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SUSTAINABLE PLANT PRODUCTION ON DEGRADED SOIL / SUBSTRATES AMENDED WITH SOUTH AFRICAN CLASS F FLY ASH AND ORGANIC MATERIALS

by

WAYNE FREDERICK TRUTER

Submitted in partial fulfilment of the requirements for the degree

PHILOSOPHIAE DOCTOR

In the Department of Plant Production and Soil Science
Faculty of Natural and Agricultural Sciences
University of Pretoria
PRETORIA

April 2007

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In loving memory of my mother

Esther M. Truter

(18 October 1954 – 02 October 2006)

To my son, Logan Joshua Truter

This degree I completed for you, so that one day you will be proud, because pride drives a man. During this time of my life, I learned many lessons, which will always be applicable to my life, your life or anyone else's life. These lessons are; anything's possible, nothing seems to be what you think it to be, what you expect it to be, what you want it to be, so don't just accept everything, question, discover and experience. You will make good and bad decisions in life, but always be humble and learn from your mistakes, because everything that happens to you in life happens for a good reason. And it is all up to you, to live with life's consequences, with a positive, happy and enthusiastic attitude.

Always smile and you will be happy!!

Love Daddy

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ACKNOWLEDGEMENTS

The author wants to acknowledge the following parties for their essential role in completing this study:

My Lord Jesus Christ,

for providing me with the strength, knowledge, wisdom, courage and love

Prof. Norman Rethman, for the tremendous support during my times of hardship, his enthusiasm, wisdom and guidance, motivation and inspiration, and for respecting me and for having faith in me

Dr. Richard Kruger, an insightful friend, a pillar of support and source of wisdom and enthusiasm

Ms. Kelly Reynolds (ESKOM) for funding the research, and for being a helpful friend.

My colleagues of the Department of Plant Production and Soil Science, University of Pretoria

Anglo Coal (Kromdraai Colliery)– For their co-operation with this research

My Father and sister for all their love, support, understanding, help, encouragement and all the faith they have in me.

My dearest mother- who always up and till her passing away, loved me, was so proud of me, believed in me, supported me and was there for me

My son, Logan, your love, your life and your future was my inspiration and motivation

Finally, to a wonderful women – Minandi
A person that believes in me, always supports me, who loves me, cares for me, no matter what
A true inspiration to my life!!

DECLARATION

I, Wayne Frederick Truter, hereby declare that this dissertation for a PhD degree at the University of Pretoria is my own work and has never been previously submitted by myself at any other university.

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Wayne Frederick Truter

April 2007

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ABSTRACT

Sustainable plant production on degraded soil / substrates amended with South African class F fly ash and organic materials.

by

Wayne Frederick Truter

Supervisor: Prof. N.F.G. Rethman

Submitted in partial fulfilment of the requirements of the degree

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South Africa is a country with very little prime farmland. A large percentage of this high agricultural capability land is generally acidic and nutrient poor, and situated in areas where large coal mining activities occur. Coal mining and agriculture are important industries in South Africa. They impact extensive land areas, and often compete for the same land. The surface mining of coal seriously damages the surface soil, local flora and fauna. Mining wastes viz. overburden, discards and mine effluents, have also created land degradation problems. Three of the most common factors that characterize degraded substrates are soil acidification, nutrient depletion and loss of biological activity. To ensure a healthy and productive vegetation, disturbed soils need to be ameliorated effectively. Using conventional methods is costly and is often not sustainable. The challenge is, therefore, to use potential alternative ameliorants in an economically, ecologically and socially sustainable manner. Fortunately, South Africa has plenty of industrial and organic by-products, which might be used as alternative ameliorants. There is an enormous amount of international literature on the use of class C fly ash, (Sub bitumious or lignite CCB – [Coal combustion byproduct]), and to a lesser extent class F fly ash (Bitumious CCB),

as opposed to South African class F fly ash, which is predominantly produced in this country. Fly ash, either by itself, or together with other wastes such as biosolids, can serve as a soil ameliorant by providing a good source of micro-, macronutrients and organic material for the reclamation of land. Previous research has shown that when sewage sludge is mixed with class F fly ash and a suitable source of reactive lime in a specific ratio, sewage sludge pasteurization will occur. The SLudgeASH (SLASH) mixture has been extensively evaluated as a soil ameliorant and has proven to be viable for the reclamation of poor and marginal soils. This study, has focused on the effect of soil ameliorants on the chemical-, physical- and microbiological properties of degraded agricultural land, mine land and other mining wastes (tailings and discards) requiring rehabilitation. This study also evaluated the affects of class F fly ash and SLASH amelioration of soils and substrates on plant production and re-vegetation, in comparison with conventional liming and fertilization methods currently in use. Species such as maize (*Zea mays)* and wheat *(Triticum aestivum);* pasture legumes such as lucerne or alfalfa *(Medicago sativa);* sub tropical grasses such as Foxtail Buffalo grass (*Cenchrus ciliaris)*, Rhodegrass (*Chloris gayana)* and Smutsfinger grass *(Digitaria erianthra)* have been evaluated. The success of enhanced plant production, re- vegetation and sustainability of once degraded soils / substrates is an indication of the amelioration success achieved. Seed germination, root development, plant yield, plant density, botanical diversity and biological activity are parameters which can all be used to support the conclusion that alternative substrate amendment practices can improve the plant growth medium. Based on the results obtained in this study, it was concluded that fly ash and fly ash/organic material mixtures (SLASH) improved soil chemical properties such as pH, ammonium acetate extractable K, Ca, Mg and Bray 1 extractable P levels. All parameters measured were significantly influenced by the fly ash and SLASH. For example, the pH of soils impacted by acid mine drainage was improved by 240% by the use of SLASH. Other results illustrate improvements in soil physical properties such as texture, bulk density, water infiltration rate and hydraulic conductivity, by class F fly ash based soil ameliorants. In addition to the beneficial effects on soil physical properties, the microbial properties were also improved, as indicated by the beneficiation of symbiotic relationship of the *Rhizobium* bacteria and the important host plant *Medicago sativa.*

Improvements in crop yields, such as: wheat yields on SLASH and fly ash treatments were 270% and 150% better than the control respectively; yields of maize and alfalfa were improved by 130 % and 450% respectively, were also registered. Fly ash and SLASH ameliorated soils resulted in approximately 850%, 266% and 110% higher dry matter production on gold mine tailings, AMD impacted soil and acidic mine cover soil, respectively, relative to the control treatments. Results also clearly illustrated that the abundance of certain species can be related to the higher fertility levels of the rehabilitated soil. Data collected over the past seven years, illustrates how the botanical composition has changed, and that soils receiving class F fly ash and sewage sludge had a higher dry matter production, whereas the control (no treatment) had a better biodiversity. With respect to the reclamation of coal discard materials, significant increases in yield, of up to 200%, were noted for soils and discards treated with class F fly ash, relative to the untreated control. The pH of cover soil was the most strongly affected soil parameter during the experimental period.

Class F fly ash and SLASH have the potential to improve the chemical, physical and microbiological properties of degraded soils and substrates. From this experimental work it can be concluded that class F fly ash from Lethabo definitely has a much higher $CaCO_3$ equivalent than what was originally assumed and that other SA sources probably have an even better neutralizing value. Class F fly ash and SLASH, are good sources of micronutrients and some macro nutrients, and may play a significant role in neutralizing acidity due to their residual alkalinity, and thus ability to continuously change the soil chemical balance so that nutrients become more available for plant uptake and use, thereby enhancing growth. Agricultural, domestic and industrial by-products unfortunately, vary greatly in nutrient content, trace metals and liming potential, and these factors can affect both re-vegetation success and the environmental impact of reclamation. Co-utilization of by-products can often combine beneficial properties of the individual by-products to eventually have a more pronounced effect on the degraded soil or substrate.

RATIONALE

By way of introduction, this study emphasizes the large-scale application of Class F fly ash and combinations of fly ash with sewage sludge as soil amendments to acidic and nutrient depleted agricultural soils, cover soils and other substrates on surface coal mines of the Mpumalanga Province of South Africa. This research has been based on the earlier small scale work conducted and reported on in the MSc(Agric) thesis entitled " The use of industrial and agricultural by-products to enhance plant productivity", where the beneficial use of fly ash and fly ash / sewage sludge mixtures was highlighted (Truter, 2002).

The motivation for the focus of the study to move into the mining environment was primarily because many acidic and nutrient depleted soils are used as cover soils in the surface mining process. Secondly it was due to practical and logistical limitations experienced in the handling of such large quantities of these materials in agricultural fieldwork. The reason for this is that mining companies are better equipped to potentially handle and apply the large quantities of these materials (which are often virtually "on site") required to amend degraded soils.

The literature review supplements the literature reviewed for the MSc(Agric)thesis (Truter, 2002). Greater emphasis, however, is placed on the field application and alternative amendment potential of Class F fly ash, and certain organic material combinations, to amend soils impacted by the agricultural and mining industries. The effects of such amelioration were evaluated by monitoring the re-vegetation of such amended soils and substrates.

The hypotheses are that class F fly ash with low CaO content, in semi –arid conditions with or without organic materials, can be used to chemically and physically ameliorate acidic and nutrient depleted soils and substrates in agriculture, degraded soils (rehabilitated surface mines) and tailings material, and to improve plant production. Sustainable amelioration can, therefore, be achieved by utilizing the residual effects, which fly ash and organic materials have on soil properties, thus beneficiating plant production.

STUDY LIMITATIONS

During the conduct of this research, many study limitations were identified, which resulted in the identification of new research problems. This study involved only one source of class F fly ash (Bitumious CCB) . The reason for deciding to concentrate on the Lethabo Power Station class F fly ash was because it has the lowest neutralizing capacity of all sources of class F fly ash presently available in South Africa (Reynolds, 1996). Results from this study would, therefore, allow a good estimate of the amendment potential of other class F fly ash sources. Due to the novelty and innovativeness of this study, many questions exist on how this industrial by-product could be used as a soil ameliorant. Much research has been done globally on the use of class C fly ash (Sub-bitumious or lignite CCB) and to a lesser extent class F fly ash as a soil ameliorant, but very little work has been done on using class F fly ash under South African conditions, especially in the rehabilitation of soils and substrates resulting from the surface coal mining industry.

The questions and concerns of using the industrial coal combustion by-products, such as class F fly ash, which has previously been termed a “waste / hazardous material”, for agricultural purposes is very relevant. Many industrial, urban, municipal, domestic and / or organic by-products / materials have unique properties that, could be used beneficially for agricultural purposes. A major concern is the pollution aspects of such materials, for example heavy metal contamination. Although initial work had been conducted in the MSc(Agric) study, a more “in depth” monitoring project conducted by other research team members is ongoing. During this study, the following aspects were addressed: studies on the physical, chemical and microbiological effects on soils and finally the impact on plant productivity.

This study has answered many questions and addressed many concerns, provided many potential solutions, but has also identified many more questions, concerns and possibilities.

SUMMARY

This study focuses on a relatively new topic of scientific research in South Africa, namely the use of class F fly ash, or combinations thereof with organic materials, as a soil and/or substrate ameliorant. The class F fly ash / organic material amelioration, which ensures a more sustainable vegetation cover, has revolutionized the use of industrial and organic by-products in the reclamation of degraded land in South Africa. International literature provided the motivation for this research, and served as a benchmark for expected outcomes. The literature cited, however, had detailed the use of a class C fly ash, which is very different from South African class F fly ash. The class C fly ash, which is known to be a very effective ameliorant, provided a good reference of what could be expected using a lower grade class F fly ash. South African climatic conditions (semi-arid) and edaphic factors also differed from many of the regions in which class C fly ash had been evaluated. This provided an additional reason to conduct such research under South African conditions. It was, therefore, imperative that South African coal combustion by-products (CCB's) and especially class F fly ash, be evaluated under South African conditions, to initiate and develop this innovative technology in South Africa, and also to contribute to the limited data bank on use of class F fly ash as a soil ameliorant.

Due to the increased rate of land degradation in South Africa, land reclamation is becoming increasingly important. The most important component of land reclamation, which forms the basis of sustainable vegetation, is the amelioration of soils and substrates. Conventional practices of soil and substrate amelioration in South Africa have been based largely on chemical amelioration of soils. This has been based on the large-scale use of calcitic and dolomitic lime, which are non-renewable resources, and inorganic fertilizers. These can be very effective, but long-term use is not economically justifiable. Because of the growing rate of requirements for such amelioration, the extensive use of alternative ameliorants to facilitate soil and substrate amelioration will inevitably increase in the future.

Soil amelioration should be seen as a method of returning nutrients and organic matter to degraded soil so that the natural cycle, on which most life depends, can be restored. By using alternative soil ameliorants for this purpose, soil conditioning is enhanced and the economic and environmental value of these by-products becomes

self-evident. Apart from the known contribution of N, P, and K nutrients supplied by organic materials, such as animal manures and sewage sludge, other supplementary traits that encourage plant growth have also been attributed to these agricultural, domestic and even industrial by-products (such as the CCB - class F fly ash [FA]) used in this study.

These additional benefits have been ascribed to plant nutrients such as Ca, Mg, or micronutrients, or to physical changes in the soil. For many years, the parameter used to evaluate effective soil amelioration has been short-term quick reaction and plant response, and long-term sustainability has been virtually ignored. Soil degradation due to the extensive use of inorganic chemical fertilizers, intensive mechanization, cultivation and utilization of arable soils has, however, increased awareness of the possible use of "alternative" ameliorants such as industrial, municipal, domestic by-products, animal manures and organic materials in scenarios which aim at a more holistic and sustainable solutions.

Research undertaken in the late 1990's, produced preliminary results, which served as the basis of this study. With the identification and recognition of the inherent characteristics of class F fly ash, a programme was initiated to evaluate the combination of this coal combustion by-product with sewage sludge to provide an alternative ameliorant for degraded soils and substrates. A product termed SLASH has been produced, which has characteristics of both class F fly ash and sewage sludge, benefiting both soil and plants. With respect to the chemical benefits, the class F fly ash is known to be a good source of micronutrients, while possessing liming qualities, and the sewage sludge is a good source of both macronutrients and organic matter. Both class F fly ash and sewage sludge also have positive effects on physical properties such as texture, density and moisture characteristics of soils and other substrates.

This research has highlighted the potential neutralizing role of class F fly ash as a possible liming material, to be used in mine-land reclamation rather than the agricultural industry, due to economical, logistical and practical reasons. These alternative soil ameliorants definitely have agricultural potential. For optimal plant production good soil conditions are required, and it is, therefore, essential that soil pH and nutrient levels meet the plant growth requirements. The beneficial effects of FA on plants have mostly to do with the adjustment of pH of an acidic soil and supplying deficient nutrients, resulting in improved plant growth.

To date, in land reclamation, conventional liming and fertilization have been the preferred method of ameliorating degraded soils, but this requires annual inputs and has not necessarily been sustainable. Sustainability of soil amelioration can be assessed in terms of the residual effects of ameliorants on soil condition, which indirectly enhances plant production. This study has demonstrated that both SLASH and class F fly ash can restore inherent poor and acidic soils and substrates in the long term, so that plants can grow optimally and sustainably with reduced input costs. The productive utilization of waste products is also important in ensuring a sustainable environment.

The hypotheses of this study, are that; class F fly ash with a low CaO content, in semi –arid conditions, with or without organic materials, could be used to chemically and physically ameliorate acidic and nutrient depleted soils / substrates in agriculture, degraded soils (rehabilitated surface mines), tailings material and coal discards, to improve plant production in more sustainable re-vegetation programmes.

Objectives

The first objective of the study was to evaluate how class F fly ash and SLASH can enhance the productivity of important agricultural crops such as maize (*Zea mays)* and wheat *(Triticum aestivum)*, as well as an important pasture legume (lucerne or alfalfa (*Medicago sativa))* commonly used in animal production systems. The objective was achieved by altering the soil chemical properties, especially soil pH, using FA and SLASH ameliorants in comparison to conventional materials used for soil amelioration.

The second objective of the study was to determine the influence of FA and SLASH ameliorants on certain physical and microbiological properties of such agricultural soils. The compaction of soils, which was not investigated in detail in this study, can be possibly due to grazing animals, especially on agricultural land that is being irrigated, and mechanization. With soil compaction, soil physical properties such as soil texture and bulk density are altered. Changes in these properties subsequently affect the soil-water balances by changing properties such as the hydraulic conductivity and infiltration rate. Microbiologically, pasture legumes grow in symbiosis with microbial populations of *Rhizobia.* This symbiotic relationship is important to ensure productive, economical and good quality legume production. These microbes, however, are often sensitive to degraded soil conditions. The other objective of the study was, therefore, to determine the effect of class F fly ash on the biological activity of the soils, as well as on *Rhizobium* nodulation.

It became evident from these studies, when investigating the use of FA and SLASH for agricultural purposes, that agriculture alone would not be the largest user of large volumes of fly ash or SLASH, due to practical, logistical and economical reasons. To date, the assumption is made, that the use of SLASH is economically restricted to areas in close proximity of the resources used in the makeup of SLASH. This aspect caused the study to determine a potentially larger user of class F fly ash and SLASH. This research, therefore, was conducted on mine soils destined to be reclaimed (rehabilitated), to address an even larger need for soil amelioration, so that these seriously degraded soils can be re-vegetated in a more sustainable manner.

Degraded mine land, as a result of surface coal mining, requires significant soil amelioration. Generally these mine soils (AMD impacted soils and acidic cover soils) and substrates (coal spoil and coal discard) are highly acidic. The acidic nature of these soils and substrates, is of such magnitude, that large amounts of alkaline material such as fly ash, are required to counteract the acidity present and continously generated by such materials.

A greenhouse study was conducted initially to determine how class F fly ash would react in the more degraded mine soils and other mining substrates (such as gold mine tailings material). This study initially concentrated on how class F fly ash and SLASH could change the chemical properties of such soils and substrates, thereby enhancing the productivity of *Cenchrus ciliaris,* which is particularly sensitive to poor soil or substrate conditions. Total plant biomass (plant and root) was measured to reflect the affects of such FA and SLASH soil amelioration. These data could be used to determine the basic trends of reaction of these soil ameliorants, when investigated on a field scale, and will eventually provide more practical applications of this research.

The next objective of the study was to apply FA and SLASH to acidic mine cover soil at field scale. Three different levels of application were investigated to determine the best application rate. This work, in conjunction with the aforementioned greenhouse study, was conducted to determine whether class F fly ash had a higher $CaCO_3$ equivalent and neutralizing capacity, than was originally assumed from international literature. Re-vegetation of degraded soils and substrates is a major challenge, and the success of re-vegetation can be ascribed to long-term sustainable soil, or substrate, amelioration. In this study, plant production, basal cover and botanical composition were the parameters used, to asses the contribution of FA and SLASH to the sustainability of a reclamation programme as compared to the conventional methods currently in use.

South African coalmines also face major challenges when it comes to the disposal, stabilization and reclamation of waste coal disposal sites, also known as coal discard dumps. Coal discard dumps have very engineered designs that often make the re-vegetation process difficult. If coal discard dumps are improperly reclaimed, many environmental hazards can occur. Most of the problems associated with coal discard dumps can be mitigated by establishing and maintaining a healthy, adapted, productive and viable vegetation cover. The objective of this preliminary study was to establish whether class F fly ash has the potential to be used as an ameliorant and/or buffer zone to counteract the acidity generated by such discard material. This acidity impacts on the covering soil used to reclaim the coal discards, by restricting plant growth on these covering soils, which subsequently results in a poor vegetation cover, a loss of soil stability, and an increase in erosion risk and finally contamination of water resources.

Results

Results obtained in this study have shown that class F fly ash has the ability to improve pH levels of acidic soils. It was, however, noted that the neutralizing potential and effectivity of class F fly ashes is most significant in highly acidic soils or substrates. It is also evident that class F fly ash tends to have a $CaCO_3$ equivalent much greater than 20%. It has been estimated, from all experimental work conducted in this study, that class F fly ash could have an approximate $CaCO_3$ equivalent of 33% or more.

The study on the influence of FA and SLASH ameliorants on the chemical properties of agricultural soil, at field scale, provided some significant results in terms of changes in soil pH. On the most acidic soil, a rise in mean soil pH of approximately 1½ - 2 pH units was recorded for most soil ameliorants containing FA. These evident changes in soil pH and the addition of micro- and macronutrients from the FA and SLASH ameliorants resulted in significant yield increases in two agronomic crops, *Zea mays* (maize) and *Triticum aestivum* (wheat), and a pasture legume, *Medicago sativa* (lucerne or alfalfa). Yield increases of up to 450 % for lucerne (alfalfa) on

SLASH ameliorated soils were noted. This study, therefore, concluded that the FA and SLASH soil ameliorants can improve soil chemical properties by improving the soil pH and providing additional micro- and macronutrients, thereby ensuring improved crop yields.

Although soil ameliorants are generally used to improve soil chemical conditions, it is also known that soil ameliorants can have other functions. This aspect is, however, often ignored, and it is assumed that soils that have poor chemical conditions also often have poor physical and microbiological properties. These properties all function together to ensure a healthy soil environment. It was decided that if FA and SLASH had such positive effects on soil chemical conditions, and subsequently plant production, it was essential to determine that they had no negative effects on other soil properties. As a result of outstanding yield increases, on both FA and SLASH ameliorated soils, other factors were investigated to establish a more holistic explanation for such positive yield responses. This component of the study indicated that FA and SLASH ameliorants had positive effects on soil physical properties such as soil texture and bulk density. These properties, however, can improve the soil-water balances by improving infiltration of water into the soil and retaining water in the root zone due to the improved water holding capacity resulting from lower hydraulic conductivity. Improved soil water balances, obtained by ameliorating the soils with FA and SLASH, provides another possible reason why plant production is enhanced, as a result of nutrients being in solution and more available for assimilation by plants.

Nutrient availability is not only determined by the amount of nutrients supplied through amelioration, but is also dependent on the microbiological activity, primarily responsible for organic matter breakdown, nutrient recycling through the mineralization of compounds normally unavailable for plant uptake. This aspect of soil health has been seriously neglected in the past. Without the help of microbial communities, no soil amelioration program will be sustainable. This study also indicated that improving soil pH from acidic to a more neutral pH, by applying FA or SLASH, a more suitable soil environment was created for the *Rhizobium* bacteria to establish a good symbiotic relationship with the host plant roots. This observation was noted by the proliferation of nodules on the leguminous plant roots, which are responsible for the efficient fixation of atmospheric nitrogen, resulting in higher quality legume pastures and more nitrogen in the ecosystem.

Similar trends for FA and SLASH amelioration of highly degraded soils and substrates in the mining environment, under greenhouse (controlled) conditions, as were evident in ameliorated agricultural soils, were noted. In comparison to the conventional method of dolomitic lime amelioration of relatively nutrient deficient soils and gold tailings, FA as well as SLASH (with the added benefit of organics) resulted in improved soil / substrate conditions, and enhanced dry matter production of *Cenchrus ciliaris* on the gold mine tailings by up to 700%. These significant plant growth responses can be ascribed to the improved pH and nutrient content of soils and tailings material. With respect to the gold tailings material, which can be described as rather inert, clearly benefited from the addition of organic material, via the sewage sludge component of the SLASH ameliorant. It is possible that not only did the chemical properties of the soils and tailings material change, but the physical and microbiological properties too, which was the case in agricultural soils. These aspects, however, need to be investigated further to substantiate such assumptions.

Following the positive results obtained in the greenhouse study, it was decided to determine whether these responses could be obtained on a field scale. This field study was conducted on a surface coal mine. The cover soil on this experimental site was the same as that used in the greenhouse study. This study compared three different levels of FA and SLASH to three levels of a conventional liming material, an untreated control and a standard mine treatment (SMT), which was the current practice of liming and fertilization, used by the mining company. This study continued for 72 months, and illustrated the long-term effect of soil ameliorants containing FA. Initially the SLASH treatments with the added benefit of an organic component did not perform as well as the FA treatments. With respect to the level of treatment, soil chemical changes were proportionate to the application levels. Regarding the effect of treatments on soil pH, it was noted that all treatments improved soil pH significantly, although in both SLASH and lime ameliorated soils the pH declined over the 72 months period. The SLASH treatments, however, did have a better pH than the lime treatments at the end of the experimental period. On the FA ameliorated soils a relatively stable soil pH was maintained, which highlights the residual alkalinity present in the FA material, due to continuous dissolution of the inherent glassy phase of fly ash particles.

With respect to the vegetation monitoring on these ameliorated soils, enhanced plant growth was evident on both FA and SLASH treatments. The SLASH treatments, however, despite the additional organic component and higher macronutrient content, did not perform as well as the FA treatments. These results were unexpected, due to good results obtained with SLASH in previous studies. These poorer results can possibly be ascribed to the high application rates of SLASH, which initially caused an observable inhibitory effect on seed germination. Forty-eight months after soil amelioration, the SLASH treatments were as good as FA treatments. For basal cover measurements, however, no significant differences occurred between levels of treatments, although, differences between different treatments were evident.

In the following phase of the study, the soils ameliorated with FA (a good micronutrient source) and SLASH (including macronutrient and organic matter source as well) were more fertile than the control (untreated), lime and the SMT. The botanical composition and production data led to the conclusion that a higher plant biodiversity and lower dry matter production occurred on the less fertile soils, whereas, a higher dry matter production and lower plant biodiversity was evident on the more fertile soils. Due to the positive plant growth responses to FA and SLASH ameliorated cover soils, the study was expanded to investigate an even more environmentally challenging opportunity; the amelioration of coal discards and their potentially acidifying cover soil. When vegetation growth is stimulated on cover soils, through improved soil properties, better root development occurs, providing a more stable surface, less susceptible to erosion. When the risk of erosion is reduced, the risk of losing cover soil and possible water pollution is also less. This preliminary study indicated that the treatment where a FA buffer zone (barrier) was placed between coal discard and the overlying cover soil provided the best plant production and most stable soil pH.

These promising results are possibly due to the prolonged neutralizing effect of the alkaline fly ash barrier on the acidity generated by the underlying coal discards. This aspect warrants, more in-depth investigations to understand the dynamics of fly ash and coal discard interactions.

Conclusion

The various objectives of this study were investigated to improve the understanding of the influence of class F fly ash on; chemical-, physical- and microbiological properties of soil and substrates, and how these effects may influence plant growth parameters, which are used as a measure of successful re-vegetation.

These objectives were achieved by incorporating class F fly ash and mixtures of FA and sewage sludge into effective root zones of various degraded soils, ranging from agricultural soils to mine soils to other mining substrates requiring rehabilitation. Fly ash and SLASH ameliorants were compared to treatments of standard practice, being no treatment, dolomitic lime treatment, and occasionally lime and minimal inorganic fertilizer treatments.

The hypotheses, that class F fly ash with a low CaO content, in semi – arid conditions, with or without organic materials, can be used to chemically and physically ameliorate acidic and nutrient depleted soils / substrates in agriculture, degraded mine soils (rehabilitated surface mines), tailings material and coal discards are therefore, true. Soil amelioration with FA improves the production of agronomic crops such as; Maize (*Zea mays)* and Wheat *(Triticum aestivum);* pasture legumes such as lucerne or alfalfa *(Medicago sativa)*and sub tropical grasses, such as Foxtail Buffalo grass (*Cenchrus ciliaris),* Rhodegrass (*Chloris gayana),* Smutsfinger grass *(Digitaria erianthra) etc*. Improved plant production through effective and long-term soil or substrate amelioration, is imperative to ensure a more sustainable re-vegetation programme.

In future it is essential that more detailed soil chemistry analyses be conducted to understand the chemical interactions and dynamics of fly ash applied to degraded soils and substrates. Another possible facet requiring investigation is that FA also contains high concentrations of silica, and that as FA is added to the soil, silica sheets may/will form and bind themselves to soil particles, encapsulating heavy metal ions, making them unavailable for plant uptake, while possibly displacing certain macronutrients on soil particles making them available for plant uptake. Various sources of class F fly ash also need to be evaluated and correlated with the class F fly ash used in these trials, to establish how different class F fly ash sources will react in different soils or substrates (Modelling). A greater range of plants also need to be evaluated on soils and substrates ameliorated with FA. Long term monitoring of such amelioration trials, needs to be continued. It is also important that more combinations of class F fly ash and other organic materials be investigated. Finally, it is critical that a detailed economic study, regarding the value of ameliorants containing class F fly ash, be conducted.

CHAPTER 1

Literature review on the *status quo* of degraded soils / substrates as a result of mining activities or intensive agronomic practices, and the alternative reclamation scenarios of such soils / substrates.

Wayne F. Truter and Norman F.G. Rethman

1. Introduction

Agricultural and industrial activities have greatly accelerated the pace of soil degradation. The mining industry plays a major role in the South African economy, and can often contribute to certain environmental challenges, with respect to soil degradation. Three of the most common factors that characterize degraded substrates are, soil acidification, nutrient depletion and loss of biological activity.

Many studies have been conducted to determine what measures can be taken to mitigate these problems, in agricultural lands. However, it has only recently been accepted world wide that there are other alkaline materials that are classified as industrial by-products, which can potentially serve the same purpose as the diminishing lime resources.

There exists an enormous amount of international literature regarding the use of class C fly ash, and to a lesser extent class F fly ash, as opposed to South African class F fly ash, which is predominantly produced in this country. This literature reflects the research outputs and findings of many scientists. It is, however, imperative to determine the local relevance and investigate the basic principles under South African conditions, with particular reference to the rehabilitation of degraded soils / substrates in the agricultural field and the mining environment.

With respect to the environmental problem of the concentration of organic wastes and the impact thereof on ground water pollution, this research has also provided an opportunity to investigate the nutrient and microbial contribution of organic materials such as sewage sludge, poultry and cattle manure, to soils degraded by intensive agronomic and mining activities.

The success of re- vegetation and sustainability of a once degraded soil / substrate is an indication, and a measure, of the amelioration success achieved. Seed germination, root development, plant yield, plant density and biological activity are parameters that can be used to support the conclusion that alternative substrate amendment practices can improve the plant growth medium.

2. Cause and effect of degraded soils / substrates

Many soils are impacted by activities such as intensive agronomic practices or surface mining activities. These soils, or newly created substrates / growth mediums, are often inhospitable to vegetation due to a combination of physical, chemical and microbiological factors. Areas disturbed by mining are highly susceptible to erosion due to a lack of vegetation, steep slopes and the presence of fine, dispersed particles (Limpitlaw *et al.* 1997).

South Africa is charaterized by a poor agricultural resource base, while the current population of 40 million continues to grow (Rethman *et al*., 1999b). Sustainable increases in food production are difficult on this limited resource base. The effective use of acidic soils is also critical in many areas. Therefore, increased food production is urgently required to improve both national and household food security (Truter and Rethman, 2000).

Acid soils occupy about 30 % of the worlds ice-free land area. In South Africa 15 % of the soils, or 16 million hectares (Beukes, 2000; Truter 2002), available for dry land cropping, are classified as dystrophic, and much of the yield instability in the higher potential, eastern parts of the South Africa is attributable to shallow root development as a result of soil acidity and consequent susceptibility to short duration midsummer droughts (Farina and Channon, 1988; Truter 2002).

In agriculture, the increasing use of nitrogenous fertiliser and the oxidation of organic residues under cultivation, combined with incorrect management practices, are important contributors to acidification of soils. The burning of fossil fuels and industrial pollution ("acid rain") have also contributed substantially to the acidification of many natural and agricultural ecosystems (Wang *et al*., 2000; Truter 2002).

Soil acidity affects plant development by influencing the availability of certain elements required for growth (Tisdale and Nelson, 1975; Truter, 2002). Soil acidity is, therefore, of the greatest importance to plant producers and one that is easily corrected if dealt with immediately after detection. (Truter, 2002*).*

Soil acidification and, indirectly, nutrient depletion are ongoing natural processes. In natural ecosystems the rate of acidification is largely determined by the loss of base minerals (Ca, Mg, K) from the soil by leaching. The central problem of acid soil management lies in the constraints, which arise from the soil condition. The most serious of these is that at low pH's; acids (H^+) can release soluble aluminium (Al) and manganese (Mn) from soil minerals. Both Al and Mn have direct toxic effects on many plants (Beukes, 2000; Truter 2002). Aluminium concentrations can be sufficiently high in acid soils, with pH values of 5.5 or below, to be toxic to plants (Ahlrichs *et al*, 1990; Truter 2002). Aluminium acts by restricting root extension growth, resulting in poor plant production and eventually a decline in food production.

Soil acidification is thus a serious socio-economic concern. Very few countries can afford a decline in food production, which often accompanies the changes, that are taking place in our soils.

Acidic conditions in the mining environment limit mined land re-vegetation through: **(i)** plant toxicity by elements that become more available to plants at a low pH, **(ii)** restriction of root growth into acidic spoil or cover material, **(iii)** reduction in the number of free living and symbiotic N fixing organisms, and **(iv)** increased populations of microorganisms that oxidize Fe and S (Alexander, 1964; Arminger *et al*., 1976; Barnhisel, 1977; Taylor and Schuman, 1988; Truter, 2002).

Nutrient management practices affect the viability of agricultural ecosystems. Nutrient management strategies based on the return of nutrients from plant and animal wastes back to the soil will require radical changes to both agriculture and society. External sources of plant nutrients will, therefore, continue to be an essential part of agriculture as we strive to replace the nutrients lost in successive crop harvests. Landowners must, nevertheless, be made aware of the need to increase the cycling of nutrients within agricultural ecosystems. Ways must be found to return plant residues to the soil. To help manage nutrient flows, it may be necessary to develop nutrient balances based on soil and plant analyses (Truter, 2002).

Crops need sixteen essential plant nutrients for growth and reproduction, thirteen of which are generally provided by the soil in sufficient quantities. These nutrients include three major (N,P,K), three secondary (Ca, Mg, S), and seven micronutrients (B, Cl, Cu, Fe, Mn, Mo, Zn). Quantities of N-P-K are usually applied in the greatest amounts to supplement the nutrients available from the soil to meet the needs of crops (Jacobs *et al.,* 1991).

The implications of chemical fertilization – inefficiency, deterioration in product quality, diminishing productivity of soils and negative effects on the environment- have created an urgent need for the study of fertility as a result of the activity of the bio-cycles of the ecosystems. With the aid of the advances of modern science, we can understand the defects and deficiencies of the chemical concept of fertility.

A few common management practices, such as application of acid forming N fertilizers, increased leaching and run-off of cations, N fixation by legumes and cation removal by harvesting crops, all contribute to soil acidification. Application of N fertilizers are essential for good crop yields, particularly on acid soils where the organic matter is low. Nitrogen fertilizers in the NH_4^+ form have long been recognized as increasing soil acidity (Tisdale and Nelson, 1975; Truter, 2002) due to the release of H^+ with plant absorption of NH_4^+ and with nitrification of NH_4^+ (He *et al*, 1999; Truter 2002). Acid (H^+) inputs into agricultural ecosystems revolve largely around the use of N fertilizers. The guidelines classifying the acidification potential of different N fertilizers are well established. The scope for managing acid conditions in agricultural ecosystems, therefore, largely revolves around the input of ammonium (NH_4^+) and the output of nitrate (NO_3^-) ions in biological cycles. The central principle in reducing acid input (N cycle) involves matching the N supply to plant demand and reducing leaching losses of NO_3^- from the system to near zero (Beukes, 2000; Truter 2002).

It is well known that when ammonium is changed to nitrate as a result of the nitrification process, hydrogen ions are released and this contributes to acidification. It has also been noted that ammonium sulphate and ammonium phosphate are theoretically twice as acidifying as limestone ammonium nitrate (du Plessis, 1986; Truter 2002).

Chemical instability of clay minerals is a result of the saturation of H^+, which with time can lead to high lime requirements due to the wide range of Al forms that accumulate between clay layers (Jackson, 1960; Fouchè, 1979; Truter 2002). It is for this reason that, the higher the concentration of clay in the soil, the more acid cations (Al^{+3}, H^{+}.... etc.) can be adsorbed.

Plant sensitivities to Al can nevertheless be expressed secondarily through changes in water and nutrient supply, which occur in response to Al, and induced changes in root development. Acid soils are generally unable to supply critical plant nutrients (Ca, Mg, P, K, and Mo). The fundamental reaction underlying soil acidification involves the replacement of exchangeable base cations (Ca, Mg, and K) present in the soil solution by protons (H^{+}), as already mentioned.

The implication for yield reduction during periods of moisture stress, when subsoil reserves remain largely inaccessible to crops because of poor root penetration is obvious. Acid soils usually lack appropriate levels of N to support healthy plant growth and the application of N fertilizer is a common practice for sustainable crop production in acid soil regions (He *et al*, 1999; Truter 2002). In various plant species, Al can interfere with the uptake and efficient use of essential nutrients (Baligar *et al*., 1987, 1989, 1993a, b. 1996; Baligar and Bennet, 1986; Foy, 1992; Baligar and Fageria 1997; Truter 2002).

With respect to physical properties of soil, this is basically the result of soil texture, quantity and quality of salts in the soil, cultivation, and climatic and vegetative influences. Soils having good initial physical characteristics, either with large or small amounts of organic matter initially, has been known to sustain good crop production for several decades without benefit of added organic matter (Azevedo and Stout, 1974).

Due to the use of large agricultural machinery, for the cultivation of soils, excessive soil compaction has also often resulted. Not only is this problem visible in the agricultural industry but also it is very prominent in the surface coal mining industry. The use of heavy equipment in the transportation and reconstruction of severely disturbed soil profiles can contribute to severe and persistent soil compaction (Wells and Barnhisel, 1992).

The effects of soil compaction on physical properties include reduced water infiltration, increased bulk density, and reduced water holding capacity and increased runoff (Sopper, 1993). When the porosity of soil is such that aeration is restricted or when the soil is so dense, and its pores so small, that root penetration, drainage, infiltration and hydraulic conductivity is impeded, the soil is compacted (Limpitlaw *et al.* 1997).

Soil consists of mineral particles of various sizes and chemical components, together with plant roots, the living soil population, and an organic matter component in various stages of decomposition (Oades, 1993; Paul and Clark, 1996). Soil aggregation is of prime importance in controlling microbial activity and soil organic matter turnover. Aggregate formation is initiated when micro-flora and roots produce fibrils, filaments, and polysaccharides that combine with clays to form organomineral complexes. Soil structure is created when physical forces (drying, shrink-swell, freeze-thaw, root growth, animal movement, compaction) mould the soil into aggregates. Clays are basic to aggregate formation. Micro-organisms and most soil organic matter constituents are negatively charged at neutral pH values (Paul and Clark, 1996). Particles involved in aggregate formation include fine clays and organic molecules measurable in nanometres; micro-organisms, coarse clays, and silt measurable in micrometers; and sands, small metazoans, and small rootlets measurable in millimetres.

Aggregates vary greatly in size. Pore size distribution in certain micro-aggregates and macro-aggregates differ in different textured soils. Pore sizes determine the entry into and occupancy of pores by micro-organisms. Chemical analysis of the soil organic matter in micro-aggregates shows that the contained sugars are mostly of microbial origin. Aggregates show greater content of nutrients (C, N, S, P) than found in the soil generally. Soil particles, differing in size also differ in nutrient content. Soil aggregates and their constituent clays influence the interaction of enzymes with their substrates (Tiessen *et al.,* 1984; Hassink *et al*., 1993; Paul and Clark, 1996).

Many of the soils of the world are affected by excess acidity, a problem exacerbated by heavy fertilization with certain nutrients, acid rain, and soil dwelling S-oxidizing bacteria. Biological nitrogen fixation is sometimes said to increase soil acidity. It does not do so directly but only after the fixed N is transformed by ammonification and nitrification. Measurements of soil pH are important criteria for predicting the capability of soils to support microbial reactions. Most of the known bacterial species grow within a pH range of 4 to 9, or within smaller segments of that range (McLaren and Skujins, 1968; Paul and Clark, 1996).

The presence of organic matter has an additive effect as it reduces the concentration of toxic metals through sorption, lowers the C: N ratio and provides organic compounds, which promote microbial proliferation and diversity (Wong and Wong, 1986; Pitchel and Hayes, 1990).

3. Soil amelioration

Liming of acidic soils is an ancient agricultural practice to ameliorate soil. Limestone (calcite, dolomite or a combination) is basically the main liming material used to date, with the infrequent use of quicklime, hydrated lime and by-products such as slag and gypsum (for sub-soil amelioration). Current levels of pollution mean that more lime is now required to offset acidification, but extensification is likely to result in a cessation or reduction of liming for economic reasons, while afforestation may result in increased acid deposition and acidification (Goulding and Blake, 1998; Truter, 2002).

Although liming is usually an effective counter to soil acidification, liming acid soils does not always make economic sense. Many low–input agricultural systems (e.g. subsistence farming practices and extensive grazing lands) cannot use large amounts of lime and remain economically viable (Truter, 2002). Nevertheless, lime is an effective method of neutralizing acidity, but it still remains a natural non-renewable resource, which is becoming depleted.

Soil quality can be improved, or degraded, by management. Since the 1950's mainstream agriculture has attempted to optimize soil fertility through the application of commercial fertilizers. The access of farmers to in- expensive fertilizers permitted short-term amelioration of nutrient-deficient soils. However, increasing the soil nutrient supply capacity may better be accomplished by improving the soil's biological activity, not adding more nutrients (King, 1990, Brosius *et al.* 1998). The long-term use of commercial fertilizers may also reduce soil organic matter and biological activity (Fauci and Dick, 1994, Brosius *et al.* 1998).

The land application of by-products from agricultural, industrial or municipal sources is certainly not a new phenomenon. Wood ashes, manures, crop residues and coal combustion by-products, etc. are being applied to the land and, dependent upon site specifics, often show beneficial responses in subsequent cropping cycles. These positive responses led to agricultural practices, which were continued over time. However, recent interest in concepts such as sustainability, biodynamic farming, and natural resource conservation has stimulated the practice of applying by-products to land (Korcak, 1998).

With respect to the function of lime and inorganic fertilizer used in conventional agronomic practices and rehabilitation processes, alternatives to these materials need to be identified in order to address the problem of non-sustainability and improved soil physical, chemical and microbiological quality.

Coal combustion by-products not only supply plant nutrients and increase soil pH but also decrease Al toxicity, enhance root penetration, improve soil structure, reduce bulk density of soil, improve water holding capacity, and act as a barrier to weeds (Chang *et al.*, 1989, Stratton and Riechcigl, 1998).

The coal combustion by-product, fly ash (a very fine, relatively inert, dry powder consisting mostly of Fe, Al, Ca, Si and O) provides a means of reducing the water content of wet mixtures, and can also provide B and other micro–nutrients. Fly ash is currently being used to improve the texture and water holding capacity of potting mixtures and artificial soils. Class C Fly ash (produced from burning coal from Western US) can have a calcium carbonate equivalency of up to 50% and may serve as a substitute for agricultural lime (Ritchey *et al.*, 1998), whereas, in South Africa only Class F fly ash is produced, with a much lower calcium carbonate equivalency. Very little work has been conducted on the use of fly ash to ameliorate degraded (acidic and nutrient poor) substrates in South Africa.

Class C fly ash usually has higher Ca concentrations than Class F fly ash. Fly ash consists of Al, Fe, Si, and O, with variable amounts of Ca and Mg, chemically bound into a glassy material. Small amounts of many plant nutrients and trace elements, such as B, Se, Cd, Mo, and As, are also present (Terman, 1978, Ritchey *et al.*, 1998). The material has been effective in improving the texture of many mixtures. Increased air-filled porosity, decreased bulk density, and improved moisture retention capacity were attributed to fly ash incorporation in West Virginia, United States (Bhumbla *et al.* 1993).

The results indicate that the combined use of fly ash and sewage sludge at a rational rate of application should not have any significant effect on drainage or water quality. Plant studies conducted using fly ash and sewage sludge mixtures indicated that these materials could also be beneficial for biomass production, without contributing to significant metal uptake or leaching. Applications of fly ash, as high as 560 tons ha^{-1} in a long-term field trial, had no detectable effect on in soil or groundwater quality and no substantial increases in plant uptake of metals and other trace elements were observed. Low to moderate rates of fly ash and sewage sludge could, therefore, be successfully used as soil amendments, particularly so when used as a mixture (Truter 2002; Sajwan *et al*. 2003).

Coal residues, especially fly ash, applied to agricultural land do not, however, supply crop requirements for essential plant nutrients such as N and P. Alkaline fly ash would also be effective in neutralizing soil acidity. Variable amounts of certain trace elements in fly ash may, however, limit its potential use for land application (Adriano *et al*., 1980).

Research to date has shown that there are many materials, such as coal combustion by-products, or various organic materials, that can be applied to soils to relieve soil physical problems such as compaction. Fly ash amended soils tend to have a lower bulk density, higher water holding capacity, lower hydraulic conductivity, increased organic carbon content and increased soil strength (Chang *et al*., 1977; Aitken and Bell, 1985; Eisenberg *et al*., 1986; Garg *et al*., 1996; Kalra *et al*., 1998).

Work done in India has proved that the addition of fly ash, at the time of maize planting, reduced bulk density and increased moisture retention and release characteristics in a sandy-loam soil in New Delhi, and that differences persisted even during the subsequent growth of a wheat crop (Garg *et al*., 1996). The favourable soil physical environment, induced by using fly ash, resulted in a greater root growth, which ensured enhanced water use by the crop and higher grain yields for maize as well as wheat. Therefore, fly ash incorporation in texturally variant soils modifies the soil physical and physico-chemical environment, which in turn may influence the crop yields (Kalra *et al*., 2000).

Jala and Goyal (2004) reported that the saturation moisture percentages of ash were higher than those of soil, but that the bulk density was lower than normal cultivated soils. The addition of fly ash, at 70 tons ha^{-1}, was reported to alter the texture of sandy and clay soils to loamy soils (Fail and Wochok, 1977; Capp, 1978; Jala and Goyal, 2004). The addition of fly ash generally decreased the bulk density of soils, which in turn improved soil porosity and workability and enhanced water retention capacity (Page *et al*., 1979). The water holding capacity of sandy/loamy soils was increased by 8% by fly ash amendment (Chang *et al*., 1977) and was accompanied by an increase in hydraulic conductivity, which helped to reduce surface encrustation.

Little data is available on the impact of fly ash on the soil microbial populations. Soil micro organisms, however, drive biogeochemical cycles of elements and are responsible for humus formation and for important degrading reactions. Microbes, therefore, play an important role in maintaining soil fertility and biochemical functionality (Vallini *et al*., 1999).

The addition of Class F, bituminous fly ash to soil, at a rate of 505 tons ha^{-1}, did not have any negative effects on the soil microbial communities. Analysis of community fatty acids indicated elevated populations of fungi, and gram-negative bacteria (Schutter and Fuhrmann, 2001; Jala and Goyal, 2004). Fly ash- sludge mixtures containing 10 % ash had a positive effect on soil micro- organisms in terms of enzyme activity, N and P cycling and reduction in the availability of heavy metals (Lai *et al*., 1999; Jala and Goyal, 2004).

Fly ash composted with wheat straw and 2% rock phosphate (w/w) for 90 days was reported to have enhanced chemical and microbiological properties of the compost and fly ash up to 40-60%, and did not exert any detrimental effect on either C: N ratio or microbial population (Gaind and Gaur, 2003; Gaind and Gaur, 2004; Jala and Goyal, 2004). It has also been found that microbial activity was increased in ash-amended soils containing sewage sludge (Pitchel, 1990; Pitchel and Hayes, 1990, Jala and Goyal, 2004). When organic matter is present in the soil it has a positive effect in the sense that it reduces the concentration of toxic metals, lowers the C: N ratio and provides organic compounds, which promote microbial proliferation and diversity (Wong and Wong, 1986; Pitchel and Hayes, 1990; Jala and Goyal, 1990). Available data indicates that microbial incidence and diversity generally increases as ash weathers and nutrients accumulate (Rippon and Wood, 1975; Jala and Goyal, 2004).

For the purposes of this study the organic materials to be discussed were sewage sludge and animal manures. Many materials termed wastes are rich sources of nutrients and organic material for use in crop production, improvement in soil physical or chemical properties, or as feed for livestock production. Agricultural, municipal, or industrial by-products may be co-utilized, or combined, so that the materials are more easily land applied, provide more complete nutrition, or enhance the soil conditioning, economic, or environmental value of the individual by-products. (Stratton and Rechcigl, 1998).

The addition of organic matter, in general, improves soil chemical and physical characteristics. A large portion of the plant nutrients ingested by livestock is excreted and are returned to the soil for another season of crops. Poultry manure is considered the richest of the manures in supplying N. So much of this N is in the ammonium form, however, that care must be taken in its use on crops. Manures are rich in P and may even contribute to over-enrichment of soil P.

The term sewage sludge has been applied to the solid human waste collected from wastewater, treated at central processing plants, and which remains as a residue after the liquid effluent is removed. The term biosolids is also used. With careful application, biosolids can be a good source of nutrients for agronomic use. Since the "503 Regulations" some biosolids are detoxified by removal of heavy metals either at the source, or by special processing known as auto-thermal aerobic digestion or liquid composting (Jewell, 1994, Stratton and Rechcigl,1998)

The National Research Council report provides considerable reassurance that properly treated and managed municipal wastewater effluents and biosolids can be safely and effectively used in food crop production, while presenting negligible risk to crop quality or consumers. Public acceptance and implementation issues, rather than scientific information or the health and safety risks from food consumption, may, however, be the critical factors in determining whether reclaimed wastewater effluents and biosolids are used in food crop production. (Bastian, 1998).

Plant and animal-based wastes may substitute for commercial fertilizers and enhance chemical and biological attributes of soil quality in agricultural production systems. Organic matter increases the soil's abilities to hold and make available essential plant nutrients and to resist the natural tendency of soil to become acid (Cole *et al.,* 1987; Brosius *et al.,* 1998). Build up of organic matter through the additions of crop and animal residues have been shown to increase the population and species diversity of micro-organisms and their associated enzymatic activity and respiration rates (Kirchner *et al.,* 1993; Weil *et al., 1993;* Brosius *et al.* 1998). Materechera and Mkhabela (2002) found that although leaf litter and chicken manure can be effective in ameliorating acidity, they were not as efficient as lime. Both amendments had a significant effect on the pH of an acid soil and markedly reduced acid saturation as compared to the control.

Sewage sludge has been utilized for agriculture and horticulture for many years and in addition to being a good source of nutrients for plant growth a soil conditioner to improve soil physical properties (Jacob, 1981; Matthews, 1984; Logan & Harrison, 1995). However, sludge can also contain a range of toxic metals and high amounts of soluble salts, which may become a problem (Chaney, 1983; Elseewi and Page, 1984). Coal fly-ash, however, is rich in CaO and MgO, which results in a high pH and makes coal fly ash a potential liming material to stabilize sewage sludge by reducing heavy-metal availability and killing pathogens in the sludge (Logan & Harrison, 1995; Wong, 1995, Rethman *et al*., 1999a,b, 2000a,b; Reynolds *et al.,* 1999, 2002; Reynolds and Kruger, 2000, Truter 2002). The coal fly ash and sewage sludge mixture can, therefore, be used as a soil conditioner to improve soil physical and nutrient properties. However, applying the ash / sludge mixture to soil may initiate the decomposition of the organic matter in the sewage sludge causing the release of NH_4^+, NO_3^-, PO_{3-}^{-}, B and possibly some trace elements. Another concern is the leaching of NO_3 from the ash-sludge mixture, leading to the contamination of groundwater. Also, the released trace elements may be toxic to plants and represent a potential hazard to animals consuming plants grown in the ash-sludge mixture (Chaney, 1983; Wong and Su, 1997). It has been shown that alkaline fly ash did not cause phytotoxic effects to plants or depress activity of microbial populations in either sandy or clayey soil. In particular, vegetable biomass production was increased in soil that was amended with fly ash composted with lignocellulose waste (Vallini *et al*., 1999).

Efforts are in progress throughout the world to find economic uses of fly ash to solve the above-mentioned environmental problems. Many research workers (Mulford and Martens, 1971; Page *et al.,* 1979; Hill & Lamp, 1980; Elseewi *et al.,* 1980; Truter 2002) have demonstrated the use of fly-ash for increasing crop yields of alfalfa, barley, white clover, Swiss chard, maize, wheat, cereal grain crops and certain sub-tropical grasses and improving the physical, chemical and microbiological characteristics of the soils.

