THE EFFECT OF VOLCANIC ASH INCORPORATION, SLOPE AND VEGETATION ON SOIL SURFACE RUNOFF AND ERODIBILITY CHARACTERISTICS

By

Charlotte Hounsell
4308743

Thesis presented in part-fulfilment of the degree of Master of Science in accordance with the regulations of the University of East Anglia

School of Environmental Sciences
University of East Anglia
University Plain
Norwich
NR4 7TJ

© 2015 Charlotte Hounsell

This copy of the dissertation has been supplied on condition that anyone who consults it is understood to recognise that its copyright rests with the author and that no quotation from the dissertation, nor any information derived there from, may be published without the author’s prior written consent. Moreover, it is supplied on the understanding that it represents an internal University document and that neither the University nor the author are responsible for the factual or interpretative correctness of the dissertation.
Abstract

Hazards related to volcanic eruptions do not necessarily cease when an eruption has ended. Ash deposited on the soil surface can cause damage to vegetation and result in accelerated erosion rates. Rainfall simulation and erosion experiments were undertaken to determine whether incorporating ash into the soil matrix resulted in reduced sediment yields without detriment to vegetation. The effect of slope angle and soil properties were also characterised to fully explore the data. Results showed that soil only, 10% and 20% plots were most effective at reducing sediment yields, with the low ash contents providing benefit to plant growth. The presence of vegetation generally decreased erosion and runoff, and increasing slope angle resulted in an increase in erosion and runoff. Increasing ash contents also resulted in an increase of delay times before erosion and runoff were recorded. This research has shown that where ash cannot fully or successfully be removed, low ash-soil ratios can reduce sediment yields and even provide benefit to vegetation growth.

Keywords: erosion, sediment yield, ash, incorporation, vegetation, slope angle.
# Table of Contents

Abstract.......................................................................................................................... 1  
List of Abbreviations....................................................................................................... 4  
Acknowledgements.......................................................................................................... 5  
1. Introduction.................................................................................................................. 5  
2. Literature Review and Justification............................................................................ 6  
  2.1 Infiltration.............................................................................................................. 6  
  2.2 Soil Erosion.......................................................................................................... 7  
  2.3 Volcanic Ash......................................................................................................... 9  
  2.3.1 Ash and Effects on Erosion........................................................................... 10  
  2.3.2 Ash and Changes to Vegetation................................................................. 10  
3. Aims and Objectives.................................................................................................... 13  
4. Methods....................................................................................................................... 14  
  4.1 Mixing Ratios....................................................................................................... 14  
  4.2 Rationale for Slope Angles.................................................................................. 14  
  4.3 Sample Preparation.............................................................................................. 14  
  4.4 Main Experiment Phase....................................................................................... 15  
  4.5 Cation Exchange Capacity by ICP...................................................................... 17  
  4.6. Extractable Ions................................................................................................. 17  
  4.7 pH....................................................................................................................... 17  
  4.8 Moisture Content................................................................................................. 18  
  4.9 Organic Matter by Loss on Ignition.................................................................... 18  
  4.10 Particle size Distribution.................................................................................... 19  
  4.11 Measurement of Vegetation Height..................................................................... 19  
  4.12 Data Analysis..................................................................................................... 19  
5. Results......................................................................................................................... 20  
  5.1 Soil and Ash Properties....................................................................................... 20  
  5.2 Ash and Vegetation Recruitment......................................................................... 24  
  5.3 Ash Content and Slope Stability......................................................................... 24  
  5.4 Vegetation and Slope Stability.......................................................................... 26  
6. Discussion................................................................................................................... 32  
  6.1 Soil and Ash Properties....................................................................................... 32  
  6.1.1 Particle Size Distribution.............................................................................. 32  
  6.1.2 pH.................................................................................................................. 32  
  6.1.3 Moisture Content............................................................................................ 33  
  6.1.4 Organic Matter Content.............................................................................. 33
6.2 Ash and Vegetation Recruitment ................................................................. 33
6.3 How ash content affects slope stability ....................................................... 35
6.4 How vegetation affects slope stability ........................................................ 37
6.5 How slope angle affects slope stability ....................................................... 39
6.5.1 Slope angle without vegetation ................................................................. 39
6.5.2 Slope angle with vegetation ...................................................................... 40
6.6 Ash and Vegetation Antagonism: Recommended Practice ......................... 41
7. Limitations and Further Research ................................................................. 43
8. Conclusion .................................................................................................... 46
9. References .................................................................................................... 47
Appendix ..........................................................................................................
List of Abbreviations

NV    Non-vegetated
V     Vegetated
CEC   Cation Exchange Capacity
ESP   Exchangeable Sodium Percentage
The Effect of Ash Incorporation, Slope and Vegetation on Soil Surface Runoff and Erodibility Characteristics

Acknowledgements
I would first like to thank my supervisors, Brian Reid and Jenni Barclay for their constructive criticism, knowledge, encouragement and reminding me to believe in my work. Special thanks to Jenni for allowing me use her doorstop for my experiment. Emma Hooper, Lynda Turner and Andy McDonald deserve thanks for giving up so much of their time over the summer to provide me with extensive technical information and helping me to problem solve. I’d like to thank my friends and family for listening to my complaints and keeping me sane, and to my coursemates for offering advice, criticisms and SPSS lessons. Finally, thank you to Mark Rivett for encouraging me every day from the North Sea.

1. Introduction
Deposition of ash on soil during a volcanic eruption can result in many primary and secondary hazards. Ash can burn vegetation and can generate conditions that mean it is difficult for vegetation to recolonize (Collins and Dunne, 1986; Ollier and Brown, 1971). In addition, ash deposition has shown to increase surface runoff and erosion rates (Ayris and Delmelle, 2012; Cook et al., 1981). In recent years, it has come to government’s attention that continued soil loss is decreasing overall soil quality, changing sediment loading in water courses and even forcing changes in land use (Bakker et al., 2004; Bakker et al., 2005). In the International Year of Soils, it is prudent to consider methods to reduce the loss of this resource upon which so much is reliant.
2. Literature Review and Justification

Surface runoff and erosion are directly related. Both of these factors are influenced by changes in soil properties and external conditions such as topography, vegetation cover, agricultural management and climate. However, this relationship is made more complex by the inclusion of ash (Figure 1). Ash has its own set of properties, and the interactions of these with soil can mean that changes in surface runoff and erosion are observed. It is important to consider the driving mechanisms behind surface runoff and erosion in order to understand the changes that ash might have.

![Diagram](image)

*Figure 1: Diagram to show the interplay between infiltration, surface runoff and erosion, the role that inherent soil characteristics play and external environmental factors such as vegetation and slope angle.*

2.1 Infiltration

Infiltration is defined as the rate at which water can penetrate into the soil that is controlled solely by soil characteristics (Liu *et al.*, 2011); the more water a soil can absorb, the higher its infiltration rate. Infiltration occurs until a soil reaches its saturation point, and results in surface water movement (Liu *et al.*, 2011). Therefore, infiltration is a direct control upon surface runoff.
Infiltration rate is influenced by the volume of water the soil is exposed to, so, increasing rainfall intensity results in increased infiltration rates (Dunne et al., 1991). It is also important to understand how soil properties are related to infiltration as their characterisation can offer insight into changes to infiltration, and therefore surface runoff. Initial soil moisture content is a primary control on infiltration as it directly affects the amount of water that can be absorbed (Liu et al., 2011); the higher the initial water content, the quicker the saturation point is reached. Organic matter is directly related to moisture content; soils with higher organic content have higher moisture contents and water holding capacities (Hills, 1971; Bot and Benites, 2005). The particle size distribution of a soil can control the rate of infiltration (Bot and Benites, 2005). Particle size has been used consistently in soil process modelling. Mazaheri and Mahmoodabadi (2012) attempted to characterise particle sizes that maximised infiltration rate. They found that with increasing sand content, infiltration rate also increases, which coincide with findings from earlier studies (Ayers and Wetscot, 1976).

Inherent soil properties and external factors, such as volume of rainfall, drive changes in infiltration. A soil’s saturation point ultimately defines the boundary between infiltration and surface runoff processes, and it is this movement of surface water that results in mobilisation of sediment.

### 2.2 Soil Erosion

Erosion is defined as the detachment, transport and deposition of material (Shi et al., 2012) due to the mobilisation of sediment through surface runoff and rainfall (Defersha et al., 2011). Areas where erosion is a particular problem suffer from drainage choking and flooding. The sediment removal and deposition results in changes to hydrological regimes (Ayris and Delmelle, 2012; Cook et al., 1981). Studies by Bakker et al. (2004) and Bakker et al. (2005) have shown in a review of mechanised agricultural system data that soil productivity decreases ~4% for every 10 cm of soil loss. They suggest that erosion can drive land use change, as a reduction in productive land results in abandonment.

Many studies have clearly demonstrated the relationship between surface runoff and erosion (Defersha et al., 2011; Van Liew and Saxton, 1983). Although surface water itself is responsible for detachment and entrainment of eroded particles (Defersha et al., 2011), the literature also provides detail on the effect of rainfall intensity and raindrop impact kinetic energy on the detachment process. Higher rainfall intensities result in greater volumes of eroded material because of the higher delivery rate of water per unit area (Singh and Khera, 2009). Greater raindrop impact kinetic energy has also been shown to increase erodibility,
where splashed particles have fallen onto the soil surface as pre-detached sediment (Kinnell, 2005). However, other studies have shown that sediment yield is not correlated with raindrop impact erosion (Defersha et al., 2011).

