Soil amended with 5%K had the smallest increase and was significantly lower than 5%B possibly associated with the higher adsorption of positively charged ions by B than K.

The combined application of clay and Pt increased potassium uptake at 5% clay rate but reduced at 2.5%B clay soils, suggesting an increase in potassium uptake with more clay when OM is co-applied. For 5%K, Pt at 20 and 30% significantly increased potassium uptake compared to the 5%K alone; the differences between 2.5%B and 2.5%B+Pt (at both rates) were not significant, while it was only significant at 30%Pt in the 5%B plot.

Table 5-13: Effects of clay and peat amendments on estimated amount of nutrient uptake of spring wheat

Treatment	Nitrogen uptake		Phosphorus uptake		Potassium uptake	
	Mean (kg ha ⁻¹)	p	Mean (kg ha ⁻¹)	p	Mean (kg ha ⁻¹)	p
Soil only	88.33	-	2.69	-	110.4	-
20%Pt	126.21*	<0.001	4.27*	<0.001	174.4*	<0.001
30%Pt	135.72*	0.001	4.76*	<0.001	193.8*	<0.001
5%K	112.77*	0.005	3.11	0.064	140.8*	0.01
5%K+20%Pt	117.19*	0.001	3.59*	<0.001	166.4*	<0.001
5%K+30%Pt	180.06*	<0.001	5.08*	<0.001	228.0*	<0.001
2.5%B	93.51	0.538	3.08	0.087	160.8*	<0.001
2.5%B+20%Pt	96.43	0.337	3.10	0.074	146.2*	0.003
2.5%B+30%Pt	79.81	0.313	3.00	0.169	154.4*	<0.001
5%B	110.75*	0.010	3.22*	0.021	171.8*	<0.001
5%B+20%Pt	110.77*	0.010	3.39*	0.003	175.0*	<0.001
5%B+30%Pt	119.13*	0.001	3.53*	<0.001	199.0*	<0.001
LSD	16.79		0.46		22.66	
SE	8.36		0.22		11.27	

Means with an asterisk (*) in the same column are significantly different from the unamended soil ($p < 0.05$). LSD = Least significant difference; SE = Standard error

5.4 Discussion

5.4.1 Soil moisture

The result of soil water retention agrees with the hypothesis that the amendments would increase soil moisture content of sandy soils. Addition of Pt increased soil moisture content when applied alone or with clay. The ability of OM to increase soil moisture content could be direct or indirect. Direct effects involve water holding by the organic materials used and through improved soil structure and aggregate formation (Annabi et al., 2007; Arthur et al., 2010; Yu et al., 2012). Knowing that the original soil in this experiment was structureless

and unconsolidated, it is likely that the presence of Pt supports the early formation of a stable soil structure, which in turn improves and creates micro and macro porosity (Kramer, 1983). Elliot and Lynch (1984) reported that OM with low N content induced and supported aggregate stability because of the low decomposition rate of OC in these soils. This could be of benefit in this work as Pt is known to have a very high C:N ratio, which slows decomposition rate. In addition, Pt water retention is also influenced by its cell structure. Sphagnum peat is known to be 'spongy'; the dry cells have a large space that could be filled with water when wet. This property of Pt may have been another factor contributing to the improved water holding capacity of Pt-amended soils.

Indirectly, the presence of OM can induce soil micro- and macro- fauna activities. Microbial products such as organic gel, exudate from bacteria, fungal hyphae, worm secretion and casts can play an important role as soil binding agents for aggregate formation and stability. Contributions of OM to aggregate stability and soil pore formation occur as a result of its ability to stimulate the above microbial reactions and products. Previous work also reported an increase in soil moisture content in soil amended with OM (Juncker and Madison, 1967; Hudson, 1994; Li et al., 2004).

Clay amendment either alone or with Pt significantly increased soil MC compared to the unamended soil. The ability of clay to hold water is discussed in detail in Chapter 2 (section 2.4.1 Water retention capacity of the amended soil and sand). The soil MC response was similar to that observed in the laboratory in Chapter 2. The ability of B to hold more water in this work is partly due to its layer structure, potential to induce the formation of micropores due to its very small particle size, and partly due to its charge density and CEC. Since soil water is held in the soil micropores, amendments that encourage soil micropore formation will increase soil water. Also, the higher CEC of B (Table 3-3 in section 3.3.2.1) invariably would have contributed to an increase MC of the soil through direct ionic reactions with water molecules and the hydration of cations adsorbed on its surfaces. Page (1952) showed in his review that clay physical properties could influence soil structure formation, aggregate stability and water holding capacity.

On a monthly basis, soil MC increased in Pt alone and 5%B amended soils as the Pt ratio increased in all seasons. For Pt alone, this might have resulted from a quantity effect, that is, the increase in the amount of OM increased water content. In 5%B, this is possibly because of the higher content of highly reactive clay B which might have induced early reactions

between clay and OM, resulting in a fairly stable performance of 5%B and Pt. Also, the formation of organo-mineral complexes either through intercalation of OM into the B structure or through the cation bridge (Bonneau and Souchier, 1982 in Theng et al., 1986; Leinweber et al., 1993; Römken and Dolfing, 1998) in the presence of divalent cation such as Ca^{2+} might have contributed to the increased water retention. The latter option is highly feasible as the B used in this project is a calcium bentonite.

In 2.5%B and Pt soils, there was higher soil moisture content in 20%Pt than 30%Pt from September to November following a dry period, and this is attributed to a re-wetting problem with Pt. When dry, the peat surface possibly consists of compounds that do not attract water, thus reducing water absorption. Fuchsman (1986) wrote that when the moisture content of peat is dried below fifty percent, rewetting usually becomes hard, and this hydrophobicity of dry peat is still poorly understood (Fuchsman, 1986; Wallis and Horne, 1992). However, the presence of symmetric organic molecules¹⁰ and hydrophobic materials such as bitumen, resins, waxes and methoxyl groups in peat could be contributing factors (Fuchsman, 1986; Szajdak et al., 2007). Furthermore, the hydrophobic surfaces of peat restrict water infiltration when dry (Kwak et al., 1986). This phenomenon was not observed at 5% B rate possibly because of the clay coating on Pt surfaces or the presence of large amounts of hydrophilic clay minerals which could function as a rewetting agent for Pt, making the effect masked at higher clay rate.

In 5%K amended soil, Pt at 30% held more water than 20% in wet seasons and vice versa in dry months. This change during dry months could be attributed to increased porosity at the higher Pt rate and differences in water release characteristics between the two Pt rates. The result of soil water characteristics and soil available water in this experiment showed that 5%K+20%Pt had higher water retention (between ca. 0.01 to 2 bars; section 3.3.3.6) and available water than 5%K+30%Pt, indicating that K+30%Pt has higher tendency to lose its water quickly as soil water tension increases. That this effect was not seen during wet seasons showed that other factors such as optimum (near saturation) soil MC by regular water supply occluded and prevented expression of this phenomenon. Thus, it could be suggested that when kaolin is used, the addition of 20%Pt to 5%K would be optimal for adequate water retention in sandy soils.

¹⁰ www.waynesthisandthat.com/peatmoss.htm (accesses 12/03/2016)

The observed higher water retention in combined clay and Pt treatments is possibly the result of formation of organo-mineral complexes between clay and OM. The interaction between clay and OM could increase their surface area (Theng et al., 1986) as well as the strength of their charge density, thus producing more reactive sites for holding water compared to when each component was applied singly. It is noteworthy that a similar result was observed in the laboratory column leaching work conducted in Chapter 2, suggesting that this result was repeatable under both field and laboratory conditions.

5.4.2 Effects of the amendments on soil nutrient concentrations

Contrary to expectation, the unamended soil had higher nutrient concentration than amended soils especially at the second sampling, and this is attributed to poor nutrient uptake by the crop and /or high mineralisation rate in the unamended soils or immobilisation in the amended soils. This suggestion is further strengthened by the nutrient uptake data in this experiment, where unamended soil had the lowest nutrient uptake for all the three nutrients (nitrogen, phosphorus and potassium) measured. It thus provides evidence that the nutrients might have accumulated in the unamended soil because of low crop growth and yield.

Also, sandy soil is characterised by a high mineralisation rate. As reported by Franzluebbers et al. (1996), sandy soils have high organic matter decomposition rate, attributed to poor soil aggregation, lack of SOM protection due to low clay content and increased aeration. The soil properties that are proxy of soil aeration such as porosity, air-filled pore area and pore size distribution measured in this research did show that except in Pt alone treated soils, unamended soils were higher in these properties than amended soils. Thus, it could be inferred that mineralisation of SOM might have occurred rapidly in the unamended soil, and might have contributed to the higher nutrient concentration. Another possible reason is the increased uptake of these nutrients by the crop biomass or immobilisation by the soil microbial biomass in amended soils. The former is reflected in the higher crop yields observed in amended soils.

The data thus show that the hypothesis that amendments would increase soil nutrient retention could not be confirmed solely by direct measurement of nutrient concentration in the soil at a given time. A better approach involving a continuous monitoring approach, measuring leaching rate and the use of isotopic nutrient labelling or the use of a model that incorporates nutrient uptake, mineralisation and immobilisation would be more appropriate.