4. Ameliorated soils: Effect on aspects of plant production

With intensive cropping, the continuous use of high levels of chemical fertilizers often leads to nutritional imbalances in the soil and a consequent decline in crop productivity (Nambiar, 1994; Rautaray *et al*., 2003). The alternative soil amendments available today, show tremendous potential as sources of macro- and micronutrients with added benefits to soil physical and microbiological properties. Research has demonstrated that fly-ash amendments improved initial seedling emergence and root development relative to untreated controls (Truter 2002). Seed germination and root length had significant negative correlations with soil EC, NH_4^+, Cu and Zn ($P<0.05$) at day 7 and day 14 of an incubation period of an experimental trial conducted by Wong and Su (1997), indicating that these were the major factors reducing seed germination and root growth, especially in the initial period following the application of an ash-sludge mixture. The rapid decomposition of sewage sludge during the initial phase also contributed to the low seed germination and poor root growth in sludge-amended soil. The results show a potential use of the "artificial soil mix", derived from coal fly ash and sewage sludge, to improve soil conditions for plant growth. (Wong and Su, 1997; Truter 2002)

Germination and crop stand establishment are prime plant-growth processes, which play a major role in deciding subsequent growth and yield, and so need to be evaluated under varying levels of ash incorporation within the soil. Kalra *et al* (1997) evaluated the effect of ash incorporation on germination of several crops, to determine the optimum level of ash application and relate germination effects with changes in soil characteristics caused by mixing ash with the soil. The incorporation of fly ash in soil may delay the germination of crops, most likely because of increased impedance offered by the soil/ash matrix to germinating seeds. This causes reduced growth of crops in the earlier stages, which subsequently may lead to reduced yields under unfavorable environments. Differential responses of crops to ash mixing in soil were noted: rice and maize were less sensitive than temperate crops; mustard was most affected by ash addition for germination and stand establishment. The delay index showed variations for crops as well as for ash levels within a crop. The effects of fly ash on germination need to be linked with subsequent plant-growth activities to understand the differences in final growth and yield. (Kalra *et al*., 1997).

There is a need to evaluate the impact of coal ash on both the environment and agriculture. In the past, various research studies evaluated the impact of fly ash on soil and crop productivity, but most of them were confined to laboratories or research stations (Singh and Singh, 1986; Mishra and Shukla, 1986; Garg *et al.,* 1996; Sikka and Kansal, 1995; Singh *et al*., 1996; Kalra *et al.,* 1997).

Applications of fly ash had a profound effect on the dry matter yield of rice in all the soils tested although the magnitude of the response to fly ash varied with the soil type. The variation in response to fly ash addition to the different soils could have been caused by the inherent differences in their physical and chemical characteristics, which are shown in the yield variations in the control treatments (Sikka and Kansal, 1995). Beneficial effects of fly ash on plant growth at a rate of 10% were achieved by Singh *et al* (1997). However, the recommendation for large-scale application of fly ash to the agricultural soils in a region cannot be made, until extensive trials have been conducted to determine the proper combination of fly ash with each type of soil and for each crop to be grown in the region (Singh *et al*., 1997; Truter 2002).

With respect to biosolid amelioration, it has been noted that rangeland restoration using surface applications of biosolids (municipal sewage sludge) is becoming an increasingly common practice. In a study conducted by White *et al*, (1997), nitrogen mineralization potentials were significantly higher ($P< 0.05$), in the 45 and 90 tons ha^{-1} applications, after nine years, indicating that site fertility remained higher even though most soil chemical properties were returning to untreated levels (White *et al*, 1997).

Long-term benefits to rangelands are the desired result of biosolid application, in addition to the direct benefit realized from its disposal. The benefit is expected to occur through increased primary production resulting in more above- and below – ground litter, which in combination with soil microbial production contributes to soil organic matter (OM) through the process of decomposition. The increase in N mineralization with increasing rates of biosolid application (significant for the 45 and 90 tons ha^{-1} applications), nine years after application, is a very good indicator that long-term benefits, in terms of site productivity, may be realized from surface-applied biosolids. Although biosolids are recognized for increasing N availability after addition to soils (Garau *et al*., 1986; Wiseman and Zibilske, 1998), these results indicate that the frequently measured short-term increase in N availability and productivity may indeed extend for much longer periods, which is the desired result. There may be no long-term benefit from applications in excess of about 45 tons ha^{-1}. This rate would be recommended because it reduces the contribution of metals compared to higher application rates yet maximizes the long-term nutrient benefit (White *et al*., 1997).

The nearly universal short-term response to N applications to rangelands is an increase in site productivity, regardless of whether the N is in the form of inorganic fertilizers or biosolids (Fresquez *et al*., 1990a,b, 1991; Aguilar *et al*., 1994; Loftin and Aguilar, 1994; Wester *et al*., 1996). However, a short-term response may not necessarily lead to long-term benefits. Soils often respond to N additions with further increases in mineralization of indigenous soil-N, a response known as the “priming effect” (Woods *et al*., 1987; White *et al*., 1997), which is seen as a short term increase in productivity. The addition of N stimulates decomposition of indigenous soil OM (Organic matter), as shown by an increase in CO_2 liberation from fertilized soils. This results in a short-term decrease in soil OM and a short-lived pulse of productivity. If repeated frequently, fertilizer-N applications deplete soil OM, resulting in long-term declines in potential site productivity (DeLuca and Keeney, 1993; White *et al*., 1997).

Plant growth may also be stimulated following the application of biosolids to semiarid calcareous soils due to the increased availability of essential micronutrients (O’Connor *et al*, 1980; White *et al*, 1997). If, however, biosolids were readily incorporated into the soil through the movement of fine biosolid particulates, and/or stimulation of plant growth, it could provide the nutrient resources necessary for long-term recovery of degraded grasslands (White *et al*., 1997).

The rationale behind co-utilized or combined agricultural, industrial or municipal by-products is that the mixture itself is a superior soil amendment than either component alone. The use of an organic material addresses the deficiency of macronutrients in coal combustion by-products, such as class F fly ash, while fly ash can act as a bulking agent for the organic materials, and these products can substantially improve chemical, physical and microbiological properties of degraded soils or substrates (Truter 2002).

5. Conclusion

Agricultural, municipal and industrial by-products are materials, which are rich sources of nutrients or organic material, and can be beneficially, utilized for crop production, to improve the physical, chemical or microbiological properties of soils or inert substrates. These materials can be co-utilized, or combined, so that the materials are more easily applied to land, or to provide a more complete/balanced nutrition, or enhance soil conditioning, economic, or environmental value of these individual by-products.

Returning nutrients and organic matter to soil, or substrates, via industrial-, municipal-, domestic by-products, animal manures or other organic materials complete the natural cycle on which all life depends. The value of these materials in supplying nutrients for crops has been noted since the beginnings of agriculture when, for example, manured crops grew visibly better than those without. In recent years, numerous studies conducted in various parts of the world have examined the nutrient supplying power of alternative soil amendments. Apart from the traditional values placed on animal manures for example as fertilizers supplying N-P-K, supplementary traits that encourage plant growth have often been attributed to manures. These accessory benefits have been ascribed to plant nutrients such as Ca, Mg, or micronutrients, or to physical changes in soil structure. Difficulties in separating individual physical and chemical effects, contributed to soils by alternative soil amendments, usually results in less than satisfactory identification of growth promoting factors, either quantitatively or qualitatively. Chemical fertilizers have mostly replaced the fertility demand formerly supplied by animal manures and organic materials, but the extensive use of chemicals and mechanization has led to the degradation of soils, and recently, the value of industrial, municipal, domestic by-products, animal manures and organic materials as soil conditioners are increasing, thereby contributing to more holistic and sustainable ameliorating solutions.

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CHAPTER 2

Prepared according to the guidelines of Bioresource Technology

The utilization of class F fly ash, and co-utilization thereof with sewage sludge, to ameliorate degraded agricultural soils and to improve plant production

Wayne F. Truter [1], Norman F.G. Rethman [1], Richard A. Kruger [2] and Kelley A. Reynolds [3]

[1] *Department of Plant Production and Soil Science, University of Pretoria, Pretoria, 0002, South Africa*

[2] *Richonne Consulting, 141 Rockwood Cr, Woodlands, Pretoria, South Africa*

[3] *Eskom CR & D, Private Bag 40175, Cleveland, 2022, South Africa*

Abstract

Prime agricultural land is a limited resource in South Africa. It is, therefore, necessary to reclaim poor and disturbed soils to feed the burgeoning population. Using conventional methods is costly and not necessarily sustainable. The challenge is, therefore, to use potential alternative ameliorants in an economically, ecologically and socially sustainable manner. Previous research has shown that by mixing sewage sludge with class F fly ash and a suitable source of quicklime, the sewage sludge can be pasteurized. The **SL**udge**ASH** (SLASH) mixture has been extensively evaluated as a soil ameliorant and has proven to be viable for the reclamation of poor and marginal soils. Many pot and raised bed studies, focusing on the effect of SLASH on plant production of various plant species, have been conducted and reported on previously.

This paper reports on subsequent research conducted to determine the effect of both fly ash and SLASH on the production of maize *(Zea mays)*, wheat *(Triticum aestivum)* and lucerne (alfalfa) (*Medicago sativa*) in field applications. The effect of treatments on soil chemical properties was also monitored in this study. SLASH and fly ash treatments were compared with agricultural lime and an untreated control. The results obtained illustrate improvements in crop yields. Wheat yields on SLASH and fly ash treatments were 270% and 150% better than the control respectively, while yields of maize and alfalfa were improved by 130 % and 450% respectively. Soil chemical properties were also improved by the SLASH and fly ash treatments. The results presented are encouraging and justify further research on the use of fly ash and it's co-utilization with other by-products to restore productivity to poor agricultural lands in South Africa.

Keywords: class F fly ash, sewage sludge, soil ameliorant, plant production

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1. Introduction

South Africa is a country with very little prime farmland. A large percentage of this high agricultural capability land is generally acidic, but is situated in areas where large quantities of fly ash are available. To ensure healthy and productive vegetation, disturbed soils need to be ameliorated effectively. To date, conventional methods of liming and fertilization to improve productivity of impacted soils have been standard practices. This process can, however, be very expensive and is often not sustainable.

South Africa has plenty of waste products, which might be used as alternative ameliorants. Fly ash is characterized as a good source of certain micronutrients beneficial to plant growth in addition to it's liming qualities and other unique properties. This resource, together with other wastes such as sewage sludge or animal wastes (which are good sources of organic material and macronutrients essential for plant growth), can serve as a soil ameliorant in crop production systems (Norton *et al*., 1998; Truter, 2002). In future, conventional landfill and lagoon disposal of rapidly accumulating coal combustion byproducts, (especially fly ash), and organic biosolid wastes (such as sewage sludge and animal manures) is unlikely to comply with increasingly stringent environmental regulations (Sopper, 1992; Walker, *et al*., 1997).

The mixing of organic waste products such as sewage sludge or poultry litter with fly ash has been proposed to increase the macronutrient content of the resultant mixture while reducing odour and improving handling properties of the organic waste (Garau *et al*., 1991; Vincini *et al*., 1994; Schumann, 1997; Jackson and Miller, 2000). Field trials utilizing fly ash/ organic waste mixtures as fertilizers for maize (*Zea mays* L.) produced comparable yields to conventional fertilization techniques (Schuman, 1997). Soil acidity affects plant development by influencing the availability of certain elements required for growth (Tisdale and Nelson, 1975; Truter, 2002). Soil acidity is, therefore, of the greatest importance to plant producers and one that is easily corrected if dealt with immediately after detection. (Truter, 2002).

Soil acidification and, indirectly, nutrient depletion are ongoing natural processes. In natural ecosystems the rate of acidification is largely determined by the loss of base minerals (Ca, Mg, K) from the soil by leaching. The central problem of acid soil management lies in the constraints, which arise from the soil condition. The most serious of these is that at low pH's; acids (H^+) can release soluble aluminium (Al) and manganese (Mn) from soil minerals. Both Al and Mn have direct toxic effects on many plants (Beukes, 2000; Truter 2002). Al concentrations can be sufficiently high in acid soils, with pH values of 5.5 or below, to be toxic to plants (Ahlrichs *et al*, 1990; Truter 2002). Aluminium acts by restricting root extension growth, resulting in poor plant production and eventually a decline in food production. Soil acidification is thus a serious socio-economic concern. Very few countries can afford a decline in food production, which often accompanies the changes, which are taking place in our soils.

Previous work to determine the feasibility of converting waste disposal problems into a soil beneficiation strategy has proven true (Reynolds *et al*., 1999). The co-utilization of fly ash and sewage sludge with added lime in a ratio of 6:3:1 on a wet basis, has delivered the product termed SLASH. The aim of this study is to evaluate the effects of alternative ameliorants such as SLASH and class F fly ash on the chemical properties of nutrient poor and acidic soils and on the plant production.

2. Methods

A field study with randomized plots (nett plot: 3.75m x 8.65m = 32.44m^2) was conducted at the Hatfield Experimental Farm of the University of Pretoria, South Africa. Situated at 25°45'S 28°16'E, this site is 1327m above sea level. A uniform sandy loam soil was ameliorated with different levels of sewage sludge, fly ash and reactive lime (CaO) and in combination (SLASH), to determine how such treatments would influence the production of wheat (*Triticum aestivum)*, maize (*Zea mays*) and lucerne /alfalfa (*Medicago sativa)* over a 24-month period on soils of different levels of acidity. This field study was also to evaluate the practicality of using these ameliorants on a large scale in agricultural practice.

An agricultural land that had been acidified to three levels of basal soil acidity **[P1]** $pH_{(H2O)}$ = 4.5, **[P2]** $pH_{(H2O)}$ = 5.0 and **[P3]** $pH_{(H2O)}$ = 5.5 in the past, were treated with 2 levels of SLASH (**[S1]** 32 tons ha^{-1} and **[S2]** 64 tons ha^{-1}) and 2 levels of fly ash (**[FA1]** 9.5 tons ha^{-1} and **[FA2]** 19 tons ha^{-1}). These were compared to a dolomitic lime treatment **[L]** (4 tons ha^{-1}) and a control **[C]** (no treatment).

Figure 1: Class F Fly ash, SLASH and lime treated field trial at the Hatfield Experimental Farm, University of Pretoria.

Application rates were based on the buffering capacity of the soil. These treatments were replicated three times (R1-R3) and were only applied at the beginning of the trial, to determine their long-term residual effect with respect to sustainability. Two seasons of wheat production, one season of maize and three seasons of alfalfa were recorded. Grain yield and dry matter production (Five replicate samples R1-R5) of both wheat and maize were measured and multiple harvests of lucerne (alfalfa) were recorded during the trial period. Soil $pH_{(H2O)}$, P (Bray 1, 1:7.5 extraction) and K, Ca, Mg, (1:10 ammonium acetate extraction method) were also measured after each growing season to determine the plant available elements.

2.1 Statistical analyses

All grain yield, dry matter production data and soil analyses were statistically analysed using PROC GLM (1996/1997 and 1997/1998). Statistical analyses were performed using SAS (SAS, 1998) software. LSD's were taken at $P \leq 0.05$.

3. Results and discussion

3.1 Biomass production

3.1.1 Wheat

From the results presented in Tables 1 to 3, it is clear that a better grain yield can be achieved on soils treated with SLASH and fly ash, as opposed to the lime and control treatments. Wheat grain yields on average increased by 575% and 335% relative to the control.

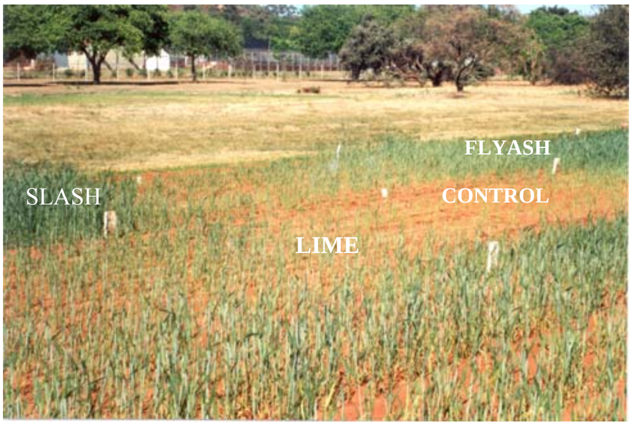

Figure 2: Wheat production as influenced by the various soil ameliorants

Table 1: Wheat grain yield (kg ha^{-1}) and (±SE) with a soil $pH_{(H2O)}$ of 4.5, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH(H_20) =4.5**	
	1st season	**2nd season**
	kg ha^{-1}	**kg ha^{-1}**
S1	1276.84 $^{A}_{a}$ **(± 35.67)**	586.52 $^{B}_{a}$ **(±10.89)**
S2	1093.95 $^{A}_{a}$ **(±24.45)**	638.19 $^{B}_{a}$ **(±11.34)**
FA1	487.86 $^{A}_{c}$ **(±15.67)**	492.43 $^{B}_{b}$ **(±13.57)**
FA2	648.34 $^{A}_{b}$ **(±12.34)**	464.00 $^{B}_{b}$ **(± 12.34)**
L	246.67 $^{A}_{d}$ **(±9.87)**	318.38 $^{A}_{c}$ **(±9.23)**
C	67.15 $^{B}_{e}$ **(±5.46)**	260.86 $^{A}_{c}$ **(±7.98)**

***A** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 2: Wheat grain yield (kg ha^{-1}) and (±SE) with a soil $pH_{(H2O)}$ of 5.0, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH(H_20) =5.0**	
	1st season	**2nd season**
	kg ha^{-1}	**kg ha^{-1}**
S1	2156.28 $^{A}_{b}$ **(±54.89)**	407.38 $^{B}_{c}$ **(± 11.93)**
S2	2593.66 $^{A}_{a}$ **(±51.23)**	624.52 $^{B}_{b}$ **(±10.87)**
FA1	1703.10 $^{A}_{c}$ **(±37.65)**	445.29 $^{B}_{c}$ **(±12.03)**
FA2	2080.72 $^{A}_{b}$ **(±47.89)**	812.05 $^{B}_{a}$ **(± 21.34)**
L	849.53 $^{A}_{d}$ **(±21.34)**	355.86 $^{B}_{d}$ **(±10.23)**
C	705.48 $^{A}_{d}$ **(± 16.78)**	406.95 $^{B}_{c}$ **(± 13.98)**

***A** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

The increase in grain yield noted on soils ameliorated with SLASH and fly ash, relative to the untreated control for the different soil pH levels, was most significant for the soil with an initial pH of 4.5. This data indicates that ameliorants containing fly ash may be more effective in soils with a lower pH.

Table 3: Wheat grain yield (kg ha^{-1}) and (±SE) with a soil $pH_{(H2O)}$ of 5.5, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH(H_20) =5.5**	
	1^{st} season	**2^{nd} season**
	kg ha^{-1}	**kg ha^{-1}**
S1	1805.60 $^{A}{}_{a}$ **(±29.89)**	597.90 $^{B}{}_{a}$ **(±13.24)**
S2	1611.09 $^{A}{}_{a}$ **(±35.67)**	463.71 $^{B}{}_{b}$ **(±14.01)**
FA1	877.13 $^{A}{}_{b}$ **(±23.45)**	597.33 $^{B}{}_{a}$ **(± 11.45)**
FA2	1077.55 $^{A}{}_{b}$ **(±23,56)**	498.19 $^{B}{}_{b}$ **(±10.89)**
L	648.93 $^{A}{}_{d}$ **(±11.23)**	366.19 $^{B}{}_{c}$ **(±16.78)**
C	769.71 $^{A}{}_{c}$ **(±14.34)**	343.86 $^{B}{}_{c}$ **(±14.56)**

***A** Row means with common alphabetical superscripts do not differ significantly ($P > 0.05$) (Bonferroni Test)

***abc** Column means with common alphabetical subscripts do not differ significantly ($P > 0.05$) (Bonferroni Test)

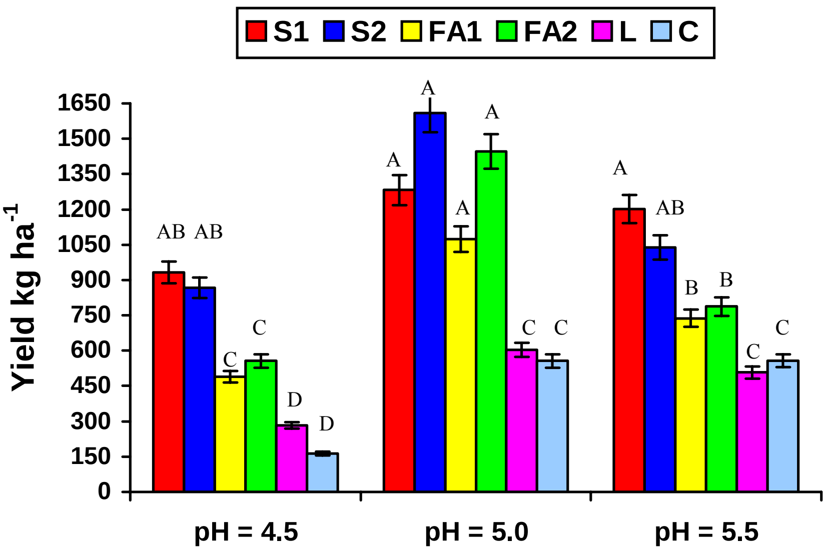

Figure 3: Mean wheat grain yield of two seasons on soils with three different pH levels.

 # Means with the same letter are not significantly different at P>0.05 (Tukey's Studentized Range Test)

With respect to the biomass production of the wheat, it is clear from Tables 4-6 and Figure 4 that the treatments containing sewage sludge, delivered 207% higher yields on average than that of the control. The trends of these results are similar to that of the grain yields, which illustrates that the higher macronutrient content of the SLASH treatments contributes significantly to the higher yields of wheat.

Table 4: Wheat DM yield (kg ha^{-1}) and (±SE) with a soil $pH_{(H2O)}$ of 4.5, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH(H_20) =4.5**	
	1st season	**2nd season**
	kg ha^{-1}	**kg ha^{-1}**
S1	5210.5 ^A_a **(± 54.27)**	4403.5 ^B_a **(±13.81)**
S2	4564.78 ^A_b **(±34.45)**	3782.39 ^B_b **(±17.32)**
FA1	2634.79 ^A_c **(±21.37)**	2211.59 ^A_c **(±15.77)**
FA2	1253.57 ^B_d **(±18.64)**	1751.19 ^A_c **(± 23.64)**
L	116.26 ^A_e **(±7.57)**	172.08 ^A_e **(±8.33)**
C	1352.16 ^A_d **(±13.47)**	1250.72 ^A_d **(±14.78)**

***A** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)
***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 5: Wheat DM yield (kg ha^{-1}) and (±MSE) with a soil $pH_{(H2O)}$ of 5.0, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH(H_20) =5.0**	
	1st season	**2nd season**
	kg ha^{-1}	**kg ha^{-1}**
S1	6238.88 ^A_b **(±43.89)**	6079.63 ^A_b **(± 17.23)**
S2	8443.92 ^A_a **(±41.27)**	6814.64 ^B_a **(±14.37)**
FA1	4162.34 ^A_d **(±27.55)**	4054.11 ^A_c **(±22.13)**
FA2	5201.95 ^A_c **(±51.39)**	4400.65 ^B_c **(± 33.64)**
L	3659.83 ^A_d **(±32.64)**	2553.28 ^B_d **(±21.73)**
C	2351.24 ^A_e **(± 20.28)**	2117.12 ^A_d **(± 19.18)**

***A** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)
***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Similarly to the results obtained for wheat grain yield, wheat DM yield increases on SLASH and fly ash ameliorated low pH soils were more significant than the DM yield on the soil with a pH of 5.5.

Table 6: Wheat DM yield (kg ha^{-1}) and (±MSE) with a soil $pH_{(H2O)}$ of 5.5, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH(H$_2$0) =5.5**	
	1st season	**2nd season**
	kg ha^{-1}	**kg ha^{-1}**
S1	7319.79 $^{A}{}_{b}$ **(±49.69)**	6439.93 $^{B}{}_{a}$ **(±17.24)**
S2	8705.61 $^{A}{}_{a}$ **(±29.37)**	6901.87 $^{B}{}_{a}$ **(±19.11)**
FA1	4951.34 $^{A}{}_{d}$ **(±43.75)**	2983.78 $^{B}{}_{d}$ **(± 18.25)**
FA2	5460.54 $^{A}{}_{c}$ **(±33.26)**	4486.85 $^{B}{}_{b}$ **(±23.79)**
L	3852.17 $^{A}{}_{e}$ **(±20.13)**	2617.39 $^{B}{}_{d}$ **(±26.28)**
C	3310.05 $^{B}{}_{e}$ **(±19.24)**	3770.02 $^{A}{}_{c}$ **(±30.76)**

***A** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

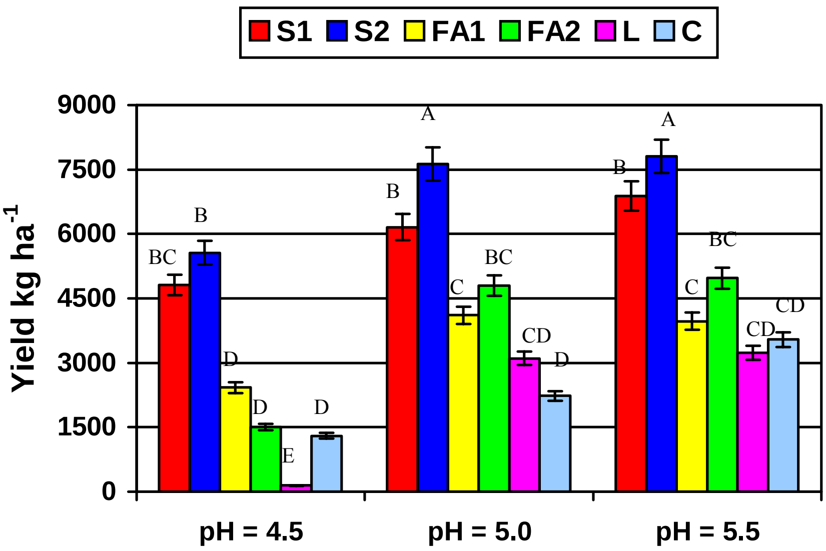

Figure 4: Mean DM production of wheat for two seasons on soils with three different pH levels.

 # Means with the same letter are not significantly different at P>0.05 (Tukey's Studentized Range Test)

3.1.2 Maize

The grain yield increases (Figure 7) obtained with maize on soils ameliorated with FA based ameliorants, can be ascribed to the improved soil pH, and a more effective uptake of macronutrients. As a result of the improved soil pH, increased yields noted for maize may also be attributed to nutrients in the soil and ameliorants being more available. Figure 8 demonstrates that maize biomass production, which is generally used for silage production, also benefited from the improved pH and certain macronutrient levels present in organic materials such as sewage sludge, especially on more acid soils.

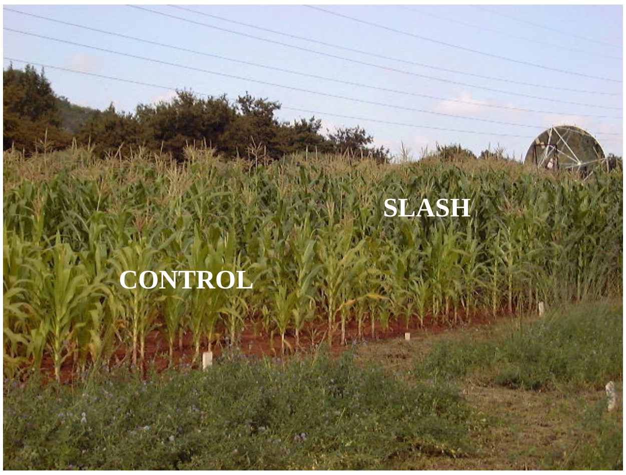

Figure 5: Maize production influenced by the different soil ameliorants.

Figure 6: Significant yields achieved for SLASH treatments.

Table 7: Maize grain yield (kg ha^{-1}) and (SE±) with a soil $pH_{(H2O)}$ of 4.5, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH(H_20) =4.5**						
	kg ha^{-1}						
	R1	**R2**	**R3**	**R4**	**R5**	**Mean**	**SE**
S1	6758.91	7865.48	8282.01	7649.34	8735.11	7858.17_b	**±123.42**
S2	10087.23	8456.98	8588.92	7771.92	9123.45	8805.70_a	**±131.81**
FA1	7765.23	6784.9	7789.34	9232.65	7654.23	7845.27_b	**±109.89**
FA2	7652.89	8345.98	6675.43	7211.34	6310.36	7239.20_c	**±112.34**
L	7012.23	6709.54	8012.34	5987.34	5325.7	6609.43_d	**± 98.78**
C	7012.34	8876.34	7456.72	5467.89	5714.71	6905.60_c	**±93.24**

***ab** Column means with common alphabetical subscripts do not differ significantly ($P > 0.05$) (Bonferroni Test)

From the data presented in Tables 7-9 it can be noted that the SLASH treated soils provided significant increases in yield. These results obtained in the second growing season, without additional ameliorant inputs, emphasize the long-term residual benefits these fly ash based ameliorants can have on acidic agricultural soils.

Table 8: Maize grain yield (kg ha^{-1}) and (SE±) with a soil $pH_{(H2O)}$ of 5.0, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH(H_20) =5.0**						
	kg ha^{-1}						
	R1	**R2**	**R3**	**R4**	**R5**	**Mean**	**SE**
S1	11456.78	10987.23	9878.77	12345.68	12377.88	11409.27_a	**±160.89**
S2	10876.43	11278.92	9834.56	10234.95	9339.49	10312.87_b	**±147.68**
FA1	9087.34	10235.67	11093.48	8234.58	8143.93	9359.00_c	**±140.80**
FA2	9245.68	8834.57	7999.89	9124.57	9867.64	9014.47_c	**±124.50**
L	8562.12	8576.23	9001.23	7896.56	7958.01	8398.83_d	**±113.45**
C	7913.90	8345.1	9001.23	7564.23	8345.69	8234.03_d	**±102.34**

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 9: Maize grain yield (kg ha^{-1}) and (SE±) with a soil $pH_{(H2O)}$ of 5.5, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH(H_20) =5.5**						
	kg ha^{-1}						
	R1	**R2**	**R3**	**R4**	**R5**	**Mean**	**SE**
S1	11234.57	8876.56	10786.34	10987.23	9070.30	10191.00_b	**±165.80**
S2	11758.00	9998.72	10034.45	12010.24	11098.23	10979.93_a	**±132.45**
FA1	8212.53	8657.45	10001.23	7976.45	9012.34	8772.00_c	**±123.45**
FA2	11225.50	9765.42	10923.34	9876.45	11234.78	10605.10_a	**±134.56**
L	7248.48	9001.23	6999.45	7986.54	8123.45	7871.83_d	**±99.78**
C	8308.28	7689.03	6897.34	9001.23	8342.12	8047.60_{cd}	**±107.45**

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

These significant grain yield increases, recorded for SLASH and fly ash ameliorated soils, as shown in Figure 7, can ultimately provide a higher economic return and, therefore, justify the use of such long-term soil amelioration strategies.

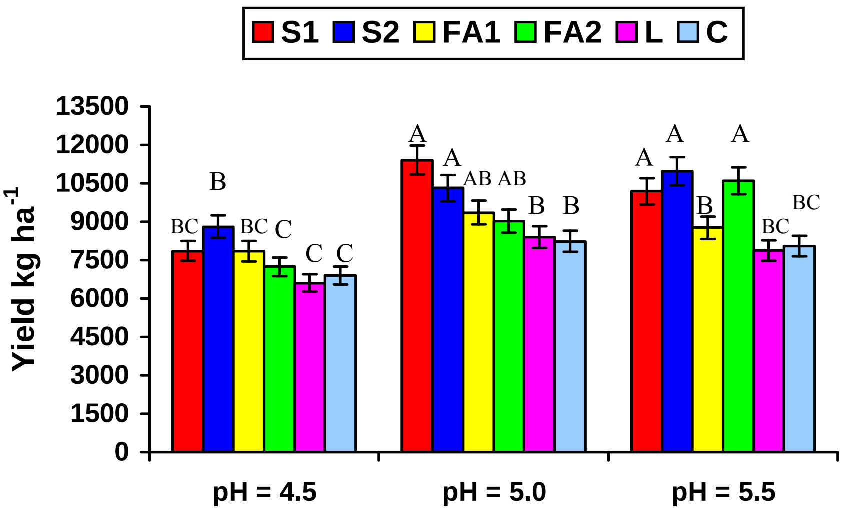

Figure 7: Mean grain production of maize on different pH level soils treated with SLASH, fly ash, lime relative to the control (no treatment) with supplemental irrigation.

. # *Means with the same letter are not significantly different at P>0.05 (Tukey's Studentized Range Test*

Tables 10-12 demonstrate the maize growth response s in terms of DM yields to different soil ameliorants. It is evident from these data, that SLASH treatments delivered significant increases in DM yields. These yield increases reflect the positive plant growth response, achieved on acidic soils ameliorated with fly ash based ameliorants. The yield increase differences noted between fly ash and SLASH treatments, highlights the additional benefit of the organic component of SLASH.

Table 10: Maize DM yield (kg ha^{-1}) and (SE±) with a soil pH$_{(H2O)}$ of 4.5, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH($H_2$0) =4.5**						
	kg ha^{-1}						
	R1	**R2**	**R3**	**R4**	**R5**	**Mean**	**SE**
S1	7685.93	8012.23	6789.32	7123.45	7889.07	7500.00$_a$	**±434.89**
S2	5567.98	4998.74	5001.98	5678.9	5314.92	5312.50$_b$	**±249.72**
FA1	4987.23	3998.56	4456.78	3786.56	3083.42	4062.51$_c$	**±327.57**
FA2	4394.57	3887.66	4908.75	3897.64	4786.43	4375.01$_c$	**±385.88**
L	5090.91	4234.5	5001.23	4213.45	4897.56	4687.53$_c$	**±358.84**
C	2816.11	2987.56	2567.98	2678.56	3012.34	2812.51$_d$	**±151.48**

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 11: Maize DM yield (kg ha^{-1}) and (SE±) with a soil $pH_{(H2O)}$ of 5.0, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH(H$_2$0) =5.0**						
	kg ha^{-1}						
	R1	**R2**	**R3**	**R4**	**R5**	**Mean**	**SE**
S1	12023.45	11675.23	11023.48	12546.78	12106.11	11875.00 $_a$	**±431.95**
S2	12897.34	11876.23	12100.98	11899.78	12163.21	12187.51 $_a$	**±283.93**
FA1	6393.05	6987.23	7123.48	6657.89	7213.4	6875.01 $_b$	**±279.63**
FA2	13092.23	11098.87	12347.67	13098.23	14425.5	12812.51 $_a$	**±471.38**
L	3653.31	4897.61	5001.25	4432.12	5453.21	4687.51 $_c$	**±515.83**
C	6474.34	7324.56	6897.65	7895.43	7345.67	7187.53 $_b$	**±401.23**

***a** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 12: Maize DM yield (kg ha^{-1}) and (SE±) with a soil $pH_{(H2O)}$ of 5.5, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH(H$_2$0) =5.5**						
	kg ha^{-1}						
	R1	**R2**	**R3**	**R4**	**R5**	**Mean**	**SE**
S1	10023.45	9987.65	8997.45	10123.01	10087.2	9843.75 $_a$	**±338.52**
S2	9001.34	8765.49	7997.34	9876.24	7328.34	8593.75 $_b$	**±744.73**
FA1	7012.57	6547.89	7123.87	6435.68	6473.79	6718.76 $_c$	**±279.57**
FA2	7862.87	9456.7	8001.23	7865.47	9001.23	8437.51 $_b$	**±633.17**
L	9654.24	9001.21	7865.46	8213.46	9015.68	8750.01 $_b$	**±568.44**
C	9101.04	9567.89	7865.43	10123.45	7098.34	8751.23 $_b$	**±401.48**

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

It is noted in Figure 8, that total DM yields were more sensitive to added fertility than grain yields, as in Figure 7.

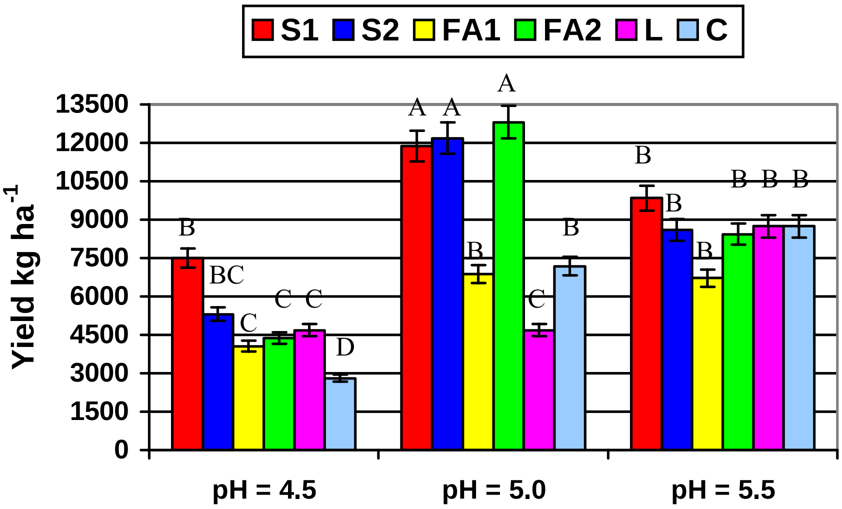

Figure 8: Mean DM production of maize on different pH level soils treated with SLASH, fly ash, lime relative to the control (no treatment) with supplemental irrigation.

. *# Means with the same letter are not significantly different at P>0.05 (Tukey's Studentized Range Test*

3.1.3 Lucerne

High quality forage, such as lucerne (alfalfa), is important in South Africa. This field trial simulated the use of a perennial crop with no annual soil cultivation. This study provided results that illustrated how soil ameliorants containing fly ash reacted in soils that remained physically intact for a 2-year period and how this affected crop yields.

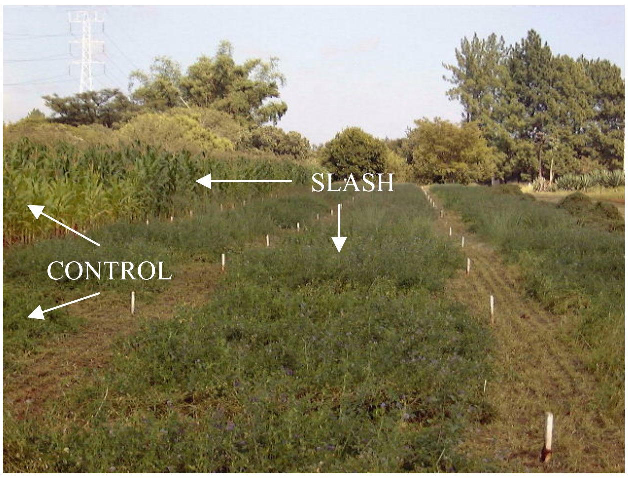

Figure 9: Lucerne (alfalfa) production as influenced by different soil ameliorants on acid soils

Table 13: Lucerne (alfalfa) DM yield (kg ha^{-1}) and (±SE) with a soil $pH_{(H2O)}$ of 4.5, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH(H_20) =4.5**							
	1st Harvest	**2nd Harvest**	**3rd Harvest**	**Total DM 1st season**	**1st Harvest**	**2nd Harvest**	**3rd Harvest**	**Total DM 2nd season**
	kg ha^{-1}							
S1	4098.78	5678.45	2701.67	12478.91^{A}_{a}	3987.67	5467.89	2132.24	11587.80^{A}_{a}
	(±102.34)	**(±89.34)**	**(± 54.78)**		**(± 86.43)**	**(± 57.98)**	**(±112.32)**	
S2	4235.68	5012.34	3739.43	12987.45^{A}_{a}	4087.45	4789.56	1324.99	10202.01^{B}_{a}
	(± 74.32)	**(± 91.23)**	**(± 43.67)**		**(± 37.89)**	**(± 99.10)**	**(± 41.29)**	
FA1	2213.34	3002.34	1771.66	6987.34^{A}_{b}	1987.67	2578.98	1239.77	5806.42^{B}_{b}
	(± 47.89)	**(± 56.98)**	**(± 32.48)**		**(± 38.94)**	**(± 58.92)**	**(± 21.39)**	
FA2	1987.67	2345.67	1431.00	5764.72^{A}_{c}	1235.67	1986.54	960.97	4183.18^{B}_{b}
	(± 59.91)	**(± 54.49)**	**(±28.93)**		**(± 41.92)**	**(± 76.32)**	**(± 29.39)**	
L	2145.61	2654.32	1764.79	6564.72^{A}_{b}	1765.98	2563.48	1351.58	5681.04^{B}_{c}
	(± 49.81)	**(± 51.29)**	**(± 39.82)**		**(± 49.87)**	**(± 55.92)**	**(± 51.01)**	
C	987.78	1234.11	564.59	2786.48^{A}_{d}	765.23	1134.58	677.07	2576.88^{A}_{c}
	(± 78.92)	**(± 68.92)**	**(± 45.92)**		**(± 76.23)**	**(± 59.82)**	**(± 61.29)**	

***A** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Lucerne (alfalfa), however, is very sensitive to low pH soils and production is severely reduced on acidic soils. Figure 10, clearly illustrates how the soil ameliorants containing fly ash improved the DM production. Although lucerne production was the best for the lime treatment at a pH of 5.0, the SLASH treated soils improved the yields overall, especially on the most acidic soils yielding 400% more DM ha^{-1} than the control treatment (Figure 10).

Table 14: Lucerne (alfalfa) DM yield (kg ha^{-1}) and (±SE) with a soil $pH_{(H2O)}$ of 5.0, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH(H$_2$0) = 5.0**							
	1st Harvest	**2nd Harvest**	**3rd Harvest**	**Total DM 1st season**	**1st Harvest**	**2nd Harvest**	**3rd Harvest**	**Total DM 2nd season**
				kg ha^{-1}				
S1	4123.23 **(±123.21)**	4989.79 **(±142.23)**	3354.85 **(±165.23)**	12467.87^{A}_{a}	3876.46 **(±112.28)**	5673.49 **(±154.98)**	2366.35 **(±87.86)**	11916.30^{A}_{a}
S2	3876.46 **(±98.23)**	5786.34 **(±134.98)**	2696.12 **(±87.24)**	12358.92^{A}_{a}	3098.23 **(±79.34)**	5446.98 **(±131.87)**	2601.29 **(±79.98)**	11330.51^{B}_{a}
FA1	3786.34 **(±68.93)**	4568.93 **(±145.98)**	1521.24 **(±68.93)**	9876.51^{A}_{b}	2348.31 **(±91.29)**	3987.23 **(±139.82)**	1874.19 **(±65.23)**	8209.73^{B}_{c}
FA2	4013.23 **(±133.32)**	6012.37 **(±198.29)**	2957.65 **(±81.12)**	12983.25^{A}_{a}	3478.23 **(±82.34)**	4879.32 **(±166.23)**	2886.55 **(±85.92)**	11244.10^{B}_{a}
L	3421.87 **(±71.12)**	4011.23 **(±187.23)**	2356.13 **(±81.24)**	9789.23^{A}_{b}	2786.2 **(±90.29)**	3982.1 **(±103.49)**	2443.91 **(±71.29)**	9212.20^{A}_{b}
C	2345.63 **(±61.29)**	4234.13 **(±132.49)**	2396.25 **(±94.39)**	8976.01^{A}_{c}	2230.34 **(±88.29)**	3450.2 **(±93.29)**	2376.89 **(±80.12)**	8057.43^{B}_{c}

***A** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 15: Lucerne (alfalfa) DM yield (kg ha^{-1}) and (±SE) with a soil $pH_{(H2O)}$ of 5.5, treated with SLASH (S1 and S2), fly ash (FA1 and FA2), dolomitic lime (L) relative to the untreated control (C).

Treatments	**pH($H_2$0) = 5.5**							
	1st Harvest	**2nd Harvest**	**3rd Harvest**	**Total DM 1st season**	**1st Harvest**	**2nd Harvest**	**3rd Harvest**	**Total DM 2nd season**
				kg ha^{-1}				
S1	4598.23 **(±117.89)**	5239.41 **(±201.28)**	3285.83 **(±98.29)**	13123.47^{A}_{b}	3873.38 **(±87.29)**	4759.34 **(±98.29)**	3439.49 **(±82.19)**	12072.21^{B}_{b}
S2	5012.23 **(±212.39)**	4875.3 **(±198.29)**	4097.71 **(±165.29)**	13985.23^{A}_{a}	4125.98 **(±132.98)**	4467.98 **(±172.39)**	3706.15 **(±101.29)**	12300.11^{B}_{b}
FA1	3761.29 **(±82.39)**	4234.01 **(±129.38)**	3128.17 **(±98.29)**	11123.47^{A}_{c}	3319.34 **(±81.10)**	4002.29 **(±113.29)**	3312.17 **(±92.39)**	10633.81^{A}_{c}
FA2	4887.41 **(±181.20)**	5783.49 **(±231.49)**	3341.48 **(±109.28)**	14012.38^{A}_{a}	4786.35 **(±178.29)**	5139.24 **(±211.38)**	3369.12 **(±103.29)**	13294.71^{B}_{a}
L	3198.23 **(±82.39)**	3981.2 **(±81.29)**	3479.8 **(±61.29)**	10659.23^{A}_{c}	3129.46 **(±72.19)**	4127.83 **(±83.29)**	2887.32 **(±62.92)**	10144.61^{A}_{c}
C	2871.29 **(±58.87)**	3349.83 **(± 77.22)**	2749.9 **(±52.28)**	8971.02^{A}_{d}	2789.34 **(±61.02)**	3598.23 **(±88.21)**	1844.89 **(±29.28)**	8232.46^{A}_{d}

***A** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

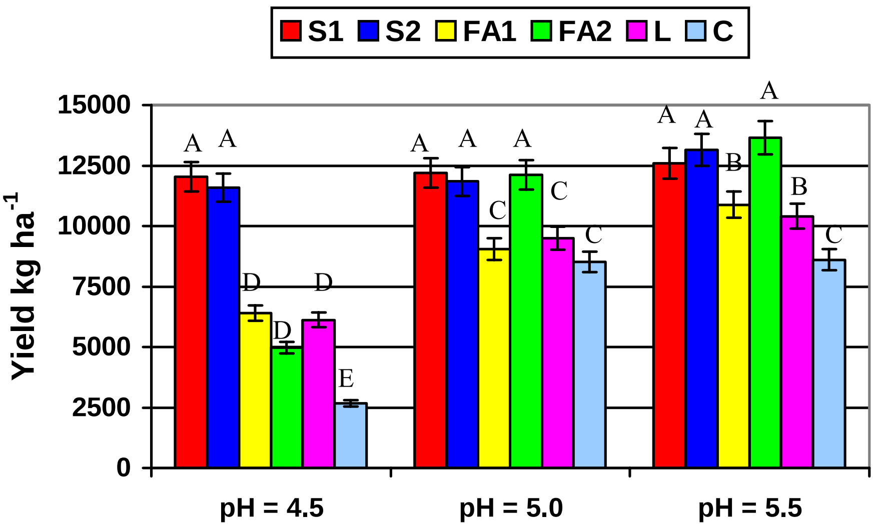

Figure 10: The influence of SLASH, fly ash and lime on the mean DM production of lucerne (alfalfa) on a soil with different pH's relative to the untreated control, with supplemental irrigation.

 # Means with the same letter are not significantly different at P>0.05 (Tukey's Studentized Range Test).

3.2 Soil chemical analyses

For optimal growth it is essential that macro- and micronutrients be supplied in desirable quantities. Inorganic fertilizers are usually the most effective and the quickest way of supplying nutrients for plant growth. These fertilizing practices are, however, not always sustainable, and new research is showing that organic materials and alkaline materials, other than lime, have beneficial soil ameliorating properties. The following data, presented in Tables 16-18, illustrates how the high-level fly ash treatment (FA2) increased the overall nutrient levels of the soil with a pH of 4.5. This trend was not, however, as prominent for the higher pH levels. The nutrient levels of the soils in Tables 16-18 clearly indicate that the treatments containing fly ash contributed significantly to these levels.

With respect to these data, it is evident that the Ca levels were significantly higher for the fly ash and fly ash containing treatments than the control and lime treatments. The Ca in the fly ash is generally supplied in the form of CaO and $CaSO_4$. It is thus important that the Mg levels of these soils are at satisfactory levels, to ensure that an acceptable Ca:Mg ratio of 4.5:1 is maintained, which is required for optimal plant production. High Ca:Mg ratios can result in either a chemical imbalance which effects other nutrients uptake, or possible phytotoxicity.

Table 16: The influence of SLASH and fly ash as alternative amendments on the mean soil chemical properties of a soil, with an initial pH of 4.5, compared to lime and control treatments, 24 months after treatment

Treatment	**P (mg kg^{-1})**	**K (mg kg $^{-1}$)**	**Ca (mg kg^{-1})**	**Mg (mg kg^{-1})**
S1	9.2 $_c$ **(± 0.78)**	59.7 $_b$ **(± 7.45)**	323.0 $_c$ **(±12.30)**	79.3 $_b$ **(±6.56)**
S2	11.3 $_b$ **(±0.98)**	43.3 $_c$ **(±5.34)**	589.7 $_b$ **(±15.67)**	61.7 $_c$ **(±4.56)**
FA1	7.2 $_c$ **(±0.65)**	61.7 $_b$ **(±5.45)**	904.3 $_a$ **(±21.34)**	83.0 $_b$ **(±6.78)**
FA2	21.7 $_a$ **(±1.23)**	70.0 $_a$ **(5.56±)**	850.0 $_a$ **(±18.79)**	73.0 $_b$ **(± 10.34)**
Lime	9.9 $_c$ **(±0.67)**	56.0 $_b$ **(±4.56)**	291.3 $_c$ **(±11.23)**	132.5 $_a$ **(±6.78)**
Control	1.3 $_d$ **(±0.23)**	34.7 $_d$ **(±5.67)**	245.7 $_d$ **(±8.90)**	75.7 $_b$ **(±6.78)**

***abc** Column means with common alphabetical subscripts do not differ significantly ($P> 0.05$) (Bonferroni Test)

The lime used in this study was dolomitic in nature, supplying high amounts of Mg to the soils. Tables 16-18, demonstrate how the initially high Mg levels of the lime treatment decreased quickly after a 24-month period in comparison to the S1 and FA1 treatments. It is noted that the fly ash and SLASH treated soils were often maintaining a better Mg content.

Table 17: The influence of SLASH and fly ash as alternative amendments on the mean soil chemical properties of a soil with an initial pH of 5.0, compared to lime and control treatments, 24 months after treatment

Treatment	P (mg kg^{-1})	K (mg kg $^{-1}$)	Ca (mg kg^{-1})	Mg (mg kg^{-1})
S1	6.1 $_b$ **(±0.65)**	74.3 $_a$ **(±6.87)**	491.0 $_c$ **(±10.98)**	118.0 $_a$ **(±9.76)**
S2	11.7 $_a$ **(±0.97)**	54.3 $_b$ **(±3.78)**	853.3 $_a$ **(± 19.06)**	75.0 $_b$ **(±5.89)**
FA1	6.4 $_b$ **(±0.52)**	63.7 $_b$ **(±5.67)**	678.3 $_b$ **(±14.56)**	102.7 $_a$ **(±8.87)**
FA2	11.4 $_a$ **(±1.40)**	53.3 $_b$ **(±5.02)**	503.7 $_c$ **(±11.68)**	86.0 $_b$ **(±7.05)**
Lime	10.8 $_a$ **(±1.80)**	53.0 $_b$ **(±6.78)**	322.8 $_d$ **(±8.98)**	99.0$_a$ **(±5.64)**
Control	7.1 $_b$ **(±0.68)**	62.7 $_b$ **(±7.88)**	342.1 $_d$ **(±6.89)**	60.7 $_c$ **(±9.87)**

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 18: The influence of SLASH and fly ash as alternative amendments on soil chemical properties, of a soil with an initial pH of 5.5, compared to lime and control treatments, 24 months after treatment

Treatment	P (mg kg^{-1})	K (mg kg $^{-1}$)	Ca (mg kg^{-1})	Mg (mg kg^{-1})
S1	16.2 $_a$ (±1.45)	52.7 $_b$ (±3.89)	288.3 $_d$ (±10.76)	82.3 $_a$ (±5.78)
S2	11.2 $_b$ (±1.10)	35.7 $_c$ (±6.12)	714.0 $_a$ (±16.00)	61.3 $_b$ (±5.42)
FA1	13.0 $_b$ (±1.23)	53.7 $_b$ (± 3.21)	345.3 $_c$ (±12.45)	61.7 $_b$ (±6.08)
FA2	12.1 $_b$ (±0.92)	71.3 $_a$ (±6.01)	449.3 $_b$ (±9.89)	60.7 $_b$ (± 5.99)
Lime	9.3 $_c$ (±0.61)	49.7 $_b$ (±2.98)	274.8 $_d$ (±11.01)	79.0 $_a$ (±4.99)
Control	7.1 $_c$ (±0.67)	28.3 $_d$ (±1.78)	261.7 $_d$ (±10.54)	65.7 $_b$ (±5.13)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Figure 11 illustrates how the pH of soils was improved by the different treatments. The best amelioration after a 24 month period was registered by the highest fly ash application treatment, FA2, on the most acidic soil.