In addition to their relationship with surface runoff, erosion is also dependant on soil characteristics. Larger average particle size distribution renders a soil more difficult to erode as a greater amount of energy is required to do so. However, finer materials may also be difficult to erode because of interparticle forces that render a material more cohesive (Nebel and Wright, 1993). Soils with a greater organic matter content have also been shown to be more resistant to erosion because of the increase in cohesiveness (Bot and Benites, 2005).

Other external factors are also responsible for changes in erosion rates. In particular, the effect of slope angle has been well studied. Most studies show that increasing slope angle results in increased erosion rates (Nammah et al., 1986; Defersha et al., 2011) largely due to the resultant increases in runoff rates and velocities that facilitate erosion (Nammah et al., 1986; Zehetner and Miller, 2006). Equation 1 (from Morgan, 2005) demonstrates the relationship between slope length and gradient with erosion, where \( E \) is soil loss per unit area, \( \theta \) is slope angle and \( L \) is slope length.

(Eq. 1)

\[
E \propto \tan^{1.4} \theta L^{0.6}
\]

Supplementary to this, research by Defersha et al. (2011) showed that erosion is directly related to slope angle until a terminal gradient, where it then plateaus or decreases. This terminal gradient is sensitive to differences in inherent soil characteristics or external soil conditions. A study by Mu et al. (2015) demonstrated that lower slope angles increased the delay time before erosion occurred; Lag time provides information on a soil’s resistance to erosion.

There is much research that identifies vegetation as a mechanism to reduce erosion. The presence of vegetation reduces erosion because it disrupts the flow of surface water, reducing erosive capacity. Vegetation cover can absorb some of the energy from raindrop impact (Morgan, 2005) and roots provide mechanical stability to the soil matrix (Xu et al., 2013; Zhang et al., 2014). It is generally recognised that ~70% vegetation cover is required to provide adequate protection to the soil surface, and that there is an exponential relationship between vegetation cover and decreasing soil loss (Elwell and Stocking, 1976; Elwell, 1981).
2.3 Volcanic Ash

Volcanic ash is the product of highly explosive volcanic eruptions. Rapid decompression of gases as they reach the surface causes highly explosive and fragmenting eruptions that can result in the production of vast quantities of ash (Parfitt and Wilson, 2008).

The composition of ash can vary greatly. It is dependent upon the non-volcanic sediment origin as well as processes and degrees of transformation that this material undergoes as magma (e.g. fractionation) (Bitschmene and Schmincke, 1990). Figure 2 shows the Total Alkali-Silica (TAS) diagram used for identifying magma type based on its composition.

![Figure 2: TAS (Total Alkali-Silica) Diagram used for classifying magma based on their alkali and silica contents. From Le Bas et al., (1986).](image)

There are many hazards associated with the eruption of ash. Vegetation is burned and buried when ash is deposited and chances of survival are low in deposits of ~1-1.5m of ash (Grishin et al., 1996). Deposition on the soil surface can result in alterations to the soil albedo, acidification from element release (Ayris and Delmelle, 2012) and changes to erosional and hydrological regimes (Tejedor et al., 2003).

Current remediation methods for ash deposition are very case specific. The USGS (United States Geological Society) have a series of recommendations for agricultural land...
subsequent to a volcanic eruption. In deposits of up to 100 mm of ash, recommended practice is to continue to cultivate land and incorporate the ash as the impact will be low and allow for system recovery. In very thick burials (100 - >300 mm), incorporation of ash is considered impossible and instead removal is recommended. (USGS, undated). It is important to understand the limitations of these methods when considering which is the most appropriate hazard response scenario. Remediation of volcanic deposits are highly dependent on the financial situation and infrastructure available. Thicker deposits are likely to need heavy machinery, some of which may not be operable on certain topographies.

2.3.1 Ash and Effects on Erosion

The eruption of Mount St. Helens in 1981 and the changes to the surrounding landscape appears to have been a catalyst for much of the relevant literature regarding ash’s influence on changes to erosion and runoff regimes. Notably, studies have shown that runoff rates from soil with an overlying ash layer were increased in comparison to natural soil conditions (Chinen, 1986; Collins and Dunne, 1986; Nammah et al., 1986). The most likely explanation for these changes is the alterations to the average particle size distribution of the soil. Cook et al., (1981) determined that ash from Mount St. Helens had lower permeability than the surrounding soil, as large pore spaces were clogged by fine-textured ash. This caused a reduction in infiltration rate. Other studies have confirmed that an unincorporated ash layer results in increased runoff rates (Chinen, 1986; Collins and Dunne, 1986; Nammah et al., 1986) and resulting erosion (Ayris and Delmelle, 2012). Methods described in Nammah et al., (1986) aimed to identify any significant difference in runoff and erodibility factors for unincorporated and incorporated ash. The authors found that sediment concentrations were always higher in experiments with an unincorporated ash layer. These results are important when understanding the different recommended remediation techniques that can be employed. Despite these conclusions, this research lacked details of methods and information of ash incorporation ratios. There was also no consideration of whether there was an upper threshold limit where the positive effects of ash incorporation are observed. This absence has identified some key parameters that require definition and exploration in this dissertation.

2.3.2 Ash and Changes to Vegetation

The presence of vegetation can reduce the detrimental effects of surface runoff and erosion (Xu et al., 2013; Zhang et al., 2014), therefore it is important to evaluate what effects ash
may have on vegetation. When ash is deposited, it can result in complete removal or significant damage to vegetation through burial and burning and the presence of ash can make it difficult for vegetation to recolonise due to lack of organic carbon and nitrogen (Ayris and Delmelle, 2012). A study by Gómez-Romero et al. (2006) states that recolonization of plants in regions effected by major volcanic activity is greatly reduced due to reduction in germination and establishment sites. This reduced recolonization rate could mean that erosion and runoff continues to occur at the increased rates. However, contrasting evidence suggests that a reduction in erosion rate can occur before any vegetation has been able to recolonise (Ollier and Brown, 1971), suggesting that while it has a prominent influence, it is not singularly responsible for changes in erosion.

Evidence shows that ash can reduce soil pH (Diaz et al., 2004). This is an important consideration of soil fertility and can be an indication of changes to the different elements available in the soil, as well as soil acidification. With ash addition, there is the potential that there will be a greater availability of phytotoxins such as sodium, iron, aluminium etc. which can be detrimental to plant growth (Pardo and Quintero, 2002; Silva, 2012; Morrissey and Guerinot, 2009). Gomez-Romero et al. (2006) showed that vegetation height was significantly reduced in soils with the addition of ash (Figure 3). It is therefore logical to expect that these detrimental effects on vegetation could mean the effect plants have on reducing runoff and erosion rate is also diminished.
Other research by Diaz et al. (2004) has shown that basaltic ash can increase soil fertility through the provision of additional nutrients to the soil, however, organic mulch was used in test pots, which may have yielded false results. It should be noted that current research has not considered whether there is a threshold ash-soil ratio where vegetation no longer grows providing an opportunity for exploration as part of this research. In addition to these chemical changes, it generally understood that surface ash can act as a physical barrier to plants growth (Ayris and Delmelle, 2012).

What is clear from the research regarding ash addition to soil is that the effects can be wide ranging and are case specific. It is therefore important that the soil and ash used in each experiment be characterised fully and accurately in order that effects and interactions are properly understood. The effects of slope angle and vegetation on erosion has been discussed in detail in the literature, however, it is rare to see these factors and secondary variables incorporated into one study. This is surprising given their inter-relationship and interdependency. The highlighted gaps in the literature provide a unique opportunity to further the research where data is lacking.

Figure 3: Relationship between vegetation height and tephra depth in greenhouse experiments. (From Gómez-Romero et al., 2006).
3. Aims and Objectives

The overall aim of this research is to identify whether incorporating ash into soil results in any significant reduction in eroded material and surface runoff without detriment to vegetation growth. The results of this research will aim to identify a difference in erosion and runoff yields at different soil-ash mixing ratios that may prompt further research.

The objectives of this dissertation are:

- To determine which ash-soil mixing ratio is the most effective at reducing erosion and surface runoff
- To determine whether plants will colonise in each of the ash-soil mixing ratios and whether any positive or negative growth effects are observed
- To identify the effect of slope angle and vegetation on erosion and surface runoff
- To identify which ash-soil ratio delays soil erosion and surface runoff the most

In order to achieve these objectives, the following hypotheses have been outlined:

1. Ash mixing will reduce runoff yields in comparison to test plots with a ash layer
2. Ash mixing will reduce erosion yields in comparison to test plots with a ash layer
3. Ash mixing will increase the delay time before runoff is observed in comparison to ash layer plots
4. Ash mixing will increase the delay time before erosion is observed in comparison to ash layer plots
5. Plants will colonise in all plots
6. Growth deficiencies will be present in plots with a ash layer
7. Plots with vegetation will have lower runoff yields than those without
8. Plots with vegetation will have lower erosion yields than those without
9. Plots with vegetation will have longer delay times before runoff is observed than those without
10. Plots with vegetation will have longer delay times before erosion is observed than those without
11. Increasing the slope angle will increase the volume of surface runoff
12. Increasing the slope angle will increase the volume of eroded material
13. Plots at 5° will have longer delay times before runoff is observed than plots at 20°
14. Plots at 5° will have longer delay times before erosion is observed than plots at 20°
4. Methods

4.1 Mixing Ratios

Five mixing ratios were chosen for the main experiment phase: soil only, 10% ash content, 20% ash content, 50% ash content and an ash surface layer (assumed to be 100% ash at the surface). Each of the mixed sample sets was measured as a percentage of the total soil weight and was thoroughly mixed for five minutes before being placed in the guttering tubes. A set of samples was generated for the following experimental scenarios: 5° slope angle without vegetation (NV), 5° slope angle with vegetation (V), 20° slope angle without vegetation (NV) and 20° slope angle with vegetation (V). Altogether, this resulted in 20 experimental scenario. Two repeats of each test were undertaken to validate results.