Amending with 20%Pt increased concentration of anions (nitrate and phosphate) more than 30%Pt, possibly as a result of increased crop uptake or nutrient loss. As shown by crop uptake data, soil amended with 30%Pt had a higher uptake of the three measured nutrients (nitrogen, phosphate and potassium) than 20%Pt. Also, 30%Pt increased wheat vegetative and grain yield more than at 20%, which in turn would have increased immobilisation of these nutrients within the wheat biomass. Other possible reasons for the lower concentration of anions is their leaching loss in infiltrated water because the addition of 30%Pt increased total porosity and the presence of large macropores more than 20%Pt.

At the first sampling, soils amended with 5%K had higher anion retention than 5%B soils, and that is attributed to the repulsion of these negatively charged ions on B surfaces because of their same charges. On the other hand, K surfaces might have become positively charged in an acidic medium, and attracted the anions. However, at the second sampling, high variability in responses was observed, possibly due to various soil reactions that might have occurred over time such as mineralisation, fixation, leaching and immobilisation processes.

The ammonium concentrations measured at both sampling dates were very small, and at the second sampling, the concentrations were lower than the detection limit of the equipment used. Several factors could be responsible for this observation. One of them is ammonium uptake by the soil microbial biomass. It has been reported that soil microbes have a preference for ammonium more than nitrate in the soil. Shi and Norton (2000) and Abro et al. (2011) attributed low ammonium in their test soils to microbial immobilization because soil heterotrophs generally prefer ammonium for their growth, so microbial consumption of nitrate nitrogen is not a particularly important process except when the concentration of ammonium nitrogen is low and the amount of available C is high. Another possible reason is the uptake of ammonium by crop biomass.

5.4.3 Wheat growth and yield response in sandy soil amended with clay and organic matter

The plant emergence photographs show Pt aided spring wheat emergence because the soil amended with Pt had more emerged seedlings with uniform and vigorous growth compared to the unamended soil and clay alone treatments. This is possibly associated with the changes in the soils' physicochemical condition such as reduced bulk density, reduced albedo and increased nutrient availability. An increase in soil temperature is required for

seed germination following winter. Addition of OM is known to reduce the soil albedo by increasing its darkness (Dobos, 2006). The dark soil surface plays a key role in increasing soil temperature by absorbing more heat radiation, thereby keeping the soil warmer than soils with low OM. Also, OM could reduce soil albedo by increasing soil surface roughness. This higher soil warmth coupled with reduced soil bulk density might have supported improved wheat germination and emergence in Pt amended soils, while low soil temperature and high bulk density might have delayed seedling emergence in the clay alone and unamended soils.

At GS29, plant vigour for all the treatments was higher than for unamended soil, except for the 5%K treatment, but only plots treated with Pt with or without clay showed significant differences. This indicates that addition of Pt improved green area cover in these plots. The effect of the amendments on plant height followed the same trend as for plant vigour. The effects of clay were not significant but peat was, indicating that claying sandy soil in this experiment did not significantly increase plant height or vigour. These results suggest that the responses to Pt are mainly associated with its effect on soil properties. Pt has been reported to contain humic acids, fulvic acids, cellulose, hemicellulose, enzymes, peptides, fats, amino acids, alkaloids, vitamins, sugars and carbohydrates (Fuchsman, 1986; Szajdak, et al., 2007). Addition of nitrogen fertiliser would have stimulated microbial activity and the resulting release of plant-available nutrients in the Pt. This will be an advantage over soils amended with clay alone, as these are composed mainly of inorganic materials. Nguyen and Marschner (2013) also reported an increase in nutrient availability in sandy soil amended with compost alone whereas no effect was observed for soil amended with fine soil as an alternative.

All amendments increased wheat shoot fresh weight, total ear weight and the thousand grain weight compared to the unamended soil, in agreement with the test hypothesis number two. The increase in yield might be due to the ability of the amendments to improve the water and nutrient supplying capacity of the soil either directly or through improved microbial activity. The ability of OM to improve crop yield has been attributed to several factors such as the effect of N fertilizer on the applied OM, increased water availability and/or improved soil physical condition (Johnston, 1986) as well as increased soil CEC. The results of soil characterisation in this research show that amendments increased soil available water and soil CEC, increased or maintained soil OC, reduced porosity and improved soil nutrient uptake. A combination of all these factors would have been responsible for the improved

yield compared to the unamended soil. Similar improvements in the yield of wheat (Barzegar et al., 2002) and potato (Li et al., 2004) have been reported for soils amended with OM.

In 2.5%B and Pt combined treatments, fresh shoot weight reduced with increasing Pt ratio. Although this reduction was not significant, the results suggest that this may have been caused by the poor root growth in these combined treatments.

One unexpected observation was that a significantly higher shoot fresh weight occurred with soil treated with 5%K+30%Pt, and the highest total ear weight in the 5%K+20%Pt treatment compared with the corresponding B treatments. The reason for this could be due to better nitrate retention capacity, as well as higher nitrogen uptake with K than with B. The results showed that soil amended with K and K + Pt had higher nitrogen uptake than soils amended with 2.5%B and 5%B rates in the absence or presence of Pt, thereby justifying this inference. Furthermore, the results of the column leaching experiment (Chapter 2) showed that soil amended with K reduced nitrate leaching more than B.

It was also observed that there were yield depressions (vegetative biomass and total ear weight) when clay and Pt were combined. The yield depression could largely be associated with reduced Pt mineralisation in the presence of the clay. Clay has been reported as having an ability to reduce organic matter decomposition by soil microorganisms either by occlusion of OM by clay coating, formation of organo-mineral complexes, intercalation of OM into the clay structure (for smectitic clay), reduced soil aeration by changing soil microporosity and /or binding to microbial enzymes to reduce their activity (Dixon, 1991; Reuter, 1994; Franzluebbers et al., 1996).

5.5 Conclusion

Clay and clay+peat increased gravimetric soil MC throughout the monitoring months compared to the unamended soil, and combined clay and peat had the highest values. Soil amended with 30% clay? constantly increased soil MC over 20%Pt in 5%B soil while fluctuation between the two peat ratios was observed in peat alone, 2.5%B and 5%K soils. K amended soils had higher anion retention (nitrogen and phosphate) while B increased cation retention (potash). At 33 weeks after application, the unamended soil had higher nitrogen, phosphorus and potassium more than amended soil, and this is attributed to higher crop uptake and microbial immobilisation in amended soils. Peat and clay+peat

amendments improved seedling emergence and vigour. All amendments increased total ear weight and thousand grain weight at harvest compared to the unamended soil. There was yield depression in combined clay and peat treatments compared to their corresponding peat alone, but this is expected to be temporary. Contrary to the Test Hypothesis 3, K amended soil had higher crop yield more than B. Among the treatments, 30%Pt, 5%K+20%Pt and 5%B+30%Pt were the most efficient at increasing soil water, soil nutrients and crop yield.

Chapter 6

Final discussion and future work

6.1 Major findings from the experimental work

6.1.1 Amendments increase water retention and availability in sandy soils

The results of the column leaching experiment (Chapter 2), the soil water characteristics (Chapter 3) and soil moisture retention in the field (Chapter 5) show that the amendments generally increased water retention of the amended soils.

The column leaching experiment compared the effect of the amendments on two types of soil and showed that all amendments (except 2.5%K in SL) increased water retention in comparison to an unamended control soil. This result demonstrated their potential to improve the water holding capacity of sandy soils. However, the effect of clay amendments was reduced as the inherent clay content of the parent soil increased. PS with no inherent clay content retained less water than SL with 18% inherent clay content. However, when the amount of water retained by the amendments alone (WRA) was compared, the result shows that amendments retained more water in PS than SL in clay amended soils. From this, it is inferred that the higher amount of water retained in SL comes from the water retention of the inherent clay and that the inherent clay limited the water retention capability of the added clay materials. This is logical because the same volume of water was added to different amounts of clay, so the amount of water retained per unit weight of clay will be smaller in soil with higher clay content in SL compared to the smaller one in PS. These results confirm the findings of other researchers who also reported an increase in soil water retention of sandy soil when amended with clay (Mojid et al., 2009; Karbout et al., 2015; Zhou et al., 2016).

Bentonite was a more effective amendment compared to kaolin. This finding is as expected because bentonite possesses a higher charge density and CEC, and therefore greater water retention capacity. Water retention also increased when combined with OM compared to the unamended soil, clay alone and OM alone at the corresponding application rate.

In the field, 5%K increased soil moisture content compared to the unamended soil. On a monthly basis, fluctuation in soil moisture was observed in both treatments (5%K alone and in the unamended soil). However, when combined with OM, K significantly increased soil moisture content compared to the unamended soil. These results show that, when used as a sandy soil amendment, K should always be co-applied with OM.

Amending sandy soil with OM alone increased soil moisture content compared to the unamended soil and soils amended with clay alone. An examination using soil physical characteristics shows that OM on its own did not improve any of the soil properties that govern soil water retention such as pore number and size, thus it is inferred that the increased soil moisture content is the result of the water holding ability of the added OM; the mechanism could be water adsorption by humic substances present in the OM and/or cations adsorbed on the humic substances (Kramer, 1983). This effect supports the results of Li et al. (2004) who reported that amending sandy soil with peat increased the soil water content owing to large water holding capacity of the added peat.