These results illustrate the long term effect which fly ash can have, over a period of 24 months, on acidic soils. This observation can be ascribed to the nature of the fly ash, in which the glass phase of the fly ash degrades slowly over time releasing the residual alkalinity it contains.

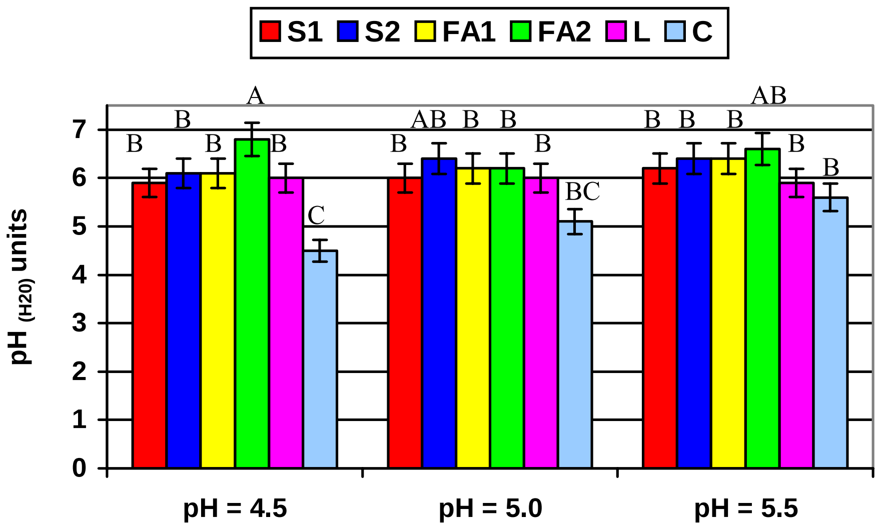

Figure 11: Influence of SLASH, fly ash and lime treatments on the pH of soil planted to two wheat crops and one maize crop, 24 months after treatment.

 # Means with the same letter are not significantly different at P>0.05 (Tukey's Studentized Range Test)

In Tables 19-21, it is evident that in the soil planted to lucerne (alfalfa), with no cultivation during the 24-month monitoring period, the nutrient status was often significantly better in amelioration treatments than in the control treatment. These results also highlight the benefits of combining alkaline materials with organic materials, to address the problem of acidic and infertile growth mediums, in a more sustainable way.

Table 19: The influence of SLASH, fly ash and lime on the nutrient levels of a soil with a $pH_{(H20)}$ of 4.5, 24 months after treatment, planted to lucerne (alfalfa).

Treatment	P (mg kg^{-1})	K (mg kg $^{-1}$)	Ca (mg kg^{-1})	Mg (mg kg^{-1})
S1	9.3 $_b$ **(±0.53)**	39.0 $_c$ **(±6.98)**	629.7 $_a$ **(±12.34)**	64.7 $_b$ **(±6.03)**
S2	20.6 $_a$ **(±1.43)**	46.7 $_{bc}$ **(±2.54)**	819.7 $_a$ **(±17.98)**	61.3 $_b$ **(±5.23)**
FA1	6.2 $_c$ **(±0.61)**	59.3 $_a$ **(±5.11)**	216.3 $_b$ **(±9.54)**	53.7 $_c$ **(±5.69)**
FA2	9.3 $_b$ **(±0.67)**	50.7 $_b$ **(±3.23)**	211.7 $_b$ **(±8.89)**	58.7 $_b$ **(±5.01)**
Lime	6.8 $_c$ **(±0.71)**	63.7 $_a$ **(±5.88)**	207.3 $_b$ **(±9.01)**	77.0 $_a$ **(±6.01)**
Control	6.6 $_c$ **(±0.86)**	42.7 $_c$ **(±6.01)**	244.7 $_b$ **(±9.56)**	56.3 $_b$ **(±4.67)**

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

The overall P content of the different pH soils was significantly increased by the S2 treatment. The FA2 treatment also tended to improve the P levels of the soil (Tables 19-21). These increases can either be ascribed to the high amounts of silica in the fly ash causing the displacement of P from the soil particles at an improved soil pH, or in the case of SLASH treatments, P is added to the soil by the sewage sludge component.

Table 20: The influence of SLASH, fly ash and lime on the nutrient levels of a soil with a $pH_{(H20)}$ of 5.0, 24 months after treatment planted to lucerne (alfalfa).

Treatment	P ($mg\ kg^{-1}$)	K ($mg\ kg^{-1}$)	Ca ($mg\ kg^{-1}$)	Mg ($mg\ kg^{-1}$)
S1	14.9_b **(±1.78)**	52.3_b **(± 4.55)**	591.0_a **(±11.56)**	82.3_b **(±6.01)**
S2	26.1_a **(±2.23)**	37.0_d **(±6.00)**	534.3_a **(±11.23)**	63.7_c **(±5.67)**
FA1	7.4_c **(±0.63)**	54.7_b **(±5.13)**	505.7_b **(±10.78)**	82.7_b **(±5.24)**
FA2	9.5_c **(±0.52)**	78.0_a **(± 6.75)**	330.0_c **(±12.01)**	99.3_b **(±10.23)**
Lime	5.6_d **(±0.54)**	69.0_a **(±5.98)**	475.7_b **(±10.45)**	129.7_a **(±11.01)**
Control	5.4_d **(±0.45)**	47.3_c **(±3.24)**	488.0_b **(±10.24)**	77.3_b **(±6.03)**

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

It is also evident from the results in Tables 19-21 that the Ca levels of the SLASH ameliorated soils are generally higher than some of the other soil treatments. These high Ca values can be attributed to the reactive CaO component of SLASH. The increase in Ca content of FA treated soils is as a result of the high amounts of Ca supplied by the calcium silicate compounds, a primary component of FA.

Table 21: The influence of SLASH, fly ash and lime on the nutrient levels of a soil with a $pH_{(H20)}$ of 5.5, 24 months after treatment planted to lucerne (alfalfa).

Treatment	P ($mg\ kg^{-1}$)	K ($mg\ kg^{-1}$)	Ca ($mg\ kg^{-1}$)	Mg ($mg\ kg^{-1}$)
S1	16.4_b **(±1.54)**	40.3_d **(±6.56)**	591.3_b **(±12.32)**	75.3_b **(± 6.77)**
S2	20.3_a **(±1.98)**	51.0_c **(±5.99)**	713.7_a **(±15.45)**	69.3_c **(±7.12)**
FA1	7.8_c **(±0.78)**	61.3_b **(±5.43)**	596.7_b **(±13.24)**	85.7_b **(±5.46)**
FA2	9.9_c **(±0.65)**	45.3_c **(±3.01)**	555.3_b **(± 13.67)**	96.0_a **(± 8.78)**
Lime	6.7_d **(±0.93)**	71.3_a **(±6.33)**	324.0_c **(±11.34)**	117.3_a **(±9.67)**
Control	5.0_d **(±0.43)**	40.0_d **(±2.98)**	363.3_c **(±11.56)**	76.3_b **(±6.23)**

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

The available K content of soils generally increased with an increase in soil pH, with no significant amounts of K being supplied by the different ameliorants. The noted increase in K is rather as a result of increased availability due to the improved cation exchange, possibly caused by the addition of high amounts of Ca, in SLASH, fly ash and lime ameliorants. The increased K level of lime treatments, is attributed to the improved Ca:Mg ratio, caused by the addition of Mg through the application of dolomitic lime.

An optimal pH and adequate nutrient levels are essential for good crop production. Figure 12 illustrates how the different treatments affected the pH of soils, 24 months after treatment. Visual observations, as seen in Figure 2 and 5, are confirmed by the data presented in Figure 12, the lower the pH the lower the yield, therefore the soil pH plays a dominant role in efficient use of nutrients by lucerne (alfalfa).

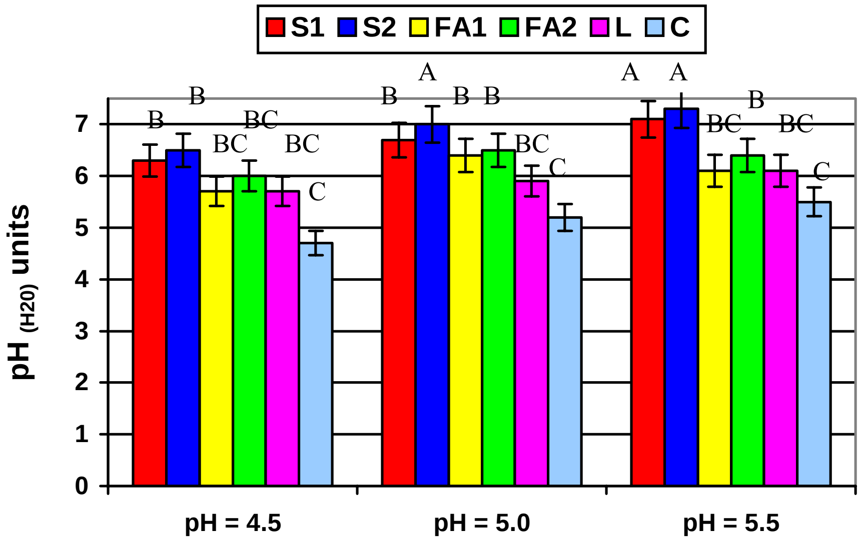

Figure 12: Influence of SLASH, fly ash and lime treatments on pH of soil planted to lucerne (alfalfa), 24 months after treatment.

 # Means with the same letter are not significantly different at P>0.05 (Tukey's Studentized Range Test).

4. Conclusions

SLASH and fly ash definitely have agricultural potential for the amelioration of agricultural soils. For optimal crop production specific soil conditions are required for specific crops. Therefore, it is important that soil pH and other nutrient levels meet crop requirements. Three different soil pH levels were monitored, and similar trends were noted for all three levels. These data, have demonstrated, that even though the SLASH ameliorant had the assumed advantage of an organic component, with a higher proportion of macronutrients, the class F fly ash treatment produced relatively high wheat grain yields of up to 335 % more than the control treatments. These results can possibly be ascribed to the fact that the correction in soil pH alone had a significant affect on crop production of the three test crops, because, nutrients already present in these agricultural soils could now be used more effectively, because of unrestricted root development. Similar observations were made for wheat and maize dry matter production. It was, however, noted that only very small differences between treatment effects for the soil pH's 5.0 and 5.5 were evident. The more acidic soil (pH of 4.5) illustrates the significant differences between the SLASH and class F fly ash treatments. The acid sensitive perennial *M. sativa* (lucerne) was also favored by treatments with class F fly ash and

SLASH producing up to 370 % higher DM yields over an extended period, with no cultivation after establishment.

Utilizing the micro-nutrient content and neutralizing qualities of fly ash, together with the macronutrients and organic content of sewage sludge, can provide an alternative soil ameliorant such as SLASH. Increased P values caused by the addition of SLASH to the soils, has illustrated that P can either be supplied by the organic component of SLASH and/or by the possible chemical interaction of silica in fly ash with soil P, making it available for plant uptake. It can also be concluded in this study that low levels of K recorded, highlight the need to provide K through an additional source, such as animal manures.

From previous work done on acidic agricultural soils, the residual effect of SLASH has been measured for up to three years. To date, conventional liming and fertilization had been the preferred method of ameliorating degraded soils, but this is not necessarily sustainable. Therefore, these preliminary results justify the expansion of the investigation of the use of SLASH to restore nutrient poor and acidic soils over the long term. The productive utilization of waste products is also important in ensuring a sustainable environment.

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CHAPTER 3

Prepared according to the guidelines of the Journal of Environmental Quality

The influence of a class F fly ash / sewage sludge mixture and class F fly ash on the physical and biological properties of degraded agricultural soils

Wayne F. Truter [1], Norman F.G. Rethman, Hester Truter, Richard A. Kruger, Kelley A. Reynolds and Chris de Jager[1]

ABSTRACT

Prime agricultural land is a limited resource in South Africa. It is, therefore, necessary to reclaim poor and disturbed soils to feed the burgeoning population. Using conventional methods is costly and not necessarily sustainable. The challenge is to use alternative materials in an economically, ecologically and socially acceptable manner.

Previous research has shown that sewage sludge can be pasteurized by mixing it with class F fly ash and a suitable source of quicklime. The **SL**udge**ASH** (SLASH) mixture has been extensively evaluated as a soil ameliorant and has proven to be viable for the reclamation of poor and marginal soils. Many studies previously conducted and reported on, have focused on the effect of class F fly ash and SLASH on soil chemical properties and consequently plant production of various plant species.

This paper reports on subsequent research conducted to determine the effect of both class F fly ash and SLASH on soil physical and microbiological properties. SLASH and class F fly ash treatments were compared with the conventional soil ameliorant of agricultural dolomitic lime with fertilizer and an untreated control. The results obtained illustrate improvements in soil physical properties such as soil texture, bulk density, water infiltration rate and hydraulic conductivity by class F fly ash based soil ameliorants. In addition to the beneficial effect obtained on soil physical properties, the microbial properties had also improved, as indicated by the improved symbiotic relationship of the *Rhizobium* bacteria and the important host plant *Medicago sativa.* The results presented are encouraging and justify further research on the use of class F fly ash and it's co-utilization with other by-products to restore productivity to poor agricultural lands.

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[1] W.F. Truter, Department of Plant Production and Soil Science, University of Pretoria, Pretoria, 0002, South Africa. Corresponding Author: wayne.truter@up.ac.za

INTRODUCTION

South Africa is a country with very little prime farmland. A large percentage of the land with a high agricultural capability is generally acidic and is situated in areas where large quantities of fly ash are disposed. To ensure healthy and productive vegetation, disturbed soils need to be ameliorated effectively. To date, conventional methods of liming and fertilization to improve productivity of impacted soils have been standard practices. This process can, however, be very expensive and is often not sustainable.

Soil physical and microbiological factors are also responsible for ensuring a healthy soil environment, which is necessary for seed germination, plant establishment and growth on any type of soil. Soil moisture retention affects the growth of all plants, especially in land rehabilitation. The ability of the soil to absorb water, however, is affected by soil characteristics such as texture, structure, organic matter and depth (Lyle, 1987). Soil texture is determined by the relative percentages of sand, silt and clay in a soil. Soils with a high sand content have a coarse texture and water will percolate easily through such a growth medium resulting in low water retention for plant use. A clayey soil can, however, reduce the movement of water through the profile resulting in waterlogged conditions. Different soil pore sizes (macro and micro) affect water infiltration and storage capacity of a soil. Without pores there would be no water or oxygen in the soil, which is essential for plant growth. Compacted soil reflects changes in bulk density, water holding capacity, hydraulic conductivity, and organic matter content and soil strength. Root growth is usually restricted when bulk density reaches approximately 1.25 x 10^{-3} kg m^{-3} in clay soils and about 1.75 x 10^{-3} kg m^{-3} in sandy soils (Hannan and Bell, 1986, Jackson, 1991), though some plants are able to grow in more highly compacted soils.

Fly ash and various organic materials have, however, been shown to improve soil bulk density, water holding capacity, hydraulic soil conductivity, organic content and soil strength, thereby creating a more favourable growth medium for plant roots to penetrate (Chang *et al.*, 1977; Aitken and Bell, 1985; Eisenberg *et al.*, 1986; Garg *et al.*, 1996; Kalra *et al.*, 1998). Soil characteristics, which affect hydraulic conductivity, are total porosity, the distribution of pore sizes and the pore geometry of the soil together with the fluid attributes such as fluid density and viscosity. (Hillel, 1982).

Another component, which is essential for a healthy soil environment, is soil organic matter. Organic matter in soils consists of the rotting or decomposing remains of plants and animals. The stage of decomposition varies from litter to humus (decomposed organic matter), which holds and absorbs water and nutrients for plant use. Soil depth is also regarded as another important aspect, which influences the soil environment. This may be defined as the distance from the soil surface to any layer, which prevents further root penetration and consequently affects the ability to absorb nutrients and water. Finally, microbial populations need to be present. If deficient they need to be re-established so that the decomposition of plant, animal and human residues and the mineralization of organically complexed nitrogen and phosphorus can be ensured.

Undisturbed and productive soils usually have the greatest diversity of species of soil organisms. The size of the microbial biomass is usually highly correlated with the amount of plant growth, soil organic matter content and the clay and silt content. The aggregation of soil is primarily responsible for controlling microbial activity. When microflora and roots produce fibrils, filaments, and polysaccharides that combine with clays to form organo-mineral complexes, aggregate formation is initiated. The quantity of micro-organisms decrease with depth in the soil, as do plant roots and soil organic matter. Factors such as tillage, micro-climate, and plant cover have considerable impacts on the microbial distribution within soil profiles. Soil organic matter is essential to provide a good soil structure and can have a great effect on the erosion resistance of a soil, the development of roots and the infiltration of water into the soil. Soil organic matter also stores nutrients such as N, S, P and many micronutrients and improves the cation absorption capacity of a soil. The amount of soil organic matter present is dependant on the balance between primary productivity and the rate of decomposition. Nitrogen (N) is the nutrient most often required by plants for growth and it is also the fourth most important element in plant composition, after carbon (C), hydrogen (H) and oxygen (O). Soil organisms commonly mediate shifts between these important plant constituents (Paul and Clark, 1996).

Many micro-organisms are responsible for processes that ensure the availability and loss of N in the soil. Various soil factors, including soil acidity, however, affect the functioning of these micro-organisms. Most micro-organisms responsible for mineralization, nitrification and denitrification, function best within an optimum pH range of 6-8. Organisms and associations involved in nitrogen fixation have been identified, and leguminous plants benefit from such beneficial effects. Nitrogen fixation in legumes is attributed to a group of bacteria consisting of a number of genera collectively known as rhizobia. Much is known about the use of rhizobia as inoculants, to establish a symbiotic relationship within the roots of host plants. Nodule development on the roots of host plants is the result of a successful inoculation, and can be affected by poor soil conditions, which needs to be ameliorated.

South Africa has an abundance of waste products, which might be used as alternative ameliorants. Fly ash is characterized as a good source of certain micronutrients; beneficial to plant growth, in addition to it's neutralizing qualities and other unique properties. This resource together with organic materials such as sewage sludge or animal manures (which are good sources of organic matter and macronutrients essential for plant growth), can serve as soil ameliorants in crop production systems (Norton *et al*., 1998; Truter, 2002). In future, conventional landfill and lagoon disposal of rapidly accumulating coal combustion byproducts, (especially fly ash), and organic biosolid wastes (such as sewage sludge and animal manures) is unlikely to comply with increasingly stringent environmental regulations (Sopper, 1992; Walker*, et. al*, 1997).

Previous work to determine the feasibility of converting waste disposal problems into a soil beneficiation strategy has proven true (Reynolds *et al*., 1999). The co-utilization of fly ash and sewage sludge with added lime (CaO) in a ratio of 6:3:1 on a wet basis, has delivered the product termed SLASH, which can be used as a soil ameliorant (Truter, 2002). This study entails an evaluation of SLASH and fly ash as alternative soil ameliorants to address the concern of poor soil physical and microbiological properties.

MATERIALS AND METHODS

A randomized field study with nett plots of 3.75m x 8.65m = 32.44m^2, was conducted on the Hatfield Experimental Farm, Pretoria, South Africa (25°45'S 28°16'E), 1327m above sea level (Figure 1). A uniform sandy loam Hutton soil was ameliorated with sewage sludge, class F fly ash and reactive lime (CaO) in combination (SLASH) at different levels and compared with fly ash and lime treatments.

Figure 1: The application of ameliorants to the Hatfield Field trial

Rep 1						Rep 2						Rep 3					
S2	FA1	S1	L	FA2	FA1	S1	FA1	FA2	S2	FA1	S2	S2	C	L	S1	L	FA1
L	FA2	S2	FA1	S2	S1	C	S2	C	L	L	FA2	L	FA1	S2	C	FA2	S1
S1	C	FA2	C	C	L	L	FA2	S1	FA1	C	S1	S1	FA2	FA2	FA1	S2	C

P1	pH 1 = 4.5
P2	pH 2 = 5.0
P3	pH 3 = 5.5

C	Untreated control
L	Dolomitic Lime
FA1	Class F Fly ash (50% of Calculated optimum)
FA2	Class F Fly ash (Calculated optimum)
S1	SLASH (50% of Calculated Optimum)
S2	SLASH (Calculated Optimum)

Figure 2: The experimental layout (Randomized Block Design) of the Hatfield Field Trial planted to *Medicago sativa* on soils with three different pH levels.

The primary objective of this study was to determine the influence of SLASH and class F fly ash treatments on the production of *Medicago sativa* (Lucerne or alfalfa) over a 24-month period on soils with different levels of acidity. The field consisted of three levels of acidity **[P1]** $pH_{(H2O)}$ = 4.5, **[P2]** $pH_{(H2O)}$ = 5.0 and **[P3]** $pH_{(H2O)}$ = 5.5. Lime application rates were based on the buffering capacity of the soil which was determined by using a $Ca(OH)_2$ titration solution. It was calculated from the buffer curve which was based on the initial soil $pH_{(H2O)}$ of the Hatfield soil, and it required 4.0 tons ha^{-1} of dolomitic lime **[L]** to raise the pH of the soil to $pH_{(H2O)}$ of 6.5 which is optimum for lucerne growth. The control **[C]** treatment was untreated (receiving no soil ameliorants). The other treatments were compared to the aforementioned control and lime treatment. These treatments included two levels (optimum level and 50% of the optimum level) of class F fly ash and SLASH. The optimum level of fly ash **[FA2]** was based on the assumption (from literature) that class F fly ash had a $CaCO_3$ equivalent of 20% (Truter, 2002). This resulted in a fly ash requirement of approximately five fold the amount of dolomitic lime required to raise the $pH_{(H2O)}$ to 6.5, thus the optimum class F fly ash level **[FA2]** was calculated as 19 tons ha^{-1}**.** Level two **[FA1]** was 50 % of this, namely 9.5 tons ha^{-1}. The 50% of the optimum treatment was included to determine whether the $CaCO_3$ equivalent of South African class F fly ash was higher than the 20% guideline presented in international literature. The optimum SLASH **[S2]** of 64 tons ha^{-1} was calculated from the ratio of fly ash, sewage sludge and lime (6:3:1 on a wet basis) used in the process of making SLASH (Reynolds *et al*., 1999). The second level, 50% of the optimum, **[S1],** was 32 tons ha^{-1}. These treatments were replicated three times and were only applied at the beginning of the trial, prior to the establishment of the lucerne, to determine the long-term residual effect on sustainability.

In addition to the soil ameliorants being applied at the onset of the experimental trial, a basal application of 250 kg of K (potassium) ha^{-1} year^{-1} was given to compensate for the relatively low K status and K removal, which resulted from the multiple harvesting of plant material each growing season.

The field was sown to *Medicago sativa* cv SA Standard (lucerne or alfalfa) in 20 cm rows using a seeding rate of 25 kg ha^{-1} and the seed was inoculated with a multi-strain inoculant of *Rhizobium* bacteria.

Figure 3: The Hatfield field trial planted to *Medicago sativa* on a soil with three different pH levels, shortly after planting.

During the growing season, irrigation was supplied to ensure that water was not a limiting factor. Two seasons of production data were collected over a period of 24 months. At the end of the 24-month period a root biomass study was conducted to determine the effect of the different soil ameliorants on root development and/or the symbiotic relationship of the *Rhizobium* bacteria. Three healthy plants were selected randomly in each soil treatment and soil cores of 30cm x 30cm x 30cm deep (representing the most active root zone) were excavated with each plant, to obtain the root sample. A root sample enclosed by soil was removed for microbial analysis and the rest of the soil was washed from the root sample using a sieve. Finally the washed roots were dried at 65^{o}C for 24 hours to obtain the root dry mass.

Subsequently, a basic microbiological laboratory study was conducted using soil collected from the aforementioned field trial, to determine the effect of the applied soil ameliorants on *Rhizobium* nodulation and the total microbial activity in treatments applied to the most acidic soil, with an initial $pH_{(H2O)}$ *of 4.5*. Microbial activity was determined according to the protocol of Inbar *et al*. (1991). All *Rhizobium* nodules on the plant roots were counted and also separated into single nodules and branched nodules.

Concurrent with this field trial, a study was conducted on the most acid soil from the Hatfield experimental site. Treatments ameliorated with optimum levels of SLASH, Class F fly ash, dolomitic lime were compared to the control (no treatment). This study was to determine the influence of SLASH and fly ash treatments on the physical properties of the most acidic soil. The following methodology was used to determine bulk density. A 100 mL graduated cylinder was weighed, and filled with soil that was sieved to 2mm. The first addition of soil to the cylinder was compacted by tapping the bottom of the cylinder ten times. Soil was added gradually and cylinder tapped repeatedly until 100ml soil was obtained. The filled cylinder was then weighed. Each ameliorated soil was replicated five times. The moisture content of the soil was determined separately and the oven dry weight of the 100 ml soil above was calculated (Tan, 2005). Equation (2.1) was used to calculate bulk density.

$$\textit{Bulk Density} = \frac{\textit{oven dry weight of 100mL soil}}{100} \qquad = \mathbf{10^{-3}\ kg\ m^{-3}} \qquad (2.1)$$

The measurement of hydraulic conductivity of a saturated soil was determined using the laboratory method of Klute (1965). The lower end of the soil cylinder (core) was covered with a filter paper to retain the soil. The soil was allowed to soak water slowly through the capillary rise and the saturated core was used for the K_s measurement. A constant head was maintained across the core and the volume of water coming out of the core was measured at specific time intervals. The flow rate along with the hydraulic head difference, length and cross section of the core are recorded and transferred into Eq. (2.2) (Lal and Shukla, 2004). This method equates to the following

$$\textit{Hydraulic conductivity } (\boldsymbol{K}) = VL / tA\,\Delta H \qquad = \mathbf{10^{-3}\ cm\ sec^{-1}} \qquad (2.2)$$

Where V *= volume of water*

L *= length of the column*

t *= time*

A *= cross sectional area of flow through the soil column*

ΔH *=hydraulic head difference*

Downward infiltration into an initially unsaturated soil generally occurs under the combined influence of suction and gravity gradients (Hillel, 1982). Darcy's equation for vertical flow Eq. (2.3) was used to determine the infiltration rate of the ameliorated soils.

$$\text{Infiltration rate } (q) = K\,\Delta H / L = \mathbf{mm\ hr^{-1}} \qquad (2.3)$$

Statistical analyses

All the data was statistically analyzed using PROC GLM (1996/1997 and 1997/1998). Statistical analyses were performed using SAS software. A Bonferroni test was conducted where LSD's were taken at P≤0.05. (SAS, 1998).

RESULTS AND DISCUSSION

The legume crop (*M. sativa*), used as the test crop in this soil amelioration study, is the most common legume grown for grazing and hay production in South Africa. This legume is widely adapted, but prefers deep, well-drained soils with a neutral pH.

Soil physical analyses

Soil texture analysis

In Tables 1-3 it is clear that the soil ameliorants based on class F fly ash (S1, S2, FA1, FA2) had significant effects on the different fractions of the experimental soil. The coarse sand fraction (Table 1) was significantly lower in both the fly ash and SLASH treated soil, as a result of higher silt fraction (Table 2) while the clay fraction was slightly lower (Table 3). With the higher silt fraction prevalent in the class F fly ash and SLASH treated soils, it can be expected (as reviewed in previous research) that the altered soil texture would affect the movement and storage of water in the profile, which is available for plant use.

The data, obtained from the texture analyses, supports the conclusion, that soil ameliorants based on class F fly ash, contribute to a higher silt fraction in the soil. This can be ascribed to the fine texture of the fly ash. At high application rates it will consequently change the texture of a soil being ameliorated.

Table 1: The influence of soil ameliorants based on class F fly ash, compared to an untreated control and conventional dolomitic lime, on the coarse sand fraction of an acidic Hutton soil on the Hatfield Experimental Farm.

	% Coarse Sand						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	*SE (+/-)*
Control	75.4	74.4	70.9	72.5	65.8	**71.8** $_a$	(2.2)
SLASH	67.8	70.9	69.3	72.9	65.3	**69.2** $_b$	(2.6)
Fly ash	67.2	65.8	65.2	63.2	59.4	**64.2** $_c$	(2.3)
Lime	75.3	65.7	69.2	71.1	75.1	**71.3** $_a$	(2.9)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 2 indicates that class F fly ash increased the silt fraction of the Hutton soil from 8.28% to 20.1%, which is a highly significant improvement. This change in the silt fraction of soil is responsible for the changes noted in other soil physical properties.

Table 2: The influence of soil ameliorants based on class F fly ash, compared to an untreated control and conventional dolomitic lime, on the silt fraction of an acidic Hutton soil on the Hatfield Experimental Farm.

	% Silt						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	*SE (+/-)*
Control	8.3	10.1	9.1	12.0	1.9	**8.28** $_d$	(1.3)
SLASH	13.8	15.7	14.5	15.1	16.5	**15.1** $_b$	(0.6)
Fly ash	18.6	21.1	19.8	23	22.4	**20.1** $_a$	(1.4)
Lime	9.2	12.9	10.8	11.6	9.9	**10.8** $_c$	(1.1)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 3: The influence of soil ameliorants based on class F fly ash, compared to an untreated control and conventional dolomitic lime, on the clay fraction of an acidic Hutton soil on the Hatfield Experimental Farm.

	% Clay						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE (+/-)***
Control	16.4	19.6	20.0	20.2	16.7	**18.6** $_a$	(1.6)
SLASH	16.4	19.6	18.1	19.6	17.6	**16.3** $_b$	(1.1)
Fly ash	14.2	16.1	15.0	16.0	18.2	**15.9** $_b$	(1.0)
Lime	15.5	11.4	12.0	17.3	16.0	**18.4** $_a$	(2.6)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Bulk density

Bulk density is an important parameter used to determine the degree of compaction. Different textured soils can experience different degrees of compaction. Clayey soils generally compact the most. Table 4 shows that soil treated with class F fly ash or SLASH had a significantly lower bulk density than the untreated control or the lime treatment.

Table 4: The comparative influence of soil ameliorants on the bulk density of an acidic Hutton soil with an original pH$_{(H2O)}$ *of 4.5*

	Bulk Density (x 10^{-3} kg m^{-3})						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE(+/-)***
Control	1.56	1.47	1.49	1.60	1.55	**1.53** $_a$	(0.04)
SLASH	1.48	1.39	1.49	1.46	1.45	**1.45** $_b$	(0.07)
Fly ash	1.34	1.27	1.39	1.32	1.35	**1.33** $_c$	(0.08)
Lime	1.58	1.38	1.45	1.49	1.59	**1.50** $_a$	(0.07)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Soil with a good organic matter content can theoretically have a lower bulk density. It was expected that the combination of sewage sludge (which contains organic matter) and fly ash, would lower the bulk density of the soil more than fly ash alone. This, however, was not the case; with fly ash reducing the bulk density the most significantly followed by SLASH. The possible reason for this result is that the soil used in this study had a high percentage of clay, and that the SLASH which has a coarser texture, did not have as significant an effect on the bulk density as it would have had on a sandier soil. The fly ash, however, with its fine texture and high silt fraction had a more significant effect on the clayey soils texture and bulk density.

These data demonstrate that class F fly ash, at high application rates, based on the neutralizing requirement of the soil, can have a beneficial effect on the bulk density, thereby ensuring a better plant root development.

Infiltration rate (q)

Sandy soils are known to have a high infiltration rate. This can often be a disadvantage if water is limiting plant growth, because the soil can dry out quickly. On the other hand if the infiltration rate increases, this causes more water to enter the soil profile and less is lost to runoff. A very low infiltration rate can be a disadvantage as it can lead to high runoff, resulting in erosion of the soil surface.

The data presented in Table 5 demonstrate that class F fly ash and SLASH treatments significantly increased the infiltration rate by 60% and 42% over the control, respectively. These results can be linked to the improved bulk density (Table 4) as well as the increased silt fraction of soil (Table 2) when class F fly ash was used as a soil ameliorant.

Table 5: The comparative influence of soil ameliorants on the infiltration rate of an acidic Hutton soil.

	Infiltration Rate (mm hr^{-1})						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE(+/-)***
Control	5.0	5.2	4.8	4.9	5.5	**5.1** $_b$	(0.3)
SLASH	8.1	7.9	7.6	7.6	6.5	**7.5** $_a$	(0.3)
Fly ash	8.3	7.3	7.9	9.0	8.6	**8.2** $_a$	(0.5)
Lime	6.0	6.1	5.7	5.9	6.4	**6.0** $_b$	(0.8)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Hydraulic conductivity (K_s)

It is clear from Table 6 that the soil ameliorants based on class F fly ash (SLASH and FA) significantly reduced the hydraulic conductivity by changing the distribution of pore sizes, total porosity and soil geometry of the soil, with the assumption that the fluid density and viscosity used in the experiment remained constant.

These results illustrate that both SLASH and class F fly ash reduce the hydraulic conductivity by, 20% and 26% respectively, as compared to the 5% reduction by dolomitic lime. The implication of a lower hydraulic conductivity is that the rate at which water percolates through the soil profile, will be reduced, which will result in a higher water retention capacity. A higher water retention capacity will enhance crop production by improving nutrient uptake by plants.

Table 6: The comparative influence of soil ameliorants on the hydraulic conductivity (K_s) of an acidic Hutton soil

	Hydraulic conductivity (K_s) **(x 10^{-3} cm / sec)**						
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE(+/-)***
Control	1.90	1.81	1.74	1.84	2.02	**1.86** $_a$	(0.08)
SLASH	1.50	1.38	1.51	1.6	1.43	**1.48** $_c$	(0.06)
Fly ash	1.40	1.21	1.36	1.52	1.45	**1.38** $_d$	(0.12)
Lime	1.84	1.72	1.78	1.86	1.74	**1.77** $_b$	(0.07)

***abc** Column means with common alphabetical subscripts do not differ significantly ($P > 0.05$) (Bonferroni Test)

Root biomass evaluation

A well-developed root system is an indication of the condition of the soil environment or growth medium. A healthy root system ensures a healthy and productive plant. The root biomass parameter is a good measure used to determine whether a plant's root system is well developed and whether sufficient nutrients and moisture are available, or whether the plant has been subjected to some form of stress. Acid soil environments restrict root development, which eventually affects the growth of the plant. *M. sativa,* is a species which is sensitive to an acidic environment and prefers a more neutral soil pH.

In Table 7 it can be seen that the untreated control had a comparatively low root biomass. Class F fly ash which is known to contain relatively little macro-nutrients produced a 74% higher root biomass of lucerne, by correcting the soil pH to 6.5 and by supplying additional micro-nutrients to the plant roots. The SLASH soil ameliorant, however, which contains the organic component of sewage sludge, and contains more macronutrients, increased the root biomass by 82%. The dolomitic lime treatment, which is devoid of macronutrients, such as N, P and K, increased the root biomass by only 14%.

Table 7: The influence of comparative soil ameliorants on the root biomass (g) of *Medicago sativa* on a Hutton soil with an original $pH_{(H2O)}$ *of 4.5*

				$pH_{(H2O)} = 4.5$			
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE(+/-)***
C	6.03	6.25	5.69	4.51	5.10	**5.52** $_{d}$	(0.43)
L	6.35	6.91	5.54	6.87	5.81	**6.30** $_{c}$	(0.54)
FA1	7.12	7.51	7.35	8.35	9.60	**7.99** $_{b}$	(0.79)
FA2	9.73	8.96	10.15	9.92	9.29	**9.59** $_{a}$	(0.39)
S1	6.78	7.22	9.26	8.80	10.80	**8.57** $_{b}$	(1.19)
S2	11.75	10.90	8.70	9.35	9.60	**10.06** $_{a}$	(1.01)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

It should be noted that the soils with originally higher pH levels (Table 8 & 9) exhibited the same trend in root biomass values, with the class F fly ash ameliorant and SLASH ameliorant on the higher soil pH value of 5.5, increasing the root biomass by 28% and 49%, respectively. The magnitude of the response to the soil ameliorants was, however, much smaller. This suggests that the soil ameliorants, based on class F fly ash, react better with the soil at a lower pH.

It is evident that the root biomass was much lower for the untreated control than the other soil pH levels. Nevertheless, the addition of both class F fly ash and SLASH increased the root biomass substantially, and these values were higher than on the other soils, with slightly higher pH levels, which had been ameliorated with the same amount of class F fly ash and SLASH.

Table 8: The influence of comparative soil ameliorants on the root biomass (g) of *Medicago sativa* on a Hutton soil with an original $pH_{(H2O)}$ *of 5.0*

				$pH_{(H2O)} = 5.0$			
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE(+/-)***
C	6.23	7.34	6.12	7.28	6.54	**6.70** $_d$	(0.49)
L	6.98	7.27	6.89	7.23	6.41	**6.95** $_d$	(0.25)
FA1	8.02	7.65	8.34	7.96	8.37	**8.06** $_c$	(0.23)
FA2	9.63	9.45	8.94	9.51	8.86	**9.27** $_b$	(0.30)
S1	9.95	9.56	9.37	10.14	9.28	**9.66** $_b$	(0.33)
S2	10.72	9.93	11.52	11.67	11.31	**11.03** $_a$	(0.56)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 9: The influence of comparative soil ameliorants on the root biomass (g) of *Medicago sativa* on a Hutton soil with an original $pH_{(H2O)}$ *of 5.5*

				$pH_{(H2O)} = 5.5$			
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***Mean***	***SE(+/-)***
C	7.56	7.02	6.57	6.33	7.60	**7.02** $_d$	(0.45)
L	8.12	6.87	7.12	7.65	7.23	**7.39** $_d$	(0.39)
FA1	8.12	8.56	7.67	8.76	7.83	**8.18** $_c$	(0.38)
FA2	8.42	9.43	8.29	9.11	9.83	**9.01** $_b$	(0.49)
S1	9.54	9.32	9.97	8.98	9.53	**9.47** $_b$	(0.25)
S2	9.87	11.23	10.61	9.95	10.52	**10.44** $_a$	(0.42)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Soil Microbiological Analyses

Microbial activity

Soil micro-organisms ensure the life of a soil. Disturbed soils, however, often need a replenishment of such organisms, either by the addition of organic matter or by creating a better soil environment through amelioration. Soil acidity is a major factor responsible for the destruction of soil microbial populations. By raising the soil's pH with the addition of an alkaline material, higher microbial activity can be obtained. As can be seen in Figure 4 it is evident that of the soil ameliorants evaluated, SLASH ameliorants improved the microbial activity by 100%. This can possibly be ascribed to a rise in soil pH, together with the addition of organic matter, via the sewage sludge component of SLASH. Class F fly ash, however, also resulted in a remarkable increase in the activity by 26% as compared to the untreated control, while the lime treatment had an insignificant effect on microbial activity.

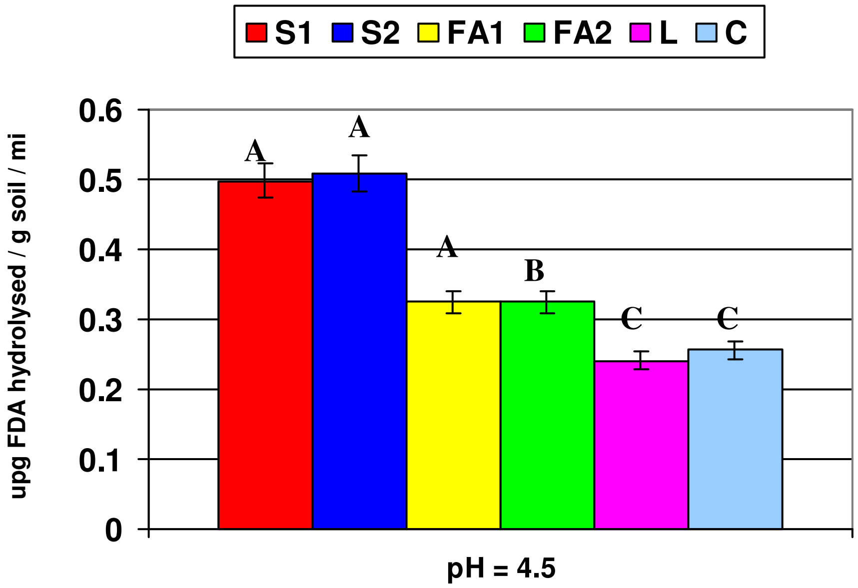

Figure 4: Mean microbial activity of the ameliorated soil with the lowest $pH_{(H2O)}$ *of 4.5.*

Rhizobium nodulation

With respect to nodule development on *M. sativa* roots, (Figure 5) higher nodule counts (total) were observed for both the SLASH treatments [S1 and S2] and the optimum class F fly ash treatment [FA1], as compared to the untreated control [C] and the conventional lime treatment [L] (Figure 5). This method was used as an assessment of whether soil conditions had improved enough to ensure successful inoculation.

It is interesting to note from Figure 6 that a higher *Rhizobium* nodulation was observed for the SLASH and class F fly ash ameliorated soils and that these results were related to the higher root mass produced on these ameliorated soils. It is evident from the data that the lower application of both fly ash and SLASH tended to have a depressing effect on the *Rhizobium* nodulation.

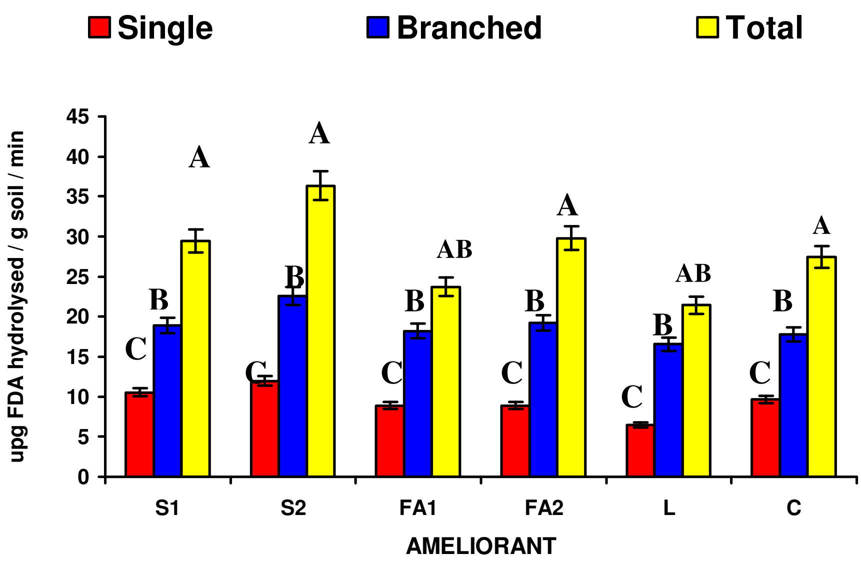

Figure 5: The mean quantity of *Rhizobium* nodulation in soils treated with different soil ameliorants.

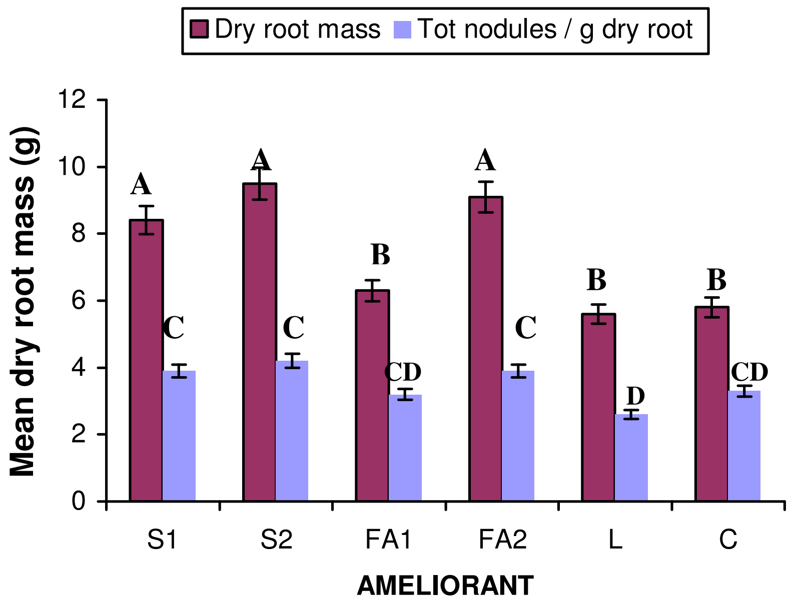

Figure 6: *Rhizobium* nodulation in relation to root biomass for ameliorated soils

With respect to the analyses, which were conducted, it is evident that the soil ameliorants based on class F fly ash resulted in significant changes in soil physical properties, such as texture, bulk density, hydraulic conductivity and water infiltration rate as well as, plant growth properties, such as root biomass, and, finally, relevant soil microbiological properties.

CONCLUSION

SLASH and class F fly ash have the potential to improve soil physical and microbiological properties. Soil texture was one of the characteristics that were modified significantly by these ameliorants, by increasing the silt fraction of the soil by as much as 143%. The increased silt fraction obtained by the addition of soil ameliorants based on class F fly ash, also improved the bulk density of the soil. The class F fly ash ameliorant was overall the best ameliorant with respect to its most significant affect on the rate of water infiltration into the experimental soil, increasing this by as much as 60%. This can possibly be ascribed to a 26% lower soil hydraulic conductivity, caused by the class F fly ash. For optimal crop production good soil conditions are required to ensure a healthy and well-developed root system.

Root biomass data were correlated with improved soil physical parameters, with an improved root biomass (of up to 74 – 82 %) where the class F fly ash based soil ameliorants were used. This was true of the SLASH ameliorant, which had the additional benefit of macronutrients in the organic component (sewage sludge). The effect that SLASH had on biomass enhancement emphasizes the importance of including organic materials, to provide the essential nutrients required for plant growth. By improving soil conditions, both chemically and physically, it was also possible to ensure an improvement in microbiological activity. The change in soil pH and soil texture, mainly as a result of the addition of class F fly ash, can - together with the organic matter introduced by the sewage sludge - help create a better soil environment for an increase in microbial activity. To date, conventional liming and fertilization has been the preferred method of ameliorating degraded soils, but this often necessitates annual applications and is not necessarily sustainable, because it's effect is mainly chemical in nature.

Agricultural, municipal and industrial by-products are often rich sources of nutrients or organic matter, that can be beneficially, utilized for crop production and to improve the physical, chemical or microbiological properties of relatively inert soils. These materials can be co-utilized, or combined, so that the materials are more easily applied, to provide a more complete/balanced nutrition, or to enhance soil condition, as well as the economic, or environmental value of these individual by-products.

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CHAPTER 4

Prepared according to the guidelines of the Journal of Waste Management

Reclaiming degraded mine soils and substrates with domestic and industrial by-products by improving soil chemical properties and subsequently enhancing plant growth: A greenhouse study

Wayne F. Truter[a], Norman F.G. Rethman[a], Kelley A. Reynolds[b] and Richard A. Kruger[c]

[a]Department of Plant Production and Soil Science, University of Pretoria, Pretoria, 0002

[b] Eskom CR & D, Private Bag 40175, Cleveland, 2022, South Africa

[c] Richonne Consulting, 141 Rockwood Cr, Woodlands, Pretoria, South Africa

Abstract

The South African mining industry has been the backbone of the country's economy for much of the past century. Mining has, however, often caused the degradation of productive soils. The amendment of these soils is often very expensive and often not sustainable. The University of Pretoria in co-operation with Eskom TSI, has over the past ten years conducted a series of trials to determine the feasibility of using alkaline class F fly ash (from the coal-based Lethabo power generating facility) and organic materials to ameliorate acidic and infertile soils and substrates. In this investigation pot trials were conducted to measure and monitor the effect of different ameliorants on dry matter production and on the chemical properties of soils and substrates. Based on the results obtained in these pot trials, it was concluded that fly ash and fly ash/organic material mixtures improved dry matter production as well as the soil pH, ammonium acetate extractable K, Ca and Mg and Bray 1 extractable P levels. All parameters measured were significantly influenced by the fly ash and fly ash / organic material mixtures. Fly ash and fly ash / organic ameliorated soils delivered approximately 850%, 266% and 110% higher dry matter production on gold mine tailings, AMD impacted soil and acidic mine cover soil, respectively, relative to the control treatments. With respect to soil chemical properties, the pH of AMD impacted soils was dramatically improved by 240% by the fly ash / organic mixture. An industrial byproduct such as fly ash, either by itself, or together with organic waste, can serve, therefore, as a soil ameliorant for the reclamation of surface mine land.

Key Words: acidic soils, fly ash, infertile soils, organic materials, soil ameliorants

[a] Corresponding author.: Email address: wayne.truter@up.ac.za

1. Introduction

Coal mining and agriculture are both important industries in South Africa. They impact extensive land areas, and often compete for the same land. The surface mining of coal seriously degrades the surface soil and local flora and fauna. Mining wastes viz. overburden, discards and mine effluents, have also created land degradation problems. To date, it has been common practice to lime and fertilize these soils to revegetate such impacted areas. This process is normally very costly because large amounts of lime and fertilizer are needed. A major problem in such a system is that when fertilization is stopped, the production and cover on more marginal sites declines.

South Africa also experiences problems with rehabilitating gold mine tailings. Many of these tailings are situated in close proximity to residential areas, and it remains a difficult task to stabilize these dumps with vegetation, to prevent dust pollution and erosion problems. Large amounts of lime and fertilizer are also used to reclaim these areas, but reclamation is often not sustainable. The challenge is thus to find alternative amelioration methods, which will be sustainable.

In future, conventional landfill and lagoon disposal of rapidly accumulating coal combustion byproducts, (especially fly ash), and organic biosolid wastes (such as sewage sludge and animal manures) is unlikely to comply with increasingly stringent environmental regulations [11; 15]. Land application of coal combustion wastes and biosolids, particularly class F fly ash, either by itself or in a mixture with sewage sludge, may offer a viable alternative to current landfill or dump disposal. It may, thereby, serve as a source of micro- and macro-nutrients essential for plant growth [3;13]. The benefits are that these nutrients will be released over time. This could possibly improve sustainability. The University of Pretoria in co-operation with Eskom TSI has over the past ten years conducted a series of trials which have demonstrated the feasibility of using alkaline class F fly ash from the Lethabo coal fired power station to make sewage sludge safe for agricultural and land reclamation purposes. This mixture, known as SLASH (60 % fly ash, 30 % sewage sludge and 10% unslaked lime on a wet matter basis), is characterized by the elimination of odour problems, the immobilization of possible metal contaminants, and the pasteurization of disease organisms. It has also been used successfully to improve soil acidity and fertility [5; 6; 7; 13].