4.2 Rationale for Slope Angles

During pilot studies, it became clear that steeper slope angles were not suitable for this study as it caused washout and failure of the soil material. Instead, a review of runoff and erosion studies was carried out to identify commonly used angles in such experiments. 5° and 20° slope angles used in this research have been selected based on their common occurrence in the literature (Table 1).

Table 1: Literature review of slope angles commonly used for runoff and erosion studies.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Slope Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Van Liew and Saxton (1983)</td>
<td>9%, 18%, 23%</td>
</tr>
<tr>
<td>Nammah et al. (1986)</td>
<td>5%, 15%, 23%</td>
</tr>
<tr>
<td>Chinen (1986)</td>
<td>4°, 33°</td>
</tr>
<tr>
<td>Zehetner and Miller (2006)</td>
<td>0 - 20%</td>
</tr>
<tr>
<td>Gomez and Nearing (2005)</td>
<td>5%, 20%</td>
</tr>
<tr>
<td>Sanguesa et al. (2010)</td>
<td>11%, 21%, 39%</td>
</tr>
<tr>
<td>Bryan (2000)</td>
<td>3 - 9°</td>
</tr>
<tr>
<td>Hall et al. (1999)</td>
<td>25 - 35°</td>
</tr>
<tr>
<td>Zhang et al. (2014)</td>
<td>3 – 40%</td>
</tr>
<tr>
<td>Cuomo et al. (2015)</td>
<td>15 – 40%</td>
</tr>
<tr>
<td>El Kateb et al. (2013)</td>
<td>10 – 30%</td>
</tr>
</tbody>
</table>

4.3 Sample Preparation

The soil was passed through a 2mm sieve to disaggregate and remove traces of plant material. The weight of an empty piece of guttering 30 cm x 0.70 cm in size was recorded and 300g of soil weighed into the tube. Ash samples were calculated as weight percentage.
of 300g and the ash and soil was thoroughly mixed for five minutes before being placed in the tube. For V samples, 100g soil was kept back and 1g of grass seed was applied randomly ensuring an even coverage. The remaining 100g of soil was spread over the seeds to roughly 5mm thickness as suggested by Clarke (2014). For ash layer samples, the same weight of ash used in 20% tests was applied to the soil surface. The ends of the tube were sealed to prevent sample from falling out and to prevent leaks. The soil surface was smoothed out as much as possible to remove any micro-topographical features. Each sample was watered using the regime in Table 2.

Table 2: Watering regime for each of the guttering samples during the 4 week incubation period. Water volume was reduced after week 1 to prevent ponding and leaking of water.

<table>
<thead>
<tr>
<th>Week</th>
<th>Amount of Water (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monday – Thursday</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
</tr>
<tr>
<td>Total Water Applied (ml)</td>
<td>700</td>
</tr>
</tbody>
</table>

The samples were kept in an incubator at the conditions specified in Table 3 as suggested by Clarke (2014). These samples were removed from the incubator after 4 weeks to begin the main experiment phase.

Table 3: Incubator conditions for the tube samples for 4 weeks prior to experiment. As suggested by Clarke (2014).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>22°C</td>
</tr>
<tr>
<td>Humidity</td>
<td>80%</td>
</tr>
<tr>
<td>Light Level</td>
<td>1LS</td>
</tr>
<tr>
<td>Hours of Light</td>
<td>12 hours</td>
</tr>
</tbody>
</table>

4.4 Main Experiment Phase

The experiment setup is show in Figure 4. Guttering tubes of 30 x 0.70 cm were used to hold the soil and ash samples. Rain was generated using a peristaltic pump and reservoir of 750ml of water so that the rate of water application could be controlled. Water application was set to approximately 4ml minute⁻¹ for the guttering surface area, as an analogue of and
average tropical rainstorm (Matthews et al., 2002). A spray nozzle was used to achieve as
even water coverage as possible. Agassi and Bradford (1999) suggest types of simulator
and nozzle that should be used for erosion experiments, however these resources were not
available for this research. The clamp mechanism was mobile so that it could be adjusted for
the changes in slope angle and was setup appropriately prior to the start of the test. A pre-
weighed collection container was placed at the base of the guttering and a plastic shield
place over it so that rain splash was not collected. A new container was switched out every 4
minutes for the 40 minute test duration (analogue length of tropical storms that allowed for
full data collection (Matthews et al., 2002)). Each of the containers was weighed immediately
after collection and again after being in the oven at 50° for 24 hours to obtain the water yield
(runoff) and sediment yield (erosion) over time. This full setup was placed inside a large
splash container so that any rain splash could be accounted for (Mutchler et al., 1994) and
the volume of splash water and total water volume used was recorded. This was used to
check whether water delivery rate was constant between experiments. All equipment was
dried and reassembled prior to each new test.

Figure 4: Main experiment apparatus. Clamps were adjustable for slope angle and
provided stability for the spray nozzle. Peristaltic pump was used to maintain constant
water delivery rate. Collection containers were covered with a plastic shield to prevent
collection of splash water, and were switched out at 4 minute intervals. Splash container
recorded volume of water that was not delivered to the guttering.
4.5 Cation Exchange Capacity by ICP

Cation Exchange Capacity of soil is measured to determine the amount of exchangeable ions that are available in the soil. The method is as per Method 9081 from the US EPA Handbook (US EPA, 1986).

5 g of each sample was weighed into a centrifuge tube and 30 ml of 1 M sodium acetate was added. Each tube was shaken for 22 hours and then placed in the centrifuge for 15 minutes at 3000 rpm to separate the solid and liquid material. The solution was decanted from the tubes and disposed of. A further 30 ml of sodium acetate was added to each sample and the process completed twice more. This same process was completed three times using 99% acetone and 1 M ammonium acetate. The decanted ammonium acetate solution was passed through Whatman No. 1 filter papers into 100 ml volumetric flasks, made up to the 100 ml mark with ammonium acetate and shaken well by hand. 1 ml of this solution was decanted into 25 ml volumetric flasks, made up to the mark with distilled water and shaken well by hand. 15ml of this new solution was syringe filtered into a 15 ml centrifuge tube to be analysed for exchangeable cations using Inductively Coupled Plasma mass spectrometry (ICP). Two repeat tests were undertaken to validate results.

4.6. Extractable Ions

The extractable ions of a sample are measured to determine soil elemental concentrations. This method is as per the suggestion of Chou et al. (1981).

3 g of each sample was weighed into a centrifuge tube and 30 ml of distilled water was added. The tubes were shaken for 22 hours and then placed in the centrifuge tube for 15 minutes at 3000 rpm to separate the solid and liquid matter. The liquid solution was decanted and syringe filtered into 15 ml centrifuge tubes ready for analysis by ICP. The solution was analysed for calcium, potassium, sodium, magnesium, iron and aluminium ions, as they are either essential plant nutrients or major elements present in the bulk ash mix (Moore et al., 2002; Hall et al., 1999).

4.7 pH

The soil pH was measured as per methods described by Schofield and Taylor (1955).

Each of the samples was passed through a 2 mm sieve to ensure disaggregation. 30 g of soil was mixed with 75 ml of distilled water and stirred well. A watch glass was placed on top
of the beaker, the sample left for an hour and stirred every 10-15 minutes. The pH meter was calibrated using buffer solutions 4.0 and 7.0. The meter was used to measure the pH of each sample, ensuring that the electrode was thoroughly washed with distilled water in between uses. Two repeat tests were undertaken to validate results.

4.8 Moisture Content

The weight of each empty sample tube was recorded, and again once 5 g of soil had been added. Subsequent to testing, each tube was placed in the oven at 50 °C for 48 hours until fully dried, and the dry weight recorded. The following calculation was used to obtain the moisture content:

\[
\text{Moisture content} = \frac{\text{Weight (wet soil)} - \text{Weight (dry soil)}}{\text{Weight (dry soil)}} \times 100
\]

Two test repeats were undertaken and the average result calculated.

4.9 Organic Matter by Loss on Ignition

Empty crucibles were weighed and again when 5 g of sample was added. The crucibles were placed in the oven at 80 °C for 24 hours and the weights recorded again before being placed in the muffle furnace at 400 °C for 24 hours. The final weights were recorded and the following calculation (Santisteban et al., 2004) was used to obtain the organic matter as a percentage:

\[
\text{Organic Matter} = \frac{\text{Weight (dry soil)} - \text{Weight (ashed soil)}}{\text{weight (dry soil)}} \times 100
\]

Two repeat tests were undertaken to validate the results.
4.10 Particle size Distribution
Each sample was passed through a 1.7 mm sieve and approximately 10 g and placed in a beaker with approximately 25ml of water. This sample was placed on a magnetic stirrer for 5 minutes to ensure all the particles were in suspension. A representative sample was pipetted into the calibrated Malvern particle size analyser. All soil descriptions are to the standard set out by Stewart et al. (1975).

