CHAPTER 4

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Comparative study on the influence of SLASH and its individual components on the production of maize (*Zea mays*) and heavy metal accumulation.

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Abstract

Utilizing a poor agricultural resource base to produce a staple commodity such as maize for a growing population, poses some significant challenges. A large percentage of South Africa's cropping soils are acidic and costs of fertilizers and lime for both subsistence and commercial farmers are becoming extremely difficult to meet. The need exists for alternative soil amendments and other forms of fertilizers to enhance plant productivity.

In many countries technologies have been developed to use waste materials with agricultural benefits, and combine them to get a product, which serves as a soil ameliorant. In South Africa, the ameliorant produced is termed SLASH. SLASH is a mixture of sewage sludge, lime and class F fly ash. Sewage sludge's agricultural application is restricted because of its pathogenicity and possible heavy metal content whereas fly ash's restriction lies in its lack of macro nutrients such as N, P and K. However, sewage sludge is a good source of macronutrients and organic matter, and fly ash has liming qualities. Together a superior product is created.

SLASH has proven to be a beneficial soil ameliorant and enhances plant growth substantially. Applications of between 7.5%-10% of the soil volume delivered the best results for maize

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production. Although heavy metal translocation and B phytotoxicity were a major concern, analyses show that insignificant amounts of Ni, Cd and the micronutrient B were translocated, and that these were well below safety limits. Heavy metals are, therefore, not as mobile in SLASH as in sewage sludge.

Keywords: Acid soils, heavy metals, maize, phytotoxicity, SLASH, soil ameliorant,

1. Introduction

In South Africa increased food production is urgently required to improve both national and household food security. (Truter and Rethman, 2000). This is quite difficult especially on a poor agricultural resource base and with a population that is growing at an exponential rate. (Rethman et al., 1999b). Acid soils make up a large percentage of South Africa's arable land. These soils are required to ensure sustainable increases in the nations staple commodity, maize.

Soil acidification is, therefore, a serious socio-economic concern. Very few countries can afford the decline in food production, which often accompanies the changes, which are taking place in our soils. Nutrient management practices affect the viability of agricultural ecosystems. Soil acidity affects plant development by its influence on the availability of certain elements required for growth (Tisdale and Nelson, 1975). Maize (*Zea mays* L.) is the third most important cereal grown in the world. In South and Central America, maize is grown mostly on acidic soils. On these soils, yields are limited by deficient levels of available P, Ca and Mg, and toxic levels of Al and Mn (Baligar et al., 1997).

Practices, which focus on reducing inputs, especially fertilizer inputs provide an important link between the needs of commercial farmers and those involved in subsistence agriculture. With commercial systems, the aim is to reduce inputs for economic/environmental reasons. Subsistence farmers have similar aims, but, in this case, it is because they have restricted access to inputs.

Many countries including South Africa are experiencing waste material disposal problems. Two waste materials of major concern, are fly ash and sewage sludge. A growing population and increasing urbanization creates the need for more electricity, resulting in more fly ash being produced. In addition to this is the higher production of sewage sludge due to the increasing population. It is, therefore, desirable that one problem should be a solution for another.

Reynolds et al., (1999) determined the feasibility of converting waste disposal problems in South Africa into a soil beneficiation strategy. The alkaline stabilization of sewage sludge with fly ash and lime, delivered a product termed SLASH (that contains 60 % class F fly ash, 30 % sewage sludge and 10% unslaked lime on a dry matter basis), which has beneficial soil ameliorant effects. This study entails the comparison fly ash, sewage sludge and lime with SLASH in maize production.

1.1 Fly ash

The potential limitation of fly ash's agronomic use includes its low levels of N, and excessive levels of B (Aitken et al., 1984). Selenium and boron, which can be the rate-limiting elements for maximum permissible loading rates of fly ash for soil amendments, did not, however, accumulate in plants in quantities that would be of concern for plant health or animal and human consumption (Cline et al., 2000). Boron in fly ash is also readily available to plants. In fact numerous investigators (Holliday et al., 1958; Cope, 1962; Hodgson and Townsend, 1973; Townsend and Gillham, 1975; Elseewi et al., 1978; Ciravolo and Adriano, 1979; Adriano et al., 1980) considered B to be a major limiting factor for successful cropland utilization of ashes, especially when such ash is not fully weathered. Crops also exhibit varying degrees of tolerance to B in soils (Bingham, 1973; Adriano et al., 1980).