2. Experimental procedures

A study was conducted at the Hatfield Experimental Farm, Pretoria, South Africa (25°45'S 28°16'E), 1327m above sea level, to evaluate how *Cenchrus ciliaris* (an indigenous grass species sensitive to acid soil conditions) would perform on different substrates treated with three different levels of class F fly ash, fly ash / sewage sludge mixture and dolomitic lime. This study was also used to assess the effect of treatments on the chemical properties of the substrates. The three substrates used were a mine cover soil, a soil impacted by acid mine drainage (AMD) and gold mine tailings. Lime application rates were based on the buffering capacity of the substrates which were determined by using a $Ca(OH)_2$ titration solution. The mine cover soil had a $pH_{(H2O)}$ of 4.3, the AMD impacted soil a $pH_{(H2O)}$ of 3.4 and the gold mine tailings a $pH_{(H2O)}$ of 4.5. It was calculated, from the buffer curve, that the different substrates required the following amounts of dolomitic lime **[L Opt.]** to raise the pH of the soil to a $pH_{(H2O)}$ of 6.5, suitable for plant growth. The mine cover soil required 10 tons ha^{-1}, AMD impacted soil required 23 tons ha^{-1}, and gold mine tailings required 19 tons ha^{-1} of dolomitic lime as shown in Tables 1-3. The class F fly ash and SLASH treatments were compared to the aforementioned control and three lime treatments. The three levels of class F fly ash, SLASH and dolomitic lime were made up of an optimum **(Opt.)** level of each material, an optimum level plus 33% **(Opt. +)** and optimum level less 33% **(Opt. -)** as shown in the Tables 1-3.

Table 1: Treatment levels applied to the mine cover soil with a basal $pH_{(H2O)}$ of 4.3

	Treatment Level (tons ha^{-1})		
Soil Ameliorant	*Opt.*	*Opt. +*	*Opt. –*
Control	0	0	0
Dolomitic Lime	10	13	7
Class F fly ash	50	67	34
SLASH	167	217	117

Table 2: Treatment levels applied to the AMD impacted cover soil with a basal $pH_{(H2O)}$ of 3.4

	Treatment Level (tons ha^{-1})		
Soil Ameliorant	*Optimum*	*Opt. +*	*Opt. –*
Control	0	0	0
Dolomitic Lime	23	31	16
Class F fly ash	116	154	78
SLASH	387	514	259

Table 3: Treatment levels applied to the gold mine tailings with a basal $pH_{(H2O)}$ of 4.5

	Treatment Level (tons ha^{-1})		
Soil Ameliorant	***Optimum***	***Opt. +***	***Opt. –***
Control	0	0	0
Dolomitic Lime	19	25	13
Class F fly ash	93	124	62
SLASH	310	414	207

The optimum level of fly ash **[FA Opt.]** was based on reports in the literature that class F fly ash had a $CaCO_3$ equivalent of 20% [13]. This resulted in a fly ash requirement of approximately five times the amount of dolomitic lime required to raise the $pH_{(H2O)}$ to a level of 6.5. The optimum level plus 33% **(Opt. +)** and optimum level less 33% **(Opt. -)** treatments were included to determine if the $CaCO_3$ equivalent of South African class F fly ash differed from the 20% guideline suggested in the international literature. The optimum level of SLASH **[S Opt.]** was calculated using the ratio of fly ash, sewage sludge and lime (6:3:1 on a wet basis), which is used in the process of making SLASH [8]. All soil ameliorants were only applied once off at the beginning of the trial and monitored over time to establish the residual effects of ameliorants.

All treatments were compared to a control **[C]**, which received no treatment, to clearly illustrate positive or negative effects. The ten treatments were replicated six times on three different substrates in a completely randomized design.

The pot trial was conducted over a period of 24 months. After a period of 12 months for treatments to stabilize in the different substrates, five *C. ciliaris* cv. Molopo seedlings were planted into 10 L pots of the different substrates. The growth was harvested every 45 days during the growing season of September 2001 – June 2002 (Figure 1).

Figure 1: *Cenchrus ciliaris* plants on three different substrates

During the growing season, four harvests were taken and the dry plant biomass was determined, by drying the material at 65 ^{o} C for 48 hours. Initial soil analyses were conducted before treatment application, then 12 months later, after the stabilization period (before the planting of the grass) with final analyses done after the last harvest, 24 months after the onset of the trial. The soil chemical analyses entailed, $pH_{(H2O)}$, P (Bray 1 Method) and K, Ca, and Mg (1:10 Ammonium Acetate Extraction Method). When the pot trial was complete, a destructive root study was conducted to determine the effect of treatments on the root development in the different substrates. The roots were sieved and washed and the dry root mass determined.

2.1 Statistical analyses

All dry matter production data and soil analyses were statistically analysed using PROC GLM (1996/1997 and 1997/1998). Statistical analyses were performed using SAS [9]. LSD's were taken at P≤0.05.

3. Results and discussion

This study entailed the measurement of both plant and soil parameters. Plant dry matter production data served as an indication of the benefits of alternative ameliorants on plant growth. Root biomass data was measured to obtain what affect alternative ameliorants had on root development, ultimately ensuring enhanced plant growth. Basic soil chemical analyses were conducted to try and explain the basic causes of changes in root development and ultimately plant production.

3.1 Dry Matter Production

Tables 4-6 clearly show that the ameliorant SLASH resulted in the most significant increases in dry matter production on all three substrates. The strong response on the more degraded soils may be partially ascribed to the organic carbon, which SLASH provides, in addition to the supply of macro-nutrients required for plant growth, as well as some micronutrients, which are supplied by the fly ash component. It is interesting to note that the lime treatments did not have as significant an effect on the dry matter production. This can possibly be because dolomitic lime has a relatively slow reaction period and after an initial effect the reactivity of the lime decreased over time.

Table 4: The influence of different soil amendments on the mean dry matter production of four harvests of *Cenchrus ciliaris* planted on cover soil.

Treatment	1st Harvest	2nd Harvest	3rd Harvest	4th Harvest	Mean
	g/plant	g/plant	g/plant	g/plant	g/plant
S Opt.	9.4 $_b$(+/-3.8)	15.0 $_a$ (+/-3.6)	13.0 $_a$ (+/-3.4)	7.0 $_{cd}$ (+/-2.7)	**11.1** $_b$
S Opt. +	13.9 $_a$ (+/2.5)	16.2 $_a$ (+/-3.5)	13.8 $_a$ (+/-3.4)	15.6 $_a$ (+/-3.9)	**14.9** $_a$
S Opt. -	11.2 $_a$ (+/- 2.2)	10.6 $_b$ (+/-1.1)	8.4 $_b$ (+/-2.0)	9.6 $_b$ (+/-1.1)	**10.0** $_b$
FA Opt.	8.3 $_b$ (+/- 2.4)	9.1 $_b$ (+/- 1.4)	10.2 $_b$ (+/-1.0)	9.3 $_b$ (+/-2.9)	**9.2** $_b$
FA Opt. +	11.0 $_a$ (+/- 2.4)	9.4 $_b$ (+/- 1.7)	8.7 $_b$ (+/- 1.7)	10.3 $_b$ (+/-1.8)	**9.9** $_b$
FA Opt. -	7.7 $_c$ (+/- 1.7)	10.8 $_b$ (+/- 1.9)	8.3 $_b$ (+/- 1.5)	9.1 $_b$ (+/-1.8)	**9.0** $_b$
L Opt.	8.5 $_b$ (+/- 1.6)	7.8 $_c$ (+/- 1.0)	6.5 $_c$ (+/- 1.2)	8.3 $_c$ (+/-1.1)	**7.8** $_c$
L Opt. +	8.9 $_b$ (+/- 2.0)	7.9 $_c$ (+/- 1.2)	7.1 $_c$ (+/- 0.9)	8.4 $_c$ (+/-1.5)	**8.1** $_c$
L Opt. -	6.9 $_c$ (+/- 0.6)	8.5 $_c$ (+/- 1.2)	7.2 $_c$ (+/- 1.3)	7.9 $_c$ (+/-1.7)	**7.6** $_c$
C	6.0 $_c$ (+/- 4.17)	8.1 $_c$ (+/- 5.4)	7.1 $_c$ (+/- 4.8)	6.8 $_d$ (+/-3.7)	**7.0** $_c$

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

The AMD impacted soil, which is the soil with the lowest soil pH of all the substrates evaluated, probably has the greatest limitation with respect to the availability of nutrients. With the significant increase in pH as a result of the class F fly ash and SLASH treatments, as shown in Figure 6, a higher availability of nutrients in soil can result, apart from the added benefit of nutrients supplied by the ameliorant itself. The high organic matter content of the SLASH ameliorant, due to the sewage sludge component, and the higher amounts of macro-nutrients in this ameliorant, are probably responsible for the significant increase in dry matter yield (Table 5) on this substrate.

Table 5: The influence of different soil amendments on the mean dry matter production of four harvests of *Cenchrus ciliaris* planted on AMD impacted soil.

Treatment	1st Harvest	2nd Harvest	3rd Harvest	4th Harvest	Mean
	g/plant	g/plant	g/plant	g/plant	g/plant
S Opt.	14.9 $_a$ (+/-2.7)	13.5 $_a$ (+/-1.8)	12.7 $_a$ (+/-1.5)	11.3 $_a$ (+/-1.9)	**13.1** $_a$
S Opt. +	17.9 $_a$ (+/-1.2)	15.2 $_a$ (+/-1.3)	13.7 $_a$ (+/-2.5)	12.9 $_a$ (+/-3.2)	**14.9** $_a$
S Opt. -	15.3 $_a$ (+/-3.9)	12.9 $_a$ (+/-1.3)	9.6 $_b$ (+/-2.5)	8.2 $_b$ (+/-3.2)	**11.5** $_b$
FA Opt.	9.2 $_b$ (+/-1.1)	7.9 $_b$ (+/-0.3)	7.4 $_b$ (+/-0.7)	6.1 $_c$ (+/-0.9)	**7.7** $_c$
FA Opt. +	10.1 $_b$ (+/-1.1)	8.2 $_b$ (+/-1.2)	7.5 $_b$ (+/-0.9)	7.1 $_{bc}$ (+/-0.9)	**8.2** $_c$
FA Opt. -	9.3 $_b$ (+/-2.1)	8.5 $_b$ (+/-1.7)	7.1 $_{bc}$ (+/-1.6)	7.2 $_b$ (+/-1.5)	**8.0** $_c$
L Opt.	7.1 $_c$ (+/-1.4)	6.4 $_c$ (+/-1.6)	5.9 $_c$ (+/-1.2)	5.1 $_c$ (+/-1.2)	**6.1** $_{de}$
L Opt. +	7.4 $_c$ (+/-1.5)	6.9 $_{bc}$ (+/-1.1)	6.1 $_c$ (+/-0.8)	6.0 $_c$ (+/-0.8)	**6.6** $_d$
L Opt. -	7.7 $_c$ (+/-1.6)	6.3 $_c$ (+/-1.2)	5.3 $_{cd}$ (+/-0.7)	4.9 $_d$ (+/-0.8)	**6.1** $_{de}$
C	6.3 $_c$ (+/-4.4)	5.5 $_c$ (+/-3.8)	5.0 $_d$ (+/-3.6)	4.6 $_d$ (+/-3.3)	**5.4** $_e$

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

The gold mine tailings material, which had a similar substrate pH to the mine cover soil, was, however, a more inert material. This material had very low levels of certain macronutrients, which has a significant affect on the growth of plants. The dry matter production on the gold mine tailings increased by 697% on the SLASH treated soils (Table 6).

The gold tailings were chemically unbalanced and they lacked organic matter, which could have improved physical and microbiological characteristics, which would provide a friendlier soil environment for plant roots to develop and then ultimately have a beneficial affect on plant growth. It is once again noted that the SLASH ameliorant with its sewage sludge organic component, had a remarkable affect on the plant growth in this material (Table 6). The different SLASH treatments did not, however, differ significantly.

Although there was a trend for improved yields with increased levels of SLASH (7.5, 7.8 and 8.6 respectively) this result did not justify the higher levels of SLASH.

Table 6: The influence of different soil amendments on the mean dry matter production of four harvests of *Cenchrus ciliaris* on gold mine tailings.

Treatment	1st Harvest	2nd Harvest	3rd Harvest	4th Harvest	Mean
	g/plant	g/plant	g/plant	g/plant	g/plant
S Opt.	10.7 a (+/-1.7)	8.7 a (+/-0.6)	6.6 a (+/-0.6)	5.3 a (+/-0.8)	**7.8** a
S Opt. +	11.2 a (+/-1.6)	9.3 a (+/-1.6)	7.3 a (+/-1.0)	6.4 a (+/-0.9)	**8.6** a
S Opt. -	9.5 a (+/-3.7)	7.8 a (+/-2.9)	6.8 a (+/-2.7)	5.8 a (+/-2.3)	**7.5** a
FA Opt.	4.7 b (+/-1.3)	3.8 c (+/-1.0)	2.9 c (+/-1.4)	2.4 c (+/-1.4)	**3.5** bc
FA Opt. +	6.2 b (+/-1.5)	4.8 b (+/-1.1)	4.4 b (+/-1.5)	3.6 b (+/-1.5)	**4.8** b
FA Opt. -	3.5 c (+/-0.8)	2.8 c (+/-0.7)	2.1 c (+/-0.5)	1.3 cd (+/-0.4)	**2.4** c
L Opt.	2.3 c (+/-0.7)	1.5 d (+/-0.7)	1.1 d (+/-0.7)	0.7 d (+/-0.3)	**1.4** de
L Opt. +	3.1 c (+/-0.9)	1.9 cd (+/-0.6)	1.6 cd (+/-0.6)	0.9 d (+/-0.4)	**1.9** d
L Opt. -	2.1 cd (+/-0.8)	1.1 d (+/-0.6)	0.9 d (+/-0.4)	0.5 d (+/-0.2)	**1.2** e
C	1.5 d (+/-1.0)	1.2 d (+/-0.8)	0.6 d (+/-0.5)	0.5 d (+/-0.4)	**1.0** e

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

The class F fly ash, although not having as beneficial an effect as SLASH, did provide additional essential micro-nutrients for plant growth and had beneficial affects on soil physical and microbiological characteristics, as has been reported by Truter (2007) [14]. This can be seen in Table 6 where the dry matter production was increased by a maximum of 370% by class F fly ash.

3.2 Root biomass study

The root study also provided significant results as it is shown in Tables 7-9. It is clear that although the SLASH treatment had the strongest influence it was only marginally better than FA. Root development is vital for stabilizing erodable substrates, and for increasing the efficiency of water and nutrient use.

Table 7: The effect of ameliorating treatments on the root biomass (g) of *Cenchrus ciliaris* on the mine cover soil

	Root biomass (g)							
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***R6***	**Mean**	*SE(+/-)*
S Opt.	64.8	37.5	43.6	29	51.3	50.8	**46.2**$_a$	(9.5)
S Opt. +	54.5	49.1	56.8	29.1	40	37.9	**44.6** $_a$	(8.9)
S Opt. -	37.9	40.7	38.6	39.2	35.8	22.3	**35.8** $_b$	(4.5)
FA Opt.	43.5	39.9	53.1	34.3	24.1	37.8	**38.8** $_a$	(5.9)
FA Opt. +	72.9	34.9	36.3	38.2	34.8	27.9	**40.8** $_a$	(12.4)
FA Opt. -	63.3	41.9	58.7	26.1	39	43.6	**45.4** $_a$	(10.4)
L Opt.	44	22.1	30	35.2	40.6	32.5	**34.1** $_b$	(5.9)
L Opt. +	40	31.8	37.3	28.1	36.4	32.4	**34.3** $_b$	(3.6)
L Opt. -	37.9	22.1	25.3	35.9	34.1	30.3	**30.9** $_{bc}$	(5.0)
C	37.1	21.4	28	16.6	22.9	34.6	**26.8** $_c$	(6.46)

***abc** Column means with common alphabetical subscripts do not differ significantly ($P> 0.05$) (Bonferroni Test)

The class F fly ash treatments applied to AMD impacted soils gave up to 40% better root mass than the control treatment. The SLASH treatment, however, had 185 % better root development. This strongly significant increase can definitely be ascribed to the combined function of improving the soil pH with the class F fly ash component, and providing the plant roots with the heightened ability to utilize the abundant macronutrients provided by the sewage sludge component and the micronutrients from the class F fly ash component. The possible improvement of a microbial population by improving the soil or substrate environment by changing the soil pH, or just the addition of organic matter may, however, have had additive effects [14].

Table 8: The effect of ameliorating treatments on the root biomass (g) of *Cenchrus ciliaris* on the AMD Impacted soil

	Root biomass (g)							
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***R6***	***Mean***	***SE(+/-)***
S Opt.	54.4	43	55.8	64.8	52.7	81.2	**58.7** $_{a}$	(9.6)
S Opt. +	56.9	50.4	87.7	50.2	81.4	92.3	**69.8** $_{a}$	(7.31)
S Opt. -	81.1	53.2	40.4	36	53.7	52.8	**52.9** $_{b}$	(9.8)
FA Opt.	44.3	36	19.4	27.6	32.7	17	**29.5** $_{c}$	(8.18)
FA Opt. +	45.1	37.6	29.7	36.6	31.8	26	**34.5** $_{c}$	(5.3)
FA Opt. -	54	18	38.6	14.4	25.6	23	**28.9** $_{cd}$	(11.6)
L Opt.	36	24.8	23.6	22.9	19.4	19.8	**24.4** $_{d}$	(6.65)
L Opt. +	52	24	18.6	24.7	31.3	21.5	**28.7** $_{cd}$	(8.65)
L Opt. -	30.4	31.4	34.2	13.6	30.8	31.8	**28.7** $_{cd}$	(5.03)
C	32	23.6	25.4	23.3	24.4	19	**24.6** $_{d}$	(2.7)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

While the SLASH and fly ash treatments applied to gold tailings, delivered extremely high root mass differences, of up to (S Opt +) 6133% and (FA Opt +) 833% more than the control, respectively, the lime treatment improved root biomass by only 167%. These improvements justify any addition of material that contains either some nutrients or organic matter, or even a different textured ameliorant, which can change the soil conditions, chemically, physically or microbiologically.

Table 9: The effect of ameliorating treatments on the root biomass (g) of *Cenchrus ciliaris* on the gold mine tailings

	Root biomass (g)							
Treatments	***R1***	***R2***	***R3***	***R4***	***R5***	***R6***	***Mean***	*SE(+/-)*
S Opt.	15.8	11.7	10.3	17	13	10.9	**13.1** b	(2.18)
S Opt. +	22.4	29.5	11.1	11.2	13.4	23.8	**18.7** a	(6.7)
S Opt. -	20.1	12.2	3.1	9.6	12.3	7.6	**10.8** b	(4.0)
FA Opt.	1.5	2.4	1.6	1.6	1.8	1.3	**1.7** c	(0.37)
FA Opt. +	3.6	1.9	3.1	1.8	3.4	2.8	**2.8** c	(0.56)
FA Opt. -	0.5	0.6	0.4	0.7	1.1	0.4	**1.5** cd	(0.3)
L Opt.	0.5	0.7	0.7	0.4	0.5	0.4	**0.5** d	(0.1)
L Opt. +	0.9	1	0.4	0.8	0.9	0.6	**0.8** d	(0.2)
L Opt. -	0.7	1.0	0.5	0.8	0.9	0.6	**0.7** d	(0.2)
C	0.3	0.3	0.3	0.2	0.4	0.4	**0.3** d	(0.1)

***abc** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

To explain the significant response of plants, on these degraded soils and substrates, to the ameliorants, it is essential that soils be analysed chemically, physically and microbiologically. In this investigation emphasis was on, chemical analyses, which are presented and discussed, to illustrate the benefits of applying alternative soil ameliorants to degraded soils as compared to conventionally used ameliorants, or no amelioration (C).

3.3 Soil analyses

The beneficial effects of FA on plants are at least partly as a result of the adjustment of soil pH of an acidic soil or substrate, hence supplying deficient nutrients, resulting in improved crop growth [13]. Each substrate under investigation had a different nature and condition, and hence soil ameliorants reacted differently in different substrates. The trends evident from amelioration effects are, however, similar for most degraded soils as will be noted in the following section.

3.3.1 Mine Cover Soil

The mine cover soil, with an initial soil $pH_{(H2O)}$ of 4.3, was a mixture of approximately 10cm of topsoil, with organic matter and a viable seed bank, and an underlying B horizon soil layer deficient in certain nutrients. The topsoil is often diluted and acidic due to the acid generated in the coal-mining environment.

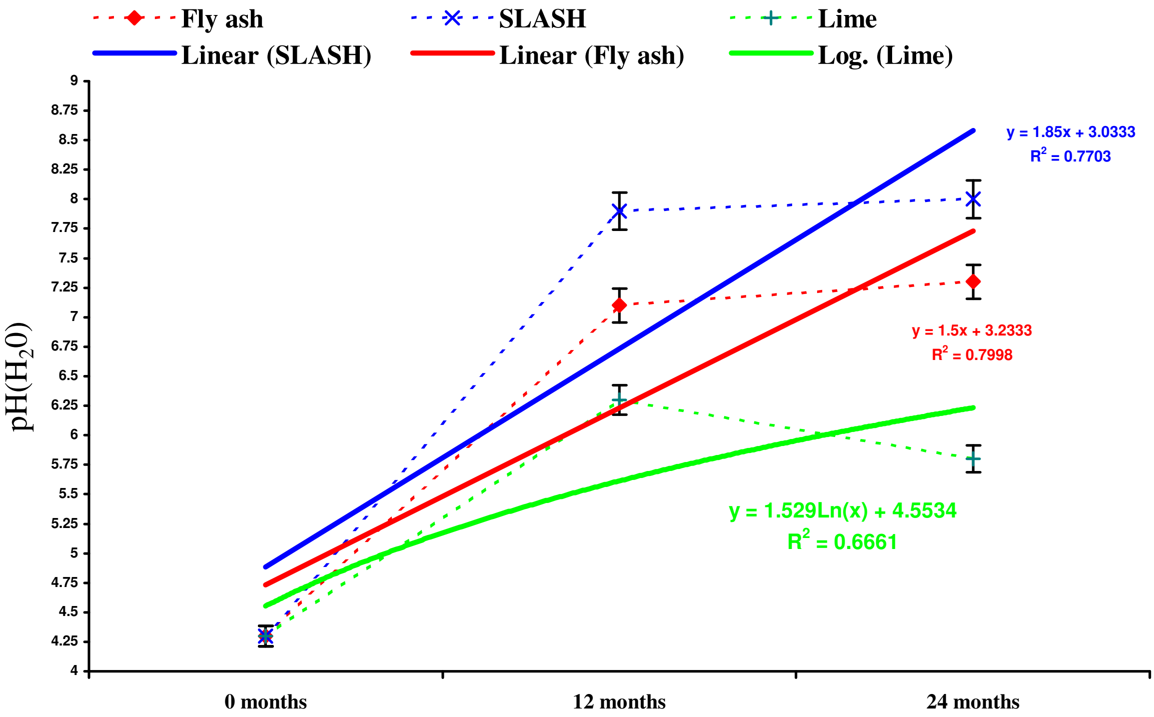

Figure 2: The comparative effect of three ameliorants (optimum levels) on the pH of a degraded mine cover soil over time.

In Figure 2, it is evident that both the SLASH and class F fly ash treatments had a strongly significant effect on the soil pH, raising it too much higher levels than was originally calculated. The calculation was based on the assumption that class F fly ash had only a 20% $CaCO_3$ equivalent, which would be sufficient to raise the soil pH to 6.5. The corrected pH of the soil, from 4.3 to approximately 7 for class F fly ash, indicates that class F fly ash may have a higher $CaCO_3$ equivalent than the 20%. The effect that SLASH had on the soil pH raising it to pH of 8.0 can be ascribed to the class F fly ash in addition to the CaO included in the SLASH mixture during processing. It is noted from

Figure 2 that the pH levels were at least maintained for 12 - 24 months by the class F fly ash and SLASH treatments and tended to increase, whereas, the pH of the lime treatment declined from 12 to 24 months. These results confirm the sustainability of such alternative ameliorants.

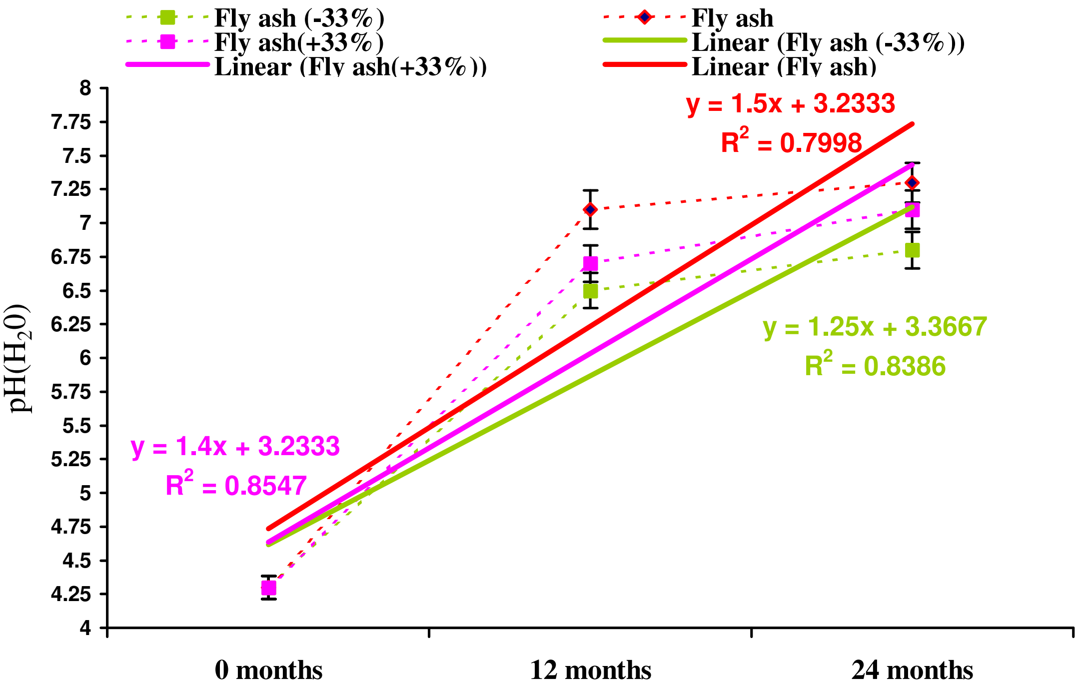

Figure 3: The effect of three different levels of class F fly ash on the pH of a degraded mine cover soil.

In Figures 3-5 the effect of different levels of fly ash, SLASH and dolomitic lime on the pH of the three substrates, is illustrated. It should be noted in Figure 3, that in the mine cover soil, the optimum level of fly ash had a more significant effect on soil pH, than the higher class F fly ash level, as had been expected. The assumption can possibly be made, as discussed in literature, that the reactive response of the soil ameliorant is also influenced by the cation exchange capacity (CEC). Soils with different cation exchange capacities will hence have a different reactive response to different soil ameliorants. This aspect requires further investigation, however, to substantiate this conclusion.

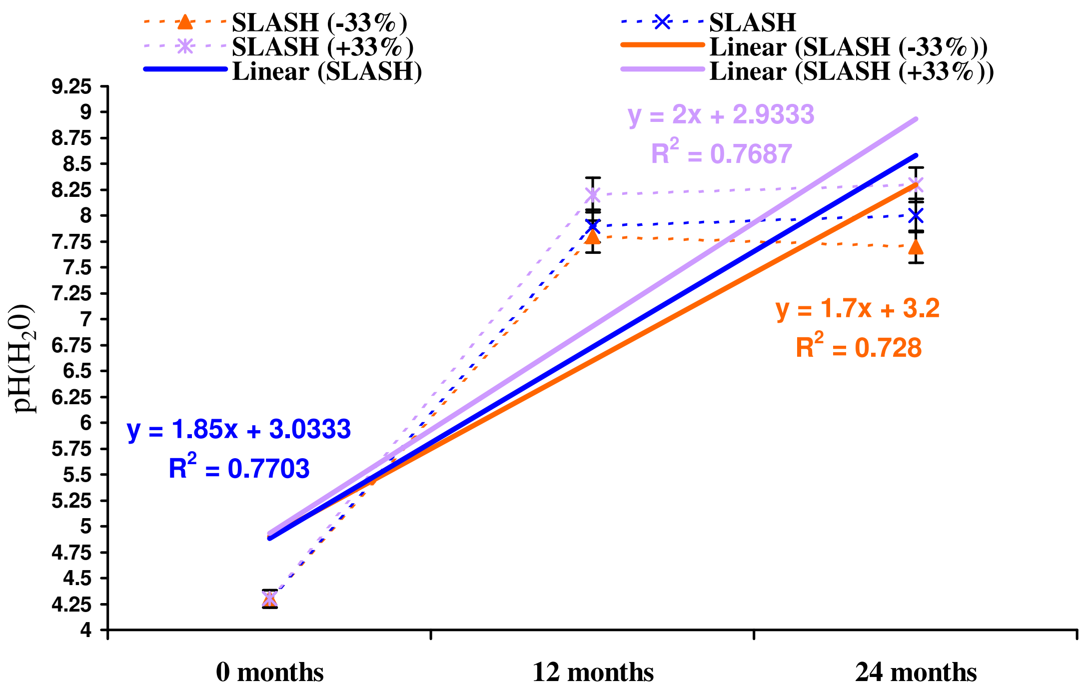

Figure 4: The effect of three different levels of SLASH on the pH of a degraded mine cover soil.

The significant affects of soil ameliorants on soil pH, as illustrated in many line graphs in this paper, clearly shows that this is not a short-term effect. Note that in the results presented, the affect that soil ameliorants have, has often decreased slightly over the period of 12 - 24 months. The dolomitic lime treatment has been the ameliorant with the highest drop in soil pH over the 12 – 24 month period. Previous research conducted by Truter (2002) [13], illustrated a similar long-term residual effect of the class F fly ash based treatments, which highlights the sustainability of using such ameliorants.

Figure 4 demonstrates that the different levels of SLASH had similar affects on the pH of the cover soil, with the increases correlated with the increase in the level of SLASH applied. The highest increase in soil pH of approximately 4 units is most significant, although, the optimum level of SLASH increased the soil pH by almost as much. This small difference between SLASH treatments, poses the question of whether the higher levels of SLASH can be economically justified.

The addition of lime to acidic degraded soils is the conventional method, and is very effective. The effect of lime, however, is limited to its affect on soil pH, with the addition of macro-nutrients being limited to Ca or Mg. Figure 5 illustrates that lime had a significant affect on the soil pH, raising it approximately 2 units. This affect, however, was not as prolonged, or as sustainable, as the other ameliorants. After a period of 12 months under cropping, the effect of lime declined markedly (Figure 5).

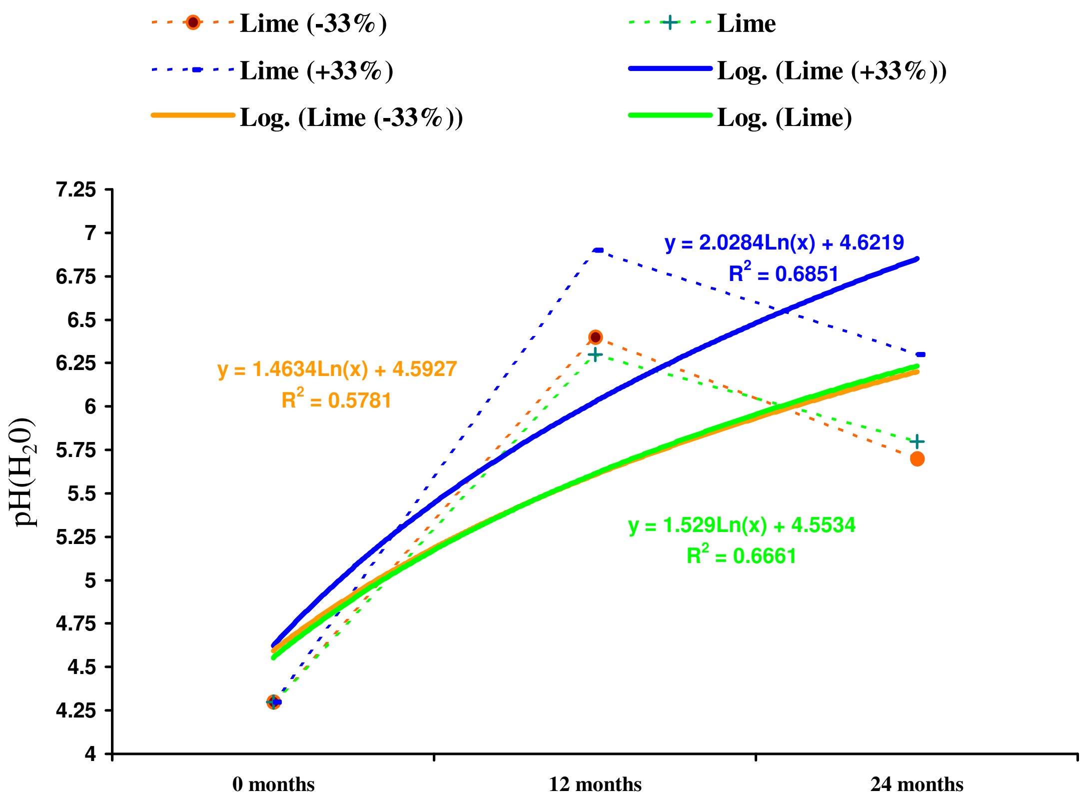

Figure 5: The effect of three different levels of agricultural dolomitic lime on the soil pH of a degraded mine cover soil.

With respect to important macronutrients (P, K, Ca and Mg) required for optimum plant growth, Tables 10-13 clearly indicates that the alternative ameliorant strategies can provide some of these nutrients. SLASH unfortunately is often devoid of the important macro-nutrient K (Table 11). This aspect, therefore, requires further investigation, to determine how an additional source of K, such as animal manures, can be incorporated into such a mixture. The SLASH treatments all contributed to higher levels of P in the mine soil. It is clear that the SLASH ameliorant also supplied large amounts of Ca, which could explain why this amendment improved the pH of the soils so markedly (Figure 4). The calcium levels of the mine cover soil were relatively low (Table 12), but with the addition of the different soil ameliorants these levels were raised significantly, especially by the SLASH treatments. The high amounts of Ca provided by the SLASH treatments are at least partly as a result of the CaO used in making SLASH.

Table 10: The influence of soil ameliorants on the phosphorus (P) content of a mine cover soil

Treatment	12 months	24 months
	mg kg^{-1}	mg kg^{-1}
S Opt.	27.4 $^{A}{}_{a}$ **(+/-2.7)**	19.7 $^{B}{}_{b}$ **(+/-3.4)**
S Opt. +	36.7 $^{A}{}_{a}$ **(+/-8.0)**	27.7 $^{B}{}_{a}$ **(+/-5.4)**
S Opt. -	21.0 $^{A}{}_{b}$ **(+/-5.8)**	14.6 $^{B}{}_{b}$ **(+/-4.3)**
FA Opt.	10.1 $^{A}{}_{bc}$ **(+/-1.2)**	7.2 $^{B}{}_{c}$ **(+/-1/0)**
FA Opt. +	13.0 $^{A}{}_{b}$ **(+/-1.9)**	8.7 $^{B}{}_{c}$ **(+/-1.6)**
FA Opt. -	7.1 $^{A}{}_{c}$ **(+/-0.8)**	5.3 $^{A}{}_{cd}$ **(+/-0.7)**
L Opt.	7.0 $^{A}{}_{c}$ **(+/-0.6)**	4.9 $^{A}{}_{cd}$ **(+/-0.4)**
L Opt. +	6.6 $^{A}{}_{c}$ **(+/-2.2)**	4.2 $^{A}{}_{d}$ **(+/-1.7)**
L Opt. -	3.0 $^{A}{}_{d}$ **(+/-1.0)**	2.0 $^{A}{}_{e}$ **(+/-0.6)**
C	2.5 $^{A}{}_{d}$ **(+/-0.9)**	1.8 $^{A}{}_{e}$ **(+/-0.4)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 11: The influences of soil ameliorants on the potassium (K) content of a mine cover soil.

Treatment	12 months	24 months
	mg kg^{-1}	mg kg^{-1}
S Opt.	18.8 $^{A}{}_{b}$ **(+/-1.6)**	9.8 $^{B}{}_{b}$ **(+/-5.1)**
S Opt. +	18.8 $^{A}{}_{b}$ **(+/-2.1)**	11.5 $^{B}{}_{b}$ **(+/-2.2)**
S Opt. -	17.2 $^{A}{}_{b}$ **(+/-1.9)**	9.9 $^{B}{}_{b}$ **(+/-1.2)**
FA Opt.	17.3 $^{A}{}_{b}$ **(+/-5.0)**	11.8 $^{B}{}_{b}$ **(+/-2.7)**
FA Opt. +	15.7 $^{A}{}_{bc}$ **(+/-4.0)**	12.5 $^{A}{}_{b}$ **(+/-2.9)**
FA Opt. -	14.7 $^{A}{}_{c}$ **(+/-1.9)**	9.2 $^{A}{}_{b}$ **(+/-3.5)**
L Opt.	24.2 $^{A}{}_{a}$**(+/-11.6)**	19.1 $^{A}{}_{a}$ **(+/-4.7)**
L Opt. +	16.7 $^{A}{}_{b}$ **(+/-4.6)**	12.4 $^{A}{}_{b}$ **(+/-3.1)**
L Opt. -	16.0 $^{A}{}_{b}$ **(+/-4.3)**	11.3 $^{A}{}_{b}$ **(+/-4.0)**
C	18.2 $^{A}{}_{b}$ **(+/-6.9)**	13.5 $^{A}{}_{b}$ **(+/-4.0)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

It is evident that in some instances a significant amount of Ca was either used or lost from the system, indicating a decreased amount of Ca over the 12 month in which cropping of the soils took place. In this respect *Cenchrus sp.* is known to have, a preference for soils with a high Ca content. Nevertheless, there is a significant amount of Ca remaining in the soils/substrate as seen in Tables (12, 16 and 20), and it is suggested that it be investigated whether such high levels of Ca can have a negative effect on plant growth or whether it can inhibit the utilization of other elements by the plants, which is not evident at this stage considering the strong plant growth on the SLASH treated soils.

Table 12: The influence of soil ameliorants on the calcium (Ca) content of a mine cover soil

Treatment	**12 months**	**24 months**
	mg kg^{-1}	mg kg^{-1}
S Opt.	2395.2^{A}_{a} **(+/-539.1)**	2203.0^{A}_{a} **(+/-430.1)**
S Opt. +	3046.3^{A}_{a} **(+/-599.0)**	2635.5^{B}_{a} **(+/-326.7)**
S Opt. -	1957.8^{A}_{b} **(+/-231.4)**	1771.8^{A}_{b} **(+/-299.3)**
FA Opt.	293.7^{A}_{c} **(+/-74.9)**	266.4^{A}_{c} **(+/-33.23)**
FA Opt. +	304.7^{A}_{c} **(+/-19.8)**	276.0^{A}_{c} **(+/-21.3)**
FA Opt. -	211.7^{A}_{c} **(+/-28.1)**	194.5^{A}_{c} **(+/-29.8)**
L Opt.	274.5^{A}_{c} **(+/-38.9)**	195.3^{A}_{c} **(+/-29.1)**
L Opt. +	272.7^{A}_{c} **(+/-92.2)**	216.8^{B}_{c} **(+/-45.8)**
L Opt. -	293.5^{A}_{c} **(+/-26.3)**	204^{B}_{cd} **(+/-71.1)**
C	149.7^{A}_{d} **(+/-24.7)**	129.0^{A}_{d} **(+/-50.3)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

In Table 11 it is noted that none of the soil ameliorants, used in this trial, contributed significantly to the K status of the mine cover soil. It may, therefore, be concluded that it will be essential to provide sufficient potassium if such soils are to be re-vegetated and the plant material utilized. With the removal of plant material, potassium levels became further depleted, although under grazing there would be an excellent re-cycling of K.

Table 13: The influence of soil ameliorants on the magnesium (Mg) content of a mine cover soil

Treatment	12 months	24 months
	mg kg^{-1}	mg kg^{-1}
S Opt.	$32.1^{A}{}_{b}$ **(+/-5.6)**	$23.1^{B}{}_{c}$ **(+/-4.3)**
S Opt. +	$31.5^{A}{}_{b}$ **(+/-10.0)**	$23.3^{B}{}_{c}$ **(+/-8.7)**
S Opt. -	$26.3^{A}{}_{bc}$ **(+/-6.6)**	$16.5^{B}{}_{c}$ **(+/-5.3)**
FA Opt.	$35.3^{A}{}_{b}$ **(+/-7.1)**	$26.1^{B}{}_{c}$ **(+/-7.1)**
FA Opt. +	$34.8^{A}{}_{b}$ **(+/-9.2)**	$24.4^{B}{}_{c}$ **(+/-7.3)**
FA Opt. -	$28.2^{A}{}_{b}$ **(+/-5.2)**	$21.1^{B}{}_{c}$ **(+/-2.9)**
L Opt.	$96.2^{A}{}_{a}$ **(+/-10.8)**	$80.3^{B}{}_{a}$ **(+/-8.1)**
L Opt. +	$122.3^{A}{}_{a}$ **(+/-20.6)**	$103.2^{B}{}_{a}$ **(+/- 15.8)**
L Opt. -	$79.8^{A}{}_{a}$ **(+/-7.5)**	$61.5^{B}{}_{b}$ **(+/-7.2)**
C	$20.8^{A}{}_{c}$ **(+/-3.5)**	$17.5^{B}{}_{c}$ **(+/-5.6)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

3.3.2 AMD Impacted Soil

The AMD impacted soil was much more degraded, and due to the water being contaminated by oxidized pyrite, the soil had a pH of only 3.4. It is evident from Figure 6 that SLASH had the most significant affect on the pH, raising it from 3.4 to just above 8.0. This significant response can be attributed to the effect the class F fly ash and the highly reactive lime (CaO), which were included in the SLASH.

All levels of class F fly ash (in Figure 7) had a significant affect on the soil pH. In comparison SLASH treatments (Figure 8), (which had additional CaO in its composition) increased the pH even further (8.2 vs 6.7). These data, demonstrate that class F fly ash can counteract acidity, especially in very acidic environments.

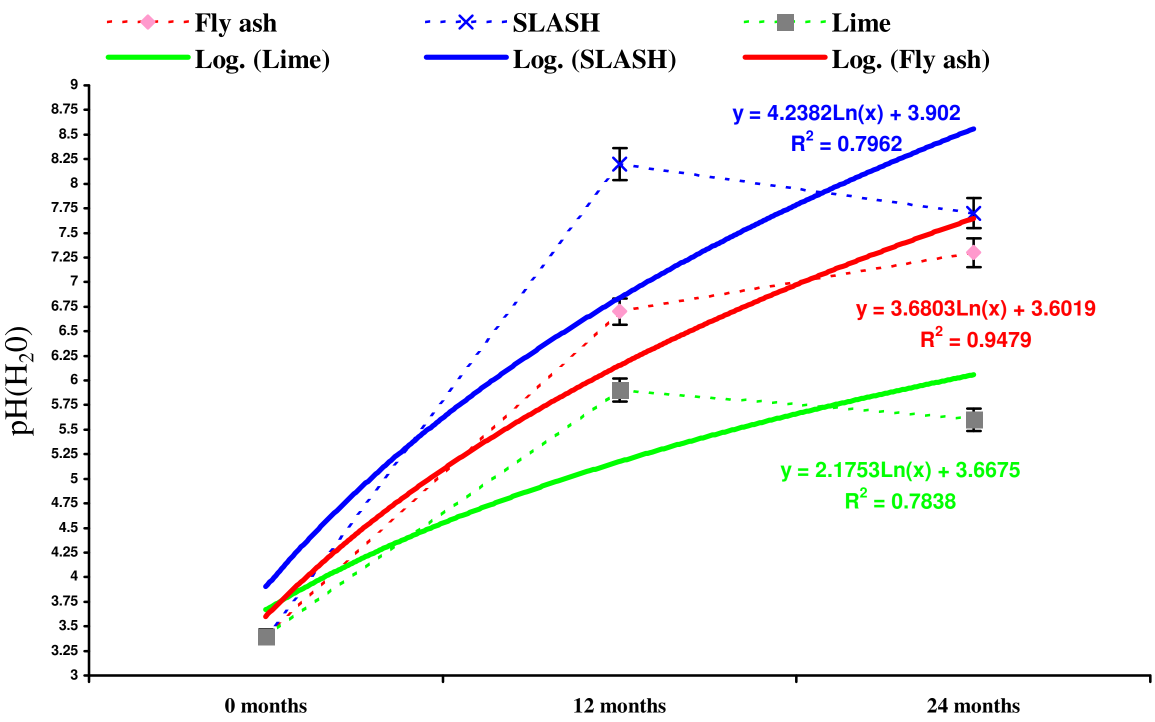

Figure 6: The comparative effect of three ameliorants on the pH of an AMD impacted soil

It can be assumed that the calcium silicates present in class F fly ash play a significant role in neutralizing the acidity (H^+) within the soil complex. The detailed soil chemistry required to establish the chemical functionality of class F fly ash within the acidic soil complex is required to better understand what the exact mechanism of acid neutralization is. This is currently being investigated in continuing research.

The SLASH treatments (Figure 8) resulted in highly significant increases in soil pH. This could, however, be a problem because the change to an alkaline condition could have a negative effect on the germination of certain seeds planted in such amended soils. This dramatic increase in soil pH can possibly be the result of too high applications of SLASH to the soil (because of an under-estimation of the neutralizing value of class F fly ash).

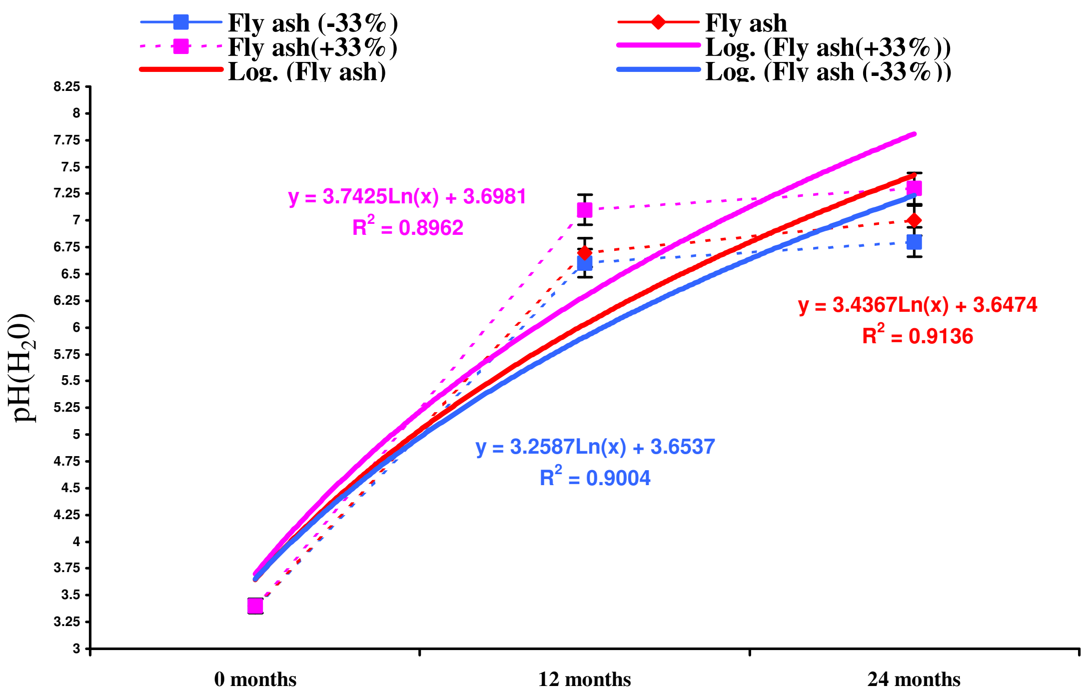

Figure 7: The effect of three different levels of class F fly ash on the soil pH of an AMD impacted soil

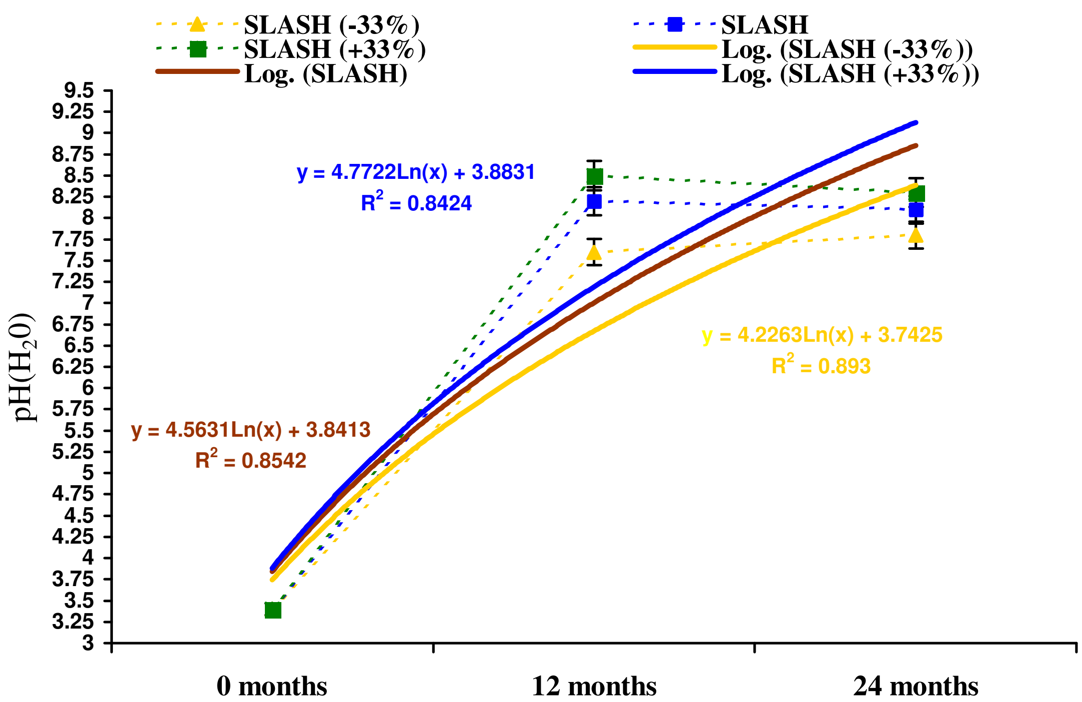

Figure 8: The effect of three different levels of SLASH on the pH of an AMD impacted soil

The lime treatment affects, as observed in Figure 9, illustrated the significant effect on the pH of AMD impacted soil. The highest level of lime (L Opt+), however, only raised the soil pH to just below 6.5 as was originally calculated for the optimum level lime required to raise the soils pH to 6.5. These slightly disappointing data may be ascribed to the poor reactivity of the lime as a result of either variability in lime quality or to an ineffective method of incorporation. In Table 13, however, it is noted that the dolomitic lime had a significant effect on the Mg content of the soil.

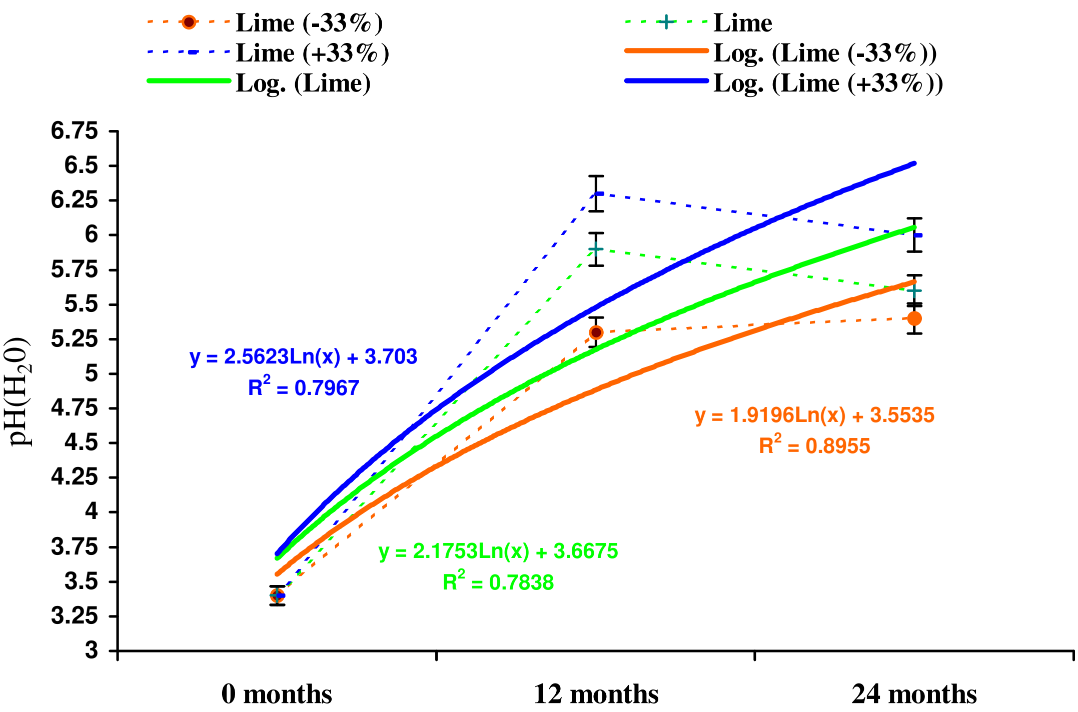

Figure 9: The effect of three levels of dolomitic lime on the pH of an AMD impacted soil

The neutralizing capacity of the ameliorant SLASH has proven itself. Both the fly ash and the lime components of the SLASH are responsible for this effect. Fly ash used in this trial had a neutralizing value in excess of 20%, and when combined with the CaO and sludge, it is estimated that the neutralizing value of the SLASH mixture was between 30 and 40% that of lime.