4.11 Measurement of Vegetation Height
Three transect positions were chosen along the guttering tube at 5 cm, 15 cm and 25 cm. At each transect, the blade length of the grass situated within a 1 cm width along the transect was measured from soil surface to blade tip. The average blade length for each was calculated and repeated on all samples.

4.12 Data Analysis
SPSS 22 was used to generate statistical information to validate results. Shapiro-Wilk values were used to assess the normality of each data set. One-way ANOVA and Kruskal-Wallis tests were used to compare means of full data sets and Independent Sample T-Tests and Mann-Whitney U tests were used to compare paired means. Where appropriate, either Pearson’s or Spearman’s Ranks Correlation Coefficients were used to identify relationships between sample variables.
5. Results

5.1 Soil and Ash Properties

Table 4 and Figure 5 show the average particle size distributions of each of the sample batches. Distribution percentages show that the batches range from sandy loam to silt loam in texture. Kruskal-Wallis tests results show that ash samples have significantly higher sand contents than 20% samples (P=0.021) and both soil only control and ash samples have significantly higher sand contents than 50% samples (P=0.003, P=0.009). Ash samples have significantly lower silt content than 20% samples (P=0.036) and both soil only control and ash samples have significantly lower silt contents than 50% mix (P=0.036, P=0.002). Ash samples have significantly lower clay content that 50% samples (P=0.043) and both soil only control and ash samples have significantly lower clay contents than 20% samples (P=0.048, P=0.034).

Table 4: Average particle sizes for each sample mix. Letters denote statistically significant differences. Errors are calculated standard deviations.

<table>
<thead>
<tr>
<th></th>
<th>% Sand</th>
<th>% Silt</th>
<th>% Clay</th>
<th>Texture Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>55.8 ± 19.6&lt;sup&gt;ADE&lt;/sup&gt;</td>
<td>41.6 ± 17.9&lt;sup&gt;AD&lt;/sup&gt;</td>
<td>2.67 ± 1.70&lt;sup&gt;AD&lt;/sup&gt;</td>
<td>Sandy Loam</td>
</tr>
<tr>
<td>10%</td>
<td>51.9 ± 16.9&lt;sup&gt;AC&lt;/sup&gt;</td>
<td>44.5 ± 15.5&lt;sup&gt;ABCDE&lt;/sup&gt;</td>
<td>3.58 ± 1.47&lt;sup&gt;ABCDE&lt;/sup&gt;</td>
<td>Sandy Loam</td>
</tr>
<tr>
<td>20%</td>
<td>38.8 ± 3.12&lt;sup&gt;CD&lt;/sup&gt;</td>
<td>56.8 ± 2.98&lt;sup&gt;ABC&lt;/sup&gt;</td>
<td>4.43 ± 0.75&lt;sup&gt;BC&lt;/sup&gt;</td>
<td>Silt Loam</td>
</tr>
<tr>
<td>50%</td>
<td>38.2 ± 8.76&lt;sup&gt;BC&lt;/sup&gt;</td>
<td>57.6 ± 8.05&lt;sup&gt;C&lt;/sup&gt;</td>
<td>4.12 ± 0.98&lt;sup&gt;AC&lt;/sup&gt;</td>
<td>Silt Loam</td>
</tr>
<tr>
<td>Ash</td>
<td>67.7 ± 6.67&lt;sup&gt;A&lt;/sup&gt;</td>
<td>29.8 ± 6.12&lt;sup&gt;D&lt;/sup&gt;</td>
<td>2.52 ± 0.55&lt;sup&gt;D&lt;/sup&gt;</td>
<td>Sandy Loam</td>
</tr>
</tbody>
</table>

Figure 5: Graph to show average particle size distribution of all samples.
Table 5 shows the mean pH results for all sample batches. Sample pH is negatively correlated with increasing ash content ($r_p = -0.669$, P<0.01). One-way ANOVA results show that mean pH for the ash sample is significantly lower than for all other samples (P<0.000).

Table 5: Table to show average pH results for all samples. Values denoted with * are significantly different to the other values (P<0.000).

<table>
<thead>
<tr>
<th>Batch</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>5.99</td>
</tr>
<tr>
<td>10%</td>
<td>6.06</td>
</tr>
<tr>
<td>20%</td>
<td>5.95</td>
</tr>
<tr>
<td>50%</td>
<td>6.02</td>
</tr>
<tr>
<td>Ash</td>
<td>5.60*</td>
</tr>
</tbody>
</table>

Table 6 shows the moisture contents of all sample batches. In the NV data, a Kruskal-Wallis test showed that moisture content is significantly lower in 50% ash content plots than soil only control plots (P=0.007), however no other results were significantly different. In the V data, results show that moisture content is significantly higher in ash layer plots that 20% content plots (P=0.003). Increasing ash content is negatively correlated with moisture content for NV plots ($r_s = -0.411$, P=0.024), however there is no correlation between ash content and moisture content for V plots (P>0.05). Moisture contents are significantly higher in V plots as compared with NV plots for 10% (P<0.000), 20% (P=0.007), 50% (P=0.004) and ash layer plots (P=0.002), however no significant difference is observed in soil only control plots (P>0.05).

Table 6: Table to show average moisture contents of each sample batch. Letters denote statistically significant differences. * indicate where NV and V moisture contents are significantly different. Errors are calculated standard deviations.

<table>
<thead>
<tr>
<th>Batch</th>
<th>Moisture Content NV (%)</th>
<th>Moisture Content V (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>48.5 ± 7.02$^A$</td>
<td>46.5 ± 2.55$^{AB}$</td>
</tr>
<tr>
<td>10%</td>
<td>42.4 ± 0.58$^{AB'}$</td>
<td>48.1 ± 1.32$^{AB'}$</td>
</tr>
<tr>
<td>20%</td>
<td>41.6 ± 1.56$^{AB'}$</td>
<td>44.5 ± 1.38$^{A'}$</td>
</tr>
<tr>
<td>50%</td>
<td>41.1 ± 1.15$^{B'}$</td>
<td>47.8 ± 2.52$^{AB'}$</td>
</tr>
<tr>
<td>Ash Layer</td>
<td>43.3 ± 1.93$^{AB'}$</td>
<td>50.4 ± 3.77$^{B'}$</td>
</tr>
</tbody>
</table>

Table 7 shows organic matter contents in all sample batches. In the NV data, a Kruskal-Wallis test showed that organic matter content is significantly higher in the soil only control plots as compared with plots with an ash layer (P=0.035), however no other results are significantly different. In the V data, organic matter content is greatest in soil only control plots, however this result is not significantly different from 10% ash content results (P>0.05). Organic matter content is lowest in 50% ash contents and is significantly different from all
other results (P<0.05). Organic matter contents are significantly different between NV and V plots for 10% (P=0.006), 50% (P=0.028) and ash layer (P=0.05) plots. For both NV and V plots, Spearman’s rank tests identified a negative correlation between organic matter content and increasing ash content for NV and V plots ($r_s = -0.873$, $P=0.000$; $r_p = -0.73$, $P=0.002$).

Table 7: Table to show average organic matter contents for NV and V plots. Letters denote statistically significant differences. * indicate where NV and V organic matter contents are significantly different. Errors are calculated standard deviations.

<table>
<thead>
<tr>
<th>Batch</th>
<th>Organic Matter (%) NV</th>
<th>Organic Matter (%) V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>1.89 ± 0.20A</td>
<td>2.29 ± 0.09AB</td>
</tr>
<tr>
<td>10%</td>
<td>1.65 ± 0.12A</td>
<td>2.09 ± 0.08ABC</td>
</tr>
<tr>
<td>20%</td>
<td>1.54 ± 0.41A</td>
<td>1.95 ± 0.14BCE</td>
</tr>
<tr>
<td>50%</td>
<td>0.98 ± 0.06A</td>
<td>1.17 ± 0.08D</td>
</tr>
<tr>
<td>Ash Layer</td>
<td>0.26 ± 0.10B</td>
<td>1.73 ± 0.11CE</td>
</tr>
</tbody>
</table>

Figure 6 shows the mean elemental concentrations for each sample mix. Al concentration is highest in the 10% ash content plots (18.68 µg/g) and lowest in the pure ash samples (10.18 µg/g) however, these results are not significantly different from each other (P>0.05). Pearson’s rank correlation coefficient shows these results are not correlated ($r_p = -0.477$, P>0.05). Ca content is highest in the pure ash samples (177.71 µg/g) and lowest in 10% ash content samples (58.71 µg/g) and are significantly different from each other (P<0.000). Increasing ash content is positively correlated with Ca content ($r_p = 0.923$, P=0.01). The highest Fe content is observed in 10% ash content samples (5.52 µg/g) and lowest in pure ash sample (0.40 µg/g). The Fe result for the ash only samples is significantly different to all other Fe concentration results (P<0.05). Ash content and Fe content are negatively correlated ($r_p = -0.804$, P<0.01). K concentration is highest in soil only samples (45.43 µg/g) and lowest for ash only samples (18.89 µg/g); the K concentration value for ash only samples is significantly lower than all other K results (P<0.05). There is a negative correlation between ash content and K concentration ($r_p = -0.865$, P<0.01). The highest Mg concentration is observed in the ash only samples (32.58 µg/g) and lowest in the soil only samples (5.51 µg/g). Mg results for 50% and ash only samples are significantly different from each other and the remaining Mg results (P<0.000). Results show a positive correlation between ash content and Mg content ($r_p = 0.852$, P<0.01). Na concentration is highest in the ash only samples (146.22 µg/g) and lowest in the soil only samples (14.48 µg/g) and these results are significantly different from each other and the remaining results (P<0.000). Na concentration is positively correlated with ash content ($r_p = 0.929$, P<0.01).
Figure 6: Mean elemental concentrations of each sample mix. Letters denote statistically significant differences in results within each element category. Error bars are calculated standard deviations.