Fly ash application may also decrease plant uptake of elements such as Cd, Cu, Cr, Fe, Mn, and Zn (Schnappinger et al., 1975; Adriano et al., 1982; Petruzzelli et al., 1986; Schumann and Sumner, 2000). Phosphorus concentrations in plant foliage were often reduced by fly ash applications (Elseewi et al., 1980; Moliner and Street, 1982; Schumann and Sumner, 2000). Corn (*Zea mays* L.) plant emergence, grain yield, percent moisture, and harvest index were not significantly influenced by fly ash applications either.

1.2 Biosolids

Local authorities, both overseas and in South Africa, are continually searching for environmentally acceptable as well as beneficial and economical means of disposal of sewage sludge. Biosolids that have not undergone pathogen destruction cannot be land applied. Land application of sludge is not common in many countries since very little research has been carried out under local conditions. While extensive overseas studies can provide some guidance to the potential for sludge utilization, ultimately sludge management practices should be developed on local soils under local conditions. Existing regulations set limits for the content of heavy metals in sewage sludge as well as the maximum annual and cumulative loadings to land. These loadings are primarily based on health risk assessments (pathogenic micro-organisms) and soil contamination aspects (heavy metals) (Barry et al., 1995).

Dowdy et al., (1983) found that the Ni and Zn content of corn (*Zea mays* L.) silage increased linearly with biosolid application rate (Sloan et al., 1997). In a study conducted in Australia on estimating sludge application rates to land, they concluded that elements Cd, Ni and Cu were all retained to a greater extent in the surface horizon, most likely due to their affinity for organic matter (Barry et al., 1995).

Liming acidic soils that have received biosolids application reduces plant uptake of Cd, Zn, and to lesser extent Cu and Pb (Braillier et al., 1996; Logan and Chaney, 1983; Mahler et al., 1987; Basta and Sloan, 1999). Alkaline biosolids, produced when biosolids is treated with alkaline materials to kill pathogens, have a relatively high $CaCO_3$ and may serve as a liming material (Little et al., 1991; Basta and Sloan, 1999). Because alkaline biosolids are effective liming materials, application of alkaline biosolids resulted in less plant uptake of Cd (Brown and Brush, 1992; Basta and Sloan, 1999) and Cu, Ni, and Zn (Mulchi et al., 1987; Basta and Sloan, 1999). Cadmium and Zn are usually the most bio-available heavy metals of sludge origin (Alloway 1995; Berti and Jacobs, 1996; Sloan et al., 1997; McGrath et al., 2000). Cadmium is of major concern in terms of the transfer into the food chain (Sanders et al., 1987; Lubben et al., 1991;Chandri et al., 1993; McGrath et al., 1995; McGrath et al., 2000), but plant species differed markedly in the transfer efficiency of Zn and Cd from soil to plants (McGrath et al., 2000).

1.3 Alkaline- biosolids

Application of alkaline biosolids to acidic soil to achieve final soil pH > 5 will minimize risk from soil solution Cd and Zn and plant uptake of heavy metals (Basta and Sloan, 1999). Metal movement is expected to increase with decreased soil pH. It is possible that the same mechanism that facilitates Ca movement may permit the movement of trace metals through the soil profile (Brown et al., 1997).

A leaching potential test of the ameliorant SLASH was conducted by Reynolds *et al.*, (2000) and shown to be within the TCLP (Toxicity Characteristics Leaching Procedure) guidelines. The TCLP leaching of the SLASH product showed that the heavy metals of the sewage sludge are immobilized within the fly ash component and do not leach out in either of the simulated conditions. Although the two methods gave similar results, it was noted that Mn, Mo, Ni, and Zn leached more in the TCLP leachate than in the acid rain leachate, while Cu leached less. This may be as a result of the differing pHs of the leachates (Reynolds et al, 2002).

Fly ash alone is a poor source of the macronutrients such as N and P (Carlson and Adriano, 1993; Jackson et al., 1999). Nitrogen is volatilized during the process of coal combustion, while most fly ash P is relatively unavailable (Bradshaw and Chadwick, 1980; Jackson et al., 1999). Sewage sludge on the other hand can be a valuable source of plant nutrients such as N, P, and S, and the organic matter contained in the sludge also can help improve soil conditions (McGrath, 2000) and enhance plant growth. The high N and P content of sewage sludge complements the higher levels of essential micronutrients in the fly ash and will thus reduce the need for inorganic fertilizers. Therefore, fly ash mixed with other organic waste will be an attractive and economical option that should be considered (Wong and Wong, 1990).