The soils, impacted by acid mine drainage, are normally very acidic and infertile. With respect to soil nutrient status, Table 14 indicates that both the fly ash and the SLASH contributed to the P status of the soil, relative to the control. The K level of the soil (Table 15), however, showed some improvement when treated with SLASH (Table 16). When compared to the previous mine cover soil, it can be seen that in the more degraded soil amelioration, evidently caused a different chemical reaction, making the small amount of K, which is in the ameliorant or in the soil, more available. The levels of K are, however, still very low and provision for extra K will have to be made. From Table 17 it is noted that while the fly ash and the SLASH treatments improved the Mg status by approximately 100%, the dolomitic lime had a much more dramatic effect because of the Mg in this lime source.

Table 14: The influence of soil ameliorants on the phosphorus (P) content of AMD impacted soil

Treatment	**12 months**	**24 months**
	mg kg^{-1}	mg kg^{-1}
S Opt.	$10.6^{A}{}_{c}$ **(+/-2.3)**	$8.0^{A}{}_{b}$ **(+/-3.8)**
S Opt. +	$14.0^{A}{}_{bc}$ **(+/-3.8)**	$9.8^{B}{}_{b}$ **(+/-2.0)**
S Opt. -	$11.6^{A}{}_{c}$ **(+/-2.1)**	$8.9^{A}{}_{b}$ **(+/-1.4)**
FA Opt.	$17.1^{A}{}_{b}$ **(+/-3.0)**	$13.4^{A}{}_{ab}$ **(+/-4.1)**
FA Opt. +	$28.5^{A}{}_{a}$ **(+/-2.8)**	$20.2^{B}{}_{a}$ **(+/-3.5)**
FA Opt. -	$12.6^{A}{}_{c}$ **(+/-2.6)**	$9.2^{A}{}_{b}$ **(+/-1.3)**
L Opt.	$1.5^{A}{}_{d}$ **(+/-0.3)**	$0.9^{A}{}_{c}$ **(+/-0.3)**
L Opt. +	$1.9^{A}{}_{d}$ **(+/-0.3)**	$1.3^{A}{}_{c}$ **(+/-0.1)**
L Opt. -	$1.4^{A}{}_{d}$ **(+/-0.2)**	$0.9^{A}{}_{c}$ **(+/-0.3)**
C	$2.1^{A}{}_{d}$ **(+/-0.5)**	$1.4^{A}{}_{c}$ **(+/-0.4)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)
***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

With respect to the Ca levels in the AMD impacted soil (Table 16), the significant contribution from the SLASH treatments was again noted. The significant level of Ca depletion over the cropping period was more evident in the AMD impacted soil than it had been in the cover soil. This leads to the possible conclusion that more Ca was involved in either the acid neutralization, or the plants, in the more degraded soil, utilized more calcium.

Table 15: The influence of soil ameliorants on the potassium (K) content of an AMD impacted soil

Treatment	**12 months**	**24 months**
	mg kg^{-1}	mg kg^{-1}
S Opt.	26.8^{A}_{a} **(+/-3.2)**	19.5^{A}_{a} **(+/-4.8)**
S Opt. +	27.7^{A}_{a} **(+/-4.7)**	19.7^{B}_{a} **(+/-4.3)**
S Opt. -	24.2^{A}_{a} **(+/-4.1)**	16.0^{B}_{ab} **(+/-3.6)**
FA Opt.	14.8^{A}_{b} **(+/-4.7)**	8.3^{A}_{c} **(+/-3.1)**
FA Opt. +	10.7^{B}_{c} **(+/-3.4)**	15.7^{A}_{b} **(+/-3.3)**
FA Opt. -	15.0^{A}_{b} **(+/-3.0)**	9.3^{A}_{c} **(+/-2.7)**
L Opt.	15.7^{A}_{b} **(+/-3.3)**	9.4^{A}_{c} **(+/-2.7)**
L Opt. +	15.3^{A}_{b} **(+/-4.1)**	9.8^{A}_{c} **(+/-3.7)**
L Opt. -	15.8^{A}_{b} **(+/-4.1)**	9.3^{A}_{c} **(+/-2.8)**
C	14.8^{A}_{b} **(+/-4.7)**	9.2^{A}_{c} **(+/-3.1)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 16: The influence of soil ameliorants on the calcium (Ca) levels of an AMD impacted soil

Treatment	**12 months**	**24 months**
	mg kg^{-1}	mg kg^{-1}
S Opt.	4471.1^{A}_{a} **(+/-469.2)**	4029.0^{B}_{a} **(+/-322.2)**
S Opt. +	4440.2^{A}_{a} **(+/-312.8)**	4102.7^{B}_{a} **(+/-459.2)**
S Opt. -	3958.7^{A}_{a} **(+/-303.9)**	3614.7^{B}_{a} **(+/-483.4)**
FA Opt.	532.2^{A}_{b} **(+/-73.7)**	458.7^{A}_{bc} **(+/-41.7)**
FA Opt. +	746.5^{A}_{b} **(+/-125.2)**	657.0^{B}_{b} **(+/-123.6)**
FA Opt. -	419.7^{A}_{bc} **(+/-42.1)**	333.0^{B}_{d} **(+/-42.3)**
L Opt.	478.5^{A}_{b} **(+/-44.7)**	403.8^{B}_{cd} **(+/-42.5)**
L Opt. +	544.0^{A}_{b} **(+/-37.3)**	427.7^{B}_{c} **(+/-29.3)**
L Opt. -	485.7^{A}_{b} **(+/-50.2)**	388.7^{B}_{cd} **(+/-49.3)**
C	356.0^{A}_{c} **(+/-60.8)**	283.5^{B}_{d} **(+/-66.1)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 17: The influence of soil ameliorants on the magnesium (Mg) content of an AMD impacted soil

Treatment	12 months	24 months
	mg kg^{-1}	mg kg^{-1}
S Opt.	52.0 $^{A}{}_{cd}$ **(+/-9.7)**	42.3 $^{B}{}_{cd}$ **(+/-9.8)**
S Opt. +	50.0 $^{A}{}_{cd}$ **(+/-9.5)**	43.5 $^{A}{}_{cd}$ **(+/-8.8)**
S Opt. -	43.8 $^{A}{}_{d}$ **(+/-7.8)**	34.8 $^{B}{}_{d}$ **(+/-11.3)**
FA Opt.	68.2 $^{A}{}_{c}$ **(+/-23.4)**	54.2 $^{B}{}_{c}$ **(+/-19.1)**
FA Opt. +	70.0 $^{A}{}_{c}$ **(+/-15.6)**	59.0 $^{B}{}_{c}$ **(+/-14.6)**
FA Opt. -	48.2 $^{A}{}_{cd}$ **(+/-10.8)**	36.3 $^{A}{}_{d}$ **(+/-10.3)**
L Opt.	188.3 $^{A}{}_{b}$ **(+/-38.0)**	165.5 $^{B}{}_{b}$ **(+/-29.8)**
L Opt. +	289.2 $^{A}{}_{a}$ **(+/-50.8)**	269.8 $^{A}{}_{a}$ **(+/-50.1)**
L Opt. -	170.8 $^{A}{}_{b}$ **(+/-54.8)**	155.5 $^{A}{}_{b}$ **(+/-48.5)**
C	25.3 $^{A}{}_{e}$ **(+/-9.6)**	18.0 $^{A}{}_{e}$ **(+/-7.7)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

3.3.3 Gold Mine Tailings

The gold mine tailings, although not classified as a soil, must serve as a growing medium for plants, during the reclamation process. This material is acidic in nature and can contain certain heavy metals, which can become available at low pH values [13]. Ideally the pH of this material should be raised to prevent any leaching of heavy metals or trace elements which are hazardous to the environment, and simultaneously create a more plant friendly environment, so as to reduce or prevent erosion. Figure 10, illustrates how SLASH, class F fly ash and dolomitic lime affected the pH of the material.

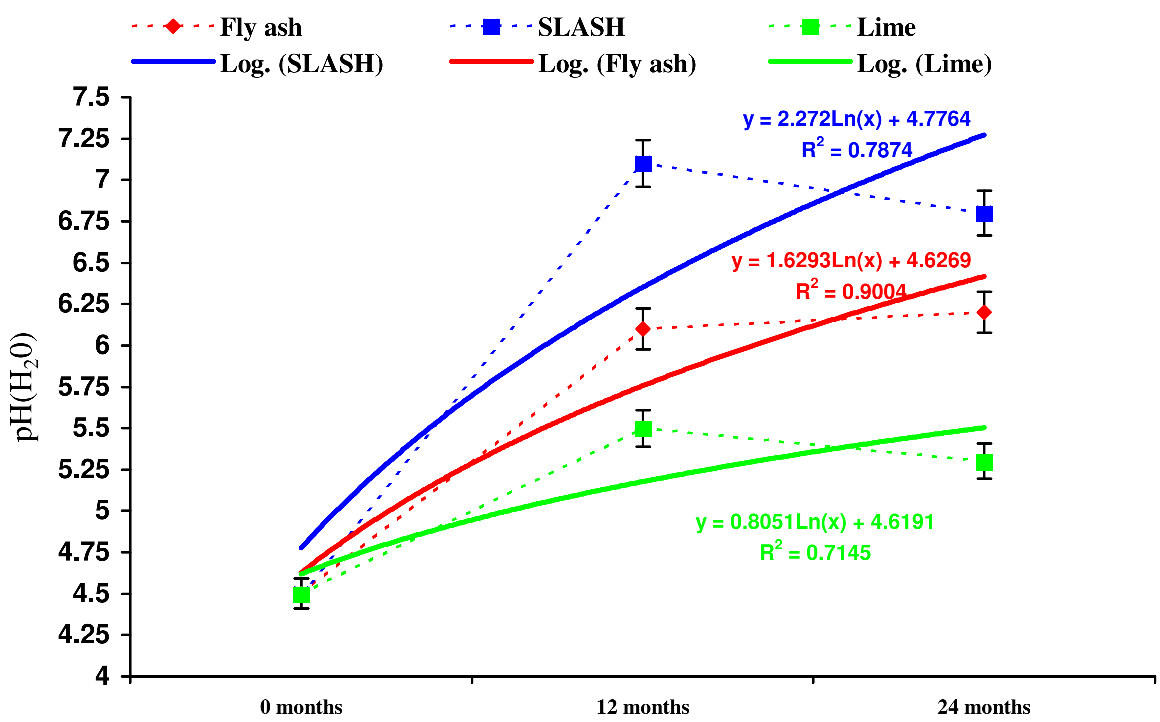

Figure 10: The comparative effect of three ameliorants on the pH of gold mine tailings

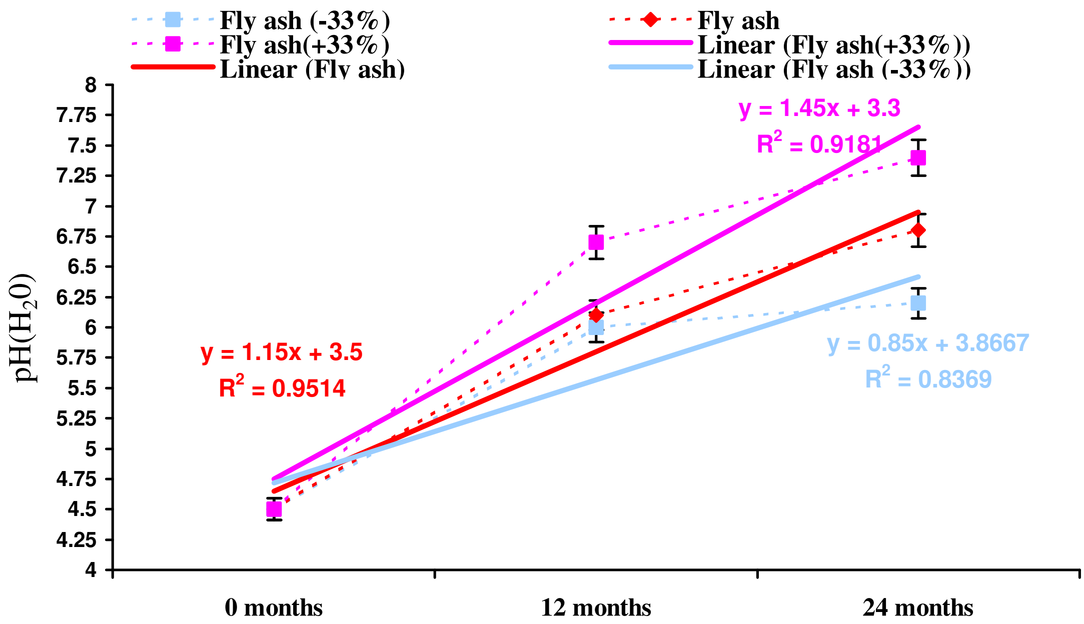

Figure 11: The effect of three different levels of class F fly ash on the soil pH of gold mine tailings

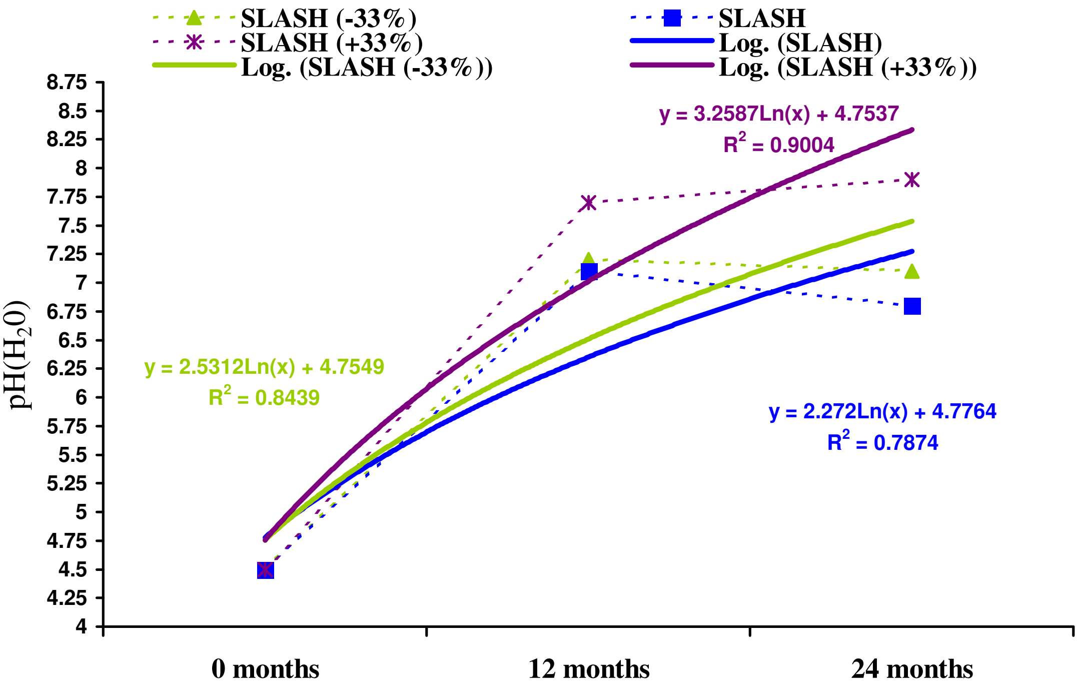

Figure 12: The effect of three different levels of SLASH on the pH of gold mine tailings

It was notable that the effect of the lime treatments, observed in Figure 13, decreased over the 12 month period during which the cropping took place, in comparison with an increased affect on the class F fly ash (Figure 12) treatments. These data illustrates the residual alkalinity present in the class F fly ash, resulting in more sustainable effects.

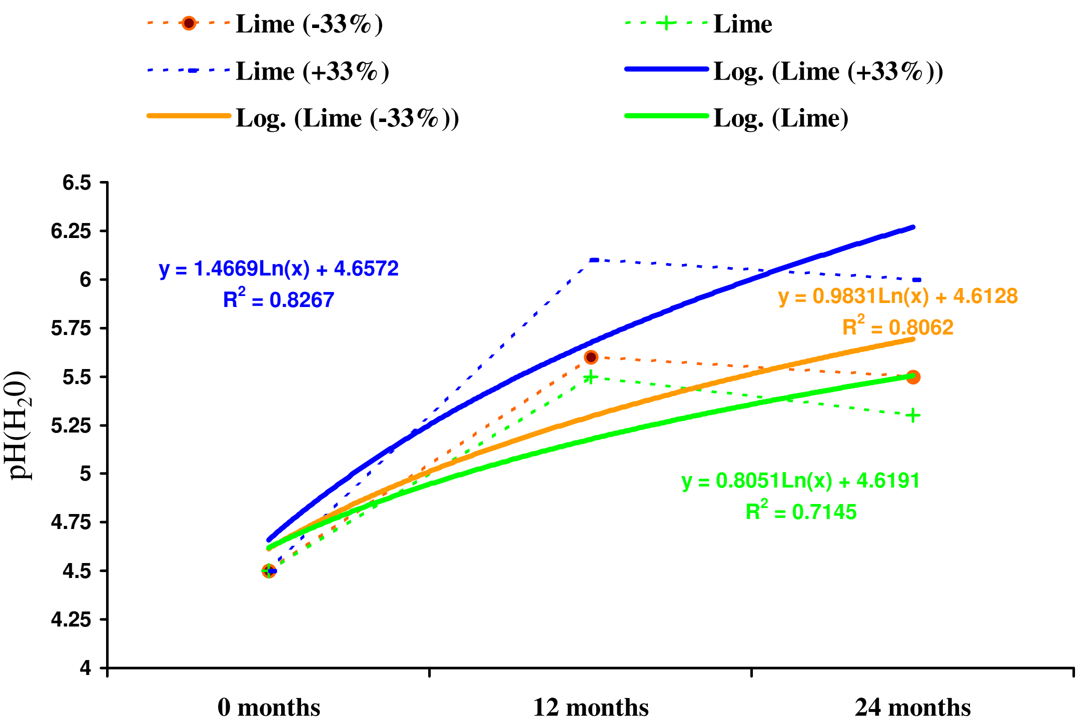

Figure 13: The effect of three levels of dolomitic lime on the pH of gold mine tailings

The pH of gold tailings is normally very low, and will often not sustain vegetation. It is noted from Figures 11 and 12 that the class F fly ash and SLASH undoubtedly improved the pH. This improvement in pH is also reflected in the growth enhancing effects of these ameliorants based on class F fly ash. Alkaline FA is most frequently used for its acid neutralizing potential, through hydrolysis of CaO and MgO [1] and the weathering of Al_2SiO_5 [10]. The degree of neutralization is dependent on the difference in pH between FA and soil, soil buffering capacity and FA neutralizing capacity, as determined by the amounts of CaO, MgO and Al_2SiO_5 present.

Numerous findings, in India, support the general findings of international literature, and conclude that fly ash on different occasions will improve soil pH, Ca, Mg and certain micronutrients levels in acidic soil [2; 4], as is the case in most of the data, presented in this paper. With respect to the effect of soil ameliorants on the nutrient status of the gold tailings, the results in Table 18 are very similar to those obtained with the AMD polluted soil. It is clear that both the SLASH and fly ash improved the P status by 100% or more. These levels are, however, still very low and will not necessarily sustain plant growth for extended periods, indicating a need for supplementary fertilization.

Table 18: The influence of different soil ameliorants on the phosphorus (P) content of gold tailings

Treatment	**12 months**	**24 months**
	mg kg^{-1}	mg kg^{-1}
S Opt.	2.4^{A}_{b} **(+/-1.8)**	1.5^{B}_{b} **(+/-1.1)**
S Opt. +	3.9^{A}_{a} **(+/0.7)**	2.6^{B}_{a} **(+/-0.6)**
S Opt. -	2.9^{A}_{b} **(+/-1.3)**	2.3^{A}_{a} **(+/-1.1)**
FA Opt.	3.1^{A}_{b} **(+/-0.8)**	1.9^{B}_{ab} **(+/-0.7)**
FA Opt. +	4.0^{A}_{a} **(+/-2.0)**	2.5^{B}_{a} **(+/-1.4)**
FA Opt. -	3.5^{A}_{ab} **(+/-2.1)**	2.4^{B}_{a} **(+/-1.8)**
L Opt.	0.8^{A}_{c} **(+/-0.2)**	0.4^{B}_{c} **(+/-0.1)**
L Opt. +	0.5^{A}_{c} **(+/-0.1)**	0.2^{B}_{c} **(+/-0.1)**
L Opt. -	0.5^{A}_{c} **(+/-0.1)**	0.3^{A}_{c} **(+/-0.1)**
C	0.7^{A}_{c} **(+/-0.9)**	0.6^{A}_{c} **(+/-)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

With respect to the K status (Table 19), both fly ash and lime improved the soil content, but not to the same extent as SLASH. These data illustrate how different substrates react differently to different ameliorants. The K present in either the gold tailings or SLASH ameliorant evidently became available, as a result of a chemical reaction that did not take place in the cover soil. This increase in available K, and to some extent P, substantiates the significant enhancement of plant growth by applications of SLASH observed in this study.

Table 19: The influence of different soil ameliorants on the potassium (K) content of gold tailings

Treatment	**12 months**	**24 months**
	mg kg^{-1}	mg kg^{-1}
S Opt.	$100.2^{A}{}_{b}$ **(+/-37.2)**	$77.8^{B}{}_{b}$ **(+/-34.5)**
S Opt. +	$151.8^{A}{}_{a}$ **(+/-18.5)**	$123.8^{B}{}_{a}$ **(+/-15.5)**
S Opt. -	$61.2^{A}{}_{c}$ **(+/-19.2)**	$43.7^{B}{}_{c}$ **(+/-16.9)**
FA Opt.	$8.2^{A}{}_{d}$ **(+/-3.5)**	$4.9^{A}{}_{d}$ **(+/-2.1)**
FA Opt. +	$9.0^{A}{}_{d}$ **(+/-3.1)**	$6.1^{A}{}_{d}$ **(+/-4.9)**
FA Opt. -	$7.3^{A}{}_{d}$ **(+/-3.0)**	$4.9^{A}{}_{d}$ **(+/-1.9)**
L Opt.	$7.3^{A}{}_{d}$ **(+/3.0)**	$4.9^{A}{}_{d}$ **(+/-1.9)**
L Opt. +	$10.7^{A}{}_{d}$ **(+/-4.3)**	$7.0^{A}{}_{d}$ **(+/-2.3)**
L Opt. -	$7.7^{A}{}_{d}$ **(+/-3.7)**	$4.9^{A}{}_{d}$ **(+/-2.8)**
C	$3.6^{A}{}_{e}$ **(+/-1.3)**	$1.9^{A}{}_{e}$ **(+/-0.9)**

***AB** Row means with common alphabetical superscripts do not differ significantly ($P > 0.05$) (Bonferroni Test)
***ab** Column means with common alphabetical subscripts do not differ significantly ($P > 0.05$) (Bonferroni Test)

The Ca levels of the tailings (Table 20) were initially very high, which is ascribed to the addition of Ca through the liming process of tailings material before disposal. The higher Ca levels of SLASH amended soils, are also attributed to inclusion of CaO in the SLASH mixture, because the Ca levels of the fly ash treatment's were not that different from the control.

Table 20: The influence of different soil ameliorants on the calcium (Ca) content of gold tailings

Treatment	12 months	24 months
	mg kg^{-1}	mg kg^{-1}
S Opt.	5033.3^{A}_{a} **(+/-653.4)**	4546.3^{B}_{b} **(+/-718.2)**
S Opt. +	6155.5^{A}_{a} **(+/-507.9)**	5413.5^{B}_{a} **(+/-686.2)**
S Opt. -	5368.5^{A}_{a} **(+/-795.2)**	4890.2^{B}_{ab} **(+/-830.1)**
FA Opt.	2969.8^{A}_{b} **(+/-574.1)**	2503.0^{B}_{c} **(+/-605.1)**
FA Opt. +	2313.7^{A}_{b} **(+/-541.5)**	1819.8^{B}_{cd} **(+/-450.4)**
FA Opt. -	2598.0^{A}_{b} **(+/-787.3)**	2093.2^{B}_{c} **(+/-643.9)**
L Opt.	2298.5^{A}_{b} **(+/-563.3)**	1832.8^{A}_{c} **(+/-511.47)**
L Opt. +	2445.0^{A}_{b} **(+/-799.0)**	2052.8^{B}_{c} **(+/-852.3)**
L Opt. -	2010.0^{A}_{b} **(+/-319.0)**	1530.5^{B}_{d} **(+/-301.1)**
C	2222.8^{A}_{b} **(+/-387.4)**	1679.8^{B}_{d} **(+/-405.4)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 21: The influence of different soil ameliorants on the magnesium (Mg) content of gold tailings

Treatment	12 months	24 months
	mg kg^{-1}	mg kg^{-1}
S Opt.	153.8^{A}_{c} **(+/- 51.8)**	132.0^{A}_{b} **(+/-45.7)**
S Opt. +	184.2^{A}_{c} **(+/-30.2)**	149.0^{B}_{b} **(+/-38.8)**
S Opt. -	146.8^{A}_{c} **(+/-50.7)**	123.3^{A}_{b} **(+/-46.7)**
FA Opt.	291.7^{A}_{b} **(+/-77.1)**	243.0^{B}_{a} **(+/-74.7)**
FA Opt. +	292.2^{A}_{b} **(+/- 82.6)**	234.7^{B}_{a} **(+/-76.5)**
FA Opt. -	368.7^{A}_{a} **(+/-110.1)**	307.2^{B}_{a} **(+/-88.5)**
L Opt.	326.5^{A}_{a} **(+/-52.7)**	266.8^{B}_{a} **(+/-52.2)**
L Opt. +	293.0^{A}_{b} **(+/- 42.0**	235.0^{B}_{a} **(+/-40.1)**
L Opt. -	290.5^{A}_{b} **(+/-24.7)**	234.1^{B}_{a} **(+/-29.3)**
C	225.0^{A}_{b} **(+/-53.0)**	159.3^{B}_{b} **(+/-58.5)**

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

In Table 21, it is noted that the natural levels of Mg are relatively high, as a result of the Mg SO_4, which is used in the gold mining process. Generally it is expected that Mg levels rise with the addition of dolomitic lime, however, there was no significant change in the gold tailings Mg levels when lime or fly ash was applied. It was interesting to note that the SLASH treatments had a depressing effect on the Mg levels of the tailings material. This can possibly be as a result of Mg participating in the complex chemical interactions caused by the addition of organic matter via sewage sludge to the tailings material, however this remains to be investigated.

4. Conclusion

Mine soils and mining wastes are generally infertile and are more acidic than natural topsoils. They will, therefore, benefit from the addition of organic wastes and an amendment with neutralizing potential. A variety of organic waste materials are available for this purpose. In particular, municipal biosolids are freely available. Animal manures can also serve as a source of organic material and certain essential macro-nutrients, (such as K), which are often lacking in biosolids. The fly ash treated soils have also given excellent results in terms of improved pH, indirectly stimulating the growth of plants. These waste materials, unfortunately, vary greatly in nutrient content, trace metals and liming potential, and these factors can affect both re-vegetation success and the environmental impact of reclamation. It can be concluded, that the class F fly ash used in this experimental work does have a higher $CaCO_3$ equivalent than what is referenced in the literature. This conclusion is based on the significant increases in soil pH and soil root biomass resulting in enhanced plant growth.

It is, therefore, imperative to combine careful analysis of both the organic material and the mine soil to which it is to be applied. The pH of the soil or substrate must be controlled to limit heavy metal mobility and ensure long-term vigour of the plant community. To reclaim a degraded soil is a major challenge, and is usually a very expensive process and it is often difficult to establish a sustainable system. The problems that many countries face, in terms of waste disposal, could possibly become solutions for many of the problems experienced in reclaiming mined soils.

The pot trials discussed in this paper indicate that there is definitely a potential for using waste products, or mixtures thereof, such as SLASH and similar waste mixtures, to reclaim degraded soils. From other work done on acidic agricultural soils, the residual effects of SLASH have been measured for up to seven years. It is expected that SLASH and class F fly ash will have the same residual effect on the more acidic soils, and this will determine how sustainable such ameliorants are in reclaiming degraded soils and substrates.

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CHAPTER 5

Prepared according to the guidelines of Agriculture, Ecosystems & Environment

The beneficiation of degraded mine land using Class F Fly ash and sewage sludge to ensure sustainable vegetation

Truter, W.F[a*]., Rethman, N.F.G., Kruger, R.A., Reynolds, K.A. and de Jager, P.C.

[a] Department of Plant Production and Soil Science, University of Pretoria, Pretoria, South Africa.

Abstract

Strip mining of coal is widespread in the grassland areas of the Mpumalanga Province in South Africa. To ensure healthy and productive vegetation during the reclamation process, disturbed soils often need to be ameliorated. To date, conventional methods of liming and fertilization, to improve the productivity of impacted soils, have been standard practices. This process is, however, very expensive and is not necessarily sustainable.

Fortunately, South Africa has an abundance of industrial and organic by-products, which might be used as alternative ameliorants. Fly ash, a coal combustion byproduct (CCB), either by itself, or together with other wastes such as biosolids, can serve as a soil ameliorant by providing a good source of micro-, macronutrients and organic material for the reclamation of land to different capability classes. Fieldwork initiated in November 1999 on a surface mine, has provided a number of significant results. Soil analyses (P, K, Mg, Ca, $pH_{(H20)}$) were conducted annually, whereas botanical composition, basal cover measurements and dry matter production data was collected seasonally.

Results demonstrate that fly ash has improved soil conditions, and enhanced the growth of the various sub-tropical grasses such as Teff (*Eragrostis tef*), Rhodegrass (*Chloris gayana*), Bermuda grass (*Cynodon dactylon)*, Smutsfinger grass (*Digitaria eriantha),* and a legume such as Lucerne /Alfalfa (*Medicago sativa).* Results clearly illustrate that the abundance of certain species can be related to the higher fertility levels of the rehabilitated soil. Data collected over the past seven years, illustrates how the botanical composition has changed, and that soils receiving class F fly ash and sewage sludge had a higher dry matter production, whereas the control (no treatment) had a better biodiversity.

Results obtained, support the conclusion that the chemical properties of soils receiving fly ash and sewage sludge were improved.

* Corresponding author: Tel: +27 12 420 3226; Fax no.: +27 12 420 4120
Email address: wayne.truter@up.ac.za

This research demonstrates that potential alternative ameliorants, such as the bituminous CCB - class F fly ash and biosolids, can provide a more sustainable way to solve one environmental problem with another.

Keywords: Class F fly ash, sewage sludge, botanical composition, legumes, soil amelioration, sub-tropical grasses, basal cover, dry matter production

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1. Introduction

The re-vegetation of mined land presents a particular challenge because cover soils are often acidic and nutrient deficient. These conditions present major limiting factors in re-vegetation programs. It is current practice to amend such soils using lime and inorganic fertilizer. Research over the past 8-10 years into the use of a coal combustion by-product (CCB's) - class F fly ash, and an organic material such as sewage sludge, has demonstrated the feasibility of using such materials to amend acidic and infertile substrates (Norton *et al.,* 1998; Truter and Rethman, 2002; Truter, 2002). The objective of this research was to determine if alternative amendments could create a more sustainable system, in which botanical composition, basal cover, plant productivity and soil chemical properties were improved. Coal mining impacts large areas in the grasslands of the Mpumalanga Province of South Africa. To mitigate such impacts, it is imperative to restore the once productive soils to the best possible condition.

There have been many investigations, which have studied re-vegetation and soil conditions on reclaimed or rehabilitated mine land. It is imperative that topsoil used in reclaiming surface coalmines, must be intended to act as seedbank, and should not be stockpiled (Schuman, 2002), however, this approach is not easily adopted due to economic reasons. For successful re-vegetation it is important to ensure a stable, soil environment with respect to physical conditions (Turner, 1995; Fox *et al.,* 1998, Schuman, 2002), chemical conditions (Bradshaw *et al.,* 1986; Fox *et al.,* 1998; Schuman, 2002) and biological conditions (Bentham *et al.,* 1992; Fox *et al.,* 1998; Truter*,* 2007).

Coal combustion by-products (CCB's) have been widely used as cost effective amendments for acid soils. It is true that ashes have several advantages, and that their application is recommended (Katsur and Haubold-Rosar, 1996, Truter, 2002). The work conducted at the University of Pretoria has been successful in improving soil acidity and fertility (Reynolds *et al.*, 1999*;* Rethman *et al.,* 2000 a,b; Truter *et al.,* 2001; Truter, 2002; Truter and Rethman, 2003).

2. Materials and Methods

A replicated field trial in a randomized block design, with five replications (R1-R5) of an untreated control and nine soil amendments of cover soil (consisting of a mixture of A and B horizons), with an average depth of 60 cm, was conducted over a seven year period on a surface strip coal mine at Kromdraai Colliery, Mpumalanga Province, situated at 29^{o}06' N 25^{o}75' E and 1500m above sea level. The area receives a summer rainfall of 600-700 mm and experiences dry frosty winters. The treatments involve three levels of fly ash (FA), sewage sludge/ fly ash mixture (SLASH) (S) (Reynolds *et al.,* 1999;Truter, 2002) and dolomitic lime (L). The optimum lime application rate was based on the buffering capacity of the substrate which was determined by using a $Ca(OH)_2$ titration solution. The mine cover soil had a $pH_{(H2O)}$ of 4.3. It was calculated, from the buffer curve, that the mine cover soil required 10 tons ha^{-1} of dolomitic lime [L Opt.] to raise the pH of the soil to a $pH_{(H2O)}$ of 6.5, ideal for plant growth.. The optimum level of fly ash [FA Opt.], 50 tons ha^{-1}, was based on the assumption (from literature) that class F fly ash had a $CaCO_3$ equivalent of 20% (Truter, 2002), and hence five times the amount of $CaCO_3$ required neutralizing acidity. The optimum SLASH [S Opt.] of 166 tons ha^{-1} was calculated from the ratio of FA, S and L (6:3:1 on a wet basis) used in the process of making SLASH (Reynolds *et al.*, 1999). The class F FA and SLASH treatments were compared to the aforementioned control and three lime treatments. The other two levels of treatment were 33% above the optimum and 33% below the optimum. The untreated control **(C)** and a standard mine treatment **(SMT)** were included to serve as yardsticks. All treatments were applied once only in 1999 (the establishment season), at the beginning of the trial.

The quantities of fertilizer and lime used in the standard mine treatment in the establishment year were, 65 kg N ha^{-1}, 203 kg P ha^{-1}, 134 kg K ha^{-1} in the form of limestone ammonium nitrate, super phosphate and potassium chloride and four tons of dolomitic lime per hectare. In subsequent years 100 kg N ha^{-1} was applied each spring to SMT with applications of 2000 kg of lime and 250 kg K every two years.

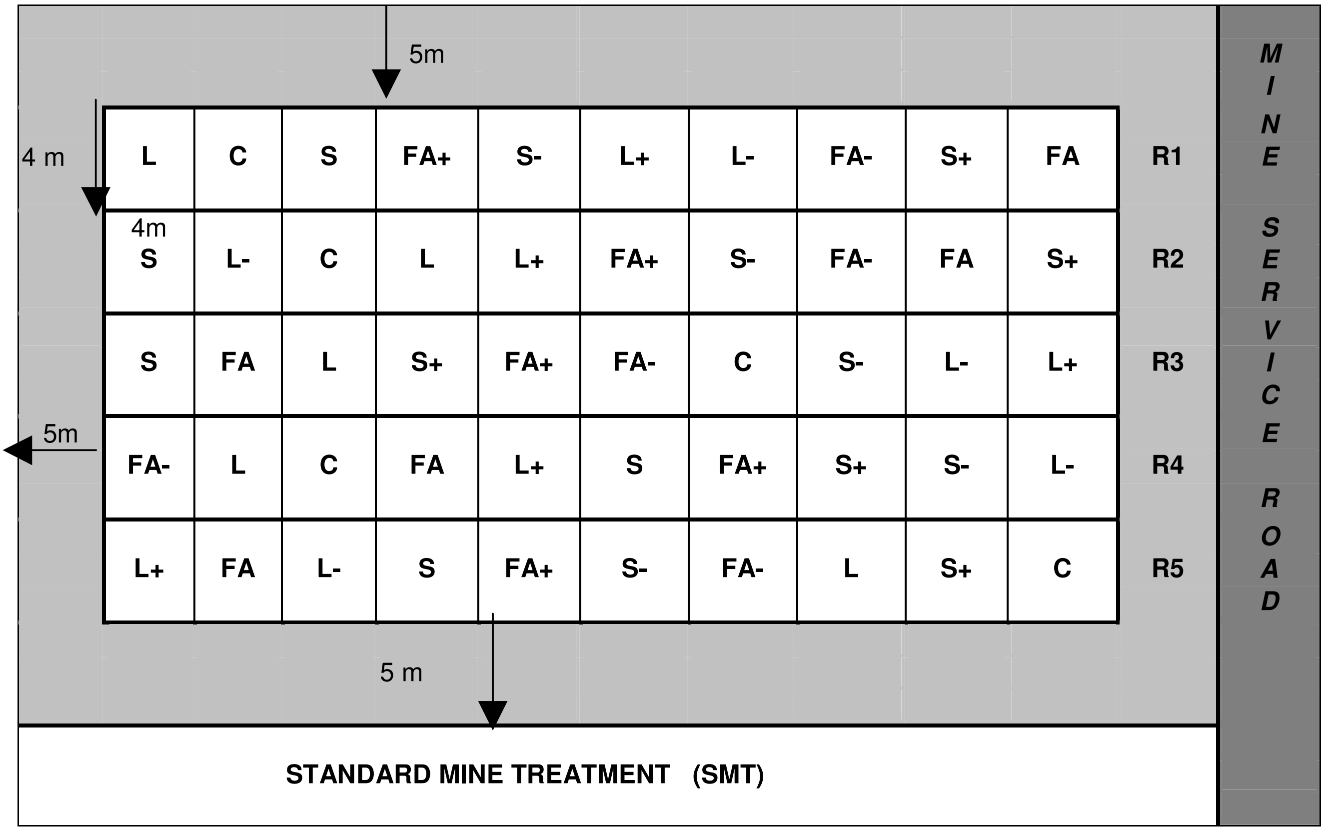

Figure 1: Experimental trial layout at Kromdraai Colliery

Figure 2: Establishment of field trial at Kromdraai colliery

The dry matter production in each season was measured by harvesting the material and drying it at 65 ^{o} C for 48 hours. The basal cover measurement was determined by using the point bridge method. Botanical composition was determined using the Step Point Method with 100 points per plot (Tainton *et al.,* 1980; Van Rooyen *et al.,* 1996).

Botanical composition, basal cover and dry matter production were monitored seasonally. Soils were seeded with a mixture of Teff (*Eragrostis tef)*, Rhodesgrass (*Chloris gayana),* Bermuda grass (*Cynodon dactylon)*, Smutsfinger grass (*Digitaria eriantha)* and lucerne [alfalfa] (*Medicago sativa)* at a combined seeding rate of 40 kgha^{-1}.

After the initial soil analysis, pH(H_2O), P (Bray 1) and K, Ca, and Mg (Ammoniun acetate extraction) were conducted 12, 24, 36, 48, 60 and 72 months after establishment.

2.1 Statistical analyses

All dry matter production data and soil analyses were statistically analysed using PROC GLM (1996/1997 and 1997/1998). Statistical analyses were performed using SAS, (SAS Ins., 1998). LSD's were taken at $P \leq 0.05$.

3. Results and discussion

3.1 Vegetation analysis

Botanical composition, basal cover and dry matter production were assessed each year with the results over 72 months being presented in this paper.

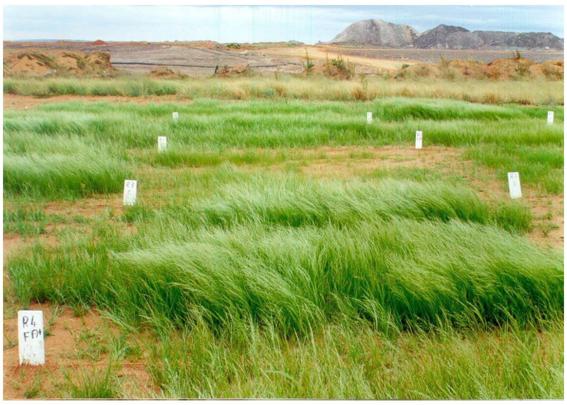

Figure 3: The vigorous growth of *Eragrostis tef* eight weeks after soil amelioration and seeding .

Figure 4: Perennial grasses predominant two seasons after establishment

3.1.1 Botanical composition

In Figure 5 it is clear that the dominant species in the first growing season was *Eragrostis tef*. This species is an annual and is generally the first to germinate in the mixture of grasses planted. This species, once germinated, creates a microclimate, which is beneficial to the establishment of the perennial grass species in the mixture provided the seeding rate of teff is not too high.

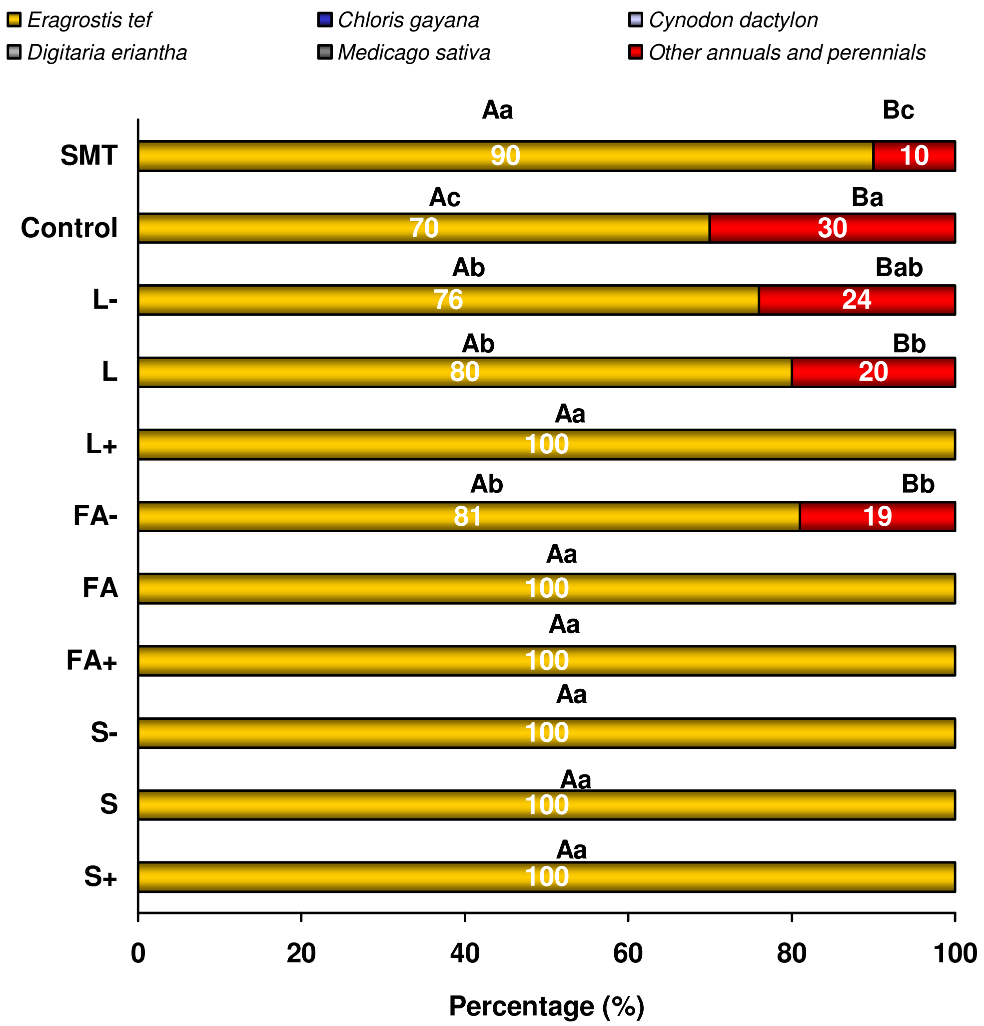

Figure 5: The influence of treatments on the botanical composition of the re-vegetated mine land in the 1999/2000 growing season.

*# **AB** means differ significantly in botanical composition within treatments at P>0.05*
*# **ab** means differ significantly between treatments at P>0.05*
(Tukey's Studentized Range Test)

It is also evident that most low-level treatments had other annual and perennial grasses present. One year later (Figure 6), it can be seen that more perennial species had become established and were more prominent. There was, however, still some E. *tef* from the previous year.

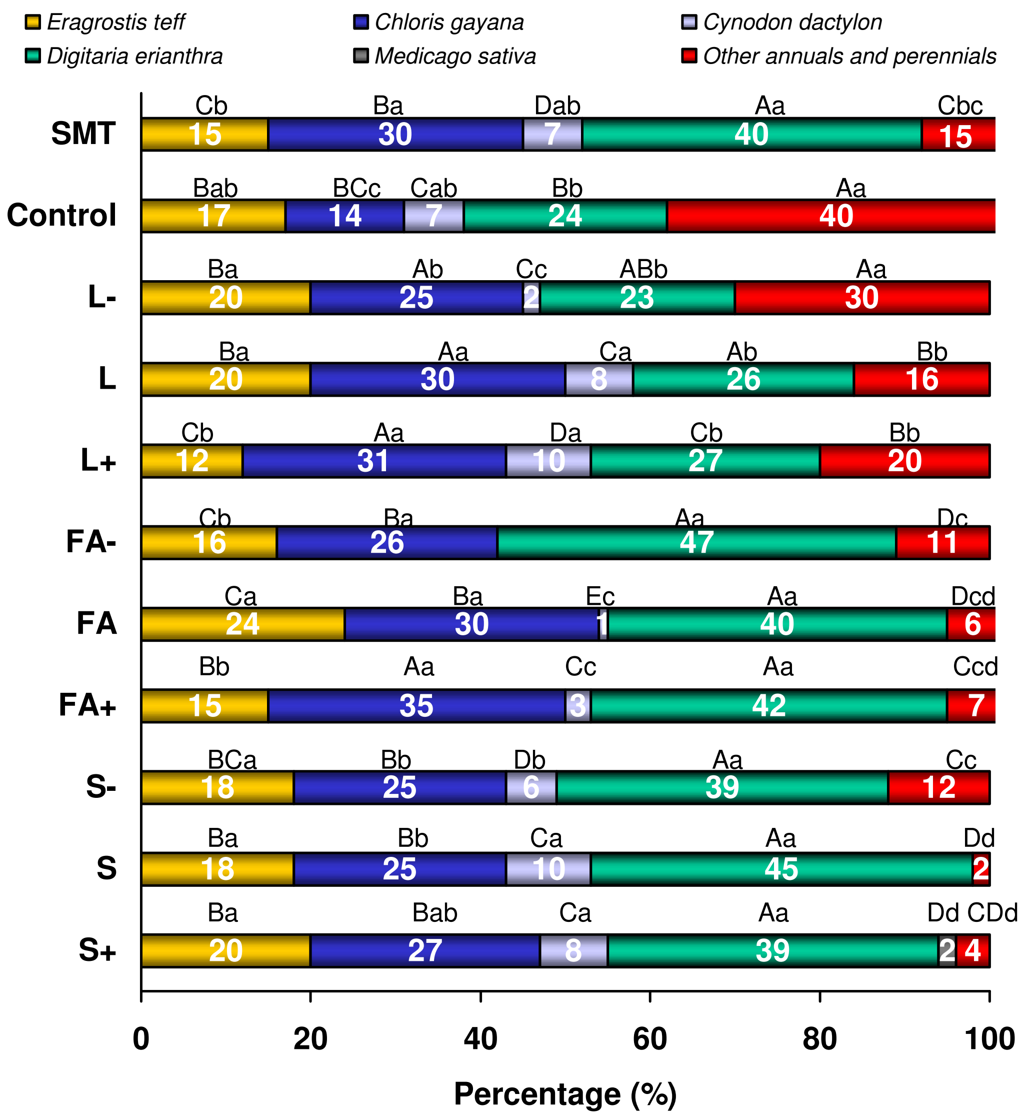

Figure 6: The influence of treatments on the botanical composition of the re-vegetated mine land in the 2000/2001 growing season.

*# **AB** means differ significantly in botanical composition within treatments at P>0.05*
*# **ab** means differ significantly between treatments at P>0.05*
(Tukey's Studentized Range Test)

Of the grasses the two most prominent species, in 2000/ 2001, were *C. gayana* and *D. eriantha.* These two species are generally more strongly perennial and are of the most productive planted pastures used in South Africa. They provide good dry matter yields for grazing and are characterized by a relatively high nutritional value (Kynoch, 2004).

In the 2000 / 2001 season, this area experienced a very high rainfall (1580mm), which was favourable for plant growth. This is reflected in the data presented for 2000/2001. It is noted that the ameliorants based on class F fly ash, had a higher proportion of the two productive grass species, *C. gayana* and *D. eriantha* and fewer other annuals and perennial species. The opposite is true for the lower level of lime (L-) and control (C) treatments. This result can be ascribed to the higher fertility level of the FA and SLASH ameliorated soils resulting in higher plant production. It is also evident that some *M. sativa* is recorded on the highest fertility treatment of S+, which supports amelioration with fly ash and SLASH, creating a more suitable soil environment for the growth of *Rhizobium* and *M. sativa.*

In the following season (2001/2002 as shown in Figure 7), it was noted that the annual grass *E. tef* had disappeared from all treatments and that the remaining species were generally perennial species. Once again it was evident that the low level treatments of lime together with the C had a much higher percentage of other annual and perennial species. The FA and SLASH treatments are regarded as the "higher fertility treatments", because of the high level of either macro and / or micro-nutrients (Truter, 2002).

As the time progressed, in year 2002/2003 (Figure 8) it is noted that the *C. gayana* and *D. eriantha* remained the most dominant species in the mixture. From Figure 8 it is evident that the proportion of other annuals and perennials was increasing on the "lower fertility treatments" such as the C, L , L+, L- and FA- treatments, while *C .gayana* and *D. eriantha* dominated the "higher fertility treatments", such as S+, S, FA+, FA, S- and SMT.