Figure 7 shows the cation exchange capacity of each sample mix. Na content is highest in 50% ash content samples (9502 µg/g) and lowest in pure ash samples (7757 µg/g). A Pearson’s rank test shows that there is no correlation between increasing ash content and Na concentration (P>0.05). A comparison of means by one-way ANOVA identified that both the results for 10% and 50% ash contents are significantly different to the results for the pure ash (P<0.05).

Figure 7: Graph to show the concentration of exchangeable Na as a measure of cation exchange capacity. Letters denote statistically significant differences in results. Error bars are calculated standard deviations.
5.2 Ash and Vegetation Recruitment

Figure 8 shows the relationship between mean vegetation height with changes in ash content. Kruskal-Wallis test results show that the vegetation grown under the ash layer is significantly shorter than vegetation grown in 10% (P=0.020), 20% (P=0.004) and 50% (P<0.000) ash contents, but is not significantly different from the soil only control plot. A Spearman’s Ranks Correlation test shows that increasing ash content and average vegetation height are negatively correlated ($r_s = -0.074$, P=0.025).

![Figure 8: Graph to show the relationship between mean vegetation heights with changes in ash content. Letters denote statistically significant differences in results. Error bars are calculated standard deviations.](image)

5.3 Ash Content and Slope Stability

Figure 9a shows that mean lag time before sediment yield is recorded is greatest in plots where an ash layer is present and 50% ash content (16:00 mins) and lowest at 10% ash content (13:20 mins), however these results are not statistically significant (P>0.05). There is no correlation between sediment lag time and increasing ash content ($r_s = 0.185$, P>0.05). Mean water lag time is greatest in plots with an ash layer (17:20 mins) and lowest in 10% and 20% ash contents (14:40 mins). There is no significant difference in lag time before water yield was recorded (P>0.05) (Figure 9b) between sample mixes, however, ash content and mean water lag time are positively correlated ($r_s = 0.337$, P<0.05).
Total mean sediment yield was greatest in 50% ash content and ash layer plots (1.48 g), and lowest in the soil only control plots (0.16 g) (Figure 10a). A Kruskal-Wallis test showed there is a significant difference in the sediment yields for different ash contents (P=0.047). However, pairwise comparisons, did not show any significant differences (P>0.05), failing to provide an indication of where the overall difference lies. Total mean water yield is greatest in 20% ash content plots (93.86 ml), however is not significantly different from 10% and 50% ash contents (Figure 10b). Mean water yield is lowest in the soil only control plots (48.99 ml), although this is not significantly different from 10%, 50% contents and ash layer plots (P>0.05). Ash content and sediment yield are positively correlated ($r_s = 0.83$, P<0.000).

Figure 9: Graphs to show the mean lag time before sediment yield (a) and water yield (b) were recorded from 5° NV plots. Results are measured to the nearest 4 minutes. Letters denote statistically significant differences in results. Error bars are calculated standard deviations.

Figure 10: Graphs to show the mean total sediment yield (a) and water yield (b) recorded for 5° NV plots. Letter denotes statistically significant differences in results. Error bars are calculated standard deviations.
5.4 Vegetation and Slope Stability

Mean sediment lag time on V plots is lowest on the soil only control plots (14:40 mins) and is greatest in plots with 10% ash contents (21:20 mins) (Figure 11a), although these results are not significantly different from other lag time results (P>0.05). There is no significant difference in sediment lag time results between NV and V plots (P>0.05). There is no correlation between increasing ash content and water lag time (P>0.05). Mean water lag time on V plots is lowest on plots with 50% ash content (16:00 mins) and greatest in plots with 10% ash contents (20:00 mins) (Figure 11b), although these results are not significantly different from other lag time results (P>0.05). Mean water lag time for 10% ash contents are significantly different for V plots as compared with NV plots (P=0.034), however no other results are significantly different.

Figure 11: Graphs to show the mean lag time before sediment yield (a) and water yield (b) were recorded from 5° NV and V plots. Results are measured to the nearest 4 minutes. Green and red bars display V data for sediment and water lag times respectively. Letters denote statistically significant differences in results. * denotes where NV and V results are significantly different (P<0.05). Error bars are calculated standard deviations.
Mean total sediment yield for V plots is highest for 50% ash content plots (0.63 g) and lowest for 10% ash content plots (0.07 g) (Figure 12a). Sediment yields for 10% and 50% ash contents are significantly different from the other ash contents (P=0.029). Sediment yield for plots with an ash layer are significantly different for V plots as compared with NV plots (P=0.046), however, no other results are significantly different. Mean total water yield for V plots is highest for 20% ash content plots (79.94 ml) and lowest for the soil only control plots (49.96 ml) (Figure 12b), however these differences were not statistically significant (P>0.05). Water yield for 10% ash content is significantly different for V plots as compared with NV plots (P=0.003), however no other results are significantly different.

![Figure 12](image.png)

**Figure 12:** Graphs to show the mean total sediment yield (a) and water yield (b) recorded for 5° NV plots. Green and red bars display V data for sediment and water yield respectively. Letters denote statistically significant differences in results. * denotes where NV and V results are significantly different (P<0.05). Error bars are calculated standard deviations.

**Slope Angle**

At the 20° NV slope angle, mean sediment lag time is greatest on the 20% ash content plots (16:00 mins) and lowest on plots with an ash layer (10:40 mins), although these results are not significantly different from other lag time results (P>0.05) (Figure 13a). There is no significant difference in sediment lag time between 5° and 20° plots (P>0.05). Mean water lag time is greatest in the 20% ash content plots (16:00 mins) and lowest in the soil only control plots (10:00 mins) (Figure 13b). A Kruskal-Wallis test showed there is a significant difference in water lag time for different ash contents (P=0.037). However, pairwise comparisons, do not show any significant differences (P>0.05), failing to show an indication
of where the overall difference lies. There is no significant difference in water lag time results between 5° and 20° plots (P>0.05).

At the NV 20° slope angle, total mean sediment yield is greatest for plots with 10% ash content (50.92 g) and lowest for soil only control plots (0.56 g) (Figure 14a), although these results are not significantly different from the other sediment yield results (P>0.05). There is no significant difference in sediment yield results between 5° and 20° plots (P>0.05). Total mean water yield is greatest for plots with 20% ash content (96.91 ml) and lowest for soil only control plots (53.51 ml). Water yield for soil only plots is significantly different to results in all other ash concentrations (P=0.002, P=0.005, P=0.002, P=0.004) (Figure 14b). Water yield is significantly different for 5° and 20° plots in 10% ash content (P=0.038), 50% ash content (P=0.008) and plots with an ash layer (P=0.009).

Figure 13: Graphs to show the mean lag time before sediment yield (a) and water yield (b) were recorded from NV 5° and 20° plots. Results are measured to the nearest 4 minutes. Teal and yellow bars display 20° data for sediment and water lag times respectively. Letters denote statistically significant differences in results. Error bars are calculated standard deviations.
At the V 20° slope angle, mean sediment lag time is greatest for soil only control and ash layer plots (13:20 mins) and lowest in 10% and 50% ash contents (9:20 mins) (Figure 15a), although these results are not significantly different from the other sediment lag time results (P>0.05). Sediment lag time is significantly different for 5° and 20° plots in 10% ash content (P=0.043) and 50% ash content (P=0.034). Mean water lag time for V 20° slope is greatest for 20% ash content and ash layer plots (14:40 mins) and lowest for 50% ash content (09:20 mins), although these results are not significantly different from the other water lag time results (P>0.05) (Figure 15b). Water lag time is significantly different for 5° and 20° plots in 50% ash content (P=0.043), however no other results are significantly different.

Figure 14: Graphs to show the mean total sediment yield (a) and water yield (b) recorded for NV 5° and 20° plots. 5° results can be seen fully in Figures 6a-b. Teal and yellow bars display 20° data for sediment and water yield respectively. Letters denote statistically significant differences in results. * denotes where 5° and 20° results are significantly different (P<0.05). Error bars are calculated standard deviations.
At the V 20º slope angle, total mean sediment yield is greatest for 10% ash content (56.85 g) and lowest for soil only control plots (0.13 g), although these results are not significantly different to the other sediment yield results (P>0.05) (Figure 16a). Sediment yield is significantly different for 5º and 20º plots with 50% ash content (P=0.05) and plots with an ash layer (P=0.046). Total mean water yield for V 20º plots is greatest for 50% ash content (104.70 ml) and lowest for plots with an ash layer (72.61 ml), although these results are not significantly different from the other water yield results (P>0.05) (Figure 16b). Water yield is significantly different for 5º and 20º plots with 50% ash content (P<0.000), however no other results are significantly different.