2. Material and Methods

A study of maize (*Zea mays*) in a raised bed trial was undertaken and was based on the work which Rethman et al., (1999a,b) conducted. Rethman et al., (1999a,b) and (Truter, 2002c) concluded that the best plant growth responses had been achieved on the 5 and 10% SLASH treated soils. Essentially it was because of those results that this study on SLASH was initiated.

A randomized layout of constructed raised beds (net plot: 1m x 0.30m = 0.3m^2) as illustrated in (Fig.1) was conducted at the Hatfield Experimental Farm, Pretoria, South Africa (25°45'S 28°16'E), 1327m above sea level. A uniform sandy loam soil was ameliorated with sewage sludge, fly ash and reactive lime (CaO) in combination (SLASH) at four different levels and individually. The treatments were: T1 (Control - 0% SLASH), T2 – [2.5% SLASH (8kg)], T3 – [5.0% SLASH (16kg)], T4 – [7.5% SLASH (24kg)], T5 – [10% SLASH (32kg)], T6 – Sewage Sludge (4.32kg), T7 – Fly ash (10.24 kg) and T8 – Lime (1.44kg) and were replicated five times.

Initially these raised beds were planted to cabbages, carrots, stocks, sweet peas and statice. These vegetable and flower crops represented the 1st cropping cycle of the raised bed trial (Ramagadza, 2002). The 2nd cropping cycle was maize (*Zea mays*). Ten seeds were planted, and the seeds that did not germinate were blanked in. After the 2nd cropping cycle of maize (*Zea mays*) the soils were planted to Triticale (*Triticale hexaploide)*, sorghum (*Sorghum sp.*) and rye *(Secale sp.*) as successive 3rd, 4th, and 5th cropping cycles (Truter, 2002c).

The objective of the study was to compare the SLASH at different levels to the separate components of SLASH. These raised beds were used to evaluate the relative effects of SLASH, sewage sludge, lime and fly ash in soil on the dry matter production of maize (*Zea mays*) at different stages of the growth cycle. Three plants were harvested when the best treatment reached a height of 20 cm (1st harvest); 40 cm (2nd harvest) and the other 4 plants were harvested when they were fully grown. (3rd harvest). This observation was to determine at what stage the various treatments started to have an effect on plant growth.

Fig. 1 Illustration of the raised beds planted to maize (*Zea Mays*)

With respect to the work done by Rethman et al., 1999a on the possible uptake of potentially toxic minerals in leaf and grain materials, a follow up observation was conducted in this study. It focused on how higher levels of SLASH compared to sewage sludge and other treatments applied to soils, would contribute to the possible heavy metal uptake problem. Rethman et al., (1999a) concluded that only Cd in leaf material and Ni in the grain material on 1% SLASH amended soil, had marginally higher elemental concentrations than the untreated soil. Since Ni and Cd had seemed to be the potentially problem minerals, this study concentrated on these two elements which could possibly translocate to the plant material at higher application rates. In addition to the analyses for the two heavy metals (Ni and Cd), the micronutrient B which can become toxic at very high levels and that can be found in high concentrations in fly ash was also analysed. Because no significant difference between SLASH treatments were observed in the leaf analyses, the analysis of grain material for Ni, Cd and B, was limited to the control, 5% (T3) and 10% (T5) SLASH treatments and sewage sludge (T6) treatment.

To investigate the effect the SLASH treatments (T2-T5), sewage sludge (T6), fly ash (T7) and lime (T8) had on the N and P content of the test crop plant material, the % N and %P had been analysed for all the treatments with respect to the leaf material and analysed for selected treatments of grain material.

Ramagadza (2002) reported that the plants of the 1st cropping cycle were showing signs of K deficiency. Due to this, K had been applied to the treatments at the beginning of the 2nd cropping cycle of maize to eliminate K deficiency as a limiting growth factor. The treated soils received regular watering, to eliminate moisture as an additional limiting growth factor.