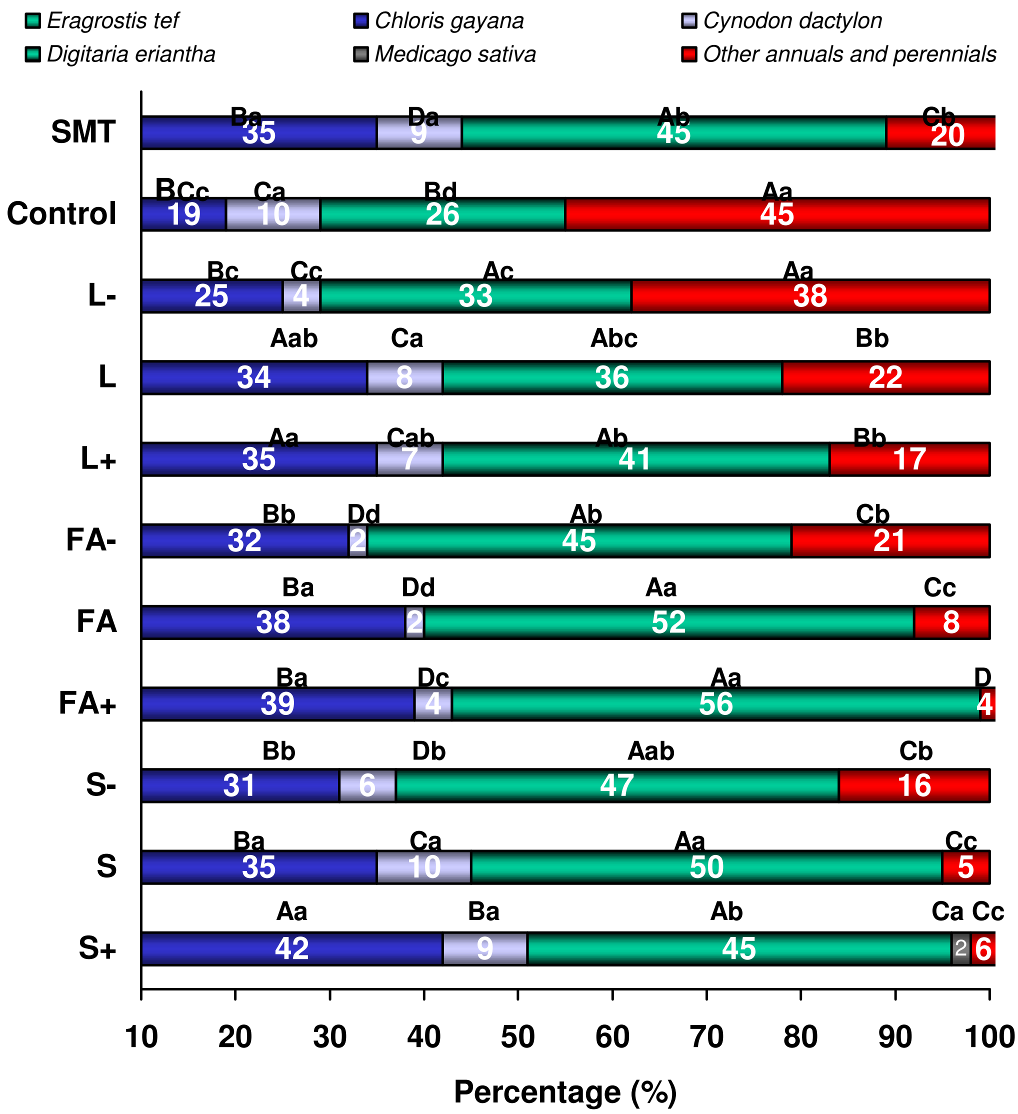

Figure 7: The influence of treatments on the botanical composition of the re-vegetated mine land in the 2001/2002 growing season

*# **AB** means differ significantly in botanical composition within treatments at P>0.05*
*# **ab** means differ significantly between treatments at P>0.05*
(Tukey's Studentized Range Test)

In the 2002/2003 and 2003/2004 (Figure 8 and 9) seasons, drier conditions prevailed. Under these stressed conditions there was a significant change in botanical composition, with other annuals and perennials increasing on the higher fertility treatments.

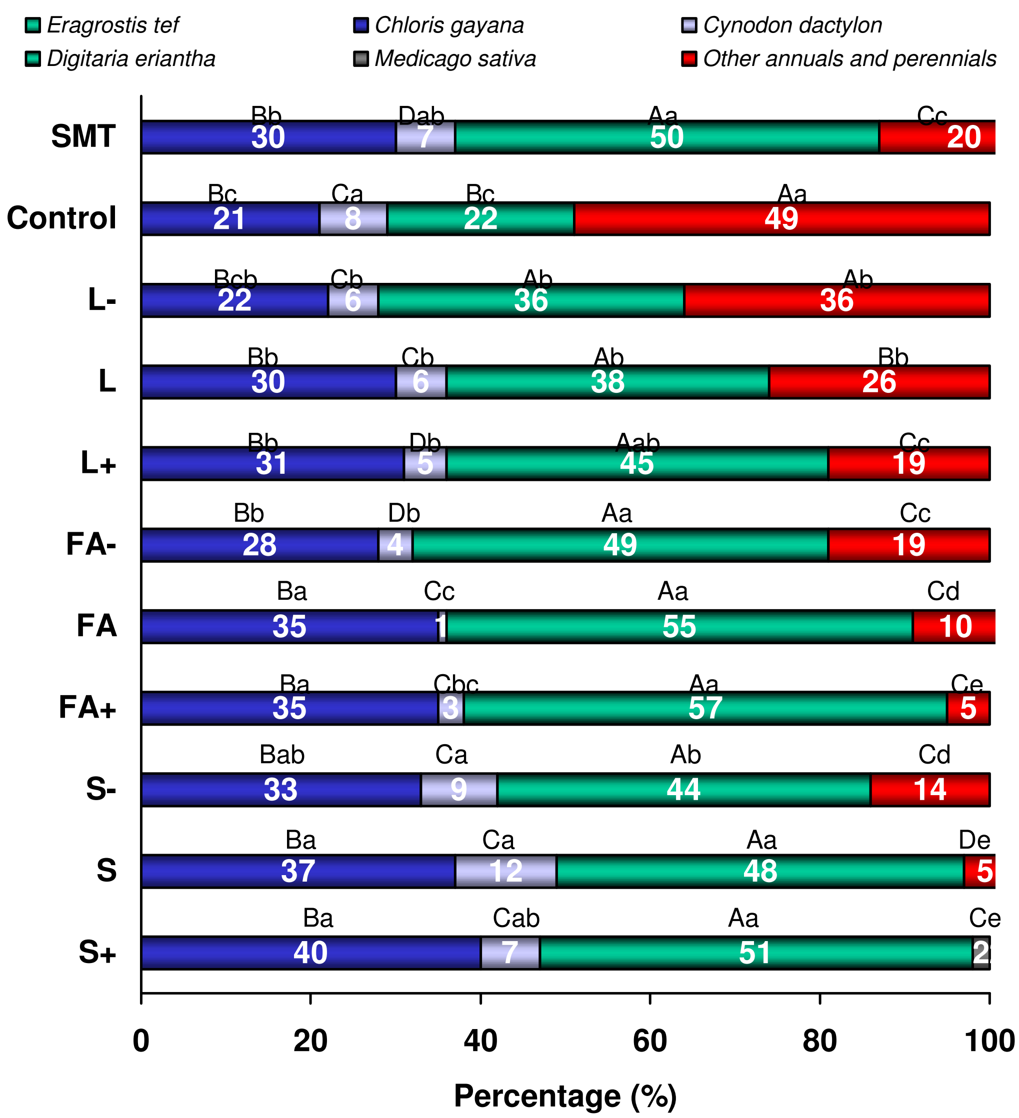

Figure 8: The influence of treatments on the botanical composition of the re-vegetated mine land in the 2002/2003 growing season

*# **AB** means differ significantly in botanical composition within treatments at P>0.05*
*# **ab** means differ significantly between treatments at P>0.05*
(Tukey's Studentized Range Test)

A higher proportion of *C. gayana* and a lower proportion of *D. eriantha* on the optimum FA and SLASH treatments, reflected this regression, when higher fertility plots were stressed.

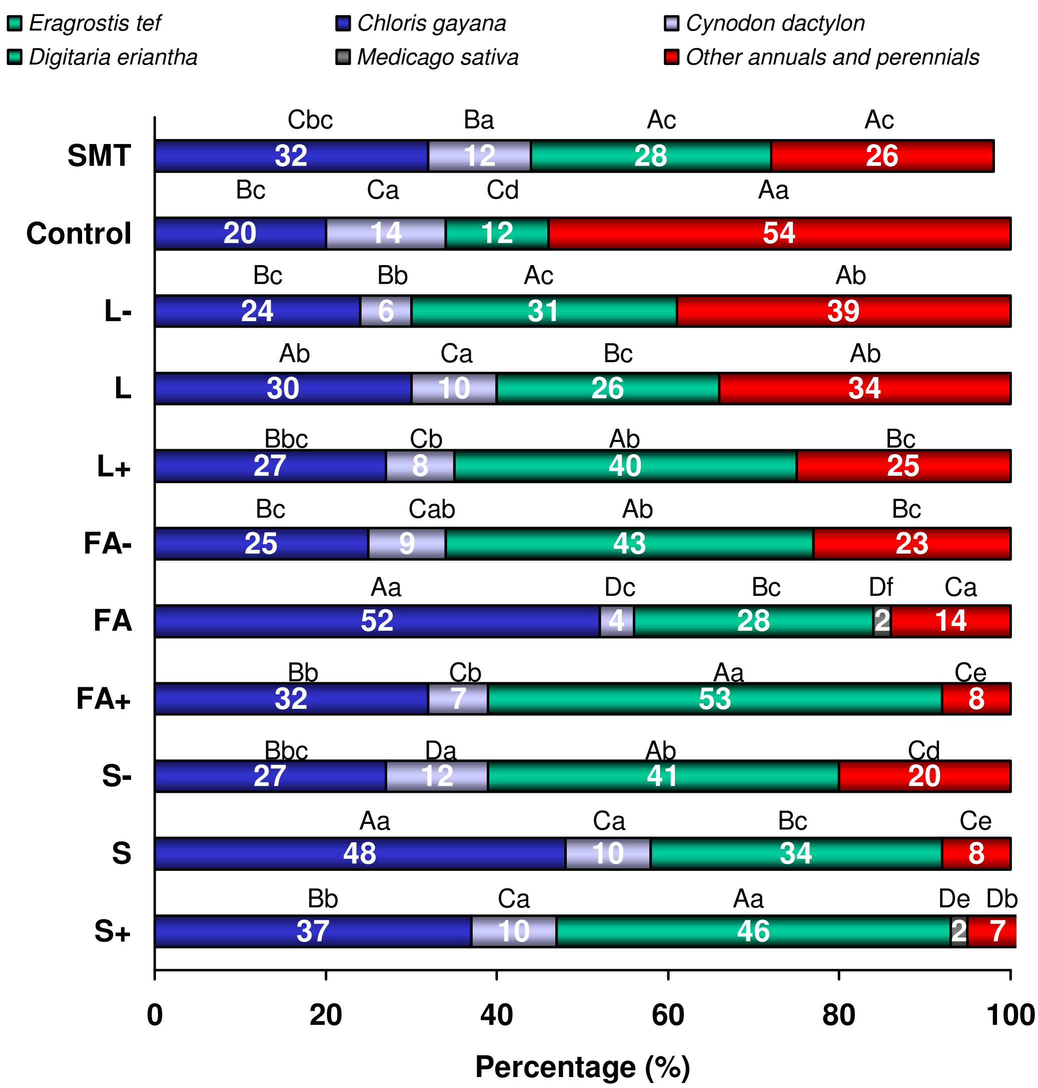

Figure 9: The influence of treatments on the botanical composition of the re-vegetated mine land in the 2003/2004 growing season.

*# **AB** means differ significantly in botanical composition within treatments at P>0.05*
*# **ab** means differ significantly between treatments at P>0.05*
(Tukey's Studentized Range Test)

In 2001/2002 and 2003/2004, the presence of *M. sativa* was observed on the S+ treatment. This legume, which was inoculated before planting, did not initially germinate and establish well. This can be ascribed to unfavorable soil conditions that did not support microbial life. The S+ treatment, in this instance, ameliorated this degraded soil micro-environment, by improving organic matter content and providing nutrients, for a very small population of Rhizobium bacteria and *M. sativa* to survive.

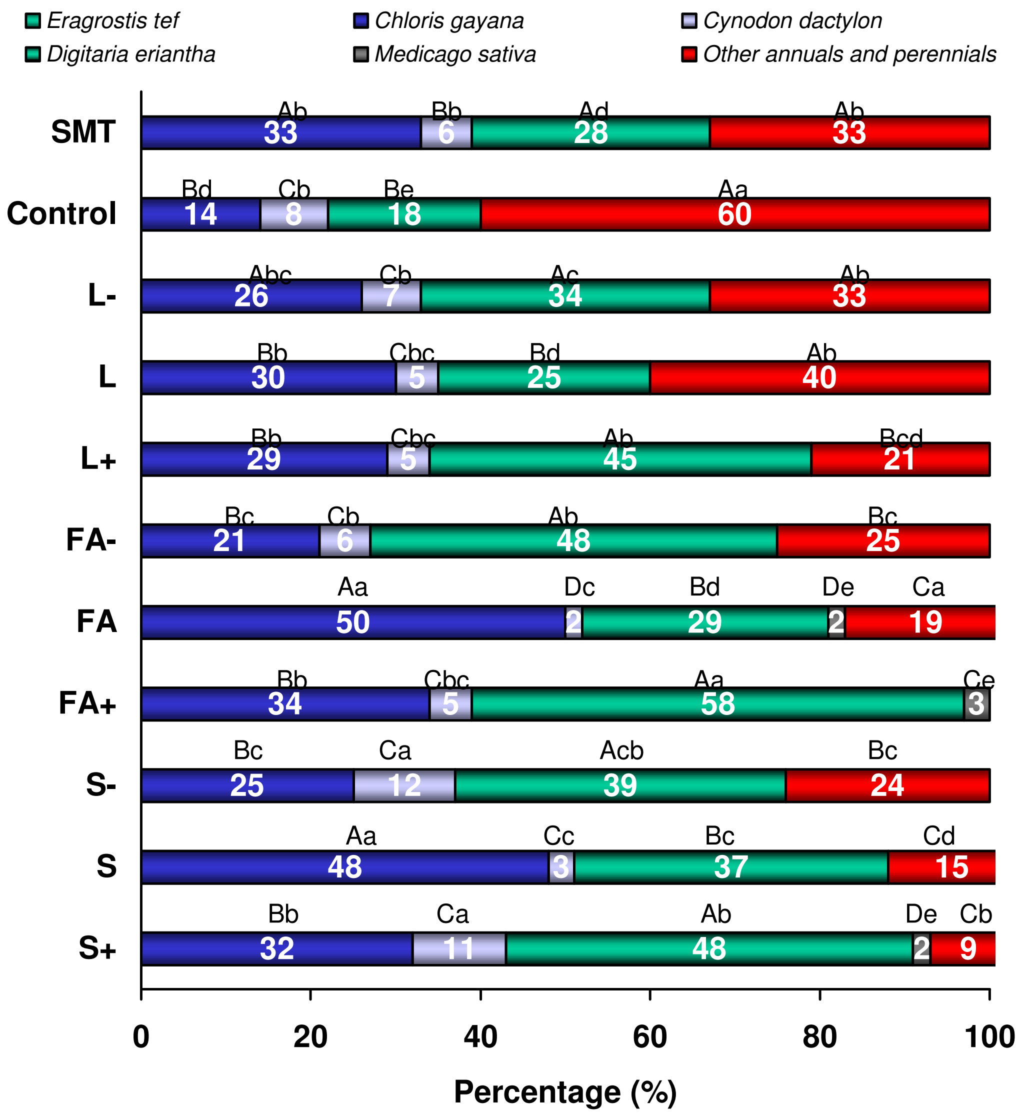

Figure 10: The influence of treatments on the botanical composition of the re-vegetated mine land in the 2004/2005 growing season.

*# **AB** means differ significantly in botanical composition within treatments at P>0.05*
*# **ab** means differ significantly between treatments at P>0.05*
(Tukey's Studentized Range Test)

The data presented for the 2004/2005 season (Figure 10), illustrates that as the years progress, the "lower fertility treatments" such as the C and L- treatments increasingly have a higher percentage of other annual and perennial species, not used in the seed mixture planted on the whole area, while *C. gayana* and *D. eriantha* remain the most dominant species on the " higher fertility treatments". Because leguminous plants are essential in a re-vegetation mixture, to ensure that nitrogen is available to contribute to a sustainable system, it is vital that the ameliorant used creates conditions suitable for legumes.

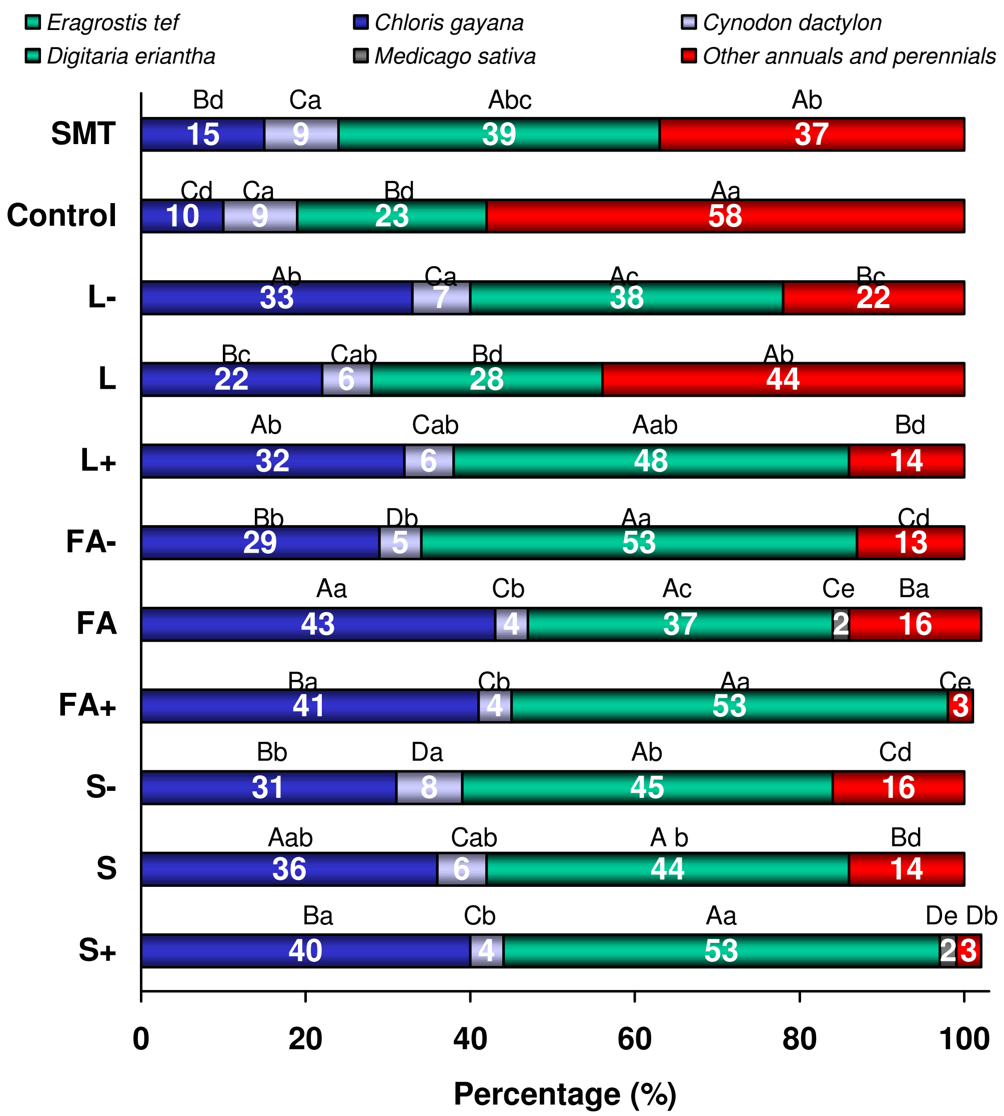

Figure 11: The influence of treatments on the botanical composition of the re-vegetated mine land in the 2005/2006 growing season.

*# **AB** means differ significantly in botanical composition within treatments at P>0.05*
*# **ab** means differ significantly between treatments at P>0.05*
(Tukey's Studentized Range Test)

In Figures 9 – 11 there was a slight tendency for *C. gayana* numbers to decline on the " lower fertility treatments", especially on the SMT, C and L treatments. A decrease in *C. gayana* vigour can be expected due to its relatively poor perenniality under local conditions. Nevertheless, the higher fertility treatments had maintained a good population, especially after the high rainfall in 2004. It is also noted in Figures 9 –11 that as the conventional ameliorants become depleted, the species composition changed and a higher proportion of other annuals and perennial species become more abundant. The other "higher fertility treatments" such as the FA and SLASH treatments, however, continued to provide a favourable soil environment for the grasses in the mixture to produce well.

The relatively small changes noticed in species composition on the FA and SLASH ameliorated soils over the past 72 months, substantiates the conclusion that the long term residual effect of these soil ameliorants are more sustainable than the traditional liming and fertilization.

3.1.2 Basal cover

Basal cover is an essential assessment in mine land reclamation. It serves as an indicator of whether the soil surface is stable so that erosion risk is minimized. It also indicates if the soil environment is suitable for plant growth, as reflected in the plant cover. The percentage basal cover in six growing seasons (72 months), of the SLASH ameliorated soils as compared to the untreated control and SMT is presented in Table 1. The data shown for the 1999/2000 growing season, is substantially higher than the other seasons as a result of *E. tef* predominating. This grass is an annual species with a good germination rate and a high density. It is clear, that there is a significant difference between the SLASH treatments, the control and SMT. In mine land reclamation the challenge remains to improve the degraded soil to a condition similar to what the surrounding natural veld would be, and such veld in a good condition, would have a basal cover of approximately 30-40 %.

Table1: The effect of SLASH treatments on the percentage basal cover of re-vegetated mine land over a 72 month period.

TREATMENT	***S+***	***S***	***S-***	***C***	***SMT***
SEASON					
1999/2000	30^{B}_{b} (+/- 1.6)	46^{A}_{a} (+/- 1.4)	52^{A}_{a} (+/- 1.9)	14^{C}_{a} (+/- 1.3)	34^{B}_{a} (+/- 1.6)
2000/2001	15^{A}_{d} (+/- 0.8)	12^{A}_{d} (+/- 0.8)	12^{A}_{d} (+/- 0.7)	5^{C}_{a} (+/- 0.3)	10^{B}_{cd} (+/- 0.7)
2001/2002	16^{A}_{d} (+/- 0.4)	13^{B}_{d} (+/- 0.6)	11^{B}_{d} (+/- 0.3)	5^{D}_{c}(+/- 0.5)	9^{C}_{d} (+/- 0.4)
2002/2003	20^{A}_{c} (+/- 0.9)	19^{A}_{c} (+/- 0.7)	16^{B}_{c} (+/- 0.8)	6^{D}_{bc} (+/- 1.0)	11^{C}_{c} (+/- 0.8)
2003/2004	27^{A}_{b} (+/- 1.1)	25^{A}_{c} (+/- 0.9)	22^{B}_{b} (+/- 0.7)	7^{D}_{b} (+/- 0.3)	14^{C}_{c} (+/- 0.6)
2004/2005	20^{A}_{c} (+/- 0.9)	19^{A}_{c} (+/- 0.3)	16^{B}_{c} (+/- 0.3)	6^{D}_{bc} (+/- 0.6)	11^{C}_{c} (+/- 0.4)
2005/2006	38^{A}_{a} (+/- 1.2)	34^{A}_{b} (+/- 0.7)	26^{B}_{b} (+/- 0.9)	8^{D}_{b} (+/- 0.2)	21^{C}_{b} (+/- 0.8)
MEAN	***23.7***	***24.0***	***22.1***	***7.3***	***15.7***

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

In Table 2 it is noted that in 1999/2000 growing season that the vegetation was once again dominated by *E. tef* and soil ameliorants based on class F fly ash had a much better cover than the C and SMT treatments.

Table 2: The effect of Class F fly ash treatments on the percentage basal cover of re-vegetated mine land over a 72 month period.

TREATMENT	***FA+***	***FA***	***FA-***	***C***	***SMT***
SEASON					
1999/2000	90^{A}_{a} (+/- 3.2)	58^{C}_{a} (+/- 2.3)	72^{B}_{a} (+/- 3.7)	14^{E}_{a} (+/- 1.3)	34^{D}_{a} (+/- 1.6)
2000/2001	17^{A}_{e} (+/- 0.6)	15^{A}_{d} (+/- 0.7)	14^{B}_{d} (+/- 0.9)	5^{D}_{c} (+/- 0.3)	10^{C}_{cd} (+/- 0.7)
2001/2002	18^{A}_{e} (+/- 0.9)	15^{B}_{d} (+/- 0.6)	16^{A}_{d} (+/- 0.4)	5^{D}_{c} (+/- 0.5)	9^{C}_{d} (+/- 0.4)
2002/2003	26^{A}_{d} (+/- 1.1)	21^{B}_{c} (+/- 0.8)	22^{B}_{c} (+/- 0.3)	6^{D}_{c} (+/- 1.0)	11^{C}_{c} (+/- 0.8)
2003/2004	30^{A}_{c} (+/- 1.3)	22^{B}_{c} (+/- 0.7)	21^{B}_{c} (+/- 0.6)	7^{D}_{bc} (+/- 0.3)	14^{C}_{c} (+/- 0.6)
2004/2005	34^{A}_{c} (+/- 1.0)	27^{B}_{b} (+/- 0.8)	25^{B}_{b} (+/- 0.4)	6^{D}_{c} (+/- 0.6)	11^{C}_{c} (+/- 0.4)
2005/2006	40^{A}_{b} (+/- 1.5)	29^{B}_{b} (+/- 0.9)	27^{B}_{b} (+/- 0.8)	8^{D}_{b} (+/- 0.2)	21^{C}_{b}(+/- 0.8)
MEAN	***36.4***	***26.7***	***28.0***	***7.3***	***15.7***

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Tables 1-2 illustrate how both SLASH and FA treatments significantly improved the basal cover from approximately 7.3% to 23.3% and 30.4% for the S and FA treatments respectively, over 72 months.

It is also noted in Table 3 that the SMT and L treatments also improved the basal cover by 15.7 % and 12.5 % respectively, over the 72 months, but not to the same degree as the SLASH and FA ameliorants.

Table 3: The effect of dolomitic lime treatments on the percentage basal cover and (SE +/-) of re-vegetated mine land over a 72 month period.

TREATMENT	***L+***	***L***	***L-***	***C***	***SMT***
SEASON					
1999/2000	24 $^{B}_{a}$ (+/- 0.9)	28 $^{AB}_{a}$ (+/- 0.9	32 $^{A}_{a}$ (+/- 0.8)	14 $^{C}_{a}$ (+/- 1.3)	34 $^{A}_{a}$ (+/- 1.6)
2000/2001	7 $^{B}_{d}$ (+/- 0.3)	8 $^{AB}_{c}$ (+/- 0.7)	6 $^{BC}_{d}$ (+/- 0.6)	5 $^{C}_{c}$ (+/- 0.3)	10 $^{A}_{cd}$ (+/- 0.7)
2001/2002	9 $^{A}_{c}$ (+/- 0.5)	7 $^{B}_{c}$ (+/- 0.2)	8 $^{AB}_{c}$ (+/- 0.4)	5 $^{C}_{c}$ (+/- 0.5)	9 $^{A}_{d}$ (+/- 0.4)
2002/2003	11 $^{A}_{bc}$ (+/- 0.7	9 $^{B}_{bc}$ (+/- 0.4)	10 $^{AB}_{b}$ (+/- 0.7)	6 $^{C}_{c}$ (+/- 1.0)	11 $^{A}_{c}$ (+/- 0.8)
2003/2004	13 $^{A}_{b}$ (+/- 0.7)	9 $^{B}_{bc}$ (+/- 0.5)	9 $^{B}_{c}$ (+/- 0.2)	7 $^{C}_{bc}$ (+/- 0.3)	14 $^{A}_{c}$ (+/- 0.6)
2004/2005	14 $^{A}_{b}$ (+/- 0.3)	11 $^{B}_{b}$ (+/- 0.3)	10 $^{B}_{b}$ (+/- 0.8)	6 $^{C}_{c}$ (+/- 0.6)	11 $^{B}_{c}$ (+/- 0.4)
2005/2006	15 $^{B}_{b}$ (+/- 0.2)	12 $^{C}_{b}$ (+/- 0.4)	11 $^{C}_{b}$ (+/- 0.6)	8 $^{D}_{b}$ (+/- 0.2)	21 $^{A}_{b}$ (+/- 0.8)
MEAN	***13.3***	***12***	***12.3***	***7.3***	***15.7***

***AB** Row means with common alphabetical superscripts do not differ significantly (P> 0.05) (Bonferroni Test)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

These results (Tables 1-3) indicate that the SLASH and FA treatments significantly improved the growth and cover of the vegetation in comparison to L, C and the SMT.

3.1.3 Dry matter production

Significant yield differences were evident in the seven growing seasons from 1999 to 2006. The trend clearly indicated that both SLASH and FA treatments significantly increased the dry matter production of the vegetation (Figures 12 – 18). In the 1999/2000 growing season the vegetation was predominantly *E. tef*. Yields of this species under normal agricultural conditions are approximately 300 – 500 g m^{2}. In Figure 12 it is noted that the FA+ and the S+ treatments had yields of up to 650 and 550 g m^{-2} respectively, compared with the 280 and 125 g m^{-2} of the SMT and untreated control, respectively.

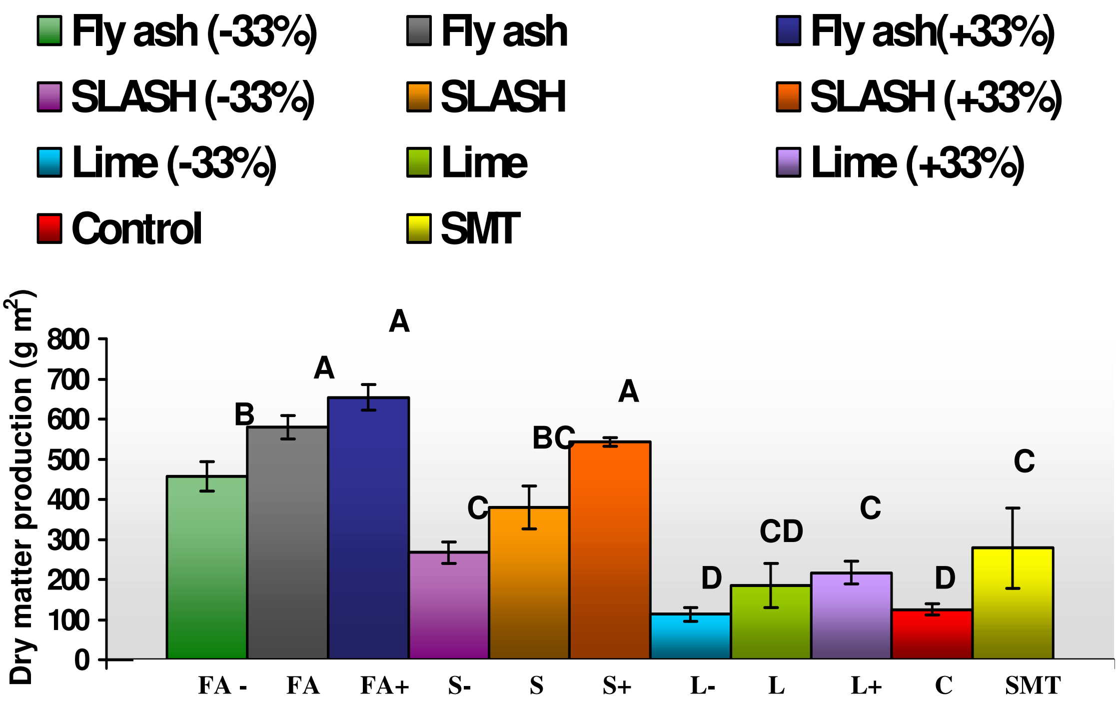

Figure 12: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 1999/2000 growing season.

 # Means with the same letter are not significantly different at P>0.05 (Tukey's Studentized Range Test)

Thegenerally higher yields evident on the FA treatments were surprising, since it was expected that the SLASH treatments, with a higher macro-nutrient content would have been more favourable for plant growth.

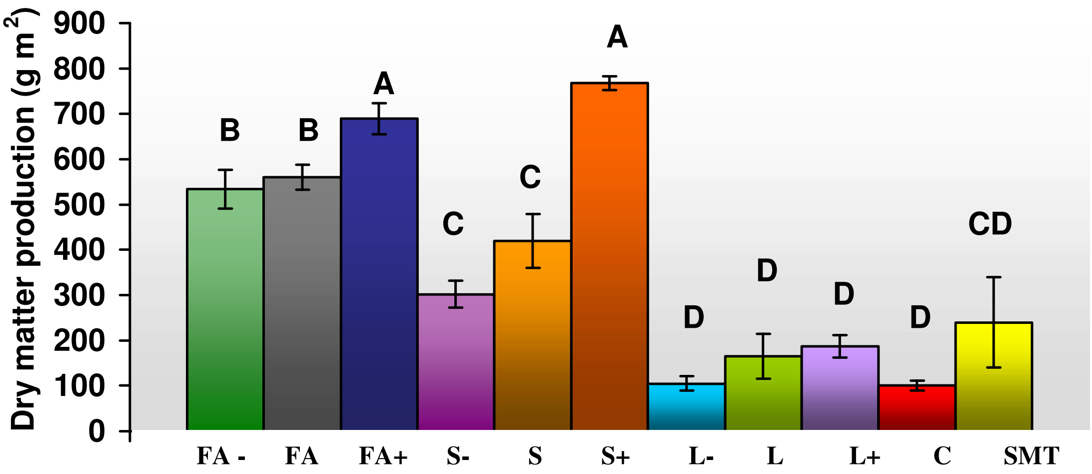

Figure 13: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 2000/2001 growing season

 # Means with the same letter are not significantly different at P>0.05 (Tukey's Studentized Range Test)

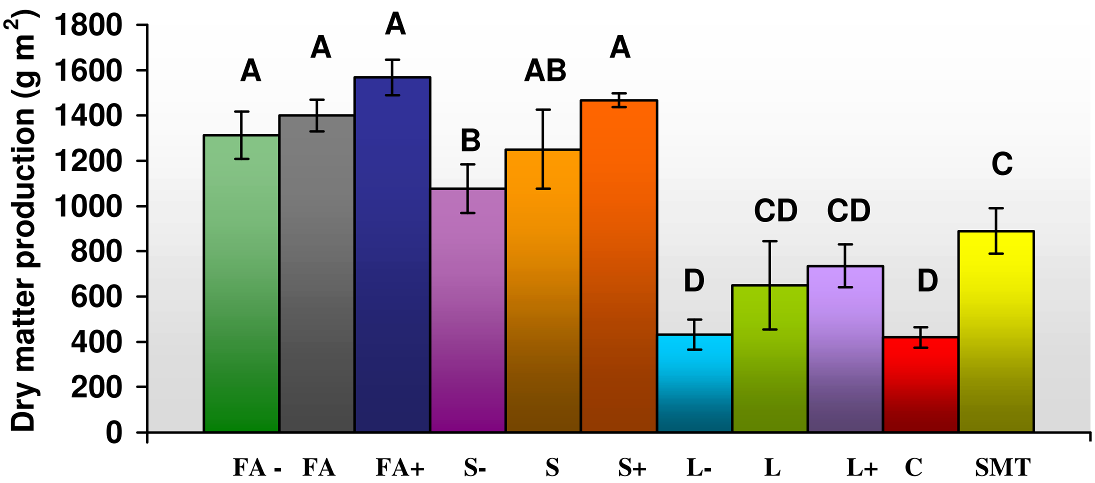

Figure 14: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 2001/2002 growing season.

 # Means with the same letter are not significantly different at P>0.05

(Tukey's Studentized Range Test)

The effect of SLASH treatments on soil pH (observed in Figures 35 and 37), however, seemed to have a depressing effect on the initial germination of *E. tef* and the establishment of seedlings. Nevertheless, in the following seasons (as is shown in Figures 13 – 18), when the perennial species dominated, the SLASH ameliorants compared well with FA ameliorants. The lime treatments generally performed poorly, and the effects weren't as pronounced as with the other soil ameliorants. The SMT had a significantly better yield, over the 72-month period, than the untreated control and some of the lime treatments. This can be ascribed to the additional nutrients provided initially and the annual nitrogen applications.

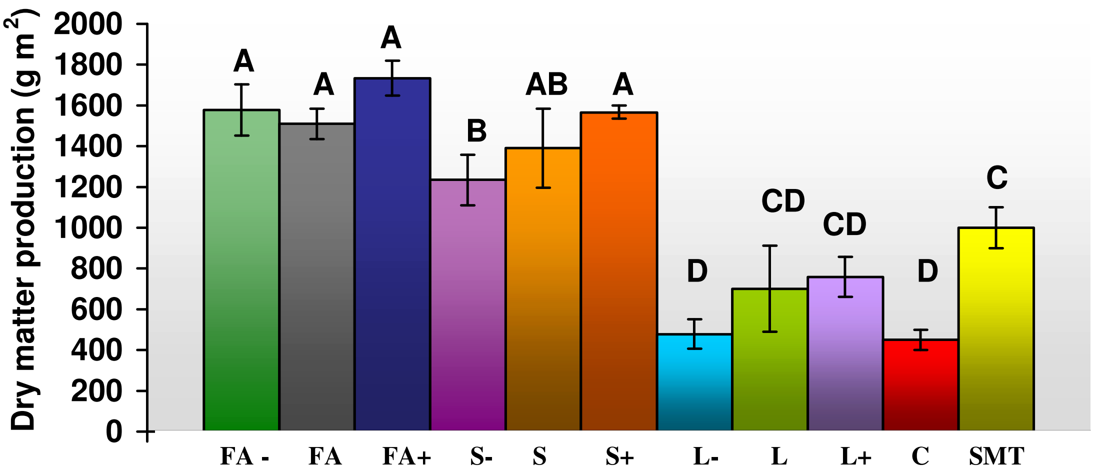

Figure 15: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 2002/2003 growing season.

 # Means with the same letter are not significantly different at P>0.05
(Tukey's Studentized Range Test)

In 2004 and 2005 above average rainfall (+/- 1160 and 920 mm annum^{-1}) was recorded, providing an excellent growth response of up to 200% increase in yield for both the SLASH and FA treatments, compared to the SMT, lime treatments and the untreated control, as reflected in Figures 17 and 18.

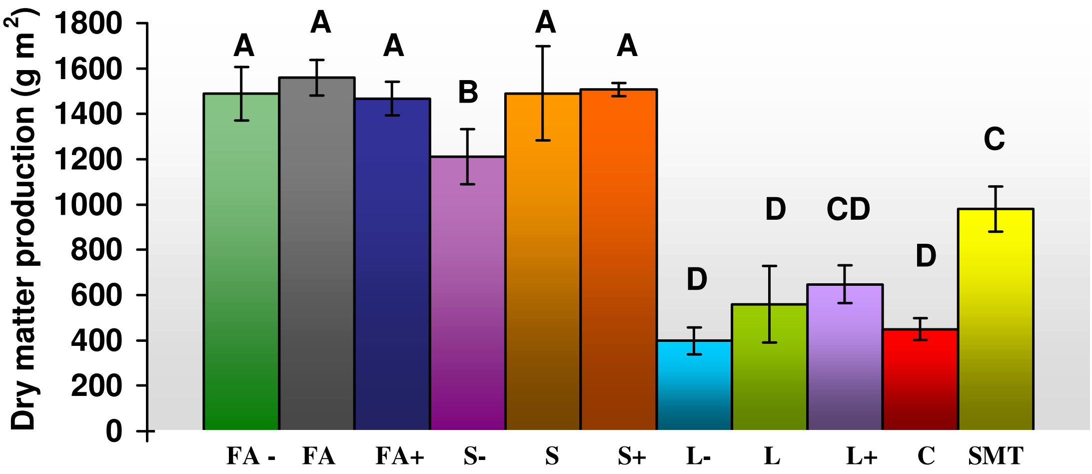

Figure 16: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 2003/2004 growing season.

 # Means with the same letter are not significantly different at P>0.05

(Tukey's Studentized Range Test)

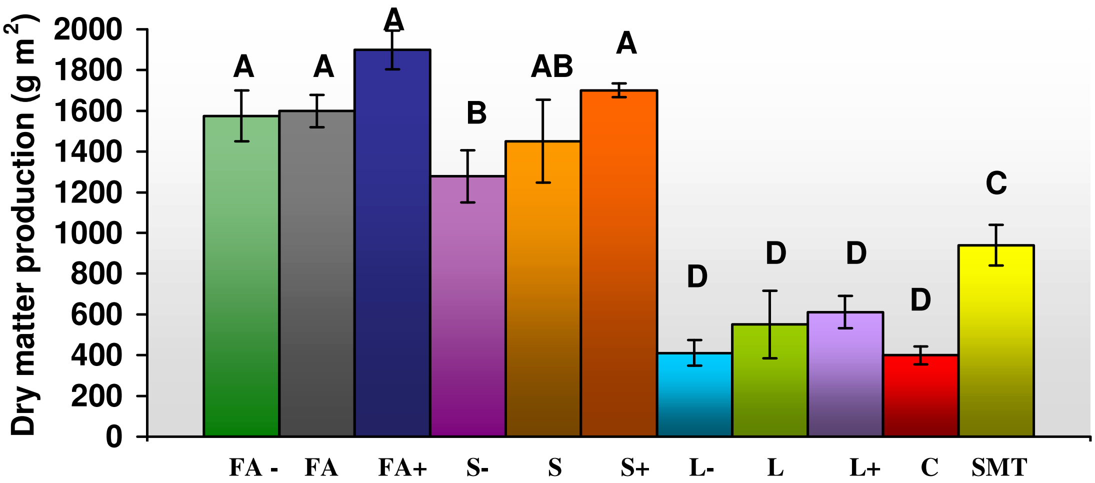

Figure 17: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 2004/2005 growing season.

 # Means with the same letter are not significantly different at P>0.05

(Tukey's Studentized Range Test)

These data clearly indicate that the SLASH and FA soil ameliorants can improve the degraded soil environment on such surface mines to the benefit of the plant production of plants established in the re-vegetation programmes.

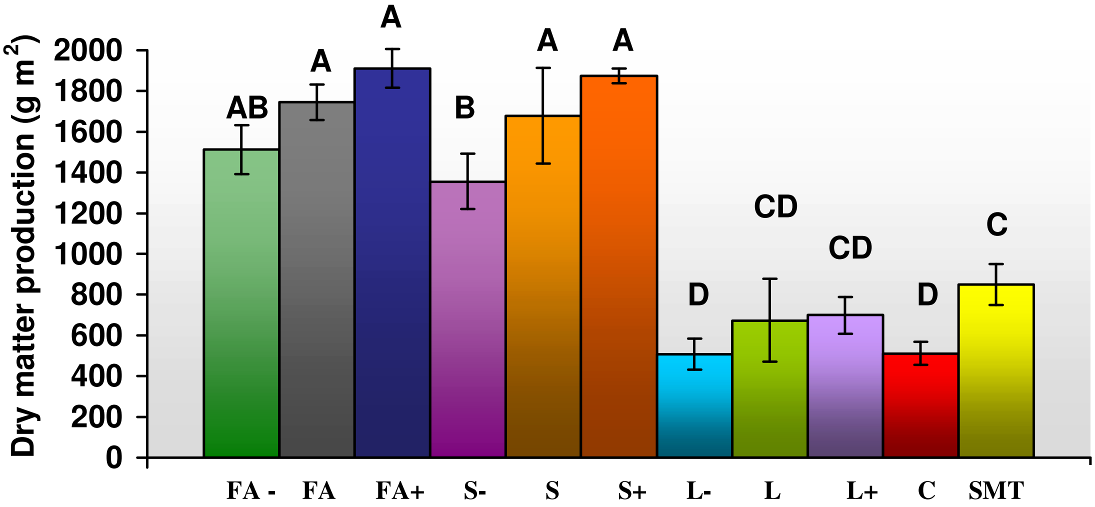

Figure 18: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 2005/2006 growing season.

 # Means with the same letter are not significantly different at P>0.05

(Tukey's Studentized Range Test)

Both FA and SLASH treatments showed a clear response to level of application and this was significant in certain seasons. This poses the question whether the optimum level of application of these two ameliorants has been achieved? Considering the effect these treatments have on soil pH at these application levels, a shift from an initially acidic soil condition towards a potentially saline condition is a potential concern. This observation, however, indicates that more frequent applications of these ameliorants at lower levels chould be considered, but this aspect requires further investigation.

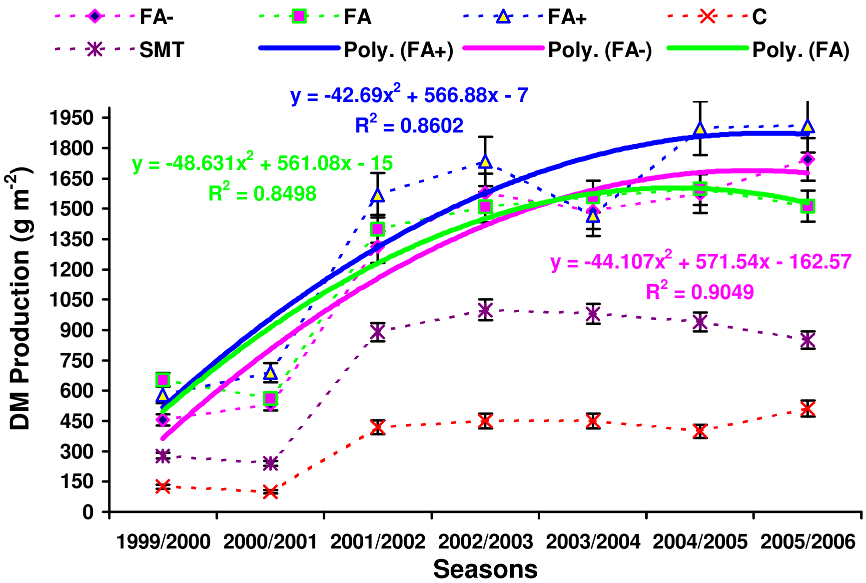

Figure 19: The dry matter production on re-vegetated soils, treated with FA ameliorants, relative to the C and SMT treatments over a 72-month period.

The regression analysis of these data sets (Figures 19 and 20), shows that the responses are not linear, and that the optimum level of ameliorants has been reached, and might in fact be too high already.

3.2 Soil Analyses

The soil analyses were conducted after every cropping cycle and the data presented includes the influence of which the different treatments on the most important macronutrients (P, K, Ca and Mg) and the pH (H_20) of the soil.

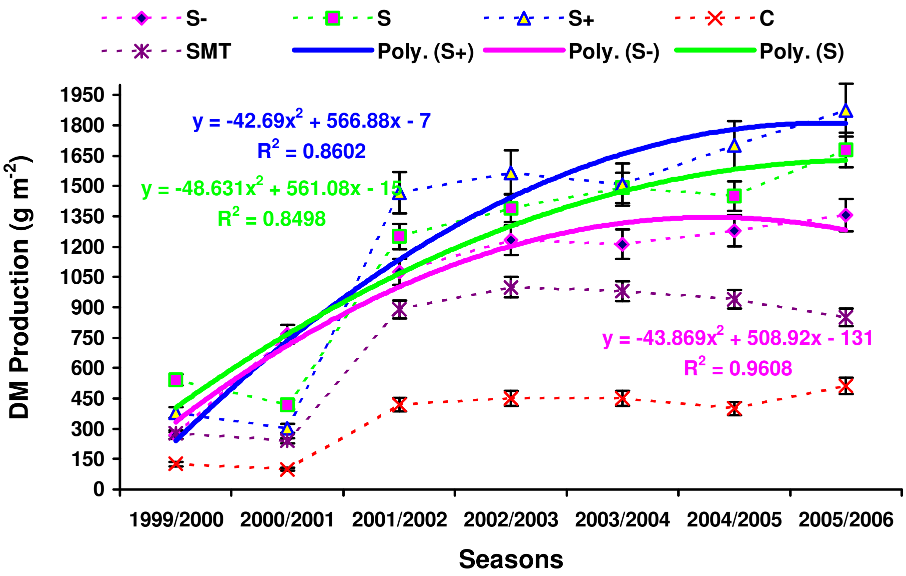

Figure 20: The dry matter production on re-vegetated soils, treated with S ameliorants, relative to the C and SMT treatments over a 72-month period.

With respect to macronutrients the FA and SLASH mixtures resulted in significant increases in the P content (Figures 22 and 23) initially after 12 months, relative to the control and other soil treatments. These levels were maintained over the 72-month period. Both FA and SLASH have a very low P content, and the question of where the P comes from, arises. Although P content might be low the high levels of FA and SLASH applied could add considerable P to the soil. This significant increase in P is also at least partly as a result of fixed P in the soil becoming more soluble and available for plant uptake. This nutrient availability can be ascribed to an increase in soil pH, as is illustrated in Figures 37-39, or it could possibly be ascribed to the competition of Si in FA with the P on soil particles, thus, making P more available. A detailed chemistry study on this topic is recommended, to better understand the dynamics of fly ash in the soil medium. Figures 22-24 illustrate the difference between the effect of different levels of soil ameliorants on soil P status, as compared to the untreated control and SMT.

