UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

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

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

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

TABLE OF CONTENTS

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

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.

____

Wayne Frederick Truter

April 2007

LIST OF TABLES

CHAPTER 2 Page

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

LIST OF FIGURES

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

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

PHILOSOPHIAE DOCTOR

in the Department of Plant Production and Soil Science
University of Pretoria

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.