Since OM appears not to modify soil pore characteristics responsible for water retention positively, its effect on water retention would likely diminish as the OM is mineralised and frequent repeated application (depending on the type of OM used) would be necessary to maintain increased water retention for crop production (Kramer, 1983; Duong et al., 2012).

Kramer (1983) and Duong et al. (2012) wrote that when OM was added to sandy soil, its humic colloids and CEC increased water and nutrient retention, but when OM is added to clayey soil, it will reduce microporosity and bulk density. While the latter remains true, the fact that the mechanisms also affect sandy soil is overlooked. The increase in pore sizes by OM is a function of OM's particle sizes and formation of soil aggregation. The first mechanism is owing to a larger particle size of OM (Sposito, 2008). When mixed with soil, OM will increase the pores sizes of aggregates smaller than its particle sizes. The second mechanism is via the role of OM in aggregate formation. OM increases aggregate formation majorly because of its support of increased microbial activity and the production of microbial exudates which are known as cementing agents for holding soil particles together (Nimmo, 2004) to form aggregate. The arrangement of soil particles into stable aggregates thereby will increase inter-aggregate pore spaces (Nimmo, 2004). When added to sandy soils, OM would also increase soil pore sizes by either or both of the mechanisms. The use of CT scanning has revealed that OM significantly increased macroporosity; OM also

reduced soil water retention at 15bars (proxy soil moisture content at permanent wilting point) compared to the unamended soil, eleven months after application. This study thus showed that there is a need for better understanding of how the application of OM alone as a sandy soil amendment could affect water retention and leaching of nutrients and/or pesticides owing to increase macroporosity. The effect of an increase in soil pores will vary from one region to another. The increase in soil macroporosity would affect water availability in dry regions or conditions, as water loss due to gravity pull will proceed rapidly. In regions with regular rainfall, increased macroporosity may not affect water availability because of frequent supply by rainfall, but can pose a greater risk of groundwater contamination by higher percolation of water containing nutrients and or pesticides.

The ability of clay and OM to increase the moisture content of soils might be due to the synergy between the two materials with the most likely mechanisms being a modification of soil pore characteristics by the clay and an increase in CEC by both clay and OM. Clay and OM interact through various processes such as, OM adsorption on clay surfaces, intercalation of OM into clay structure or organo-mineral complexes through cation bridges (Leinweber et al., 1993; Baldock and Skjemstad, 2000), which increases OM protection and soil CEC. The observed higher CEC, the combined effect of the water retention capacity of the added clay and OM, as well as a reduction in soil pore size and amount when clay and OM are co-applied are possibly responsible for the observed higher soil moisture content. None of the currently available studies on the use of combined application of clay and OM in sandy soil directly report the effect on soil water retention, so the current study thus provides a new addition to knowledge for the use of combined clay and OM to improve water retention of sandy soil.

The plant available water (PAW) result shows that water retention in soils is not directly proportional to water availability to plants in clay amended soils. In OM alone soil, available water was similar to water retention, and PAW increased with OM rate. However, in clay amended soils, over time, the clay + 20%OM treatments have the highest PAW, and this was true for the two types of clay used, and for both B rates, showing that more water would be available for crop uptake at this combination.

A comparison of the two clays weight for weight shows that K amended soil has higher PAW than for B. This is due to the strong forces of attraction between water molecules and

B, as well as the possible high microporosity of B meaning that water is tightly held and not released for plant uptake. However, in K, the possible reduced attraction between the clay and water molecules might have aided the higher water release. The higher PAW potential of K could be an added advantage compared to B under droughty conditions or where water availability is limited. Suzuki et al. (2007) also reported an increase in available water in sandy soil amended with termite mound material and bentonite compared to an unamended sandy soil two years after application and attributed the performance of the clay to an alteration of pore size distribution and improved porosity.

6.1.2 Amendments reduce water infiltration

One of the aims of this work was to reduce water infiltration and percolation in sandy soils but to do so without jeopardising soil quality and usability. A soil in good condition should have enough macropores for water infiltration and redistribution as well as good aeration for optimum root growth. There should be enough micropores to prevent excessive water loss through gravitational pull, but not too small to hinder water availability to crops (Cary and Hayden, 1973). The results of the field trials, where amended soils out-performed unamended soil, seem to satisfy these criteria.

Additional evidence is supplied by the clay amendments, which reduced the number of total soil pores over time but did not significantly increase the soil bulk density compared to the unamended soil. From this, it is concluded that a reduction in the infiltration volume would not have an adverse effect on crop growth and yield in the amended soil system. None of the current work on claying of sandy soils had reported an effect of clay alone or combined with OM on infiltration reduction, thus the current project provides a better understanding of the processes occurring in sandy soil amended with clay. A reduction in infiltration could lower the rate at which soil nutrients travel with the percolating water. Reduction in the volume of infiltrating soil water helps to increase retention time and interaction between the soil matrix and water and/or nutrients, which could result in increased adsorption of water by soil colloids or increase uptake by crops. This could have overall positive effects on minimising groundwater contamination, by limiting nutrient loads in leaching water.

Where soils were amended with higher rates of OM, infiltration was not reduced which is probably due to their high porosity and permeability (Karbout et al. 2015). So, where the main objective of soil management is to reduce infiltration in sandy soils, the use of OM alone cannot be recommended.

Clays reduced infiltration through their physico-chemical properties, either by direct effects on soil pore size and morphology, or through increased water retention. In this study, both clays reduced water infiltration with kaolin being more effective than bentonite. This was unexpected as bentonite has a higher CEC and surface charge density, as well as higher swelling capacity, which could reduce soil hydraulic conductivity compared to kaolin. However, it appears that the highly dispersive property of kaolin is more effective at reducing infiltration.

Co-application of K and OM illustrated the fundamental difference between the materials. Infiltration reduced with OM application rate but there was no significant difference between the OM rates and K on its own (at both rates). This suggests that the main factor responsible for the reduced infiltration is K. From this, it can be inferred that the addition of K to OM would reduce infiltration (in sandy soils). An alternative would be to add only K; however, this would have an adverse effect on soil fertility and water retention. These results have shown that soil CEC, soil water retention, nitrate retention, soil OC, soil EC and crop yield would increase when K is co-applied with OM. Moreover, the combined application of K and OM (especially up to 30% OM) would reduce runoff and soil loss. Consequently, it would be appropriate to combine the two for an improved performance of K amended soils. No similar work has been reported previously, and the mechanisms responsible for the observed result are possibly associated with the combined effect of the increased CEC and reduction in soil pores by K as previously explained.

Co-application of B and OM significantly reduced infiltration with reductions occurring at higher application rates, which might be associated with higher swelling volume arising from larger amount of clay. Also, it could be as a result of higher water retention as clay rate increases. In contrast to K, the combination of 5% clay and OM significantly reduced infiltration compared to B and OM alone, suggesting that some form of synergy is occurring.

Synergy refers to a condition where the combined application of clay and OM effect is higher than the sum effect of adding the two separately. The possible mechanism is through higher water retention owing to increased CEC. In addition to direct water adsorption by clay and OM, cations adsorbed on clay and OM could attract layers of water. The first layer is attracted to the cations by electrostatic force, while other layers are attracted to water

molecules through hydrogen bonding (Hillel, 1998). Since combined B and OM has a higher CEC, this might have increased water retention, thereby reducing the infiltration volume. These results of combined B and Pt show that combined application of B and OM can be used to reduce infiltration in sandy soils, and to improve its water retention capability. Lee et al. (2015) suggested that combined biochar and polyacrylamide could reduce water infiltration. Though they did not measure infiltration in their experiment, they attributed the increase in runoff to a reduction in infiltration since it is inversely related to runoff. This work thus provides quantitative evidence that combined use of OM and fine materials such as clay and polyacrylamide could reduce infiltration.

6.1.3 Clay amendments at higher application rates increase runoff and soil loss.

All the amendments increased runoff in comparison to unamended soil. During rainfall, rain drops reaching the soil surface are either infiltrated or accumulate to form potential runoff. Therefore, any change in soil surface condition that reduces infiltration would increase surface runoff. Those soils amended with just OM, with clays at the lower rate and their combinations, did not have a significant runoff, probably as a result of their higher infiltration potential. The effect of claying on sandy soil hydrology has not been previously reported. However, Lee et al. (2015) reported increased runoff in soil amended with biochar and polyacrylamide when rainfall was simulated but the only polyacrylamide increased runoff in the field. The difference in their report and the current work is associated with the different materials used; while they worked with biochar and polyacrylamide, the current work used clay and peat. Also, the soil amended was loamy soil with 45% sand, while the soil used in this experiment was sandy loam with 65% sand. Also, Li et al. (2014) reported a reduction in runoff and soil loss when a loamy sand (79% sand) soil surface was mulched with leaf litter in China. Although the methodology used is different from that of this project, it did provide further evidence that OM can reduce runoff and soil loss.