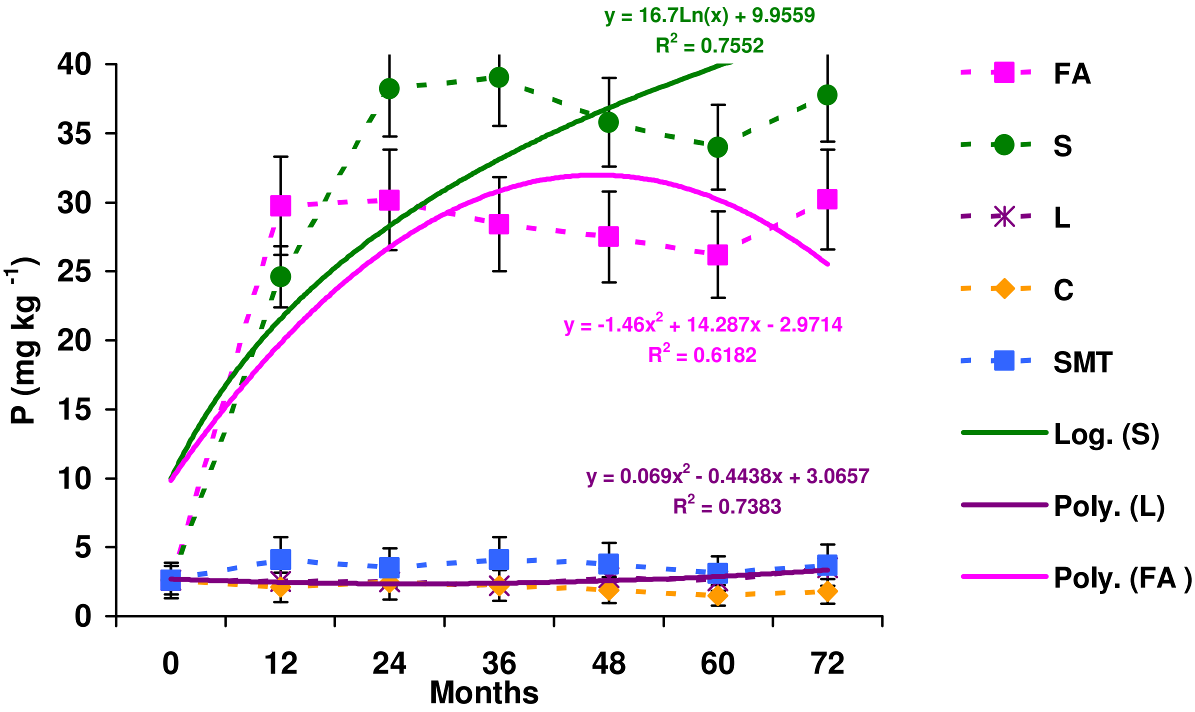

Figure 21: The influence of treatments, relative to C and SMT treatments, on the soil P status over a 72-month period

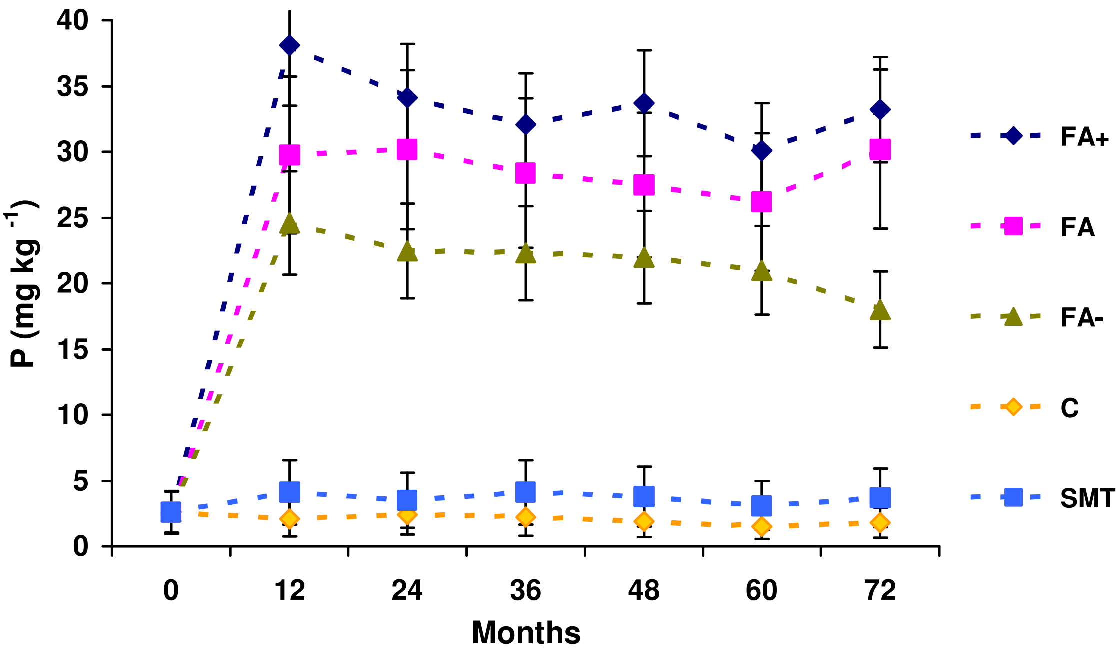

Figure 22: The influence of FA treatments, relative to C and SMT treatments, on the soil P status over a 72-month period

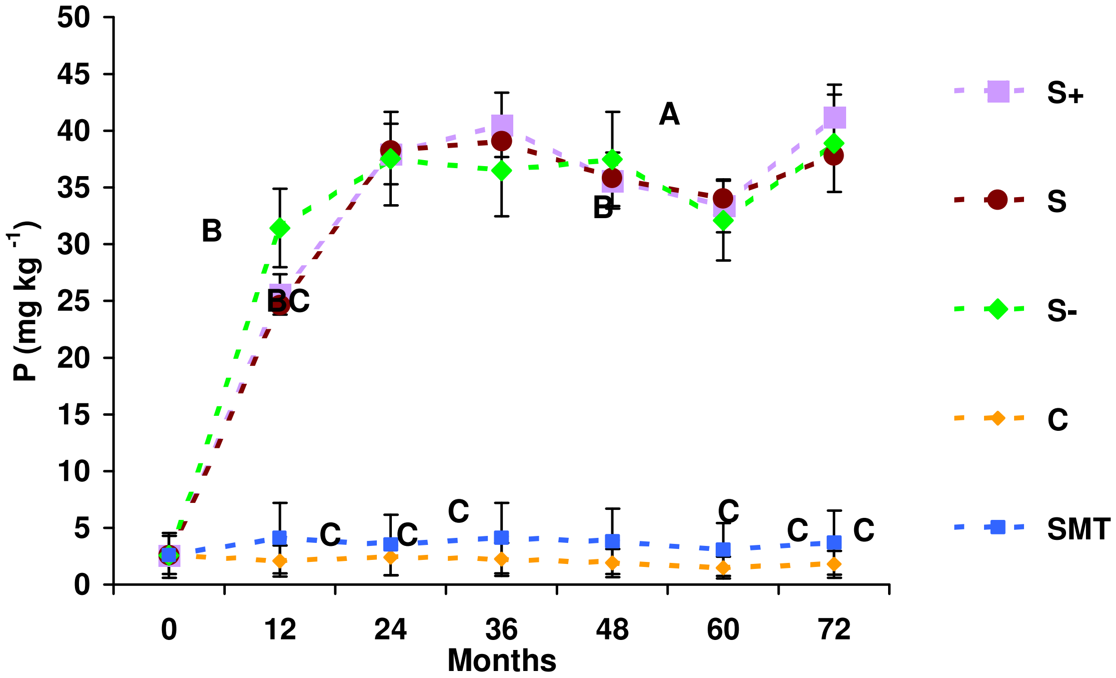

Figure 23: The influence of S treatments, relative to C and SMT treatments, on the soil P status over a 72-month period

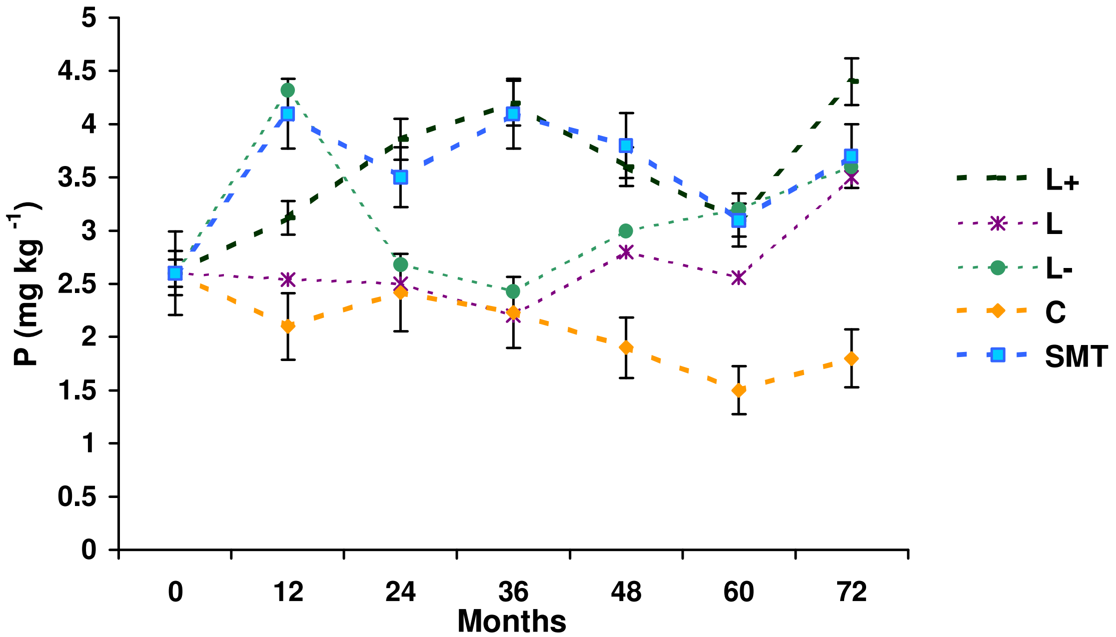

Figure 24: The influence of L treatments, relative to C and SMT treatments, on the soil P status over a 72-month period

With respect to the influence of different treatments on the soil K status, the standard mine treatment, had the highest K content at 24 months This is due to the basal K fertilization every two years, which improved the K levels. The K content (Figure 25) was, however, also markedly improved by the addition of FA and SLASH treatments. As these ameliorants contain little or no K this effect must be due to the improved pH, where they had been applied.

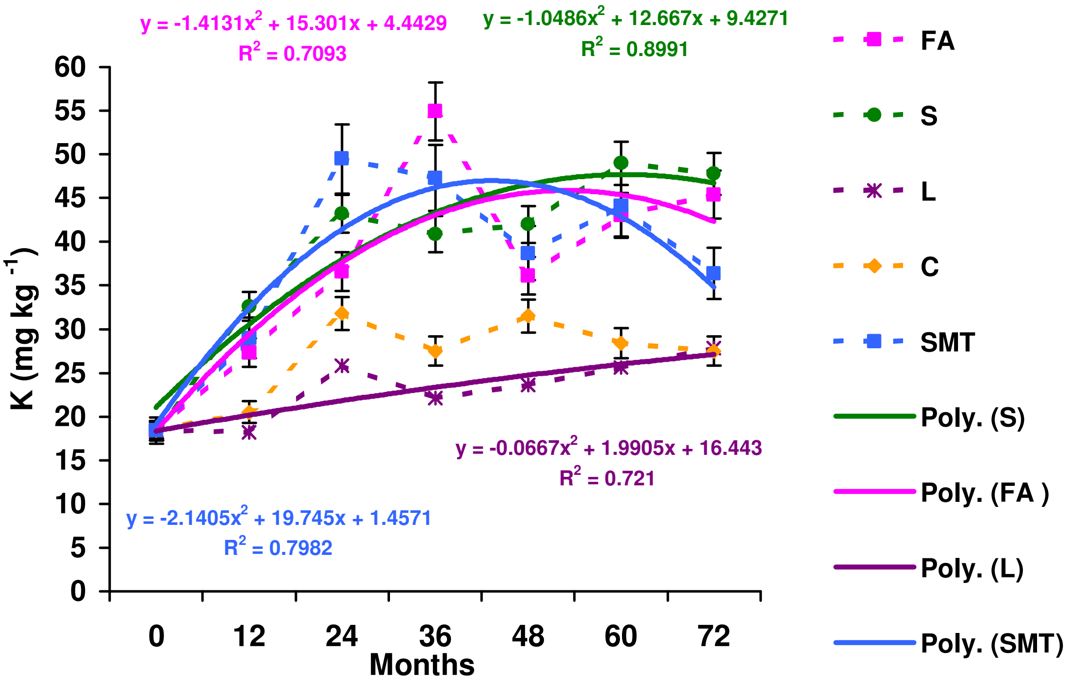

Figure 25: The influence of treatments, relative to C and SMT treatments, on the soil K status over a 72-month period

The results in Figures 26 – 28 indicate that the high levels (optimum + 33%) of FA and SLASH had the most significant effects on the K levels of cover soils. Over the 72-month period, K levels increased only slightly for the untreated control, and the lime treatments, while SMT after an initial increase over 24 months tended to fall thereafter, until a increase after 48 months due to a basal application of K. This pattern was also maintained for the FA treatments. The SLASH and FA treatments continue to demonstrate that the chemical reactions within the soil are ongoing and provide a slow release effect causing the nutrient levels to be maintained, or to increase slightly over the experimental period.

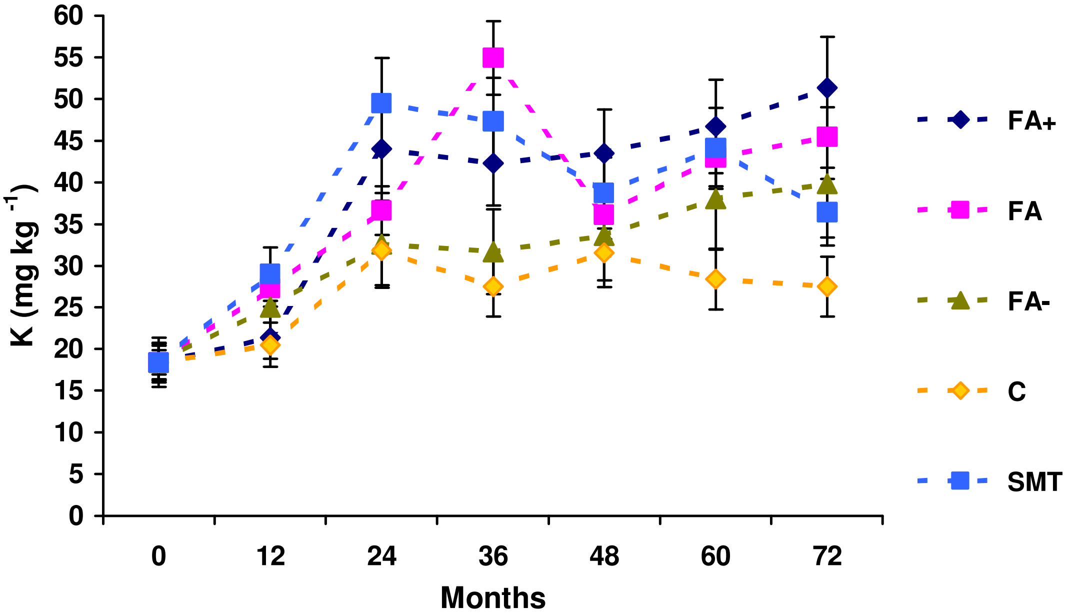

Figure 26: The influence of FA treatments, relative to C and SMT treatments, on the soil K status over a 72-month period

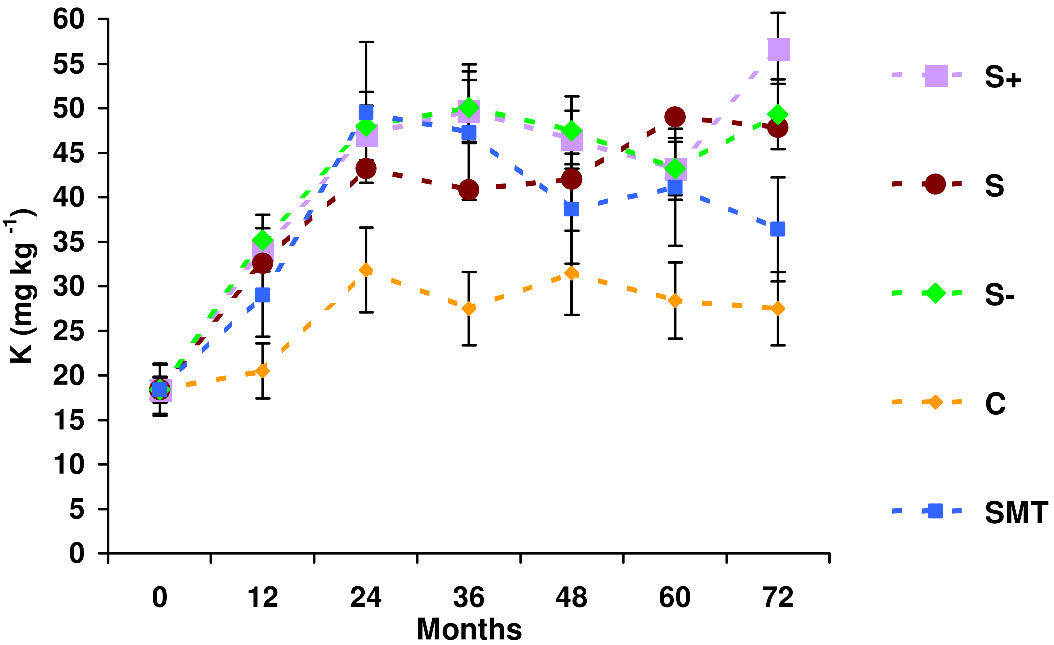

Figure 27: The influence of S treatments, relative to C and SMT treatments, on the soil K status over a 72-month period

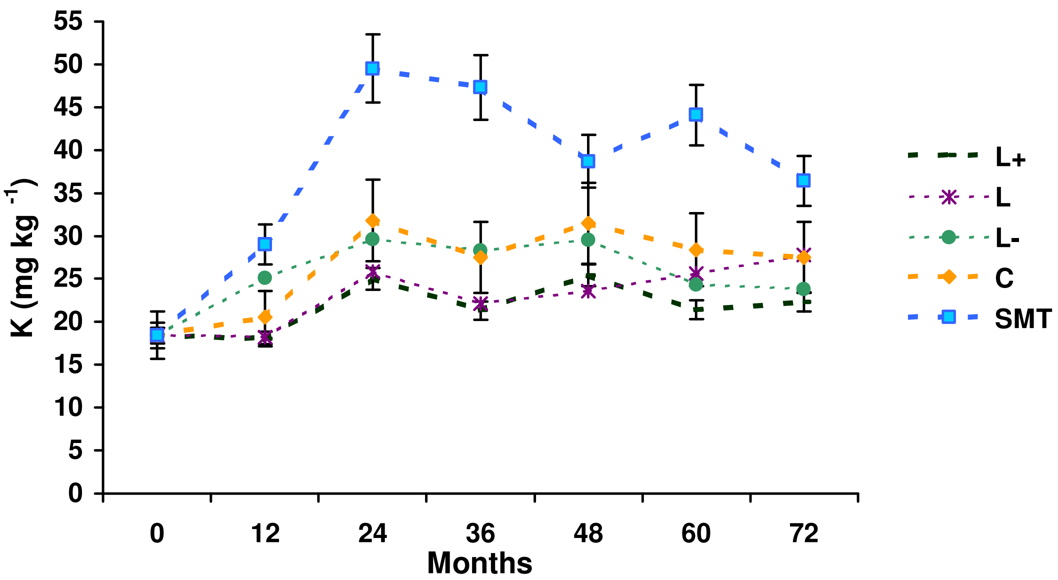

Figure 28: The influence of L treatments, relative to C and SMT treatments, on the soil K status over a 72-month period

Calcium is a very important macro-nutrient for plant growth, and the degraded soils that had not been ameliorated had very low levels thereof (<150 mg kg^{-1}). Fly ash, which has a large component of calcium silicates, can be a source of Ca for improving the soil status, as illustrated in Figure 30. The SLASH treatments, however, also include a CaO component, which supplies a significant amount of Ca and raises the soil Ca content markedly, as shown in Figures 29 and 31. Calcium functions as both a plant nutrient and also facilitates the neutralization of soil acidity to some extent. The large amounts of Ca provided by the SLASH treatments can, however, have a possible negative effect, causing an imbalance with other macro-nutrients. The FA treatments also improved the Ca levels of the soil, but not to the same extent as the SLASH treatments. The lime treatments had a very small effect on soil Ca status (Figure 31), although SMT (which included lime) did not differ from the C.

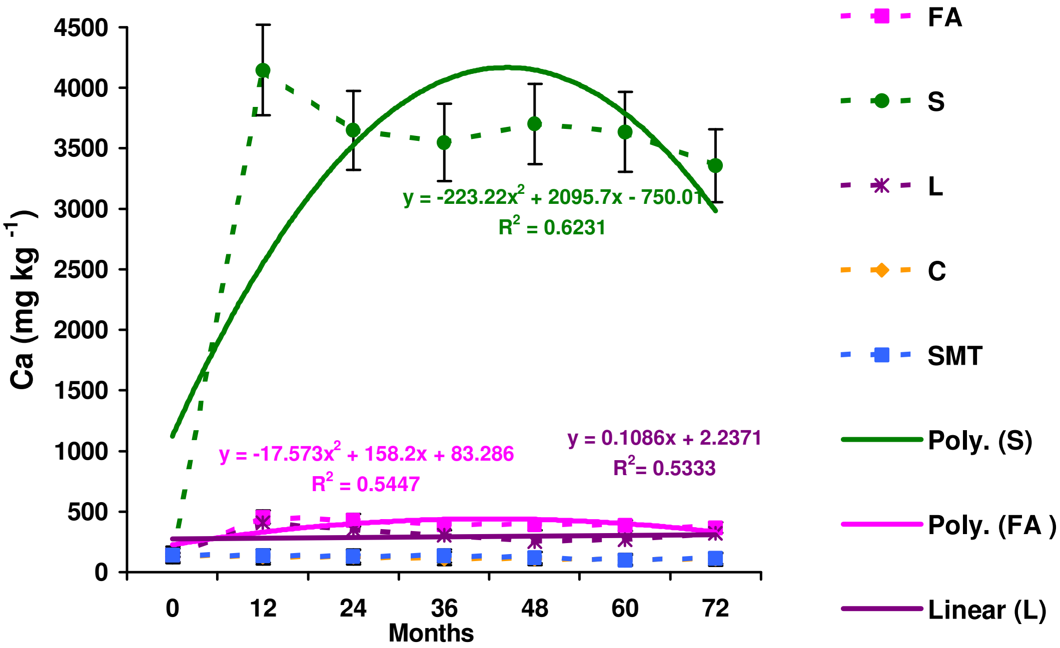

Figure 29: The influence of treatments, relative to C and SMT treatments, on the soil Ca status over a 72-month period

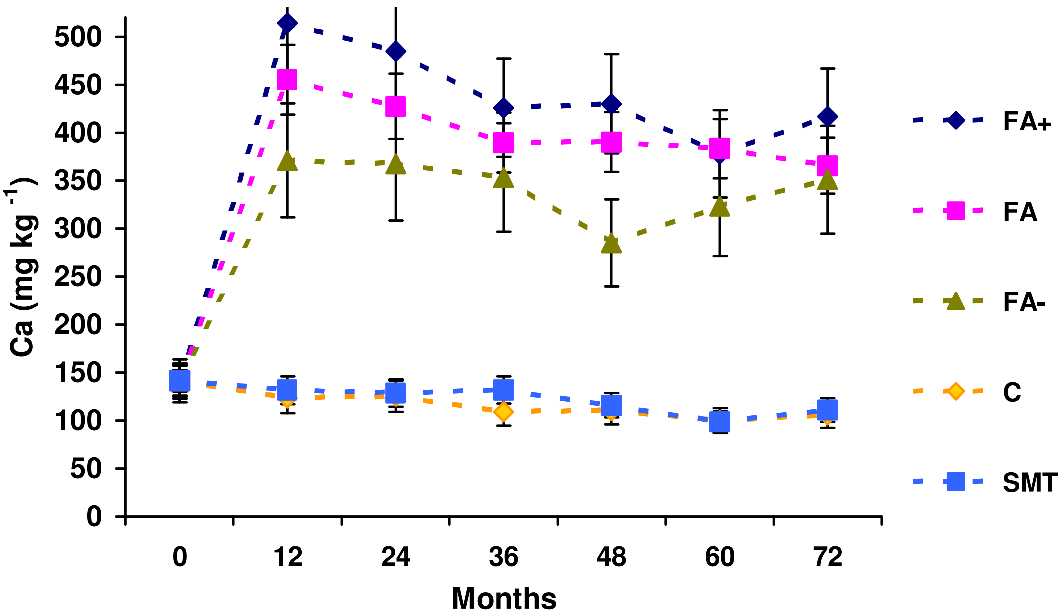

Figure 30: The influence of FA treatments, relative to C and SMT treatments, on the soil Ca status over a 72-month period

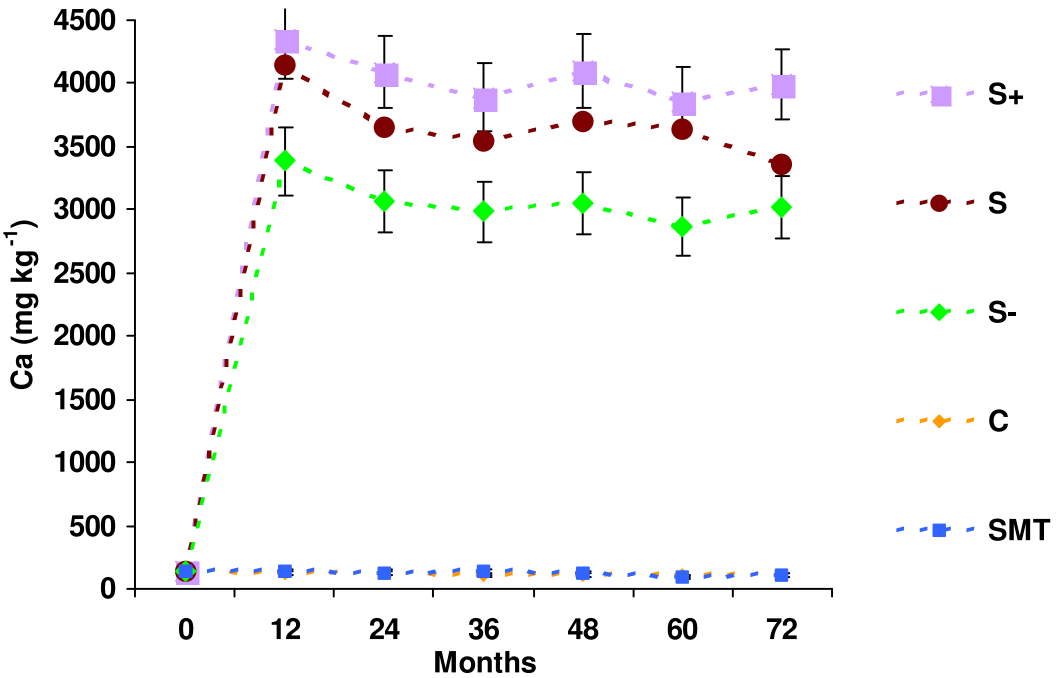

Figure 31: The influence of S treatments, relative to C and SMT treatments, on the soil Ca status over a 72-month period

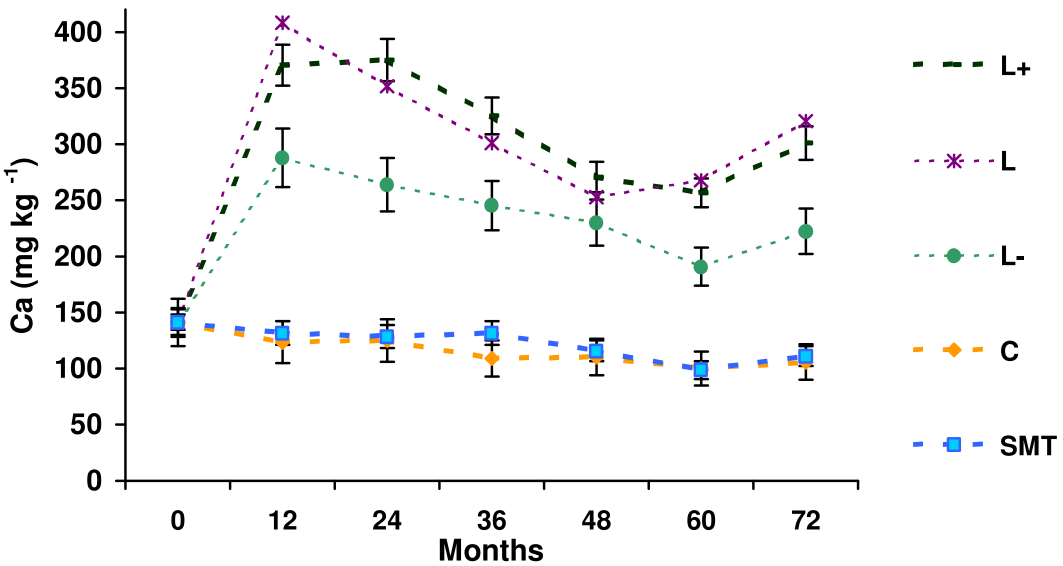

Figure 32: The influence of L treatments, relative to C and SMT treatments, on the soil Ca status over a 72-month period

Fly ash and SLASH ameliorants have relatively low levels of Mg kg^{-1}. Heavy applications of these ameliorants can, however, contribute to an increase in soil Mg content, as is noted in Figures 33-36. The lime is of dolomitic origin, has a significant Mg content, and is often used in agricultural practice to correct the soil Mg levels. Figures 33 - 36 clearly indicate the extremely low levels of Mg in the C and SMT treatments, and the significant effects of dolomitic lime (L), FA and SLASH, relative to the untreated control and SMT treatments, but levels were still lower than what is required (+/- 125 mg kg^{-1} of soil) for optimum pasture production (FSSA, 1975).

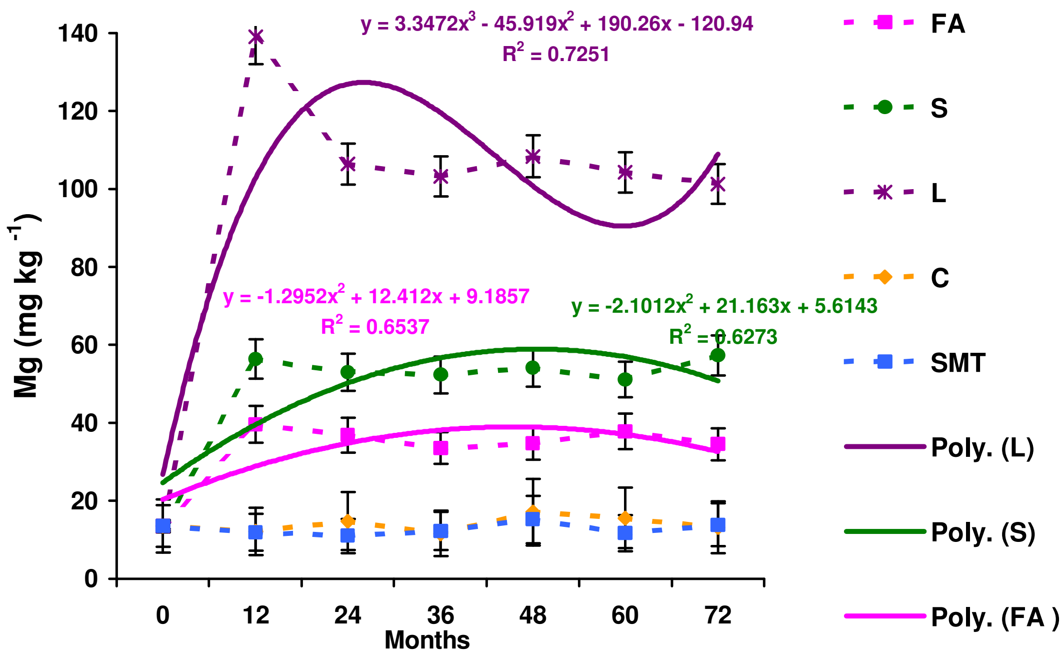

Figure 33: The influence of treatments, relative to C and SMT treatments, on the soil Mg status over a 72-month period

Figures 34-36 illustrate how the different levels of soil ameliorants affected the Mg status of the soil over the 72-month period. Soil status tended to decline after an initial increase on the lime and FA treatments, while the SLASH treatments maintained a relatively constant status after the initial 12-24 months. Significant differences between different levels of L and FA were observed in the first 24 months, although these differences became smaller as time progressed. The data presented on these macro-nutrients, illustrates the significance of soil amelioration, while the effects of alternative ameliorants, to lime, are highlighted.

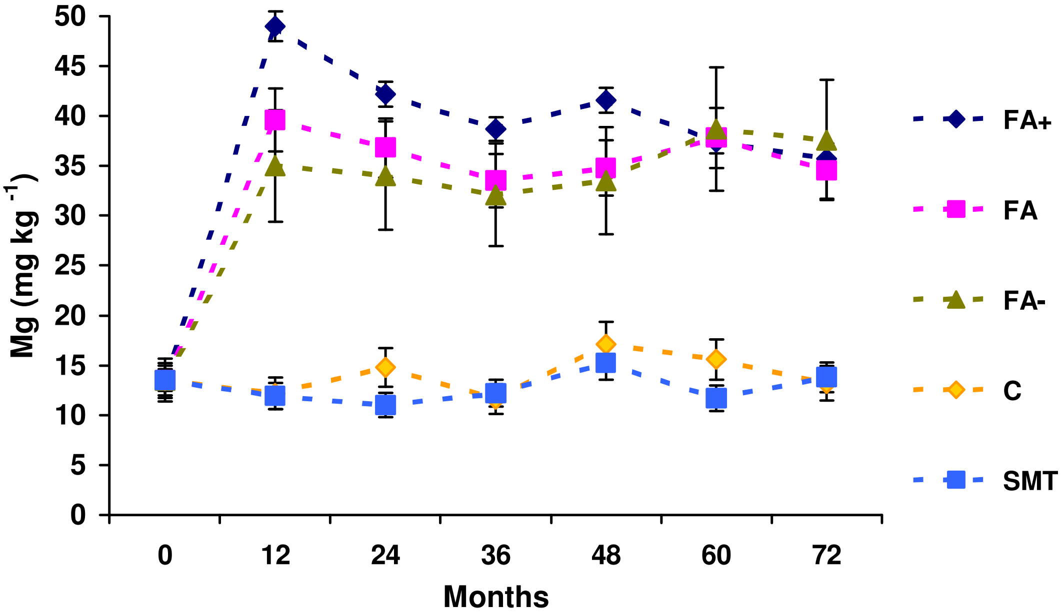

Figure 34: The influence of FA treatments, relative to C and SMT treatments, on the soil Mg status over a 72-month period

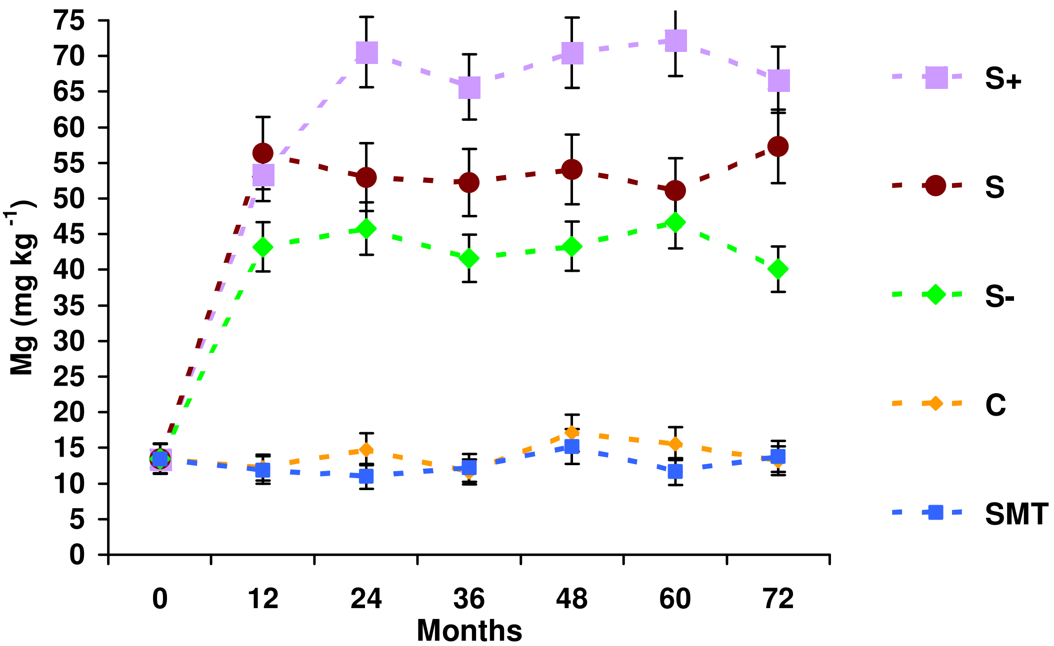

Figure 35: The influence of S treatments, relative to C and SMT treatments, on the soil Mg status over a 72-month period

The pH of the soils (Figure 37) was strongly affected by FA, SLASH and lime. An improvement of up to 2 pH units was evident after 12 months (Figures 37-40) after treatment, and as cropping continued, and no further soil ameliorant applications were given in the 72-month period, soil pH gradually declined even on the S and L treatments.

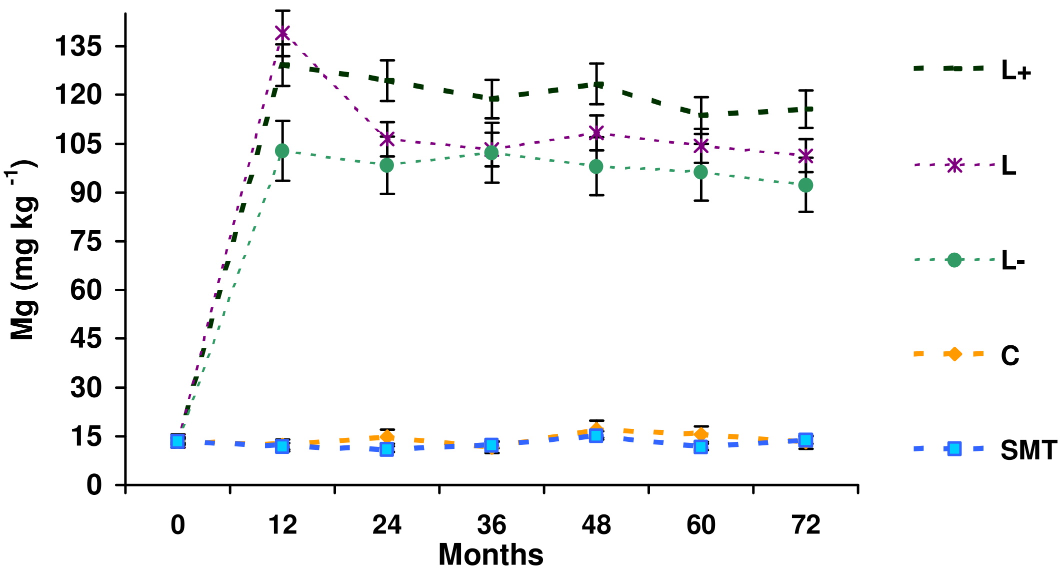

Figure 36: The influence of L treatments, relative to C and SMT treatments, on the soil Mg status over a 72-month period

The FA treatments, however, as shown in Figure 38, maintained the soil pH, in the optimum range for good plant production (between 6 and 7). These data emphasize the residual alkalinity of FA, and supports the use of FA as a more sustainable soil ameliorant. This residual alkalinity of FA is present in the glassy phase of the fly ash particle (Reynolds *et al*, 1999) and with the dissolution of this phase; alkalinity is released to facilitate the neutralization of soil acidity. With the correction of soil pH as initially calculated, plant nutrients in the soil are more soluble and available for plant uptake as can be seen for all the data presented in this paper. It can, therefore, be concluded that class F fly ash definitely has a much higher $CaCO_3$ equivalent than was originally assumed. The stable pH noted for the SMT is due to the bi-annual application of a small amount of lime applied together with the limestone ammonium nitrate fertilizer given each year. It is evident from Figure 39 that SLASH did not maintain pH as well as

FA, although containing the same amount of fly ash and additional CaO. This observation can possibly be ascribed to an acidifying effect of sewage sludge, which has been noted in previous work reported by Truter (2002).

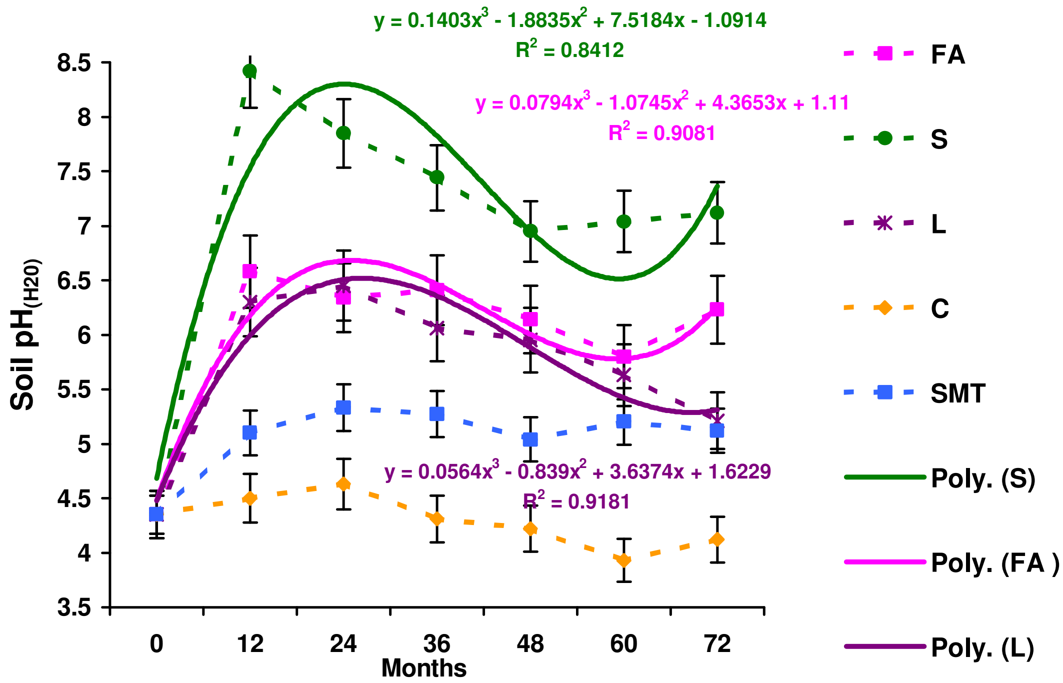

Figure 37: The influence of treatments, relative to C and SMT treatments, on the soil soil $pH_{(H20)}$ over a 72-month period

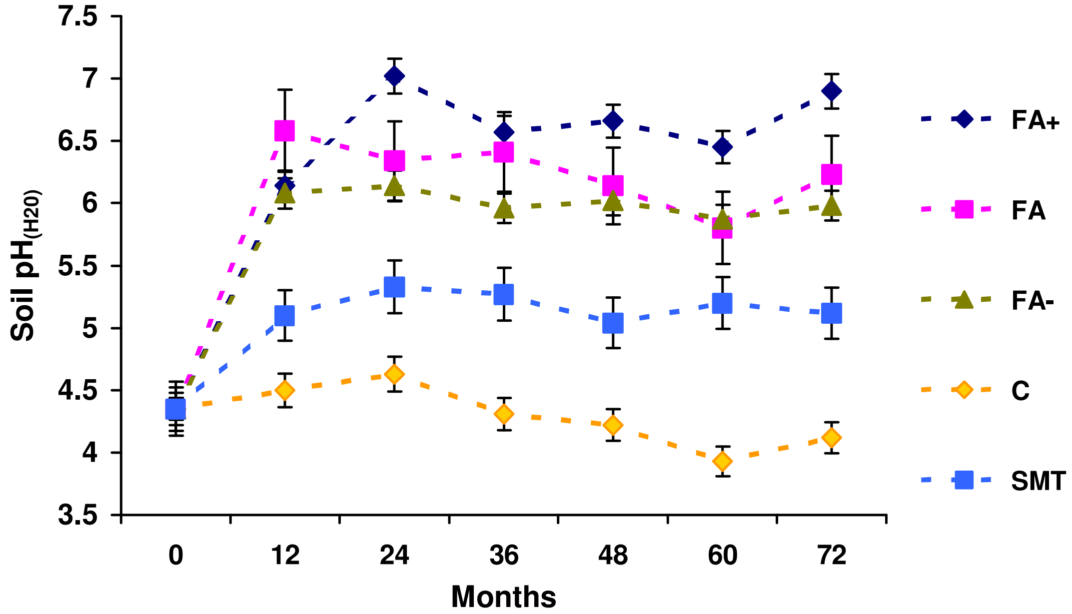

Figure 38: The influence of FA treatments, relative to C and SMT treatments, on the soil soil $pH_{(H20)}$ over a 72-month period

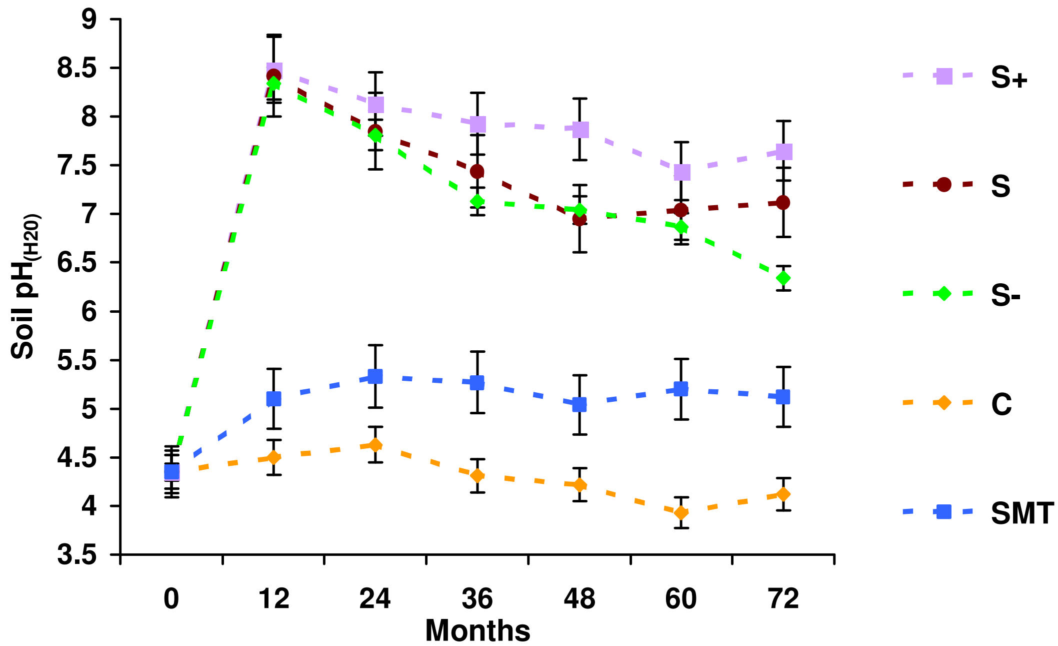

Figure 39: The influence of S treatments, relative to C and SMT treatments, on the soil soil $pH_{(H20)}$ over a 72-month period

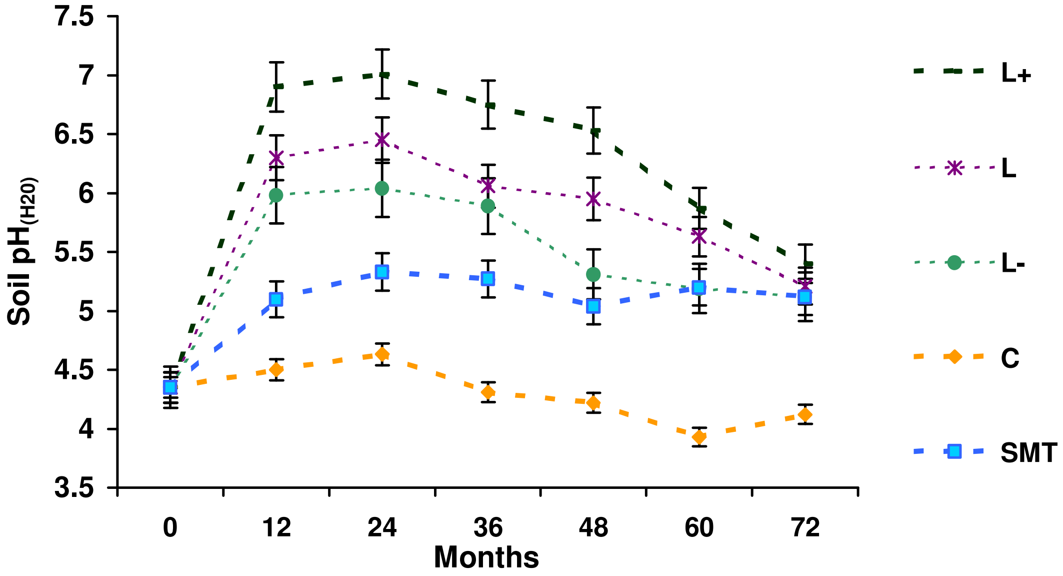

Figure 40: The influence of L treatments, relative to C and SMT treatments, on the soil soil $pH_{(H20)}$ over a 72-month period

4. Conclusions

Results from this investigation indicate that alternative ameliorants (fly ash and organic waste mixtures such as SLASH) can have a marked beneficial effect, which is still evident in the 7th year after establishment, despite no fertilizer being applied since the 1st season to all treatments, except the SMT. This would indicate that such ameliorants produce more sustainable vegetation than current practice, and due to their chemical nature and reactivity, long-term residual soil effects are evident. It can be concluded from this experimental work, that this class F fly ash definitely has a much higher $CaCO_3$ equivalent than the 20%, which was originally assumed.

Fly ash and SLASH treatments had significantly higher DM yields while the lower fertility treatments, such as the lime and the control, had a greater diversity of species. Excellent basal cover and yields were obtained when planted pastures on reclaimed soils were fertilized with some kind of nutrient source, organic or inorganic. The challenge, therefore, is to establish a sustainable system, when inorganic fertilization is either reduced or stopped. Industrial and urban by-products have unique properties and release both micro- and macro-nutrients slowly over time, to sustain productivity, and to effectively reclaim degraded soils. On the basis of these results, investigations of using alternative materials as ameliorants to reclaim degraded mine soils should be expanded.

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CHAPTER 6

Prepared according to the guidelines of Bioresource Technology

Re-vegetation of cover soils and coal discard material ameliorated with class F fly ash.

Wayne F. Truter[1*], Norman F.G. Rethman[1], Catharina, E. Potgieter[1], Kelley A. Reynolds[2] and Richard A. Kruger[3]

[1]Department of Plant Production and Soil Science, University of Pretoria, Pretoria, 0002, South Africa

[2] Eskom CR & D, Private Bag 40175, Cleveland, 2022, South Africa

[3] Richonne Consulting, 141 Rockwood Cr, Woodlands, Pretoria, South Africa

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Abstract

Coal discard material is a difficult medium to prepare for successful re-vegetation. It is possible to revegetate the covering topsoil, but the sustainability of conventional procedures is often poor. Liming and fertilizing the covering topsoil, does not necessarily ensure a viable growth medium for plants for prolonged periods. This covering topsoil is acidified, over time, by the capillary action of water generated by the underlying coal discard material. Roots are unable to grow properly and vegetation eventually dies. As a result, the covering topsoil becomes unstable, and susceptible to erosion. The objective of this experimental work was to identify other amelioration strategies for the cover soil and coal discard, using bituminous coal combustion by product - class F fly ash as a soil ameliorant. The effectivity of this material in counteracting the acidic conditions prevalent in the cover soil was observed. Due to the lower $CaCO_3$ equivalent of class F fly ashes compared with agricultural lime, heavier applications are required to neutralize such acidity. This research, concentrated on different combinations of amelioration of both the cover soil and the discard material compared to an untreated control, and the agricultural lime and fertilizer treatment. One treatment also included the use of class F fly ash as a barrier (buffer zone) between the covering topsoil and the coal discard. The cover soil was then planted to two grasses, Rhodegrass (*Chloris gayana*) and Smutsfinger grass (*Digitaria eriantha*) commonly used in rehabilitation in South Africa. This preliminary study focussed on the effect of different treatments on the production of these species and to the extent to which soil chemical status changed over a 24-month period. Significant increases in yield, of up to 200%, were noticed for class F fly ash treated soil and discards relative to the untreated control in a specific season. The pH of cover soil was the most strongly affected soil parameter during the experimental period. Class F fly ash as an ameliorant has, therefore, the potential to be used in creating a more sustainable soil environment to ensure a more stable vegetation to facilitate effective reclamation of coal discards. This work provides the basis for more detailed follow-up research.

Keywords: Coal discard, Class F fly ash, amelioration, acidity, re-vegetation

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* Corresponding Author: Tel no.: +2712 420 3226; email: wayne.truter@up.ac.za

1. Introduction

South African coalmines face a major challenge when it comes to the disposal, stabilization and reclamation of coal refuse disposal sites, also known as coal discard dumps. The coal discard materials vary from very fine materials removed by the flotation and density separation processes, also known as coal washing and coarse materials removed by the physical screening of coal. Coal discard dumps are very engineered designs that often make the re-vegetation process difficult.

If coal discard dumps are improperly reclaimed, many environmental hazards can occur. These hazards include the contamination of surface and ground waters by acidic leachates and runoff, erosion and sedimentation into nearby water sources, spontaneous combustion, and damage from landslides if failure of steep slopes occurs. Most of the problems that are associated with coal discard dumps can be mitigated by establishing and maintaining a healthy, adapted, productive and viable vegetation cover. Vigorous root development of identified adapted plant species can reduce the percolation of water and the ingress of oxygen into the coal discard profile. The establishment of a perennial vegetative cover, will also reduce sediment loss and stabilize the surface areas of dumps. Many problems are associated with the stabilization and re-vegetation of coal discards, and this paper introduces preliminary research that highlights the need for more detailed research under South African conditions.

To reclaim coal discards, it is essential that the discard characteristics are known and understood. Very little comprehensive information is available on coal discard properties. Haynes and Klimstra (1975), Medvick and Grandt (1976), Bland *et al.* (1977), Buttermore *et al*. (1978), Sobek and Sullivan (1981), as cited by Daniels and Stewart, (2000) have examined coal refuse characteristics from a reprocessing perspective in the United States, but comprehensive literature on these aspects is scarce especially in South Africa.

Of the few studies conducted globally on coal refuse “discards”, the description of the following characteristics are considered imperative in the planning of the reclamation of coal discards. These include particle size, pH, electrical conductivity, sulphur content, total elemental analysis, and mineralogy and soil solution chemistry. Once the properties of coal discards are known, it remains a challenge to integrate them with reclamation concerns. Many factors influence the reclamation potential of such a dump. A few important factors include the geologic source of the refuse, the processes involved in the preparation of plant establishment, local site conditions such as microclimate, inherent variability of materials, slope and aspect effects of dumps, pyrite oxidation and potential acidity of the materials, spontaneous combustion, low fertility of the cover soils, moisture retention, rooting depth, the compaction of the materials and also the high surface temperature. When taking all these factors into consideration it is necessary that a successful discard reclamation strategy be developed with guidelines for discard area vegetation such as the characterization of the area to determine the re-vegetation potential, the site preparation, fertilization, seeding rates and species mixtures, as well as the consideration of tree planting.