2.1 Statistical analyses

All dry matter-, grain production data and elemental analyses was statistically analyzed using PROC GLM (1996/1997 and 1997/1998) and PROC ANOVA (1997/1998). Statistical analysis was performed using SAS (SAS Institute, 1996) software. LSD's were taken at $P \leq 0.05$.

3. Results and Discussion

Previous studies reported on the growth response of various crop species to SLASH and the ingredients on which it is based (Rethman et al 1999a,b; Rethman 2000a,b; Rethman and Truter, 2001 Truter and Rethman 2000; Truter, 2002a,b, c). The findings of those studies have been confirmed in this study. From all the work conducted on SLASH the conclusion has been drawn that levels of SLASH at 5-10% of the soil volume enhanced plant growth remarkably.

Table 1 clearly indicates that even at an early stage of the maize growth cycle SLASH had an effect on growth rate. Sewage sludge had the most substantial influence on the growth of the maize plants. These results emphasize the importance of organic matter, which is evidently supplied by sewage sludge. Despite the good results obtained from the sewage sludge (T6) treatment, it can not be recommended because of the variability of the sludge sources which can possibly contain a wide range of heavy metals and can often be pathogenic.

Similar results had been observed for the harvest taken at 40 cm with sewage sludge maintaining an exceptionally higher yield than the rest of the treatments. SLASH treatments were performing slightly better than the control, fly ash and lime treatments, but not significantly. Nevertheless, treatment effects could be seen throughout the cropping cycle.

Table 1

Dry matter production (g/plant) of maize (Zea mays) at different stages on soils treated with SLASH (T2-T5), sewage sludge (T6), fly ash (T7) and lime (T8).

	1st Harvest	2nd Harvest	3rd Harvest
	(20 cm)	(40 cm)	(Full grown)
	(g/plant)	(g/plant)	(g/plant)
T1- Control	0.92^{b}	12.30^{b}	263.52^{d}
T2- 2.5% SLASH	1.36^{b}	14.94^{b}	445.10^{bc}
T3- 5% SLASH	1.42^{b}	16.18^{b}	486.94^{b}
T4- 7.5% SLASH	1.62^{b}	14.74^{b}	526.96^{ab}
T5- 10% SLASH	1.14^{b}	14.06^{b}	529.06^{ab}
T6- Sewage sludge	15.34^{a}	52.94^{a}	629.92^{a}
T7- Fly ash	1.26^{b}	13.00^{b}	320.28^{cd}
T8- Lime	1.02^{b}	12.54^{b}	295.72^{d}

* **abc Column means** with common alphabetical superscripts do not differ significantly ($P > 0.05$)
(Tukey's Studentized Range Test)

Individual plants harvested at maturity illustrate how SLASH treatments had benefited plant growth by as much as 100% on average. The sludge treatment yielded 140% more on average than the control (Table 1). Although it seems that when combining sewage sludge with fly ash, the effect of sewage sludge on plant growth is reduced. It has been shown that even though this comment is true, the compromise is reached evidently in the conclusion drawn from the work done by Truter, (2002a,b, c), that SLASH has a longer residual effect than sewage sludge. SLASH therefore, prolongs significantly higher yields than the sewage sludge treatment relative to the control. Sewage sludge eventually becomes depleted, while SLASH maintains it's "slow release" of nutrients over a longer period of time (Truter, 2002c).

As for grain production, similar trends, as for the plant material, are noted in Fig. 2. SLASH treatments gave up to 225% better yields than the control while the sludge treatment gave 385% better yields. Once more, the 7.5% (T4) and 10% (T5) SLASH treatments delivered the best results for the SLASH treatments for both dry matter yields and grain yields.