Figure 15: Graphs to show the mean lag time before sediment yield (a) and water yield (b) were recorded from V 5º and 20º plots. Results are measured to the nearest 4 minutes. Teal and yellow bars display 20º data for sediment and water lag time respectively. Letters denote statistically significant differences in results. * denotes where 5º and 20º results are significantly different (P<0.05). Error bars are calculated standard deviations.
Figure 16: Graphs to show the mean total sediment yield (a) and water yield (b) recorded for V 5° and 20° plots. 5° results can be seen fully in Figure 6a-b. Teal and yellow bars display 20° data for sediment and water yield respectively. Letters denote statistically significant differences in results. * denotes where 5° and 20° results are significantly different (P<0.05). Error bars are calculated standard deviations.
6. Discussion

The intention of this research is to determine whether the incorporation of ash reduces surface runoff and erosion, as well as investigating the effects of secondary variables such as soil properties, slope angle and vegetation. The aim is to identify which soil-ash ratio results in the greatest reduction in erosion. In addition, this discussion intends to explore whether any of the mixing ratios has a detrimental effect on plant growth, and the implications of this when considering ash incorporation as a remediation method.

6.1 Soil and Ash Properties

6.1.1 Particle Size Distribution

The particle size of all solid mediums were identified because of their relationship to soil erosion. The particle sizes of each of the samples ranged from sandy loam to silt loam. It was expected that the ash only sample would have the finest particle size, however, it contained a greater percentage of coarse material (67.7± 6.67%) than the other mixes possibly due to the inclusion of small fragments of igneous rock. This suggests that the sampling technique was not fully representative. The 20% ash content samples contained the greatest proportion of fines material (4.43%± 0.75%).

6.1.2 pH

pH is an important measure of soil fertility that is an indication of soil acidification (Diaz et al., 2004; Ayris and Delmelle, 2012). The results of this study are in agreement with the literature that has shown that the addition of ash to soil can cause a reduction in pH (Diaz et al., 2004). However, pH was only significantly lower in ash only plots. This suggests that while mixing ash and soil results in no change to pH, a deposited layer of ash has a lower pH than the underlying soil and has a lower overall fertility. However, the effect of an ash layer on the underlying soil pH has not been investigated. In addition, pH cannot be used as a singular indicator of soil fertility, and in most fertility studies is often combined with measurement of electrical conductivity, organic carbon and nitrogen, available phosphorous and micronutrients (Diaz et al., 2004; Del Moral and Clampitt, 1985).
6.1.3 Moisture Content

Initial moisture content, and its relationship with saturation point, is the ultimate driver behind surface runoff and erosion processes (Liu et al., 2011). Results showed a negative correlation between increasing ash content and moisture content in NV samples. Samples were not rotated during their time in the incubator, and it is possible that this correlation may be somewhat explained by variations in temperature and humidity within the incubator. However, it is known that ash forms a cemented crust when wetted that results in a major barrier to infiltration (Black and Mack, 1986). It is possible that increased water ponding on the surface of the soil, which was observed during sample watering, was more easily evaporated in the warm conditions. In addition, moisture contents in vegetated plots were generally significantly higher than those without, due to the ability of organic matter to increase water retention capabilities (Hills, 1971; Bot and Benites, 2005).

6.1.4 Organic Matter Content

Organic matter influences a soil’s water holding capacity (and therefore its relationship to saturation point) and matrix stability through presence of fibrous material (Xu et al., 2013; Zhang et al., 2014). Results showed a negative correlation between increasing ash content and organic matter content. This result was expected considering that ash has a lower overall organic matter percentage, and makes up a greater proportion of the mixes in higher ash content plots. In both NV and V data, the highest organic matter content was observed in the soil only control plots likely due to existing plant material in the soil samples which was not successfully removed during sieving. Organic matter contents were higher in V plots than NV for similar reasons, although this was not significant.

6.2 Ash and Vegetation Recruitment

Results from this study showed that vegetation recruitment occurred in all sample batches (Figure 8), which is concurrent with the literature that ash can be a suitable medium for plant growth (Shoji and Takahashi, 2012) and this supports hypothesis 3. Data in the literature has shown that vegetation growth in ash-soil mediums is possible but is dependent on the ash layer thickness (Collins, 1969; Gómez-Romero et al., 2006). Authors have shown that vegetation growth did not occur in thick ash layers as it prevented roots from reaching the more fertile soil (Gómez-Romero, 2006). In this dissertation, the ash layer should not have exceed ~1cm therefore vegetation growth was recorded in all plots. The vegetation used in
this experiment was resistant quick-grow grass seed, which may have contributed towards its tolerance of the conditions. Collins (1969) observed that many non-resistant plant species will not or struggle to grow in ash or ash-soil mixes. The same tolerance to conditions may not be displayed if less resistant vegetation were used in further experimentation. In addition, these results are likely best-case and may differ from field experiments, as the vegetation growth phase was undertaken in ideal conditions (Clarke, 2014).

The average vegetation height decreased with increasing ash content. Results showed that vegetation grown in the ash layer plots was shorter (87 mm) than that grown in all other sample mixes, however this result was not significantly different from heights in soil only plots. This supports hypothesis 4. These results are concurrent with the literature that ash layers act as a physical barrier to plant growth (Gómez-Romero et al., 2006). The tallest mean vegetation height was interestingly observed in the 20% ash content plots (99 mm), although this result was not significant. Research has shown that while pure volcanic ash does not enhance plant growth, low quantities combined with mineral soil or fertiliser, can increase plant productivity (Mahler, 1984; Diaz et al., 2004; Suriadikusumah et al., 2013). It is possible that the 20% ash-soil ratio mimics these conditions in some way, resulting in taller vegetation. While these results reveal information on the viability of soil-ash mixes as growth mediums, vegetation height should be used in conjunction with other indicators of plant health and productivity to understand the effects more fully.

Elemental concentrations were characterised to identify if ash resulted in chemical as well as physical barriers to vegetation growth. Calcium concentration was positively correlated with increasing ash content, with significantly higher results in ash samples. Burström (1968) showed that calcium concentrations of greater than $10^{-3}$ M may inhibit root and plant growth. Calcium contents from this dissertation are below this threshold ($\sim 10^{-6}$ M), therefore it is unlikely that this element has contributed to plant growth deficiencies. Magnesium concentrations showed the same trends. Venkatesan and Jayaganesh (2010) showed that tea plants showed no signs of severe magnesium toxicity (surplus of magnesium) at a concentration of 2000 µg/g. The results displayed in Figure 6 are well below this threshold and the increase in magnesium content in higher ash contents may provide benefit as photosynthesis and protein synthesis are highly controlled by the availability of magnesium.

Several of the elemental concentrations may have resulted in detriment to plant growth. Iron was negatively correlated with increasing ash content and significantly lower in ash samples (Figure 6). A deficiency in iron can result in iron chlorosis and reduced growth rates (Brown, 1961), however the values from this research are likely not low enough to cause growth
deficiencies. Potassium is used to stave off plant disease, and a deficiency in potassium often means other nutrients cannot be utilised (Edwards, 2001). Increasing ash content decreased potassium concentration in the soil, with a significantly lower concentration in ash samples. However, Adams (1971) states that soil potassium levels are commonly 0.1-6 mM. The results in this dissertation convert to ~0.48-1.16 mM and so the reduced potassium levels are unlikely to have caused growth deficiencies.

CEC was measured because of the effect it can have on soil cohesion (Figure 7). CEC was not correlated with ash content, however CEC values were lowest in ash only samples due to the low clay percentage (2.52%) and low organic matter content (0.265). This suggests that ash only samples would display less cohesive properties, relative to the other samples. CEC is generally used to calculate Exchangeable Sodium Percentage (ESP), which provides information on the level of salinity and sodicity of a soil. However in this instance, this was not possible as other base cations were not measured. While increasing ash content resulted in increased total sodium concentration (Figure 6), it is difficult to draw conclusions regarding its potential effects on plant growth due to the lack of supporting ESP data.

This research has shown that vegetation recruitment occurs in all of the tested mixes but vegetation height is significantly reduced in ash layer plots. These results support both hypotheses 3 and 4. As none of the elemental concentrations were at toxic levels, it is assumed that reduced growth rate in ash layer plots is a result of the ash as a physical barrier to growth. However, this study has not evaluated the interactions between increases/decreases in elemental concentrations and the levels measured are total concentrations of the soil as opposed to bioavailable concentrations to the plants. Therefore this conclusion is based upon assumption. Hepper et al. (2006) have shown that the effect that ash has on elemental concentration and CEC changes over time. This study characterised these properties prior to testing and therefore does not represent temporal variation.

6.3 How ash content affects slope stability

Results showed that increasing ash content was positively correlated with time before water yield was recorded (Figure 9b) and that mean water lag time is greatest in plots with 50% ash content (17:20 mins). Although there was no significant difference in the values, these results do not support hypothesis 3. Cook et al. (1981) showed that the increased proportion of fines material in ash can block pore spaces and reduce infiltration, and other studies have shown that crusting of volcanic ash deposits is very common especially when wetted.
(Seymour et al., 1983; Ayris and Delmelle, 2012). Several authors have emphasised that this crusting process is the major barrier to infiltration as opposed to the ash deposit itself (Black and Mack, 1986; Cook et al., 1981).

This barrier to infiltration suggests that surface runoff would increase, contrary to the results shown in this dissertation. However, during the experiments, it was observed that the main source of water yield was from water infiltrating until it reached the base of the impermeable tubing and ran down into the collection container. The 50% ash content plots had the highest fines content (4.12%) (Table 4) and lowest moisture content (41.1%) (Table 6) relative to the other samples, and longest water lag time. It is therefore assumed that a reduction in infiltration explains the increased water lag time and reduced water yield. This reduced water yield is thought to be a product of the increased lag time, constrained by the test duration. In contrast, the shortest lag time was recorded for 10% and 20% ash contents (14:40 mins), but these plots did not have correspondingly low fines contents or high moisture contents. As there is no statistical significance in these results, it is possible that these trends are due to natural variation in the data.