A comparison of the two clays alone showed that although 5%K increased runoff more than 5%B as rainfall progressed, less soil was lost in 5%K compared to 5%B, suggesting that there might be less total sediment load in the runoff volume of the K compared to the B amended soils. This could mean that the dispersed K particles underwent gravity transport in the infiltrated water and were deposited in the soil pores rather than being lost as a sediment load. The 5%B amended soils increased soil loss as rainfall duration increased. It is also noteworthy that soil amended with 5%B and 20% OM showed lowest infiltration volume and highest increased surface runoff, suggesting that the synergistic effect of B and

OM on infiltration reduction is at a maximum in this treatment. It is thus recommended that when B is to be used along with OM, the OM application rate should be increased to 30% (v/v) to effectively reduce infiltration, and avoid an excessive runoff and soil loss. Also, it is suggested that management practices that could reduce surface runoff and soil loss such as retaining crop residues, mulching and cover crop should be incorporated along with claying, at least at the initial stage, to mitigate runoff and soil loss effects.

The observed results are believed to represent the soil condition immediately after amendments, however, the effect on soil loss and runoff is expected to decrease as interactions between clay and OM increase over time. The soil used in this experiment is structureless, and the interaction between clay and the soil biological component has not yet developed, since the amendments were mixed and the rainfall simulation was conducted within 48 hours. Over time, the added clay and OM are expected to interact with the soil biological components to form a stable aggregate. Exudate of microbial biomass and fungi hyphae are important in soil aggregate formation and stability. Furthermore, crop growth could increase soil aggregation via their roots. Also, under field conditions, the plant canopy would reduce raindrop impact by reducing their kinetic energy before reaching the soil surfaces. The developed soil structure and aggregate would, in turn, reduce the impact of erosivity of raindrops on soil particle detachment, and soil losses (Hillel, 1998).

6.1.4 Amendments improve spring wheat growth and yield

All amendments increased the yield of spring wheat in comparison to an unamended soil. This can be attributed to the general improvement in soil physical, chemical and biological conditions provided by the amendments. The greatest performance was observed in soils amended with K rather than B, and there are three possible factors: (1) higher nitrate retention; (2) activity coefficient of the K minerals and (3) greater plant available water.

When in an acidic medium, kaolinites would develop positive charges on the edges due to protonation, which allows attraction of the negatively charged nitrate ion. Since the K soils in this work are acidic, it can be concluded that this mechanism would occur. In contrast, the surfaces and edges of B are negatively charged and therefore repel nitrate. Thus, it could be inferred that sufficient availability of nitrogen during crop growth is responsible for the increased yield in K amended soils. This inference is further strengthened by higher nitrogen uptake in the K treatment compared to the B amended soils. Nguyen and

Marschner (2013) and Tahir and Marschner (2016) also reported an increase in nitrate in soils amended with kaolin in laboratory incubation experiment.

The second reason is the activity coefficient of the different clay minerals. The activity coefficient is the measure of the ease of dissociation of clay salts or the ease of release of cations. The stronger a cation is adsorbed, the less the ease of release for crop uptake. Marshall (1942; in Burhrer, 1952) measured the dissociation of cations on four types of clay, and reported that the activity coefficient of clay minerals follows the order: kaolinite > montmorillonite > beidellite > illite. The clay mineral in kaolin is kaolinite while bentonite contains montmorillonite. The stronger dissociation of K compared with B is associated with its lattice structure, which has balanced charges due to lack of isomorphous substitution reaction (Burhrer, 1952). Because the cations are adsorbed on the edges of the K minerals, they are feebly held and could be accessed readily by plants. However, in B, the cations are adsorbed not only on the edges but also in the lattice structure, so they are not readily dissociated because of the very strong force of attraction between the cation and the clay lattice. On the basis of this phenomenon, K amended soils will readily exchange cations with the soil solution for crop uptake more than B.

A third factor is the plant available water. Over time, K amended soils had higher plant available water than those amended with B at all corresponding application rates. This is because the forces of attraction between B and water are stronger than that of K and water, possibly as a result of microporosity and adsorption of water within the B lattice. Thus, though B had higher water retention than K, this was not available for plant uptake, unlike for K. Since water availability often restricts crop growth, this might explain the difference between yield in K and B soils. Al-Omran et al (2005) also reported highest squash fruit yield (*Cucurbita pepo*) in Saudi Arabia in soil amended with crude clay containing a higher percentage of kaolinite compared to clays high in bentonite and vermiculite.

Reuter (1994) recommended that kaolin should not be used as a soil amendment because it has a low CEC. However, the results of this study refute that recommendation since kaolin improved soil porosity, had higher plant available water, higher nitrate retention and increased grain yield compared to B. In addition, when combined with OM, K further increased the availability of soil water; increased soil water retention, soil moisture at FC and PWP; increased soil CEC, EC, OC and C:N ratio; reduced carbon mineralisation, soil porosity, total pore area, number of pores and number of large pores (reduced

macroporosity); improved seedling emergence and vigour, as well as crop yield compared to the unamended sandy soil. These results suggest that factors other than CEC should be taken into account when considering amendments for sandy soils. It also highlights that other soil properties, such as nutrient availability and good soil physical conditions, are essential for crop growth and yield. It is suggested that when combined with OM, kaolin can be used as sandy soil amendment. None of the recent studies on sandy soil amendments directly compare the two clay minerals in a pure form as sandy soil amendments under the same experimental conditions. This finding thus provides fundamental information for making choices about which clay to be used in amending sandy soils, where applicable.

6.1.5 Combined applications of clay and OM result in yield depression compared to OM alone

Spring wheat yield (ear weight) was higher in majority of OM only treatments compared to the combination of clay and OM, and this might be caused by the reduced mineralisation of OM due to the addition of clay.

The reduction in OM mineralisation in the presence of clay has been reported by many researchers (Kramer, 1983; Djajadi et al., 2012; Nguyen and Marschner, 2013; Tahir and Marschner, 2016). The suggestion that mineralisation increased in OM alone soils is supported by the higher C:N ratios in all clay and OM amended soils compared to the OM alone at a corresponding application rate, as carbon mineralisation increases with reducing C:N ratio. Over time, as decomposition of the added OM occurs, the OM remaining may diminish faster in OM alone treatments due to a high oxidation rate (Mekuria et al., 2015), thereby reducing water retention and nutrient availability to subsequent crops. Kramer (1983) wrote that the benefits of amending sandy soil with OM do not persist in the absence of enough soil clay. These findings were supported by Karbout et al. (2015) and Zhou et al. (2016) who wrote that while OM could improve soil fertility, its effect usually diminishes over time due to its mineralisation, unlike clays which are not biodegradable. Without re-application, increased carbon mineralisation could reduce soil quality over time. However, combined clay and OM with a slower oxidation rate would support long-term stability of the soil aggregate, increased microbial biomass and activity, increased soil water and nutrient retention, which could result in a higher yield or cumulative higher yield over time. Also, the reduced mineralisation will require less frequent application of OM, which also would have an economic advantage.

6.1.6 Amendments increase soil carbon, and kaolin tends to have higher potential to increase SOC at the same application rate as bentonite.

Soils amended with OM had higher levels of soil organic carbon (SOC) compared to unamended soils; this was a direct result of adding organic material. Over the eleven months of the field trials, SOC increased in OM alone and K amended soils but declined in B amended soils. The decrease in B amended soils is attributed to higher rates of decomposition of added organic material mediated by the increased microbial abundance and activity. A similar effect was observed for the soil carbon to nitrogen ratio, where soil amended with 5%K had a higher C:N ratio in comparison to 5%B, although unlike SOC, the C:N ratio increased or remained stable in all the treatments over time. This observation was unexpected as B, which is a highly reactive clay with better aggregate stability, is expected to offer higher protection to SOC against microbial decomposition. The main reason for this variation is likely to be soil pH where the lower pH of K and OM alone might have excluded or impaired the activity of certain groups of soil microbial biomass, such as bacteria (Rousk et al., 2009).

Rousk et al. (2010) used quantitative PCR and bar-coded pyrosequencing techniques to measure the soil microbial abundance and diversity in an arable land with a wide pH gradient (4.0 to 8.3). They reported that bacterial abundance and diversity were positively related to soil pH, and that diversity was almost double as pH increased from 4 to 8, while a weak response was found between fungi and pH. They concluded that soil pH affected bacteria because they have a narrow optimum pH growth range, while fungi would generally grow over a wide range of pH values. On the basis of their report, it could be inferred that both bacteria and fungi were active in B amended soils resulting in the rapid decomposition of SOC, while the active microbes in K and Pt soils were limited to acid-tolerant communities, possibly dominated by fungi (Rousk et al., 2009; Rousk et al., 2010). This inference is supported by the high microbial respiration rates measured in the B amended soil compared to the K: 5%B had the highest respired CO₂ contrary to the expectation that OM alone would have the highest decomposition rate because of low clay content and increased aeration.

Djajadi et al. (2012), and Nguyen and Marschner (2013) reported reductions in soil respiration with increasing clay content when sandy soils were amended with clay. In both experiments, they used a kaolinitic clay material, and attributed their observations to increased protection of OM by soil clay. None of these studies measured the pH of the soil

after amendments; however, the pH values of the soil, the kaolinitic subsoil, and compost used by Nguyen and Marschner were 8.8, 8.7 and 8.2 respectively, but Djajadi et al. did not report any pH, making it difficult to compare the influence of soil pH on their observed results. While the result from K amended soils in the present study agrees with those authors, the primary reason is attributed to the low pH which might have hindered the soil microbial community diversity and abundance, hence the observed OC protection. Of course, it is also possible that K being a highly dispersive clay might have coated soil aggregates more rapidly than B, and contributed to the reduced decomposition of OC. The comparison of K and B under the same experimental field conditions shows that at a higher application rate, combined B and OM did not reduce carbon mineralisation. The current results show that it is not appropriate to simply generalise results to all clays, rather specific experiments under different climatic conditions with different clay types should be carried out to help make sound recommendations. The current results show that K has a higher potential to increase soil carbon storage, while improving the yield of wheat.