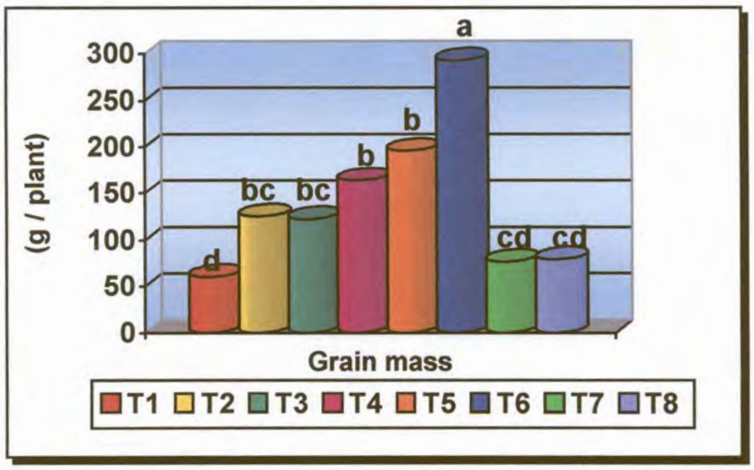

Fig. 2. Maize grain production (g/plant) on soils treated with SLASH (T2-T5), sewage sludge (T6), fly ash (T7) and lime (T8) relative to the control. * **Means with the same letter are not significantly different (P>0.05) (Tukey's Studentized Test)**

Sewage sludge can be a valuable source of plant nutrients such as N, P, and S, and the organic matter contained in the sludge can also help improve soil physical conditions such as; increased infiltration and reduced runoff, which in turn result in increased biomass growth and quality. (McGrath, 2000). Fig. 3 and 4 illustrate how the N and P content of plant material and grain material was influenced by the different treatments.

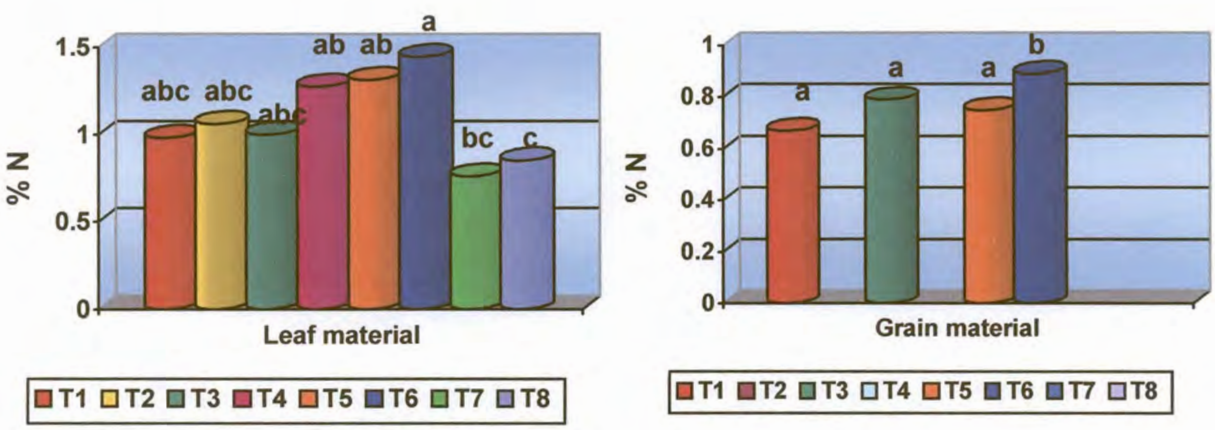

Fig. 3. % N in leaf and grain material of maize (*Zea mays*) produced on soils ameliorated with different levels of SLASH (T2-T5), sewage sludge (T6), fly ash (T7) and lime (T8).
* **Means with the same letter are not significantly different (P>0.05) (Tukey's Studentized Test).**

Based on the analyses of leaf material, it was concluded that it would only be necessary to analyse selected grain material and therefore analyses were limited to four selected treatments.

It is clear that only the two highest SLASH treatments (T4 & T5) and the sewage sludge treatment (T6) contributed to a higher %N in leaves, while the effect on %N in grain was not as marked inconsequential.

Phosphorus concentration of sewage sludge is normally high as it has been reported by Truter, (2002d). Phosphorus can become unavailable to plants if the P is fixated in the soil due to extremely high levels.