It is well known that saturation point and therefore surface runoff, are driving mechanisms behind erosional processes (Liu et al., 2011; Defersha et al., 2011). The general trend of the graph for sediment lag time matched that of water lag times because of this relationship. There was no significant difference in the values or correlation between lag time and ash content, therefore these results also do not support hypothesis 4.

The data showed that increasing ash content was positively correlated with sediment yield. This supports hypothesis 2. The greatest sediment yield was observed in both ash layer and 50% ash content plots (1.48 g) (Figure 10a). Ash on the surface of those soils was likely more susceptible to erosion because of its non-cohesive properties; it had a higher coarse particle size fraction (67.7%), which provides little cohesion, and had low organic matter content (0.26%). In addition, Nammah et al., (1986) showed that greater sediment yield was observed in ash layer plots in comparison to incorporated ash plots, as more ash was available to water flow. The lowest sediment yield values were observed in soil only plots (0.16 g) and this result is concurrent with the work by Nammah et al., (1986). Likely reasons for this lower yield are the high proportion of coarse material (55.8%) which is harder to transport and the highest organic matter content (1.89%) which provides stability and cohesion to the soil matrix (Xu et al., 2013; Zhang et al., 2014). The second lowest sediment yield was observed in the 10% ash content plots (0.17 g), as there was a lower proportion of
ash available to the flow of water, a high coarse particle size fraction (51.9%) and high organic matter content (1.65%) relative to the other samples.

This research seeks to identify which ash-soil mixing ratio would result in the greatest reduction of soil erosion. At 5° slope angle without vegetation, the biggest reduction in sediment yield as compared with the ash surface layer was observed in the soil only control plots, and the second biggest reduction in sediment yield was observed in 10% ash content plots. Both sediment and water lag times were shown to be greatest in 50% ash content plots, however there was no significant difference in the results.

6.4 How vegetation effects slope stability

Studies have shown that different plant species in different conditions will not or struggle to colonise an area covered in ash (Collins, 1969) and therefore, may change the effects of vegetation upon erosion rates. Results showed that there was no correlation between increasing ash content and water lag time in V plots and no difference in the means (Figure 11b). There was a significant increase in water lag time in 10% ash content plots between NV plots (14:40 mins) and V plots (20:00 mins) and this result supports hypothesis 9. None of the remaining results showed any significant difference between NV and V water lag time. Studies have shown that the presence of ash reduces a soils infiltration rate (Tejedor et al., 2003). In contrast, vegetation is known to increase infiltration (Peng et al., 2004). It is possible that at higher ash contents, the barrier to infiltration is too great for the presence of vegetation to overcome, resulting in no significant difference in lag times between NV and V plots. Therefore, a significant difference is only observed in lower ash contents. It is also possible that disparity in vegetation density was responsible for variation in results.

This pattern of results was reflected in the water yield results (Figure 12b). There was no significant difference in the mean water yield results in V plots. Water yield was significantly decreased in V plots (54.18 ml) as compared with NV plots (80.19 ml) for 10% ash contents. This results supports hypothesis 7. This reduced water yield is thought to be a product of the increased lag time, constrained by the test duration.

There was no correlation between sediment lag time and ash content for the V plots and comparison of the NV data to V data showed there to be no significant difference in sediment lag times for each ash content (Figure 11a). These results do not support hypothesis 10. While not significant, the largest increase in sediment lag time occurred in the
10% ash content plots (from 13:20 mins to 21:20 mins) and this is likely due to the increased water lag time also observed.

The sediment yield data (Figure 12a) displayed more interesting and complex results. A comparison of means of the V results showed that 10% ash content plots displayed the lowest sediment yield. The lower proportion of ash available to the water flow and a higher organic matter content relative to the other results could explain the difference in sediment yield (Nammah et al., 1986) as well as the addition of vegetation. The 50% ash content plots likely displayed greater sediment yields due to the higher proportion of ash available to the water flow (Nammah et al., 1986), having a high fines content and low organic matter. However, by this logic, surface ash layer plots should have displayed the greatest sediment yields. Sediment yield was significantly reduced from 1.48 g to 0.25 g in V plots as compared with NV plots, for ash layer tests and this result supports hypothesis 8. Nammah et al. (1986) showed that sediment yields were always higher for plots with unincorporated ash as opposed to incorporated ash. It is possible that stabilisation by vegetation was not uniform throughout the soil profile and therefore has greater positive effects at the surface in ash layer plots. This can be inferred from studies that show variations in other properties, such as soil moisture, because of non-uniformity of root zones through the soil profile (Choi and Jacobs, 2007). Unfortunately this experiment was not designed to investigate this, so this relationship is speculative. In addition, standard lawn grass was used for these experiments, therefore application of these results should be undertaken with caution as different vegetation types may vary the effects on erosion.

Significant results show that the presence of vegetation increased water and sediment lag times, but only for 10% ash contents. V plots also displayed reduced sediment yields. The relationship between lag time and erosion meant that vegetation reduced sediment yield, but only significantly for plots with an overlying ash layer due to potential variability in stabilisation processes throughout the soil profile. Understanding this variability further would help to quantify this relationship. Although the mixed samples did not show any significant reduction in sediment yield with vegetation, this relationship might be explore more fully if a wider range of mixing ratios were experimented with.
6.5 How slope angle affects slope stability

6.5.1 Slope angle without vegetation

Results showed that there was no correlation between increasing ash content and water lag time and no significant difference in the mean values (Figure 13b). This shows that at 20°, ash content does not appear to have a direct relationship with water lag time. This may be because, at steeper inclines, the velocity of water is increased (Zehetner and Miller, 2006) and that perhaps this factor is a bigger control on water lag time than the ash content. Statistical analysis showed there was a significant difference in 5° data when compared with 20° data, however pairwise comparison could not specify this difference. Therefore, these results do not support hypothesis 13. This indicates the interplay between these variables, therefore further statistical analysis (such as multiple regression) is required to identify which variable might be most responsible for changes in water lag time.

At 20° slope, there was no correlation between ash content and water yield results, however water yield results were significantly lower in soil only plots in comparison to the other results (Figure 14b). These plots had the highest organic matter results, suggesting an increased water holding capacity of these samples, however, it is possible that there was also a discrepancy in the amount of water that was applied to these plots. There was a significant increase in water yield on 20° plots as compared with 5° plots in 10%, 50% content and ash layer plots. These results support hypothesis 11 and are concurrent with the literature (Nammah et al., 1986; Morgan, 2005).

There was no significant difference between sediment lag time results at different ash contents for 20° plots and no correlation or general trend between 20° and 5° results (Figure 9a). These results were expected considering the relationship of sediment lag time with water lag time, and do not support hypothesis 14. Sediment yield was lowest in soil only control plots (0.56 g). There was no correlation between sediment yield and ash content (Figure 14a). The general trend shows that sediment yield does increase in 20° plots as compared to 5° plots, but these results are not significant. However, as the trend agrees with data from Nammah et al. (1986), Zehetner and Miller (2006) and Defersha et al. (2011), it suggests that the results do support hypothesis 12. The lack of correlation between sediment yield and ash content is contrary to similar results presented by Nammah et al. (1986) which showed that sediment yields were always greatest in unincorporated ash plots in comparison to incorporated ash. This disagreement of data may be due to the large error in results (Figure 14a). During testing, it was observed that some plots lost sediment in “failure events” whereby large sections of the plots would slide from the tube. It is thought
that the smooth, impermeable tube surface reduced traction for the test material at steeper slopes, despite undertaking pilot studies to prevent this. Other erosion studies use a combination of stones and packed sand or overlying screen material at the base of soil pans to avoid this (Defersha et al., 2011; Mutchler et al., 1994).

At 20° NV, lag times were reduced in comparison to 5° results, and sediment and water yields were higher than those recorded for the 5° slope. There was no significant difference in the results at the different ash contents and large errors were present in the data. Due to the lack of significant results, it is only suggested that sediment and water lag times and yields were lowest in soil only control plots, however this cannot be stated with any certainty.

6.5.2 Slope angle with vegetation
Results showed that there was no significant difference in the mean water lag time at different ash contents for 20° plots (Figure 15b). It is likely that 50% ash content plots showed the shortest water lag time due to variations inherent in the methodology, i.e. differences in volume of water application, as there does not appear to be a reason for this relating to soil properties. Water lag times were significantly shorter for 20° plots than 5° plots in 50% ash contents, and generally shorter for all other sample mixes, although these results were not significant. These results therefore support hypothesis 13.

Figure 15a shows that there is no significant difference in sediment lag time at 20° at any ash content. However, there was a significant reduction in lag time between 5° and 20° plots for 10% ash content and ash layer plots, which supports hypothesis 14. Reduction in sediment lag time for the ash layer plots are expected when the water lag time results are taken into consideration. In addition, the surface ash layer presents a more vulnerable surface to erosion (Nammah et al., 1986) where relative increases in water velocity occur on steeper slopes (Morgan, 2005). It is interesting that the 10% ash content plots also display a significant decrease in sediment lag time as there is a lower proportion of ash available to the flow. Some plots became cracked at the surface prior to testing and it is possible that this contributed towards “failure events” that may have resulted in the large errors of this dataset.