6.1.7 Amendments improve soil properties. Clay amendments optimise soil pore characteristics and EC compare to OM alone.

Generally, amendments improved all the soil physical, chemical and biological properties measured in this project. Compared to an unamended soil, the addition of OM and K separately reduced initial soil microbial biomass carbon (MBC), pH, bulk density and soil cracking, while B additions increased them. Amending with clay alone (K and B) reduced soil porosity, number of pores, pore diameters and soil electrical conductivity over time in comparison to the unamended soil. The soil pore characteristics results agree with findings of Suzuki et al. (2007) that clay amendments altered soil pore distribution in sandy soil compared to an unamended soil.

Amending sandy soils with OM alone significantly increased soil total pore count, macropores >1mm, soil porosity and pore diameter compared to the unamended and clay only amended soils. The increase in soil pores and porosity shows that OM has the overall effect of increasing pore sizes of the test soil, and the increase is responsible for the significantly low electrical conductivity of the soil when amended with OM alone. The current work agrees with findings of Li et al. (2004) that amending with peat increased soil EC in an amended sandy soil in Canada, and attributed their observation to the increase in macroporosity by peat. None of the currently reported research measured the effect of OM used as sandy soil amendments on soil pore characteristic using CT scanning. So, these

results from CT scanning provide a new insight into the impact of similar OM used in this experiment on soil pore characteristics.

While the addition of OM alone increased spring wheat yield, the increase in pore sizes and abundance could increase nutrient leaching and potential contamination of groundwater as dissolved nutrients infiltrate with soil water. The increase in pore sizes and abundance would increase the leaching rate of soil nutrients, and that might be the reason why salt concentration was low in this soil as shown by the EC value over time. While the water absorption capacity of the OM used was able to offset the effect of the increase in soil porosity, it has a low potential to reduce nutrient leaching.

6.1.8 Amendments and nutrient uptake

Amendments increased the uptake of nitrogen, phosphorus and potassium by the crop compared to the unamended soil in the majority of the treatments. Higher nutrient uptake not only contributes to increase crop yield, but could also help to immobilise the nutrients in the crop residues. This could help reduce leaching losses, and when returned to a field, microbial mineralisation of the residues would make the nutrients available for future crops. Comparison of the two clays shows that over time, K increased nitrogen uptake more than B. The higher uptake of nitrate is possibly associated with the increased availability of K compared to B amended soil.

Soil nutrient concentrations after harvest show that the unamended soil had a higher nutrient concentration than the amended treatments. This is possibly associated with poor nutrient utilisation and/or increased mineralisation. Strong et al. (2004) reported that OM binding sites in sandy soil are limited, compared to finer textured soils. The low number of binding sites coupled with high porosity and aeration as shown in this work, therefore could induce a faster rate of OM decomposition, hence the higher nutrient level in the unamended soil. Tahir and Marschner (2016) also reported that claying did not reduce phosphorus concentration in sandy soil amended with combined clay and OM.

6.1.9 Recommendation and practical application

The results showed that amending sandy soil with clay and OM under field conditions is possible. Where subsoil has clay accumulation, this could be delved and brought to the surface to improve water and nutrient retention within the root zone. Also, soils high in clay content could be used as amendment sources. The immediate economic return in the form

of increased yield, while reducing nutrient losses from cultivated land, might offset the initial cost of the amendment. Amendments would reduce the cost of production such as increased fertiliser and irrigation application. Also, when applied in combination, clay can reduce the OM mineralisation rate thereby reduce the frequent application.

As shown in Table 6-1, all amendments have the capacity to improve the properties and productivity of sandy soils, but there are trade-offs. Amending with OM (peat) alone improved soil MC at FC, PAW and bulk density but reduced soil water retention at PWP which might lower the water retention capacity of the soil under dry conditions. Also, sole application of OM had a negative effect on the pore characteristics by increasing porosity and pore diameter, which may lead to increase in water and nutrient losses especially in humid zones. This is further strengthened by the nil effect on infiltration reduction and negative effect on EC at higher OM ratios. There is a call for further research for better understanding of the effect of using OM alone on nutrient leaching and groundwater contamination. OM alone will improve soil CEC, SOC nutrient uptake and crop yield, but there would be a gradual decline as OM decomposition progresses.

The addition of clay and combined clay and OM increased soil MC at both FC and PWP, as well as PAW except 5%B. Clay addition can improve porosity and soil pore characteristics; improve soil chemical properties, optimise infiltration but will increase runoff and soil loss. This effect of clays on runoff and soil loss implies that soil management techniques that can minimise erosion such as mulching, residue retaining and cover crops should be used along with claying. All clay treatments increased spring wheat growth and yield. This suggests early economic return on investment, but full economic analyses of adopting this soil management system would be necessary to aid adoption by the end users. The combined application of clay and OM improved all the soil properties and spring wheat yield. The only major negative effect of combined clay and OM is the increase in runoff and soil loss, and could be managed with other soil erosion reduction techniques as mentioned earlier.

The major limitation of kaolin is low CEC, but this can be readily improved by co-application with OM. Kaolin can also reduce soil respiration but does not have an adverse effect on spring wheat growth and yield. Although bentonite alone is very effective at increasing soil MC, even? at 5%, it reduces PAW due to higher forces of attraction between water and B. Clay has higher nutrient retention capability than OM alone especially at 30%.

Table 6-1: Conceptual model showing trade-offs between soil and plant properties in response to the amendments

Soil property	<u>Peat(%)</u>		<u>5% Kaolin</u>			<u>2.5% Bentonite</u>			<u>5% Bentonite</u>		
	20	30	5K	20%Pt	30%Pt	2.5B	20%Pt	30%Pt	5B	20%Pt	30%Pt
Soil MC (%)	+	+	nil	+	+	nil	+	+	+	+	++
FC (%)	nil	+	+	++	++	+	++	++	+	++	++
PWP (%)	-	-	+	++	++	+	++	++	++	++	++
PAW (%)	+	++	+	++	+	+	++	+	-	+	+
Bulk density (g cm ⁻³)	+	+	nil	nil	+	-	nil	nil	nil	+	+
Porosity	---	---	+	+	++	+++	++	+	+	+	+
Pore diameter (mm)	-	nil	+	+	++	++	++	++	++	+	++
Pore count	---	---	++	++	++	+++	++	++	++	++	++
Infiltration (ml)	nil	nil	++	++	++	++	++	++	++	+++	++
Runoff (ml)	+	+	--	--	-	-	-	-	-	---	--
Soil loss (g)	+	+	-	-	-	-	-	-	-	---	--
pH	--	--	-	--	--	+	+	nil	++	++	++
EC (µS cm ⁻¹)	+	-	++	++	++	++	++	++	++	++	++
CEC (cmol kg ⁻¹)	nil	+	nil	+	+	+	++	++	++	++	++
Soil nitrogen (mg kg ⁻¹)	+	-	++	+	+	++	+	+	++	+	+
Soil phosphorus (mg kg ⁻¹)	++	-	++	++	++	++	+	-		-	-
Soil potassium (mg kg ⁻¹)	-	-	-	++	++	-	-	-	++	-	-
Nitrogen uptake (kg ha ⁻¹)	++	++	++	++	++	+	+	-	++	++	++
Phosphorus uptake (kg ha ⁻¹)	++	++	+	++	++	+	+	+	++	++	++
Potassium uptake (kg ha ⁻¹)	++	++	++	++	++	++	++	++	++	++	++
MBC (µgC g ⁻¹)	+	+	nil	-	+	-	+	+	-	++	++
Soil respiration (mg g ⁻¹ soil)	++	++	--	-	+	++	++	++	-	++	++
SOC (%)	++	++	-	++	++	-	++	++	++	++	++
C:N	+	++	nil	+	++	nil	+	++	nil	+	++
Seedling emergence	+	+	nil	+	+	nil	+	+	nil	+	+
Plant height (cm)	++	++	+	++	++	+	++	++	+	++	++
Fresh shoot wt. (g)	++	++	++	++	++	++	++	++	++	++	++
Ear wt. (g m ⁻²)	++	++	++	++	+	+	++	+	+	++	++
TGW(g)	++	++	++	++	+	+	++	++	++	++	++

+ = effective;

++ = very effective;

+++ = extremely effective;

nil = no effect;

- = negative effect;

-- = very negative effect

--- = extremely negative effect

All amendments, with the exception of kaolin alone up to 5%, can be used to increase water retention of sandy soils. However, for optimum water retention and availability, 30%OM, 5%K+20%OM and B+30%OM would be appropriate. When choosing an amendment basically for infiltration reduction, the use of OM alone should be avoided because OM alone has little or no effect on infiltration reduction. Where clay alone is to be used, 5% kaolin and 2.5% bentonite (w/w) would be appropriate. If using combined clay and OM, kaolin with 20% OM and bentonite with 30% OM is suggested. The combined bentonite and 20% OM should be used along with soil management practices that could reduce runoff and soil loss such as growing a cover crop, mulching and residue retaining. For crop yield and nutrient uptake, use of 30%OM, 5%K+20%OM and B+30%OM is recommended. It is strongly recommended that kaolin should always be applied with OM to enhance its low CEC and water retention.