In South Africa soils and discards are conventionally treated with very high levels of lime to create a suitable pH for the establishment of a good vegetation cover. A good vegetation cover ensures stability of the coal discard to prevent any sort of erosion of the cover soil. The problem, however, is that the cover soil becomes acidic as a result of the capillary action of generated acidic water from the underlying coal discard and, with time, the vegetation dies. The objective of this experimental work was to treat the soil and discard with class F fly ash as an alternative amendment, and to determine the ability of this material to improve pH of the soil and discards and maintain it as long as possible, thereby creating a more favourable and sustainable rooting medium. Fly ash is basically an amorphous ferro-alumino silicate, which is also characteristically high in Ca, and many other macro- and micro-nutrients. Virtually all natural elements are present in coal ash in trace amounts. There is a general consensus that most trace elements increase in concentration with decreasing size of fly ash particles (Adriano *et al*., 1980). The alkaline nature of fly ash has led to an examination of its use as a liming agent to supplement the reagent grade $CaCO_3$ on acidic agricultural soils and coalmine spoils (Martens, 1971; Moliner and Street, 1982; Wong and Wong, 1989).

Furthermore, the enriched macro- and micronutrients contained in fly ash enhances plant growth in nutrient-deficient soils (Plank and Martens, 1974; Martens and Beahm, 1978; Wong and Wong, 1989; Truter *et al.,* 2001, Truter, 2002, Truter and Rethman, 2003, Truter 2007). Laboratory studies have shown that an alkaline fly ash was equivalent to approximately 20% of reagent-grade $CaCO_3$ in reducing soil acidity and supplying plant Ca needs (Phung *et al*., 1978; Adriano *et al*., 1980; Truter 2002). However, depending on the source of fly ash, and the extent to which it is weathered, its neutralizing capacity could range from none to very high (Doran and

Martens, 1972; Adriano *et al*., 1980; Truter, 2002). When spoil areas are reclaimed, the quantities of fly ash, which need to be applied, usually, exceed those required for cropland amelioration. The quantities of fly ash required to reclaim discards, however, will be different and it will depend upon the pH of the fly ash, the degree to which it is weathered, and the pH of the discard to be reclaimed. For example, spoil areas having a pH of 4.4. to 5.0 were reclaimed using fly ash at rates of 70 metric tons ha^{-1} (Fail and Wochok, 1977; Adriano *et al*., 1980), while on discards with pH values of 2.0 to 3.5 rates from 335 to 1790 metric tons ha^{-1} were used (Adams *et al*., 1972; Adriano *et al*., 1980).

Previous research has shown that fly ash has residual alkalinity. This supports the use of fly ash as a more sustainable soil ameliorant (Truter, 2002, Truter, 2007). This residual alkalinity of fly ash is present in the glassy phase of the fly ash particle (Reynolds *et al.,* 1999) and with the dissolution of this phase, alkalinity is released to facilitate the neutralization of acidity. With the correction of low pH's, plant nutrients in the soil are more soluble and available for plants. Data obtained in previous research supports the conclusion, that class F fly ash definitely has a much higher $CaCO_3$ equivalent than what was originally assumed (Truter, 2002, Truter 2007).

Another objective of this study was to investigate the capping of the discard material with a fly ash layer, which would serve as a buffer zone, delaying or preventing the acidification of the soil by the acid generating coal discard, and thereby facilitating better re-vegetation of such materials.

2. Materials and Methods

A randomized study, using large pots, was conducted on the Hatfield Experimental Farm, Pretoria, South Africa (25°45'S 28°16'E), 1327m above sea level (Figure 1) in 2003, 2004 and 2005.

Figure 1: Greenhouse pot study on coal discard reclamation

A 15 cm layer of cover soil, collected from a surface coal mine, was used to cover the coal discard that was placed in 50 *l* pots with different treatments. Figure 2 illustrates of how coal discard pots were constructed to simulate coal discard design.

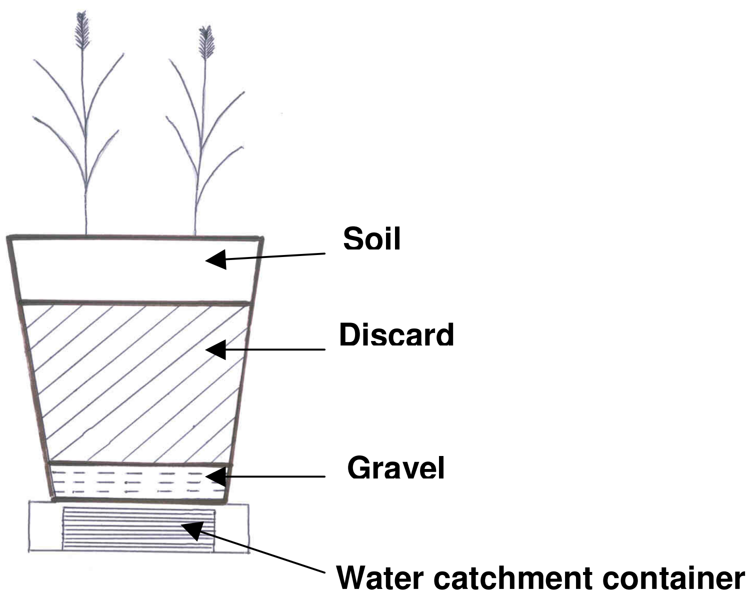

Figure 2: The pot simulation of coal discard dumps

The experimental design was a randomized block design with six treatment combinations replicated four times. These included the incorporation of fly ash into the cover soil, the incorporation of fly ash into the discard material, and the use of fly ash as a buffer to cap the discard before soil placement as illustrated in Table 1.

Table 1: Treatment combinations for coal discard study.

Sample	Treatment
T1	Fly ash treated cover soil over fly ash treated discard
T2	Untreated cover soil over untreated discard (CONTROL)
T3	Fly ash treated cover soil over untreated discard
T4	Untreated cover soil over fly ash treated discard
T5	Fly ash treated cover soil over fly ash treated discard with fly ash interlayer
T6	Lime and NPK treated cover soil over lime treated discard

The optimum lime application rate for the cover soil and coal discard was based on the buffering capacity of the two substrates. The mine cover soil and the coal discard had a $pH_{(H2O)}$ of 4.3 and 2.8, respectively. It was calculated, from the buffer curve, that the mine cover soil and coal discard, would require 10 and 50 tons ha^{-1} of dolomitic lime, respectively. These lime requirements would raise the pH of the substrates to a $pH_{(H2O)}$ of 6.5, suitable for plant growth. The level of fly ash to be used would thus be five times the amount of lime, which was based on the assumption (from literature) that class F fly ash had a $CaCO_3$ equivalent of 20% (Truter, 2002). In September 2002, the cover soil treatments received an equivalent of 50 tons ha^{-1} of fly ash, and discard treatments received an equivalent of 250 tons ha^{-1} of fly ash. The fly ash interlayer used in T5, was based on a layer thickness of 15 cm, which equates to 1688 tons ha^{-1} calculated using a calculated bulk density of 1125kg m^3 for fly ash. The quantities of fertilizer and lime used in T6 treatment in the establishment year was 65 kg N ha^{-1}, 200 kg P ha^{-1}, 135 kg K ha^{-1}, in the form of limestone ammonium nitrate, superphosphate and potassium chloride respectively. The equivalent of 10 tons and 50 tons of dolomitic lime per hectare was applied to the soil and discard, respectively. In the following seasons 100 kg N ha^{-1} was applied to all treatments each spring.

Two tufts of each of two popular rehabilitation and forage grasses, Rhodegrass (*Chloris gayana*) and Smuts finger grass (*Digitaria eriantha*), were planted in January 2003, in each of these pots. Biomass production was used to determine the survival and persistence of the vegetation. Monthly harvests were taken in the 2002/2003, 2003/2004 and 2004/2005 growing seasons.

The aim of this study was to determine if potential acidity would enter the growing medium from the underlying coal discard by means of capillary movement, and affect the growth of the two test grass species. This would change the soil conditions for root growth and development and ultimately effect biomass production.

2.1 Statistical analyses

All dry matter production data and soil analyses were statistically analysed using PROC GLM (1996/1997 and 1997/1998). Statistical analyses were performed using SAS (1998). LSD's were taken at $P \leq 0.05$.

3. Results and Discussion

3.1 Plant Measurements

The data collected in this study was used to illustrate to what extent fly ash affected the chemical properties of soil and discard and facilitated plant growth on topsoiled coal discard. In this first summer T3 and T4 were the best treatments for *C. gayana.* The results presented in Tables 2 and 3, show clearly which of the two species was best adapted to the different treatments. The *D. eriantha* proved to be the better species, in terms of yield. Dry matter production data is presented separately for different seasons. This highlights the different growth responses of the two species in the different seasons. The T1 and T5 treatments proved to be the most effective amelioration treatments in comparison to T2 treatment, which served as the untreated control. This observation, however, only held true for *D. eriantha* in the first summer. The results are slightly different when the second year's data (Tables 4 and 5) is interpreted. In the second year it was the *C. gayana,* which was the stronger species, and treatments T4 and T6, which occasionally had the more pronounced effect on the biomass production in the actively growing season.

Table 2: Mean biomass production data for *D. eriantha and C. gayana* during the summer of 2003 (after planting in the early summer of 2002/2003 season)

	2003		
	March	April	TOTAL
	***D. eriantha* (g / plant)**		
T1	9.64 (+/-3.21)	10.51 (+/-4.3)	**20.15**$_{a}$
T2	6.29 (+/-2.34)	4.60 (+/-2.5)	10.89$_{c}$
T3	6.75 (+/-2.56)	7.46 (+/-2.13)	14.21$_{b}$
T4	5.85 (+/-2.34)	7.18 (+/-2.45)	13.03$_{b}$
T5	7.01 (+/-2.98)	12.69 (+/-3.21)	**19.79**$_{a}$
T6	6.92 (+/-3.04)	5.75 (+/-3.45)	12.67$_{b}$
	***C. gayana* (g/plant)**		
T1	5.32 (+/-2.67)	3.76 (+/-1.56)	9.08$_{bc}$
T2	5.48 (+/-2.99)	4.99 (+/-2.14)	10.47$_{b}$
T3	7.28 (+/-3.87)	5.54 (+/-3.56)	12.82$_{a}$
T4	6.22 (+/-2.90)	5.66 (+/-3.78)	11.88$_{a}$
T5	3.84 (+/-2.21)	5.60 (+/-3.98)	9.44$_{bc}$
T6	3.17 (+/-2.01)	4.47 (+/-2.78)	7.64$_{c}$

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

Table 2 only includes the production data for the first two months (60 days) after establishment. It should be noted that the production of the T1 treatment (Fly ash ameliorated soil and discard) and T5 treatment (fly ash ameliorated soil and discard with fly ash barrier) produced the most significant yields of approximately 90% higher than the control in the case of *D. eriantha*. In the case of *C. gayana* there were not as clear-cut results, although T6 (the lime and fertilizer treatment) yielded, once again, some of the poorest results.

It is clear, from Table 3 that the species growth rate declined by approximately 50 % in the winter season of 2003 (despite this work being conducted under greenhouse conditions). However, significant differences in yields were still noted in this season. The T5 treatment continued to provide the best yields for both species. It is evident from these dry matter production data that the *D. eriantha* responded more strongly than *C. gayana* in the first year.

Table 3: Mean biomass production data for *D. eriantha* and *C. gayana* during the winter of 2003 (after planting in the summer of the 2002/2003 season)

	2003					
	May	June	July	August	September	TOTAL
	***D. eriantha* (g / plant)**					
T1	5.37 (+/-3.24)	5.03 (+/-3.45)	3.87 (+/-2.45)	5.31 (+/-3.03)	5.67 (+/-2.15)	25.25_{ab}
T2	2.82 (+/-1.56)	2.66 (+/-1.33)	2.39 (+/-1.56)	2.88 (+/-1.45)	2.99 (+/-1.43)	13.74_{d}
T3	3.69 (+/-2.87)	2.80 (+/-1.67)	1.90 (+/-0.67)	2.51 (+/-1.99)	2.92 (+/-1.23)	13.82_{d}
T4	4.70 (+/-2.20)	3.43 (+/-2.11)	2.51 (+/-0.78)	3.27 (+/-1.01)	3.23 (+/-1.22)	17.14_{c}
T5	6.11 (+/-3.12)	6.50 (+/-3.87)	4.03 (+/-2.24)	5.10 (+/-2.46)	6.03 (+/-2.12)	27.77_{a}
T6	5.37 (+/-2.98)	5.05 (+/-4.1)	3.42 (+/-1.21)	4.71 (+/-2.45)	5.39 (+/-2.11)	23.94_{b}

	***C. gayana* (g / plant)**					
	05	06	07	08	09	TOTAL
T1	2.32 (+/-0.55)	1.64 (+/-0.99)	1.21 (+/-0.45)	1.94 (+/-0.98)	3.08 (+/-1.87)	10.19_{d}
T2	3.14 (+/-1.87)	2.39 (+/-1.44)	1.62 (+/-1.02)	2.86 (+/-1.45)	4.29 (+/-2.12)	14.30_{b}
T3	3.95 (+/-2.32)	3.01 (+/-1.24)	1.66 (+/-0.78)	2.79 (+/-1.78)	4.02 (+/-1.24)	15.43_{a}
T4	3.57 (+/-1.34)	2.63 (+/-0.74)	1.38 (+/-0.99)	2.51 (+/-1.23)	3.88 (+/-1.22)	13.97_{b}
T5	2.07 (+/-1.45)	2.28 (+/-1.87)	3.89 (+/-1.56)	4.99 (+/-2.01)	3.05 (+/-1.78)	16.28_{a}
T6	2.66 (+/-1.01)	2.37 (+/-1.45)	1.39 (+/-0.64)	2.71 (+/-1.32)	3.63 (+/-1.66)	12.35_{c}

***ab** Column means with common alphabetical subscripts do not differ significantly ($P > 0.05$) (Bonferroni Test)

In Table 2 it is noted that T6 was very poor for both species, however, +/- 6 months after initial treatment (Table 3) the lime and fertilizer treatment (T6) now had a very positive effect on *D. eriantha*, while the effect on *C. gayana* still did not reflect a very clear pattern.

In the following 7 months, presented in Table 4, the observation is made that the dry matter production of the *C. gayana* (36.2g plant^{-1}) was improving, and compared well with that of *D. eriantha* (34.3g plant^{-1}). Once again, it is evident that the T5, T1 and T6 treatments were the best for the *D. eriantha*, whereas the T3, T4 and T5 treatments were the better treatments for *C. gayana*.

Table 4: Mean biomass production data for *D. eriantha and C. gayana* during summer growing season of 2003/2004

	2003			**2004**				
	October	November	December	January	February	March	April	TOTAL
				***D. eriantha* (g / plant)**				
T1	5.00 (+/-2.11)	6.19 (+/-2.87)	7.52 (+/-3.57)	6.08 (+/-3.02)	4.92 (+/-2.54)	8.35 (+/-4.56)	1.48 (+/-0.98)	39.54 $_b$
T2	2.93 (+/-1.11)	2.77 (+/-1.02)	4.38 (+/-2.45)	3.64 (+/-1.78)	2.48 (+/-1.21)	0.43 (+/-0.12)	0.58 (+/-0.21)	17.21 $_e$
T3	3.49 (+/-1.34)	3.54 (+/-1.23)	5.96 (+/-3.21)	5.47 (+/-2.34)	4.92 (+/-2.34)	2.56 (+/-1.33)	0.95 (+/-0.43)	26.89 $_d$
T4	2.48 (+/-1.25)	4.64 (+/-2.11)	7.11 (+/-3.33)	7.02 (+/-3.76)	6.75 (+/-3.54)	2.52 (+/-1.17)	1.40 (+/-0.65)	31.92 $_c$
T5	6.48 (+/-3.02)	8.19 (+/-3.45)	11.07 (+/-4.56)	10.45 (+/-4.32)	9.56 (+/-4.67)	4.77 (+/-2.29)	1.80 (+/-1.01)	52.32 $_a$
T6	4.60 (+/-2.13)	5.72 (+/-3.12)	10.25 (+/-5.67)	8.41 (+/-3.56)	6.88 (+/-3.76)	2.04 (+/-1.00)	0.79 (+/-0.32)	37.97 $_b$
				***C. gayana* (g/plant)**				
T1	2.16 (+/-1.43)	2.87 (+/-1.87)	5.69 (+/-2.43)	5.69 (+/-2.33)	6.39 (+/-3.22)	4.21 (+/-2.31)	4.90 (+/-1.34)	31.91 $_c$
T2	3.70 (+/-2.65)	4.66 (+/-2.56)	6.46 (+/-4.57)	5.00 (+/-2.89)	5.01 (+/-4.71)	4.29 (+/-2.22)	5.61 (+/-2.35)	34.73 $_b$
T3	4.57 (+/-2.74)	4.99 (+/-2.78)	8.77 (+/-4.11)	7.50 (+/-3.47)	6.94 (+/-2.86)	4.80 (+/-3.11)	5.05 (+/-2.09)	42.62 $_a$
T4	3.56 (+/-2.10)	5.43 (+/-3.76)	8.45 (+/-3.88)	7.64 (+/-3.65)	7.21 (+/-3.23)	3.74 (+/-2.02)	4.60 (+/-2.14)	40.63 $_{ab}$
T5	5.50 (+/-3.03)	4.01 (+/-2.67)	6.33 (+/-3.93)	5.18 (+/-2.96)	4.01 (+/-2.76)	5.41 (+/-2.77)	5.94 (+/-2.44)	36.47 $_b$
T6	4.37 (+/-2.78)	5.01 (+/-3.01)	4.71 (+/-2.07)	4.89 (+/-2.31)	4.68 (+/-1.34)	4.21 (+/-1.87)	3.07 (+/-1.26)	30.94 $_c$

***ab** Column means with common alphabetical subscripts do not differ significantly ($P > 0.05$) (Bonferroni Test)

The yields of *C. gayana* in the winter of 2004, as presented in Table 5, indicate a better growth of this grass in comparison with the *D. eriantha* (2.1 2g plant^{-1}). This clear reversal in production of the species can possibly be ascribed to the roots of *D. eriantha* reaching the coal discard material and consequent negative effects. The *C. gayana*, however, proved to be better adapted. As a result of the growth form of this species (having the advantage of stolons), new plants were established on the surface. This contributed significantly to a higher dry matter production.

Table 5: Mean biomass production data for *D. eriantha* and *C. gayana* during the winter of 2004

	2004					
	May	June	July	August	September	TOTAL
			***D. eriantha* (g / plant)**			
T1	0.65 (+/-0.21)	0.39 (+/-0.13)	0.73 (+/-0.25)	0.55 (+/-0.21)	0.97 (+/-0.39)	3.22_a
T2	0.03 (+/-0.01)	0.00 (+/-0.00)	0.00 (+/-0.00)	0.30 (+/-0.22)	0.01 (+/-0.01)	0.34_d
T3	0.22 (+/-0.10)	0.08 (+/-0.02)	0.19 (+/-0.09)	0.79 (+/-0.32)	0.31 (+/-0.12)	1.59_c
T4	0.46 (+/-0.12)	0.21 (+/-0.11)	0.42 (+/-0.14)	0.61 (+/-0.34)	1.88 (+/-0.78)	3.58_a
T5	0.74 (+/-0.24)	0.37 (+/-0.18)	0.41 (+/-0.26)	0.43 (+/-0.18)	0.54 (+/-0.32)	2.49_b
T6	0.34 (+/-0.14)	0.22 (+/-0.12)	0.35 (+/-0.15)	0.15 (+/-0.07)	0.51 (+/-0.23)	1.57_c
			***C. gayana* (g / plant)**			
T1	2.38 (+/-0.98)	0.82 (+/-0.46)	1.99 (+/-1.01)	2.55 (+/-1.16)	2.72 (+/-1.04)	10.46_b
T2	2.46 (+/-1.13)	1.06 (+/-0.62)	1.37 (+/-0.65)	1.07 (+/-0.67)	1.97 (+/-0.97)	7.93_c
T3	2.17 (+/-1.09)	0.83 (+/-0.51)	0.89 (+/-0.34)	2.05 (+/-1.34)	2.49 (+/-1.21)	8.43_c
T4	2.02 (+/-1.02)	0.61 (+/-0.32)	1.35 (+/-0.57)	2.95 (+/-1.76)	5.32 (+/-2.45)	12.25_a
T5	1.54 (+/-0.67)	1.49 (+/-0.58)	1.48 (+/-0.89)	1.97 (+/-1.04)	2.26 (+/-1.32)	9.04_{cb}
T6	0.82 (+/-0.54)	0.72 (+/-0.12)	1.95 (+/-1.04)	1.66 (+/-0.65)	0.90 (+/-0.24)	6.05_d

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

It is evident from Table 5, that treatments T4, T1 and T5 were overall the better soil ameliorant combinations, providing a better environment for plant growth. It is also clear, from both Tables 5 and 6, that the *D. eriantha* tufts were deteriorating, due to the possible restriction on it's roots. In comparison *C. gayana* becomes relatively better and better. This is a clear reversal of the agricultural situation where, *C. gayana* starts well and fades out, while *D. eriantha* starts slowly and gets better and better. It is, therefore, important that a wider range of species be evaluated for tolerance to discard conditions. The well-known tolerance of *C. gayana* to saline soil conditions may be a possible explanation for these results and saline tolerance might be a basis for the identification of species suitable for the reclamation of discards with class F fly ash.

Table 6: Mean biomass production data for *D. eriantha* and *C. gayana* during summer of 2004/2005

	2004			2005	
	October	November	December	January	TOTAL
			***D. eriantha* (g / plant)**		
T1	1.15 (+/-0.43)	0.64 (+/-0.33)	0.33 (+/-0.14)	0.14 (+/-0.07)	2.26_{b}
T2	0.01 (+/-0.00)	0.00 (+/-0.00)	0.00 (+/-0.00)	0.00 (+/-0.00)	0.01_{d}
T3	0.37 (+/-0.12)	0.13 (+/-0.07)	0.04 (+/-0.01)	0.00 (+/-0.00)	0.54_{c}
T4	2.23 (+/-1.16)	1.07 (+/-0.43)	0.46 (+/-0.18)	0.24 (+/-0.12)	4.00_{a}
T5	0.64 (+/-0.34)	0.34 (+/-0.11)	0.10 (+/-0.04)	1.02 (+/-0.78)	2.10_{b}
T6	0.60 (+/-0.27)	0.82 (+/-0.31)	0.29 (+/-0.10)	0.16 (+/-0.05)	1.87_{b}
			***C. gayana* (g/plant)**		
T1	3.23 (+/-1.76)	5.10 (+/-2.56)	3.91 (+/-1.06)	3.94 (+/-2.01)	16.18_{b}
T2	2.33 (+/-1.22)	4.04 (+/-2.21)	3.12 (+/-2.19)	3.00 (+/-1.46)	12.49_{c}
T3	2.95 (+/-1.65)	5.39 (+/-3.03)	4.07 (+/-2.06)	3.43 (+/-1.97)	15.84_{b}
T4	6.31 (+/-3.25)	7.06 (+/-3.87)	4.27 (+/-1.56)	3.77 (+/-1.38)	21.41_{a}
T5	4.68 (+/-1.23)	4.84 (+/-2.14)	3.41 (+/-1.87)	5.20 (+/-1.21)	18.13_{ba}
T6	2.62 (+/-1.87)	2.46 (+/-1.02)	3.46 (+/-1.46)	3.52 (+/-1.11)	12.06_{c}

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

In summary, *D. eriantha* and *C. gayana* responded differently to the different treatments. Shortly after soil and discard amelioration in the summer season of 2002/2003, until the following summer 2003/2004, *D. eriantha* was the predominant specie on all the treatments. Thereafter, *C. gayana* was the predominant species by far. It is evident from the treatment responses, that *C. gayana* is more adapted to the higher soil pH levels and possible saline conditions, and *D. eriantha* is more adapted to acidic soils.

3.2 Soil Analysis

The soil analyses presented in Table 7, do not give any indication of possible reasons for the improved growth of the two grasses on different treatments. The improvement in pH (12 & 24 months after treatment – Tables 7 & 8) may to some extent be responsible for the better utilization of nutrients in the soil. It is also noted that the neutralizing effect of L and FA could be expected to be greater on more acid substrates. However, these two ameliorants had similar effects on pH, with FA having a slightly better persistence. The treatment of discard material seemed to have a marginal effect on the pH of the cover soil, which, tended to become stronger with time.

The possible effect of micro- nutrients, provided by the fly ash should, nevertheless, not be excluded. The topsoil used in this experiment had a relatively good nutrient status, except for K. From Table 7, it can be seen that treatments T1, T3, T5 and T6 had slightly better levels of nutrients and good soil pH levels 12 months after treatment.

Table 7: Analyses of cover soils 12 months after treatment application

		Bray I	*Ammonium Acetate Extraction*				
	pH water	P	*Ca*	*K*	*Mg*	*Na*	C
		mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	%
T1	6.98_a (+/-1.12)	36.8_a (+/-12.31)	551_a (+/-56.89)	27_a (+/-6.5)	93_b (+/-23.11)	48_a (+/-6.75)	0.43_a (+/-0.11)
T2	6.25_b (+/-0.99)	37.0_a (+/-11.72)	528_a (+/-76.32)	25_a (+/-11.21)	87_b (+/-11.23)	49_a (+/-3.56)	0.49_a (+/-0.21)
T3	7.28_a (+/-101)	37.7_a (+/-9.35)	532_a (+/-34.86)	18_b (+/-5.89)	82_b (+/-8.97)	54_a (+/-9.87)	0.54_a (+/-0.34)
T4	6.20_b (+/-0.76)	31.7_a (+/-10.78)	484_a (+/-57.91)	27_a (+/-9.67)	83_b (+/-12.32)	44_a (+/-3.89)	0.48_a (+/-0.25)
T5	7.15_a (+/-0.66)	39.0_a (+/-7.98)	582_a (+/-61.01)	27_a (+/-7.90)	96_{ab} (+/-9.05)	51_a (+/-5.48)	0.51_a (+/-0.19)
T6	7.25_a (+/-0.56)	22.1_b (+/-6.98)	588_a (+/-59.80)	33_a (+/-9.89)	122_a(+/-9.11)	46_a (+/-4.44)	0.47_a (+/-0.26)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

It is noted in Table 8, however, that 12 months later all nutrient levels were lower, and that pH had also declined. This is probably as a result of cropping and nutrient removal during harvesting. These data, presented in Tables 7 and 8, show that the pH of the untreated cover soil treatments (T2 and T4) remained relatively constant from 12 months to 24 months. The fly ash treated soils T1, T3 and T5, however, revealed a slight increase in pH, irrespective of the cropping of the soil and the annual N topdressing the plants received. This to some extent, can cause slight acidification of the soil, which is noted in the decline of the soil pH of the lime treated soil, T6.

Table 8: Analyses of cover soils 24 months after treatment application

		Bray I	*Ammonium Acetate Extraction*				
	pH water	P	*Ca*	*K*	*Mg*	*Na*	C
		mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	%
T1	7.03 $_a$ (+/-1.02)	23.0 $_a$ (+/-4.65)	415 $_a$ (+/-34.51)	16 $_b$ (+/-5.87)	67 $_b$ (+/-15.67)	29 $_b$ (+/-8.96)	0.52 $_a$(+/-0.12)
T2	6.18 $_b$ (+/-0.56)	16.3 $_a$ (+/-5.78)	363 $_a$ (+/-45.62)	18 $_b$ (+/-4.32)	67 $_b$ (+/-12.34)	48 $_a$ (+/-9.22)	0.51 $_a$(+/-0.23)
T3	7.15 $_a$ (+/-0.87)	13.1 $_b$ (+/-3.46)	438 $_a$ (+/-54.67)	16 $_b$ (+/-5.21)	72 $_b$ (+/-17.89)	31 $_b$ (+/-5.43)	0.56 $_a$(+/-0.18)
T4	6.30 $_b$ (+/-0.56)	12.4 $_b$ (+/-4.67)	372 $_a$ (+/-35.67)	18 $_b$ (+/-3.78)	65 $_b$ (+/-15.76)	27 $_b$ (+/-2.56)	0.52 $_a$(+/-0.31)
T5	7.05 $_a$ (+/-0.67)	20.9 $_a$ (+/-7.89)	424 $_a$ (+/-33.21)	30 $_a$ (+/-5.78)	82 $_a$ (+/-21.11)	26 $_b$ (+/-6.78)	0.49 $_a$(+/-0.21)
T6	6.98 $_a$ (+/-0.45)	9.3 $_b$ (+/-2.34)	437 $_a$ (+/-49.84)	22 $_{ab}$ (+/-6.94)	96 $_a$ (+/-17.99)	30 $_b$ (+/-7.93)	0.55 $_a$(+/-0.27)

***ab** Column means with common alphabetical subscripts do not differ significantly (P> 0.05) (Bonferroni Test)

The data presented on nutrient levels (Tables 7 and 8), indicate that there were no obvious treatment effects on P, K, Ca, Mg, Na and C. The C content, however, remained relatively constant from 12 – 24 months for all the treatments. It is also evident from the data that the P, Ca, Mg and Na contents of the different treatments, all declined significantly 0 –24 months. This can possibly be ascribed to plant uptake, leaching or the immobilization of nutrients. The K content of soils also declined for all the treatments, except T5, which remained relatively constant between 12 and 24 months (Tables 7 & 8). The overall results for T5, poses the question, whether the fly ash interlayer, has an additional advantage of buffering the cover soil from the coal discard effects.

4. Conclusion

It is evident from the preliminary research results presented in this paper, that class F fly ash has the potential to be used as an alternative ameliorant to improve the sustainability of coal discard reclamation. Increased yields were noted for all the monitored seasons where the treatment had class F fly ash as a barrier (buffer zone). This affect can possibly be ascribed to the prolonged counter-action of the alkaline material to the acidic water generated from the oxidization of pyrite present in the discard material, which via capillary action tends to move upward towards the cover soil. It was evident from the data that while *D. eriantha* was the best species initially, the *C. gayana* with a different growth form and saline tolerance, became totally dominant as the trial progressed

pH was the only soil property, which showed a possible affect of the different treatments. A slight reduction in pH was noted over the 24-month period for the untreated control and conventional amelioration treatment, whereas the treatments containing class F fly ash showed no major reduction in soil pH. Many questions remain. How does class F fly ash react with acid generating coal discard? How can it be used to facilitate the reclamation of coal discard dumps? The most important challenge in the reclamation of coal discards, is to ensure stable vegetation, through improved soil conditions as a result of effective amelioration, to allow effective root development to stabilize these soils for sustainable periods to ultimately prevent loss of cover soil.

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CHAPTER 7

General Conclusions and Recommendations

7.1 The utilization of soil ameliorants, containing Class F fly ash, to enhance plant production by improving soil chemical properties

The utilization of the micronutrient content and liming qualities of class F fly ash together with the macronutrient and organic content of sewage sludge, can provide an alternative soil ameliorant such as SLASH. SLASH and class F fly ash definitely have agricultural potential. For optimal crop production specific soil conditions are required for a specific crop, it is , therefore, important that soil pH and nutrient levels meet crop requirements. It is concluded from this study that the class F fly ash and SLASH soil ameliorants had a significant effect on the dry matter production of the test crops. The crops planted on a relatively nutrient poor and acidic Hutton soil, were two annual crops, maize (*Zea mays*) and wheat (*Triticum aestivum*) and the perennial pasture legume (*Medicago sativa)*. Crop performance overall was much better on the class F fly ash and SLASH ameliorated soils. High grain yields, of up to 575 % more than the controls were registered for prolonged periods on the SLASH treatment, without annual inputs of fertilizers and conventional soil amelioration practices, even under intensive cultivation practices. Three different soil pH levels were monitored, and similar trends were noted for all three levels. These data, have demonstrated, that even though the SLASH ameliorant had the assumed advantage of an organic component, with a higher proportion of macronutrients, the class F fly ash treatment produced relatively high wheat grain yields of up to 335 % more than the control treatments. These results can possibly be ascribed to the fact that the correction in soil pH alone had a significant affect on crop production, because, baseline nutrients present in these agricultural soils could now be used more effectively, because of improved conditions for better root development. Similar observations were made for wheat dry matter production. It was, however, noted that only very small differences between treatment effects for the soil pH's 5.0 and 5.5 were evident. The more acidic soil (pH of 4.5) illustrates the significant differences between the SLASH and class F fly ash treatments. The acid sensitive perennial *M. sativa* (lucerne) was also favored by treatments with class F fly ash and SLASH producing up to 370 % higher DM yields over an extended period, with no cultivation after establishment.

From previous work, conducted on acidic agricultural soils, the residual effect of SLASH persisted for up to three years. To date, conventional liming and fertilization has been the preferred method of ameliorating such acidic and nutrient poor soils, on which these legumes are grown, but this is not necessarily sustainable. With the initial focus of this study being on the affect of class F fly ash and SLASH on the chemical properties of degraded soils / substrates, it has been concluded that SLASH is a good source of a variety of essential micro- and macro-nutrients, while also having the potential to improve pH. The significant role of coal combustion by-products (CCB's) in neutralizing acidity is due in part to the residual alkalinity, and hence it's ability to modify the soil chemical balance over extended periods so that nutrients become more available for plants.

It is also concluded that both SLASH and class F fly ash have contributed to higher nutrient levels. No significant differences in nutrient levels, were noted between the different soil pH levels. It is, however, evident that the ameliorants reacted differently in soils with the different soil pH's. These phenomena can possibly be ascribed to variability of ameliorant reactivity, composition, application and different frequency of soil cultivation. It was noted that SLASH, at the lowest soil pH, had the most significant effect on the Ca levels of the ameliorated soil, which, was planted to the lucerne and only cultivated at establishment. Thereafter, the FA ameliorants had the most significant effect on the soil Ca levels. The opposite is true in soils that were cropped with annual species. Under more frequent cultivation, FA was more reactive in the lower pH soil, while the effect of SLASH on Ca content was more prominent in the higher pH soils. This difference in reactivity of ameliorants is possibly as a result of the CaO component of SLASH being more reactive in soils with a lower pH. The Ca availability of FA treatments, however, is more evident at slightly higher pH levels, or when soils are more actively mixed during annual cultivation. From the results obtained it is clear that the SLASH and fly ash ameliorants significantly improved the P content of the soils. This can possibly be as a result of the silica in the calcium silicates, which are the major components of FA, competing with phosphorus on soil particles, making P more available for plant uptake. Similar results were noted at the higher levels of SLASH amelioration. It was consistently noted that the dolomitic lime treatments significantly improved the Mg levels of the soils, due to the lime's chemical makeup of $MgCO_3$. It is also evident that FA ameliorated soils illustrated a significantly higher K level, which is surprising because fly ash contains very little or no K. This increase in K, however, may be as a result of an improved soil pH, making K more available, and possibly as a result of the calcium and aluminum silicates displacing K from soil particles.

The chemically improved soil conditions resulting from the use of class F fly ash and SLASH were possibly as a result of relatively high application levels of these ameliorants. On the basis of these class F fly ash studies it is concluded that class F fly ash used has a higher $CaCO_3$ equivalent than the 20% referred to in international literature. It is estimated that the $CaCO_3$ equivalent was approximately 33% or more. It is, however, recommended that more detailed studies be conducted to scientifically substantiate this value, especially on fly ash from different sources, and to standardize a method to determine the true neutralizing capacity of fly ash based ameliorants.

7. 2 The utilization of soil ameliorants, containing class F fly ash, to improve the physical and microbiological properties of soils

SLASH and class F fly ash have not only the potential to improve the chemical properties of substrates but can also have a beneficial affect on soil physical and microbiological properties. One of the most important properties affecting other soil physical properties, and regulating many moisture related processes, is soil texture. With the addition of soil ameliorants based on class F fly ash, the silt fraction of the soil was increased by 143%. With an increased silt fraction, in soils and substrates ameliorated with SLASH and class F fly ash, the bulk density of the medium was improved by a 5 % and 14% reduction in density, respectively. These modified soils physical properties resulted in a change in moisture characteristics, such as water infiltration rate and soil hydraulic conductivity. The class F fly ash was, overall, the best ameliorant with respect to the significant affect on the rate of water infiltration into the experimental soil, increasing this by as much as 60%. This can possibly be ascribed to a 26% lower soil hydraulic conductivity. For optimal crop production good soil conditions are required to ensure a healthy and well-developed root system. Soil physical conditions, together with soil nutrient status, determine the extent and health of plant roots. A healthy and vigorous root system will ensure a productive growing plant. Root biomass is a good parameter to determine the effectivity of soil ameliorants, in creating more favourable soil rooting environments. Good correlations were observed between enhanced plant production, increased nutrient and soil pH levels, improved soil physical properties and well developed root systems. Root biomass data were correlated with improved soil physical parameters, with an improved root biomass (of up to 74 – 82 %) where the class F fly ash based soil ameliorants were used. This was also true of the SLASH ameliorant, which had the additional benefit of macronutrients in the organic component (sewage sludge).

By improving chemical and physical soil conditions, improvements in microbiological properties can also be ensured. The effect that SLASH had on biomass enhancement emphasizes the importance of including organic materials, to provide the essential nutrients required for plant growth. The added organic matter, provided in sewage sludge, and the improved pH, provided by class F fly ash, also create a more favorable soil environment for microbial activity. This was the conclusion in the preliminary study conducted on microbiological aspects. Humans and animals use many agricultural legume crops grown for protein production. The soil requirements for such crops have to be such that good root development occurs and that microbiological symbiotic relationships are promoted to ensure nitrogen fixation. This aspect was substantiated by data that illustrated how SLASH and fly ash ameliorants improved soil microbial activity by 200% and 172%, respectively. Similar trends were evident for *Rhizobium* nodulation, with increases of 35 % and 15 %, respectively for SLASH and fly ash ameliorants

By improving both chemical and physical soil conditions, an improvement in microbiological activity was also registered. The change in soil pH and soil texture, as a result of the addition of class F fly ash, can - together with the organic matter introduced by the sewage sludge - help create a better soil environment for microbial activity.

Due to intensive agricultural practices, such as chemical fertilization and mechanical cultivation, microbial communities are often stressed and eventually diminish. Soil amelioration, thus has an additional role in improving soil conditions, which promote the life of the soil through improved microbial and biological activity.

7.3 The utilization of soil ameliorants containing Class F fly ash to reclaim mine soils and mining substrates to facilitate sustainable re-vegetation

Soils disturbed for non-agricultural reasons, such as surface coal mining, are generally more degraded as a result of the exposure to more extreme mechanical / chemical processes. The stripping of topsoil in the surface coal mining process does not concentrate on the preservation of different soil horizons due to apparent economical and practical reasons. The A- horizon generally contains a viable indigenous seed bank, organic matter, microbial and biological organisms and the nutrients available for plant growth. These factors determine soil health and health of a living soil. The underlying horizons are, however, generally nutrient poor and often cannot sustain good plant growth. These soil horizons are unfortunately mixed during topsoil stripping and placement, and the properties of each horizon are lost due to the dilution effect. This is to the disadvantage of the vegetation established on such soils. It is as a result of this dilution effect, that soil amelioration of degraded mine soils is essential to establish or develop, a sustainable, healthy and living growing medium for plants.

Mine soils and waste disposal sites, such as gold tailings, ash dumps or coal discard dumps, are generally lower in fertility and are more acidic than natural topsoil and will benefit from the addition of organic materials together with an amendment with neutralizing potential. A variety of organic waste materials are available for this purpose. In particular, municipal biosolids are often freely available. Animal manures can also serve as a source of organic material and certain essential macronutrients, (such as K), which are often lacking in South African biosolids. Soils treated with FA have an improved pH, indirectly stimulating the growth of plants. These waste materials, unfortunately, vary greatly in nutrient trace metal content as well as liming potential. These factors can affect both re-vegetation success and the environmental impact of reclamation. It can be concluded, that the class F fly ash, used in this experimental work, does have a higher $CaCO_3$ equivalent than what is referenced in international literature. This conclusion is based on the significant increases in soil pH and soil root biomass, which have resulted in enhanced plant growth.

It is, therefore, imperative to combine careful analysis of the organic material, the fly ash and the mine soil or substrate to which it is to be applied. The pH of the soil or substrate must be controlled to limit the mobility of heavy metals and to ensure long-term plant vigour on rehabilitated sites. To reclaim a degraded soil or substrate is a major challenge, and can be a very expensive process if a sustainable ecosystem is to be established. The problems which many countries face, in terms of waste disposal, could possibly become solutions for many of the problems experienced in reclaiming mined soils or other substrates. The pot trials, discussed in this investigation, indicate that there is definitely a potential for using waste products, or mixtures thereof, such as SLASH and similar waste mixtures, to reclaim degraded soils or substrates. It was evident from the results that the addition of SLASH and fly ash enhanced the mean DM production of *Cenchrus ciliaris* by 72 % and 24 %, respectively on degraded mine cover soil. Similar results were obtained where SLASH and fly ash, enhanced the mean DM production on AMD impacted soils and gold mine tailings, by 144% and 48 %, and 697 % and 257 %, respectively. The most significant effect of fly ash based ameliorants on root biomass can be seen in the results obtained in the amelioration study of gold mine tailings. Root biomass of *C. ciliaris*, was improved by 4633% by SLASH and 566 % by fly ash amelioration. In comparison to current practice of amelioration, dolomitic lime and inorganic fertilization only improved root biomass by 122%.

With reference to the influence of fly ash based ameliorants on degraded soil and substrate chemical conditions, it evident that firstly SLASH, and secondly fly ash, have positive effects on soil or substrate pH relative to the lime and control treatments. It is clear from the data presented in this study that both SLASH and fly ash had a more pronounced effect in the most acidic medium (such as the AMD impacted soil), raising the soil pH from 3.4 to approximately 8.2 and 6.8, respectively. Similar trends were noted for mine cover soil and gold mine tailings. These significant increases in pH evidently occurred in the first 12 months of soil conditioning after treatment application, during which period crops were not produced. Only after the 12 month soil conditioning period, because of initial unsuccessful germination, were soils cropped, and no further reduction in pH was noted for the mine cover soil, for both SLASH and fly ash treatments, in comparison with the reduction in pH on the lime treatment. The AMD impacted soil, however, registered a slight reduction in pH of the SLASH treatment, but this was still 38% higher than the reduced pH of the lime ameliorated soil. Gold mine tailings, showed a similar reaction to the different ameliorants. After the cropping period of 12 months it was evident that the pH levels of soils ameliorated with SLASH and fly ash were above pH levels suitable for optimal crop production. These data, therefore, substantiate the conclusion that fly ash has a longer residual alkalinity, enabling it to maintain a good pH for longer periods.

These by-products are rich sources of nutrients or organic matter, which can be beneficially, utilized for crop production, to improve agricultural soils or the physical, chemical or microbiological properties of relatively inert substrates. Co-utilization of byproducts can often combine beneficial properties of the individual components to have a more significant effect on the degraded soil or substrate. They can provide a more complete/balanced nutrition, enhance soil condition and improve the economic, or environmental value of these individual by-products. The macro-nutrient levels of degraded soils and substrates in this study were positively influenced by the addition of SLASH and class F fly ash. Phosphorus levels were generally increased by SLASH, fly ash and lime ameliorants. More significant increases in P levels by the fly ash ameliorant were, however, noted for the more degraded AMD impacted soil and gold mine tailings. This observation was also true for Ca, although basal levels of Ca where initially high. All ameliorants caused an increase in Ca levels, but the most significant impacts were with SLASH and fly ash applied to AMD impacted soils and gold mine tailings. Potassium levels were significantly higher in lime treated mine cover soil, SLASH treated AMD impacted soil, fly ash treated gold mine tailings and most significantly SLASH treated gold tailings.

After approximately seven years of field scale research on a surface coal mine, it was concluded that both class F fly ash and SLASH have long-term residual affects on the soil condition of a mine cover soil. Consequently these effects, affect plant production, despite no fertilizer being applied since the 1st season to all treatments accept the standard mine treatment (SMT). The newly identified soil ameliorants used in the experimental work to date, have performed better than conventional ameliorants currently in use on surface coalmines. The effects of class F fly ash and SLASH ameliorants are highlighted when results are compared to the untreated controls used in the various studies. It would also appear that such ameliorants produced more sustainable vegetation than current practice. Due to their chemical nature and reactivity, long-term residual soil effects were noted. From these data it can be concluded, that this class F fly ash definitely has a much higher $CaCO_3$ equivalent than the 20%, which was originally assumed.

Subsequent to the pot trial study, a field scale study evaluating class F fly ash and SLASH amelioration of mine cover soils, provided results demonstrating significantly higher DM yields, in comparison to the lime and control treatments.

After 72 months, soils ameliorated with fly ash were still producing 236 % and 219% and SLASH ameliorated soils, 103% and 92% more DM than the control and SMT, respectively. Lower fertility treatments, such as the lime and the control, did, however, have a greater diversity of species in comparison to the higher fertility treatments, SLASH and class F fly ash, which were dominated by *Digitaria eriantha* and *Chloris gayana*. Excellent basal cover and yields can be obtained when planted pastures on reclaimed soils are fertilized with some kind of nutrient source, organic or inorganic, which is evident in the basal cover from SLASH and fly ash treatments. An acceptable basal cover percentage, used as a measure of grassland in good condition in South Africa, is between 30-40%. Mean basal cover percentages of 33% for SLASH and fly ash ameliorated soils were obtained 72 months after initial ameliorant application, relative to the 7.3% and 15.7 % basal cover percentage of the control and standard mine treatment (SMT).

Significant increases in the macronutrient (P, Ca, K, Mg) content of treated soils were also evident in this field study. The results obtained in the pot trials were confirmed in this field study. Optimum levels of fly ash, SLASH, lime and SMT improved P levels by 1577%, 2000%, 94% and 105%, respectively 72 months after initial treatment application. Potassium levels were increased by 65%, 74% and 32% by fly ash, SLASH and SMT respectively. The most significant increase in Ca levels was noted for the SLASH ameliorated soil, mainly as a result of the CaO component of SLASH, raising the Ca level by 3072%. This increase could raise concerns about possible phytotoxicity, but requires detailed investigation. Finally, the influence of alternative soil ameliorants on the soil pH, has presented similar trends noted in the earlier pot trial. SLASH, in the first 12 months had a significant influence on soil pH, raising the pH by approximately 4 pH units. This increased pH can possibly have a negative effect, on seed germination, which was observed after the establishment of test grass species. This pH, however, dropped over 72 months to just below 7.0, which remained approximately 2 and 3 pH units higher than the SMT and control, respectively. Fly ash alone, however, raised the soil pH by approximately 2 pH units and maintained it over the 72-month experimental period. These data substantiate the residual alkalinity of FA, to provide a more sustainable amelioration option. The significant rise in pH caused by SLASH, has led to the conclusion, that SLASH was possibly applied in too high a level. This incorrect calculation of SLASH application rate and results showing that soil pH is maintained by fly ash over the 72-months is partly due to an underestimation of the 20 % $CaCO_3$ equivalent of fly ash and partly due to CaO content of SLASH.

The challenge, therefore, is to establish a sustainable system, when inorganic fertilization is either reduced or stopped. Industrial and urban by-products have unique properties and release both micro- and macronutrients slowly over time, to sustain productivity, and to effectively reclaim degraded soils. On the basis of these results, investigations into the use of alternative materials as ameliorants to reclaim degraded mine soils should be expanded.

It is thus recommended that such soils/substrates be evaluated to determine the main requirements to make such media optimal for plant growth. It is also recommended that ameliorants available for use, be evaluated to establish their inherent characteristics, which will ultimately determine their suitability for the task envisaged and the volumes required. Economic and environmental considerations should not be neglected.

7.4 The utilization of class F fly ash to reclaim coal discard materials and discard cover soils

The use of an alternative ameliorant, such as class F fly ash, in reclaiming coal discards and their cover soils in a more sustainable manner, has tremendous potential. A preliminary study highlighted the positive chemical reactions caused by class F fly ash in these acidic mediums. The incorporation of class F fly ash into the coal discard and the potentially acidic cover soil, or the use of fly ash as a barrier (buffer zone) between the soils and discard material, has delivered positive results. Increased yields were noted for all the monitored seasons where the treatment had class F fly ash as a barrier (buffer zone). This affect can possibly be ascribed to the prolonged counter-action of the alkaline material to the acidic water generated from the oxidization of pyrite present in the discard material, which via capillary action tends to move upward towards the cover soil. It was evident from the data that while test crop *D. eriantha* was the best species initially; the *C. gayana* with a different growth form and saline tolerance became totally dominant as the trial progressed. This study provides an unexpected performance of the two well known species used in mine land reclamation. Under well known reclamation conditions in South Africa, it was expected that *D. eriantha* would become the dominant species in re-vegetated mine land. However, *C. gayana* is proving to be the more adaptable species under even more harsh conditions, such as on coal discard.

With respect to the influence of class F fly ash on the chemical properties of discard cover soil, pH was the only soil property, which responded slightly to the different treatments. A slight reduction in pH was noted over the 24-month period for the untreated control and conventional lime treatment, whereas the treatments containing class F fly ash showed no major reduction in soil pH. In this study there were no obvious treatment effects on soil macronutrient levels. A dramatic reduction in soil nutrient levels, between 12 and 24 months, was, however, evident and can either be ascribed to the high nutrient uptake of plants and/or the possible immobilization of nutrients due to unexplained chemical reactions.

The research conducted in this study has raised many questions and theories, and provides the opportunity to develop scenarios which will explain the dynamics of utilizing, or co-utilizing, agricultural, domestic and industrial by-products to ameliorate degraded soils / substrates, which are to be re-vegetated with certain plants for specific purposes. Although promising results were obtained in this study, many questions remain on how class F fly ash reacts with acid generating coal discard; and how it can be used to facilitate the reclamation of coal discard dumps. The most important challenge in the reclamation of coal discards is to ensure stable vegetation, through improved soil conditions using effective, economic and sustainable amelioration.

7.5 Recommendations

The recommendations, which can be made at this stage, are that once degraded soils and /or substrates are identified, and if an alkaline material or micronutrient sources are required for amelioration, class F fly ash should be seriously considered as an ameliorant. If there is an additional requirement for organic matter and macronutrients it is recommended that an organic material such as animal manures and/or sewage sludge (biosolids) be co-utilized to create a similar product to SLASH. It is also essential that plant species for the re-vegetation of degraded soils / substrates, should always be selected according to their adaptation to the environment and proposed post-mining land use.

The coal combustion by-product, class F fly ash, has many beneficial characteristics, and has the potential of being an effective soil / substrate ameliorant when used in relatively large volumes. Together with other agricultural and municipal by-products, such as animal manures and sewage sludge, these mixtures can be used as sources of nutrients and/or organic materials to enhance plant production and make it more sustainable.

Agricultural, municipal and industrial by-products are materials, which are rich sources of nutrients or organic material, and can be beneficially utilized for crop production, to improve the physical, chemical or microbiological properties of soils or inert substrates. These materials can be co-utilized, or combined, so that the materials are more easily applied to land, or to provide a more complete/balanced nutrition, or enhance soil conditioning and to improve the economic, or environmental value of these individual by-products.

Returning nutrients and organic matter to soil, or substrates, via industrial-, municipal-, domestic by-products, animal manures or other organic materials completes the natural cycle on which all life depends. The value of these materials in supplying nutrients for crops has been noted since the beginnings of agriculture when, for example, manured crops grew visibly better than those without. In recent years, numerous studies, conducted in various parts of the world, have examined the amelioration values of alternative soil amendments. Aside from the traditional value placed on animal manures (for example, as fertilizers supplying N-P-K) supplementary traits that encourage plant growth have often been attributed to manures. These additional benefits have been ascribed to plant nutrients such as Ca, Mg, or micronutrients, or to physical changes in soil structure. Difficulties in separating individual physical and chemical effects of alternative soil amendments, usually results in less than satisfactory identification of growth promoting factors, either quantitatively or qualitatively. Chemical fertilizers have mostly supplied the nutrient demand formerly supplied by animal manures and organic materials, but the extensive use of chemicals and mechanization is increasing the awareness of the potential value of industrial, municipal and domestic by-products, animal manures and organic wastes as soil conditioners, thereby contributing to a more holistic approach to sustainable amelioration scenarios.

"Create opportunity by using one environmental challenge to solve another environmental challenge"