Results show that there was no significant difference in sediment yield at any ash content, which does not support hypothesis 2 (Figure 16a). Large error bars are also present in several of these data sets, indicating high variability of results and it is thought this is also due to the failure events observed during testing. In some cases, the presence of vegetation aided this process whereby the root systems would pull more material into the collection
containers. Sediment yield was significantly increased in 50% ash content and ash layer plots at 20° as compared with 5°, and although the remaining results were not significant, they still support hypothesis 12. This is consistent with findings from the literature (Van Liew and Saxton, 1983; Liu et al., 1994; Fu et al., 2011; Sun et al., 2015). The significant results display the differences likely because they were most vulnerable to erosion due to the higher proportion of ash available to water flow (Nammah et al., 1986).

The results showed that lag times were not increased significantly by any ash-soil mixing ratio. Plots at 5° had longer delay times compared to 20°, but only in the NV results. Sediment yield was not correlated with ash content at 20°, but significant results are concurrent with the literature that increasing slope angle increases sediment yield. The high variability of the data makes it difficult to draw conclusions. This suggests that ash incorporation does not significantly increase sediment yield at steeper slope angles, however, a more multi-variable analysis is required in order to quantify the interrelationships between slope angle, ash mixing and sediment yield.

6.6 Ash and Vegetation Antagonism: Recommended Practice

The primary aim of this research was to identify if, and at what ratio, ash mixing would reduce the effects of erosion subsequent to an eruption without detriment to plant growth. At 5° slope NV, sediment yield was lowest in soil only control plots (0.16 g). As the aim was to identify which mixing ratios might also result in a reduced sediment yield as compared with a surface ash layer, it is essential to point out that the 10% mixing ratio resulted in the second lowest sediment yield (0.17 g) and this result was not significantly different from the soil only control plot result. While these results were not significantly different from the others, they did result in the biggest reductions in sediment yield. At 5° slope V, a similar pattern emerged, with 10% mixing ratio displaying the lowest sediment yield (0.07 g). However, this result was not significantly different from the 20% yield results (0.17 g), which is important when considering the effect on vegetation. Vegetation height was greatest (as compared with ash layer plots) in 20% plots (98.96 mm), although this result was not significantly different from 10% plots (95.27 mm). The chemical data did not provide conclusive information on which concentration changes would be beneficial/detrimental (Figure 6), but it is suggested that the ash acts as a physical barrier to growth (Gómez-Romero, 2006), therefore lower ash contents are less detrimental. Given the lack of significance between these two datasets, in this experimental scenario, either 10% or 20% ash mixes would be sufficient in reducing erosion rates without any detrimental effect on plant growth.
At 20° slope NV, the lowest sediment yield results were also observed in the soil only control plots (0.56 g), however this result was not significantly different from the other results. These results are difficult to draw conclusion from because of the failure events that skewed the data set. At 20° slope V, the lowest sediment yield was once again observed in soil only control plots (0.13 g), however this result was not significantly different from the 20% plots (0.17 g). As the aim was to identify which mixing ratios might also result in a reduced sediment yield as compared with a surface ash layer, it is essential to point out that the 20% mixing ratio had the second lowest sediment yield in the experimental scenario (0.89 g). Again, it is important to note that vegetation height was significantly higher in 20% mixes (98.96 mm) as compared with ash layer plots. However, there was no significant difference between soil only and ash layer plot vegetation heights. While 20% and soil only vegetation heights were not significantly different from each other, the vegetation grown in 20% ash contents have clearly benefitted more so than that in soil only plots when compared with ash layer plot data.
7. Limitations and Further Research

While some limitations of this study have been addressed in the discussion, there are others, particularly relating to the methodology of the research require further attention. Each of the sample tubes was kept in the incubator for the same amount of time, however heat, humidity and light were not uniform throughout. The tubes were not rotated in the incubator so they may have experienced slight variations in, for example temperature, which may have caused changes to the natural moisture contents.

Perhaps one of the biggest weaknesses of this project is the use of analogue ash and soil materials. As a large enough volume of one type of ash could not be obtained, a mixture was required and therefore made the application of this research to a case study area inappropriate. While the results may still show general relationships, it is suggested that representative soil and ash samples are used in order that the results be more directly applicable.

Mutchler et al. (1994) suggest suitable methods for testing soil erosion. Their suggestion for runoff experiments is to use permeable layered mesh at the base of the soil to mimic natural infiltration. The tubing used in these experiments resulted in an impermeable layer at the base of the samples, causing water to infiltrate to this point and then run down the inside of the tube. While this effect was present in all experiment, therefore not changing the importance of results with respect to one another, this means that these results may not be suitable for real world application. There are concerns in the literature regarding plot size and the influence edge effects may have on the results. It is recognised that the plots used in this experiment are not representative of field conditions, therefore reducing the applicability of the results. Instead it is recommended that the plot size be increased to those more standardly used (Mutchler et al., (1994). It was noticed during the experiments that water application was not consistent. Pilot studies were undertaken to ensure failure and washout did not occur, and while this was not observed initially, some plots in the main experiment experienced failure events. Although the apparatus was minimally disassembled, it is possible that this caused changes in the amount of water delivered to the tube. Every care was taken to avoid this, and the rate of water delivery recorded for each experiment to minimise its effect, however, it is possible that variation in water application influenced the results. Should time and resources allow, more sophisticated rain simulators should be used to control this, however the financial and practical implications of this are duly noted.

Discussion of the results presented here has also highlighted areas where the data measurement and analysis could be improved in order that the objectives of this research
are fully met. Most studies of erosion are concerned with the effect of raindrop impact as an erosional mechanism (Zehetner and Miller, 2006; Kinnell, 2005). These studies tend to characterise the mechanics of rainfall as it helps maintain consistency in water application. As previously discussed, this research may have encountered problems with sustaining constant water delivery rate, and so characterisation of these parameters might help to alleviate this issue.

One of the aims of this research was to identify which soil-ash mixing ratio reduced erosion by the greatest amount. Although a conclusion was reached, this experiment did not identify which material was being eroded. Defersha et al. (2011) characterised the particle size of the eroded material to classify it as either ash or soil. It would be useful to understand this information as it would allow for more detailed exploration of the primary and secondary hazards related to ash and erosion. In addition, the effects of vegetation could have been characterised more fully. While the data were presented for NV and V plots at both slope angles, a direct comparison between these data sets was only carried out for 5° plots. It is likely that this does not diminish the relationships identified in this dissertation, as they are concurrent with the extensive literature, however, this data comparison would contribute to the robustness of the conclusions.

Much of the chemical analysis carried out was done on samples prior to the main experiment phase. While this was deemed sufficient to understand the basic soil properties, this offers no temporal consideration of chemical changes to the soil; instead incremental chemical should be undertaken to fully characterise these changes. The elements tested in the soil extracts were selected for their ability to affect plant growth. It would also have been useful to identify changes to other elements, such as heavy metals, that may have been prominent in the ash samples, therefore it is recommended that the bulk composition be characterised in further research.

This research is very case specific and the reader is made aware throughout that care should be taken when applying the results. It would be beneficial to carry out similar works using different analogue materials, and experimenting with different mixing ratios, vegetation species and slope angles to build up a bigger picture of how erosion is effected by the presence of ash.

Perhaps the most important aim of this research was to identify the joint relationship of slope angle, ash and vegetation on erosion; something that is missing from the literature. While all these variables were investigated and were discussed in relation to one another to some degree, there was no statistical analysis included that provided quantitative evidence of
which variable had the greatest influence. This was difficult to achieve when several sets of results displayed unusual trends due to failings in the experiment design; therefore any complex statistical analysis would be heavily skewed. However, if these methodological issues were overcome, multiple regression analyses could be used to identify these interrelationships, and hopefully contribute original research to the existing knowledge base.
8. Conclusion

This study set out to identify whether ash mixing could reduce the detrimental effects of erosion, and how this relationship changed with variations in slope angle and vegetation. Soil and ash mixing has been previously studied, but use of acidic ash is not common and there is lack of studies comparing multiple variables in a single experiment.

This research showed that increasing ash contents resulted in increased erosion, therefore soil only control, 10% and 20% plots were most efficient at reducing sediment yields, depending on the experimental scenario. Vegetation grew in all plots and 20% plots showed an improvement in vegetation growth in comparison to ash layer plots. Increasing slope angle resulted in increased surface runoff and erosion, however it is difficult to draw to draw solid conclusion from this due to the large data errors that skewed the significance values. The inclusion of vegetation caused a reduction in both runoff and erosion. Results showed that lag times were increased by increasing ash content, and that the longest lag times for both surface runoff and erosion were generated by 50% ash content plots. The discussion showed that, while soil only control plots resulted in the greatest reduction in erosion, lower ash content plots (10% or 20%) also reduced erosion in comparison to ash layer plots, as well as providing an apparent benefit to plant growth.

Although not all the data are significant, and while a specific ratio cannot be universally recommended as a remediation method, this research has shown that lower mixing ratios or complete ash removal produce the most beneficial results for both erosion and vegetation growth than higher ash ratios. Limitations of the data made drawing conclusions difficult, however, these results are concurrent with findings in the literature (Nammah et al., 1986), and provide more detail on exact mixing ratios.

These recommendations are case specific and can only be considered with any confidence to the scenarios simulated in these experiments. Similar conclusions have been drawn in the literature, whereby each case study location would likely need its own analysis in order that the results can be applied with confidence (Nammah et al., 1986). It is hoped that these results can be used to expand the existing knowledge base on the effect of ash on soil erosion and vegetation growth. It is not always feasible to completely remove deposited ash (USGS, undated), therefore research that contributes towards alternative remediation is highly valuable.
9. References