In this project, peat was used as the OM source, however, the use of peat as OM under field conditions is not recommended because of the sustainability of peat bogs. Rather, peat was used as a model OM because it is homogenous and consistent in term of their chemical composition and particle sizes, thus making it easy to establish a principle for using OM. Other OM such as manure, compost, crop residue, bioethanol wastes and biosolids can be used. However, it is suggested that these should be tested to understand their performance before recommending them to farmers.

6.2 Final Conclusions

The work carried out in this thesis investigated the potential of organic and inorganic materials to improve the resilience of sandy soils to degradation processes. A laboratory column leaching method and field trial measured water and nutrient retention of the test soils. The effects of the amendments on sandy soil hydrology were examined using rainfall simulation, and possible mechanisms controlling infiltration reduction in soils amended with different clays (K and B) and /or OM were identified. Also, the effects of the amendments on soil properties were measured over time using various approaches including Computed Tomography (CT) scanning, to provide an understanding of any changes in soil physical characterisation. Finally, the project measured how the amendments influence the growth and yield of spring wheat in order to develop field-based management options for sandy soils.

The results obtained from this project shows that amendments overall can improve quality and productivity of sandy soil. The benefit of amendments includes increased water retention; reduced water infiltration; improved seed emergence and seedling vigour; increased crop growth and yield, improved soil pore characteristics; reduced porosity; increased CEC, C:N ratio, microbial activity, nutrient uptake and soil organic carbon compared to the unamended soil. On the down side, sole application of OM increased soil macroporosity; amending with clay alone tends to increase soil bulk density; claying increased runoff and soil loss compared to unamended soil, but runoff and soil loss would decrease as a stable soil structure develops. Also, combined application of clay and OM reduced spring wheat yield compared to the OM alone.

The project has added to the available knowledge on the management of sandy soil by showing that combined clay and OM can consistently increase water and nutrient retention as well as the measured properties of sandy soils. The rainfall simulation experiment revealed hydrological processes occurring in sandy soil amended with clay, and have identified possible mechanisms governing these processes in soil amended with different clay minerals in the absence or presence of OM. Furthermore, with the aid of CT scanning, the project has shown that the use of OM with a large particle size will increase soil macroporosity. It has identified the underlying mechanisms responsible for the increased macroporosity as a direct effect of the OM's particle size and indirect effect associated with soil aggregation, and raised a concern that it could affect groundwater contamination in wet humid weather. The CT scanning results on soil pore characteristics agree with the results of soil bulk density measured in the field by displaying the known inverse relationship between soil porosity and bulk density, thereby showing the reliability of the method. The field trial has shown that amendments can increase the yield of spring wheat compared to the unamended soil. Yield depression where clay and OM are co-applied is possible compared to OM alone due to a reduction in soil carbon mineralisation as a result of OC protection by clay. This could be an initial effect, as diminishing returns on yield due to reduced OC would begin earlier in OM alone soil, and a higher yield emanating from the accumulated yield over several years in combined clay and OM is expected.

The results refute the belief that kaolin is unsuitable for amending sandy soil because it has a low CEC. When combined with OM, the CEC of kaolin increased. The study has revealed that both in the laboratory and in the field, kaolin has a higher nitrate retention than B, and that would be important in managing soils where nitrate leaching is a major problem.

Contrary to expectation, combined kaolin and OM had higher available water than combined bentonite and OM at the same application rate. Kaolin alone and with up to 20% OM increased spring wheat yield more than bentonite; also, kaolin amendment increased nutrient uptake and anion retention compared to bentonite. All this evidence, along with kaolin's positive effect on soil physical properties, demonstrated that amendments cannot be chosen based on a single characteristic, and that kaolin can be used to amend sandy soil.

The project has shown that amendments increase or maintain soil organic carbon. This study also shows that protection of soil organic carbon (OC) by clay would be affected by clay type and soil pH, as soil OM decreased in bentonite amended soil over time while increasing in the kaolin-amended soil, suggesting that carbon mineralisation would be slower in kaolin amended soil than that of bentonite. The project has demonstrated that the use of clay, OM or combined OM and clay as a sandy soil amendment is possible under field conditions, and could be a profitable approach with a possible economic return within a short term. The combined application of clay and OM proved to be most effective at improving properties of sandy soil and crop yield, and is thereby recommended for management of sandy soils.

6.3 Possible future work

6.3.1 Replication of the current experiments in space and in time on crop growth and yield is recommended to test the robustness of the observed data. The yield trial in the current project was conducted over one growing season using one type of crop. It is essential to repeat the same experiment over time and space with different crops to understand if amendment will be crop specific. Repetition in space would enhance our understanding of influences of different climatic conditions on the effectiveness of the amendments. Long-term experiments would help to test the hypothesis that over time, accumulated yield in combined clay and OM will offset the yield depression observed in these treatments compared to the OM alone at the early stages of the field trial.

The current study used only one sandy soil that has 18% inherent clay. As shown by the column leaching experiment (Chapter 2), sandy soil with different amounts of inherent clay will respond differently. Since sandy soils vary in their inherent clay content, repetition of the current experiment using soils with different amounts of inherent clay will be necessary for further understanding of the performance of the amendments. Furthermore, it will reveal

the threshold of clay content in sandy soil above which addition of further clay will become unnecessary for yield improvement.

Also, this project worked with only one OM and it is essential to use other organic materials such as compost, crop residue and manure, both alone and in combination with clay to enhance the robustness of the performance of combined clay and OM in sandy soils. This will provide a wider view of the performance of these OM sources when combined with clay, and provides extended information on the influence of combined OM and clay on the properties of sandy soil.

6.3.2 Comparing the effectiveness of kaolin (K) and bentonite (B) on OM decomposition under similar soil pH is recommended to clarify the role of clay amendments in OC protection. It has been reported that clay can protect organic matter against microbial degradation (Leinweber et al., 1993; Duong et al., 2012; Nguyen and Marschner, 2013). The current research has found that OC reduced over time (33 weeks) in bentonite amended soil but increased in kaolin amended soil. The discrepancy is attributed to differences in the pH of the two soils (kaolin is acidic while bentonite is alkaline). According to Rousk et al. (2009, 2010), most soil bacteria can only survive in neutral/alkaline soils while fungi can grow successfully across a wide range of soil pH. Although microbial diversity was not measured in the current project, the results for soil respiration and MBC were higher in bentonite than kaolin soils, indicating that bentonite has a more favourable growth condition for soil microorganisms, resulting in the higher rate of carbon mineralisation. The major soil property that varies significantly between the two soils, and can favour microbial growth in bentonite is pH. Thus, it is hypothesised that the low pH in kaolin reduced the soil microbial activity resulting in less carbon mineralisation compared to bentonite. It is suggested that an experiment that tests the above hypothesis should be conducted using 2:1 and 1:1 clay minerals with similar pH.

6.3.3 Long-term experiments to monitor soil structure and aggregate stability in sandy soil amended with clay and OM, and how they affect runoff and soil loss is recommended. Soil aggregate stability plays an important role in the management of erodibility of a soil (Hillel, 1998). The result of soil erosion in this experiment shows that clay at 5% increased runoff and soil loss. The increase is attributed to the unconsolidated and non-aggregated condition of the mixed soils. It is thus hypothesised that long-term interaction between the soil and the amendments will result in improved aggregate stability

compared to the unamended soil. The development of erosion resistant aggregates is expected through the cementing actions of microbial exudates, fungi hyphae, cation bridges and plant roots (Nimmo, 2004; Annabi et al., 2007; Arthur et al., 2010; Yu et al., 2012; Duong et al., 2012). Therefore, a future experiment to investigate a long-term effect of combined clay and OM on soil aggregates and erosion in sandy soil is recommended.

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Appendix A

Conferences attended and publications

“Effectiveness of combined applications of clay and organic materials on the hydrology of a sandy loam using rainfall simulation”. Oral presentation at the 1st World Conference on Soil and Water Conservation under Global Change (CONSOWA), Lleida, Spain, June 12 – 16, 2017.

“Effect of inorganic and organic amendments on water retention and yield of wheat in a sandy soil”. Oral presentation at the 1st World Conference on Soil and Water Conservation under Global Change (CONSOWA), Lleida, Spain, June 12 – 16, 2017.

“Comparative evaluation of effectiveness of kaolin and bentonite mixed with organic material as sandy soil amendment”. Oral presentation at the Biannual Early Career Conference organized by the British Society of Soil Science, University of Lancaster, April 19-20, 2017.

“Improving the resilience of sandy soils to degradation pressures”. Oral presentation at the International Conference on Conservation Agriculture and Sustainable Land Uses (CASLU), Budapest, Hungary, May 31 -June 2, 2016.

"Improving water retention of sandy soil using clay and organic matter" poster presented at Early Career researcher for Agriculture Conference organized by KTN in conjunction with industries, Birmingham, March 22, 2016.

Publications:

Ogunniyi Jumoke Esther, Jane Rickson and Robert Lillywhite (2017). Effect of inorganic and organic amendments on water retention and yield of wheat in a sandy soil. In: Simó, I., Poch, R. M., Pla, I. (Eds). Proceeding of 1st World Conference On Soil And Water Conservation Under Global Change (CONSOWA), Lleida, Spain, June 12 – 16, 2017, pp 468-471. ISBN: 978-84-697-2909-0

Ogunniyi Jumoke Esther, Jane Rickson and Robert Lillywhite (2017). Effectiveness of

combined applications of clay and organic materials on the hydrology of a sandy loam using rainfall simulation. In: Simó, I., Poch, R. M., Pla, I. (Eds). Proceeding of 1st World Conference On Soil And Water Conservation Under Global Change (CONSOWA), Lleida, Spain, June 12 – 16, 2017, pp 472 – 475. ISBN: 978-84-697-2909-0

Ogunniyi Jumoke Esther, Jane Rickson and Robert Lillywhite (2016). Improving the resilience of sandy soils to degradation pressure. Book of abstract of the International Conference on Conservation Agriculture and Sustainable Land Uses (CASLU), Budapest, Hungary, pp 74.

Appendix B

Calculation of soil and clay for the column leaching experiment

The column leaching experiment was carried out using acrylic tube

The height of the tube = 50 cm

The diameter of tube = 11.7cm

Radius of the tube = $(11.7/2)$ cm
= 5.85 cm

Bulk density of the soils = 1.5 g/cm³

$$\begin{aligned}\text{Volume of a sphere} &= \pi r^2 h \\ &= (3.142 \times (5.85)^2 \times 30) \text{cm}^3 \\ &= 3,225.813 \text{ cm}^3\end{aligned}$$

For soil ((SL and PS)

For weighing convenience, the volume was converted to soil weight

$$\begin{aligned}\text{Weight of soil} &= \text{density (g/cm}^3\text{)} \times \text{volume (cm}^3\text{)} \\ &= 1.5 \text{ (g/cm}^3\text{)} \times 3,225.813 \text{ cm}^3 \\ &= 4,838.720 \text{ g soil}\end{aligned}$$

So, amount of soil used was 4,838.720 g soil / column

For peat

$$\begin{aligned}\text{At 10\% peat rate, volume used} &= (10 \times 3,225.813 / 100) \text{ cm}^3 \\ &= 322.581 \text{ cm}^3\end{aligned}$$

$$\begin{aligned}\text{At 20\% peat rate, volume used} &= (20 \times 3,225.813 / 100) \text{ cm}^3 \\ &= 645.163 \text{ cm}^3\end{aligned}$$

$$\begin{aligned}\text{At 30\% peat rate, volume used} &= (30 \times 3,225.813 / 100) \text{ cm}^3 \\ &= 967.7439 \text{ cm}^3\end{aligned}$$

But,

1L of peat \equiv 290g

The volume of peat was converted from cm^3 to L and multiplied with 290g to get the equivalent amount of peat used at different peat rate.

At 10%Pt rate:

$$= (322.581 / 1000) \text{ L}$$

$$= 0.3226\text{L}$$

Convert L to g

$$0.3226\text{L} \equiv (290 \times 0.3226) \text{ g}$$

$$= 93.55\text{g}$$

At 10%Pt rate:

$$= (645.163 / 1000) \text{ L}$$

$$= 0.6452\text{L}$$

Convert L to g

$$0.6452\text{L} \equiv (290 \times 0.6452) \text{ g}$$

$$= 187.10\text{g}$$

At 30%Pt rate:

$$= (967.7439 / 1000) \text{ L}$$

$$= 0.9677\text{L}$$

Convert L to g

$$0.9677\text{L} \equiv (290 \times 0.9677) \text{ g}$$

$$= 280.65$$

Therefore, the amount of used are:

10%Pt rate = 93.55g

20%Pt rate = 187.10g

30%Pt rate = 280.65g

For clay (K and B)

Determination of amount of clay (w/w) of soil to the depth of 30 cm of the soil column is given as follow:

$$\begin{aligned} 5\% \text{ clay} &= (5\% \times 4,838.720) \text{ g} \\ &= 241.94\text{g} \end{aligned}$$

$$\begin{aligned} 2.5\% \text{ clay} &= (2.5\% \times 4,838.720) \text{ g} \\ &= 120.97\text{g} \end{aligned}$$

Appendix C

Determination of amount of ammonium nitrate required per column

The N application rate is 150kg N per hectare

Molecular formula of ammonium nitrate = NH_4NO_3

Molar mass = 80

The percentage N in the ammonium fertiliser used = 34.5%

Therefore,

$$34.5 \text{ kg N} \equiv 100 \text{ kg NH}_4\text{NO}_3$$

$$1 \text{ kg N} \equiv (100/34.5) \text{ kg NH}_4\text{NO}_3$$

So,

$$\begin{aligned} 150\text{kg N} &\equiv ((100/34.5) \times 150) \text{ kg NH}_4\text{NO}_3 \\ &= 434.78 \text{ kg NH}_4\text{NO}_3 \end{aligned}$$

This means that amount of ammonium nitrate that is required to achieve 150kg N per hectare is 434.78kg.

Calculate the area of the soil column used, when

The diameter of tube = 11.7cm

$$\begin{aligned} \text{Radius of the tube} &= (11.7/2) \text{ cm} \\ &= 5.85 \text{ cm} \end{aligned}$$

Convert cm to m

$$\begin{aligned} &= (5.85/100) \text{ m} \\ &= 0.0585\text{m} \end{aligned}$$

$$\text{Area} = \pi r^2$$

$$\begin{aligned} &= (3.142 \times (0.0585)^2) \text{ m}^2 \\ &= 0.010753 \text{ m}^2 \end{aligned}$$

Given that:

The area of a hectare = $10,000\text{m}^2$

So,

$10,000\text{m}^2$ will require $434.78 \text{ kg NH}_4\text{NO}_3$

Therefore,

0.010753 m^2 will require $(434.78/10,000 \times 0.010753) \text{ kg NH}_4\text{NO}_3$

$$= 0.0004675 \text{ kg NH}_4\text{NO}_3$$

Convert kg to g

$$= (0.0004675 \times 1000) \text{ kg NH}_4\text{NO}_3$$

$$= 0.47\text{g NH}_4\text{NO}_3$$

So the amount of ammonium nitrate applied / soil column is 0.47g

Appendix D

Calculation of amount of soil and amendments used for field trial

Soil

The soil depth = 30 cm

The ring internal diameter = 92cm

Volume of the soil to the depth of 30 cm of the ring = $\pi r^2 h$

$$= (3.142 \times (0.46)^2 \times 0.30) \text{ m}^3$$

$$= 0.1995 \text{ m}^3$$

Convert soil volume to weight

Assuming soil bulk density of 1500kg/ m³

Soil weight = density x volume

$$= 1500 \text{ kg/ m}^3 \times 0.1995 \text{ m}^3$$

$$= 299.25 \text{ kg}$$

The amount of soil was approximated to 300 kg for ease of measurement

So the amount of soil used per plot was 300 kg. This was applied as the 300kg soil in unamended soil or 300kg soil + amendments in amended soils.

Peat

Peat was calculated as volume by volume of soil

Given that soil volume was to the depth of 30 cm of the lysimeter ring is 0.1995m³

20% Pt rate:

$$20\% \text{ of the soil volume} = (20/100 \times 0.1995) \text{ m}^3$$

$$= 0.03989 \text{ m}^3$$

Recall that 1 m³ = 1000 L

Therefore,

$$0.03989 \text{ m}^3 = (0.03989 \times 1000) \text{ L}$$

$$= 39.89\text{L}$$

30%Pt rate:

$$\begin{aligned} 30\% \text{ of the soil volume} &= (30/100 \times 0.1995)\text{m}^3 \\ &= 0.05983 \text{ m}^3 \end{aligned}$$

Therefore,

$$\begin{aligned} 0.05983 \text{ m}^3 &= (0.05983 \times 1000) \text{ L} \\ &= 59.83\text{L} \end{aligned}$$

Convert peat volume (L) to weight (kg)

Given that the density of the peat used was 290g/L,

1L of peat \equiv 290g

So,

At 20%Pt rate:

$$\begin{aligned} 39.89\text{L} &= (39.89 \times 290) \\ &= 11.56\text{kg} \end{aligned}$$

At 23%Pt rate:

$$\begin{aligned} 59.83\text{L} &= (59.83\text{L} \times 290) \\ &= 17.34\text{kg} \end{aligned}$$

So, the amount of peat used was 39.89L (11.56kg) and 59.83L (17.34kg) for 20 and 30 % rate, respectively.

Clays

Clay applications were calculated as weight by weight of the soil

Given the weight of soil calculated = 299.25kg / plot

$$\begin{aligned} \text{Clay at 2.5\%} &= (2.5/100 \times 299.25)\text{kg} \\ &= 7.48\text{kg} \end{aligned}$$

$$\begin{aligned}\text{Clay at 5\%} &= \\ &= (5/100 \times 299.25)\text{kg} \\ &= 14.96\text{kg}\end{aligned}$$

So clay amendment was applied as 7.48 and 14.96 at 2.5% and 5% clay rate, respectively.

Appendix E

Calculations for packing soil and amendment for soil hydrology experiment

The amount of soil used was determined by direct measurement using the tray at different percentage mixtures

Size of the tray was 20cm x 11cm x 6cm

Effective depth of the Kathryn tray is 5cm

Amount of soil for the total volume of the tray was 1663g

Amount of soil to the 70% of the total volume was 1164g

Amount of soil to the 80% of the total volume was 1330.29g

Amount of peat to the 30% of the total volume was 123g

Amount of peat to the 20% of the total volume was 82g

Unamended soil

a) Treatment 1: for 100% soil, the tray was filled with 1663g soil.

Peat alone treatment

At 20% peat only:

b) Treatment 3: 80% soil + 20% peat

Tray was filled with 1330.29g soil + 82g peat

At 30% peat only:

c) Treatment 2: 70% soil + 30% peat

Tray was filled with 1164g soil + 123g peat

Soil + clay treatments

At 2.5% clay:

d) Treatment 5: Soil + 2.5% clay.

$$\begin{aligned} &\text{Amount of clay at 2.5\% (w/w) of the soil} \\ &= (2.5/100 \times 1663)\text{g} \\ &= 41.575\text{g} \end{aligned}$$

To arrive at equal volume, amount of clay at 2.5% of the soil weight (41.575g) was deducted from total soil weight and substituted with clay.

$$= ((1663 - 41.575\text{g soil}) + 41.575\text{g clay})$$

So, the tray was filled with 1579.85g soil + 41.575g clay.

At 5% clay:

e) Treatment 4: Soil + 5% clay.

$$\begin{aligned} &\text{Amount of clay at 5\% (w/w) of the soil} \\ &= (5/100 \times 1663)\text{g} \\ &= 83.15\text{g} \end{aligned}$$

To arrive at equal volume, amount of clay at 5% of soil weight (83.15g) was deducted from total soil weight and substituted with clay.

$$= ((1663 - 83.15 \text{ g soil}) + 83.15\text{g clay})$$

So, tray will be filled with 1579.85g soil + 83.15g clay

Soil + Peat + clay

At 20% peat:

Recall

Soil at 80% of tray volume = 1330.29g

Peat to 20% (v/v) = 82g

Clay at 5% (w/w) = 83.15g

Clay at 2.5% (w/w) = 41.575g

NOTE: To maintain equal volume, we would work with soil at 80% of the total volume because the volume of the peat has to remain at 20%.

f) Treatment 8: Soil + 20%Peat + 5% clay

$$\begin{aligned}\text{Amount of soil required} &= (1330.29 - 83.15) \text{ g} \\ &= 1247.14\text{g soil}\end{aligned}$$

So, the tray was filled with 1247.14g soil + 82g peat + 83.15g clay.

g) Treatment 9: Soil + 20%Peat + 2.5% clay

$$\begin{aligned}\text{Amount of soil required} &= (1330.29 - 41.575) \text{ g} \\ &= 1288.715\text{g soil}\end{aligned}$$

So, the tray was filled with 1288.715g soil + 82g peat + 41.575g clay.

At 30% peat:

Recall

Soil at 70% of tray volume = 1164g

Peat to 30% (v/v) = 123g

Clay at 5% (w/w) = 83.15g

Clay at 2.5% (w/w) = 41.575g

NOTE: To maintain equal volume, we would work with soil at 70% because the volume of the peat has to remain constant (at 30%). In summary, for the soil-peat-clay mixtures, the amount of the amendments (clay and peat) remained the same in all the treatments while that of soil keep changing to achieve equal volume but different weight.

h) Treatment 6: Soil + 30%Peat + 5% clay

$$\begin{aligned}\text{Amount of soil required} &= (1164 - 83.15) \text{ g} \\ &= 1080.85 \text{ g soil}\end{aligned}$$

So, the tray was filled with 1080.85g soil + 123g peat + 83.15g clay.

i) Treatment 7: Soil + 30%Peat + 2.5% clay

$$\begin{aligned}\text{Amount of soil required} &= (1164 - 41.575) \text{ g} \\ &= 1122.425 \text{ g soil}\end{aligned}$$

So, tray was filled with 1122.425g soil + 123g peat + 41.575 clay

Appendix F

Summary of the soil available and total nitrogen at 2nd (initial) and 33rd (final) weeks after amendment

Treatment	Initial NO ₃ (mg/kg)	Final NO ₃ (mg/kg)	Total N (%)	Total N (%)	Initial avail. P (mg/kg)	Final avail. P (mg/kg)	Initial total P (mg/kg)	Final total P (mg/kg)	Initial avail. K ₂ O (mg/kg)	Final avail. K ₂ O (mg/kg)	Initial total K ₂ O (g/k)	Final total K ₂ O (g/kg)
Unamended soil	6.3	17.8	0.106	0.091	44.70	64.06	118.42	135.78	81.2	122.0	2.74	3.07
20%Pt	7.1	10.1*	0.109	0.096	52.06*	50.40*	114.79	124.40	72.8	117.2	2.80	2.98
30%Pt	4.5	8.7*	0.109	0.091	40.98	40.60*	116.05	127.06	73.2	110.5	2.84	2.69*
5%K	10.3*	9.8*	0.093*	0.080*	61.98*	43.72*	114.95	133.18	78.9	130.6	3.07*	3.34*
5%K+20%Pt	8.6	10.8*	0.105	0.084	53.38*	48.68*	111.11*	128.64	98.1*	118.5	3.23*	3.42*
5%K+30%Pt	8.0	16.6	0.103	0.090	62.08*	55.20*	108.93*	126.85	162.4	120.0	3.24*	3.31
2.5%B	9.8*	6.7*	0.101	0.083	54.68*	54.76*	121.31	132.17	71.2	105.9*	2.99*	2.99
2.5%B+20%Pt	8.6	4.2*	0.103	0.092	50.86	34.58*	114.29	133.70	73.1	102.3*	2.96*	3.16
2.5%B+30%Pt	7.9	8.1*	0.111	0.083	42.76	60.24	117.66	126.82	76.9	110.0	2.75	2.94
5%B	9.7*	9.5*	0.091*	0.078*	44.80	51.92*	116.31	127.17	103.6*	113.1	2.99*	3.05
5%B+20%Pt	8.6	8.2*	0.101	0.086	43.90	52.82*	113.88*	126.65	71.0	124.9	3.04*	3.04
5%B+30%Pt	7.0	5.0*	0.108	0.084	40.32	49.32*	109.37*	122.69	76.0	133.2	2.90	3.03

Appendix G

Plant nutrient concentration and dry matter (vegetative) used for calculating nutrient uptake

Treatment ID	N (%)	P (%)	K ₂ O (%)	Dry matter (kg/ha)
1	3.48	0.10	4.46	2462
2	3.38	0.09	3.89	2961
3	3.10	0.10	3.90	2907
4	3.23	0.10	4.04	2403
5	3.45	0.10	5.20	2934
6	2.77	0.10	4.64	4077
7	3.28	0.11	4.21	4464
8	3.10	0.10	3.88	4284
9	2.49	0.10	4.17	4199
10	3.50	0.10	4.04	3825
11	2.49	0.10	3.31	4568
12	2.81	0.10	4.03	3776
13	3.14	0.12	4.43	4703
14	3.36	0.10	4.49	5108
15	3.20	0.11	5.27	4347
16	3.03	0.09	4.46	3398
17	3.56	0.10	4.58	2745
18	3.36	0.09	4.10	3789
19	3.50	0.10	4.10	3200
20	3.61	0.10	4.07	3438
21	2.56	0.10	3.83	4014
22	3.26	0.10	4.76	3159
23	3.65	0.10	5.01	3488
24	2.98	0.09	4.42	4158
25	3.07	0.09	4.04	4190
26	3.71	0.10	4.43	5301

28	2.91	0.10	3.55	5027
29	2.95	0.09	3.73	5652
30	3.16	0.10	4.49	5486
31	2.91	0.10	4.72	3137
32	3.01	0.10	4.95	2867
33	2.57	0.08	3.97	3204
34	3.27	0.11	5.43	3438
35	2.53	0.08	5.31	3758
36	2.54	0.09	4.08	4248
37	2.77	0.07	3.52	3848
38	2.67	0.10	4.88	3191
39	2.56	0.09	3.66	3510
40	2.55	0.08	3.79	3627
41	1.93	0.09	5.11	3735
42	2.32	0.09	5.57	3609
43	2.37	0.09	3.80	3137
44	3.09	0.09	4.20	3227
45	2.43	0.09	4.41	2826
46	2.96	0.09	4.92	3879
47	2.82	0.10	4.49	3231
48	3.28	0.09	3.49	3564
49	2.76	0.08	3.28	4158
50	2.87	0.08	6.50	4055
51	2.82	0.09	4.59	4176
52	2.76	0.08	4.17	4091
53	2.32	0.08	3.92	3618
54	2.64	0.08	4.55	4163
55	3.29	0.09	5.02	3627
56	2.89	0.09	5.14	3857
57	2.32	0.10	4.64	4019
58	3.08	0.08	5.16	3974
59	3.21	0.08	4.94	4194
60	2.69	0.09	-	4023

- missing value