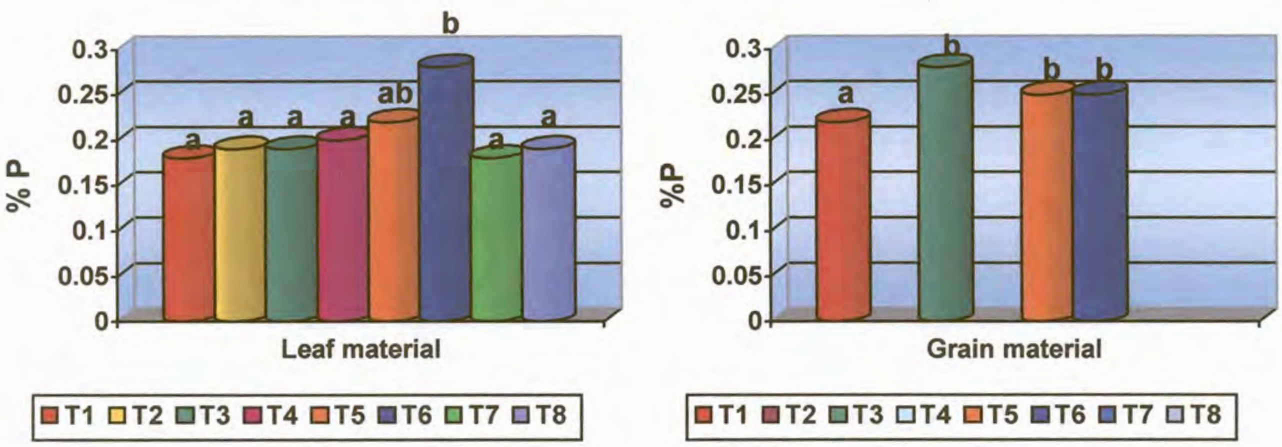

Fig. 4. %P in leaf and grain material of maize (*Zea mays*) produced on soils ameliorated with different levels of SLASH (T2-T5), sewage sludge (T6), fly ash (T7) and lime (T8)
*** Means with the same letter are not significantly different (P>0.05) (Tukey's Studentized Test).**

From Fig. 4 it is evident that sewage sludge did improve the P content of the leaf material significantly but did not contribute as markedly to the P content of grain. This indicates that P mobility is higher in stem and leaf material and is not translocated as strongly to the grain. SLASH had no significant effect on the leaf P content, although it did improve the P levels in the grain and the soil. (Truter, 2002d).

The risk of heavy metal translocation from sludge will depend on the source of sludge. In contrast, SLASH ensures the immobilization of heavy metals and a safer product to handle and apply in terms of possible disease organisms.

With respect to the micronutrient B and heavy metals analyses of leaves (Table 2) the results obtained were compared to the limits set by law (Kabata-Pendias and Pendias, 1984). In Table 2 the B, Cd and Ni analyses indicate that all treatments had insignificant levels and that they were well below these limits (Kabata- Pendias and Pendias, 1984).

However, the SLASH treatments tended to have a higher B concentration, and this can possibly be ascribed to the contribution of B, which is usually found in fly ash.

Table 2

The mean elemental concentration and (±MSE) in maize leaves (mg kg^{-1}) grown on SLASH (T2-T5), sewage sludge (T6), fly ash (T7) and lime (T8) treated soils

Treatments	B	Cd	Ni
	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})
T1-Control	2.90^a (±0.45)	2.59^a (±1.06)	27.96^a (±0.45)
T2- 2.5% SLASH	2.91^a (±0.54)	3.18^a (±1.45)	23.93^a (±0.45)
T3- 5% SLASH	10.77^a (±13.03)	3.96^a (±1.76)	45.71^a (±0.45)
T4- 7.5% SLASH	5.64^a (±4.07)	5.64^a (±3.75)	34.41^a (±0.45)
T5- 10% SLASH	3.93^a (±1.30)	6.19^a (±5.22)	38.66^a (±0.45)
T6- Sewage sludge	3.30^a (±0.78)	3.32^a (±2.40)	25.05^a (±0.45)
T7- Fly ash	3.65^a (±1.18)	3.91^a (±3.81)	24.30^a (±0.45)
T8- Lime	3.24^a (±0.0.48)	2.86^a (±2.00)	26.40^a (±0.45)
Safety limit	80	15.7	400

***a Column means** with common alphabetical superscripts do not differ significantly (P> 0.05) (Tukey's Studentized Range Test)

The concern about heavy metals (Ni and Cd) translocation was not supported by the results obtained for the leaf analysis, although the concern about translocation to the most important plant component, grain, prevailed. Although Rethman et al., (1999a) found no significant translocation of heavy metals to the grain at 1% SLASH applications, grain produced on soils treated with higher SLASH applications was of concern.

Table 3 provides the results obtained for heavy metal content of selected treatments. The analysis of grain indicated that there was heavy metals present in all the treatments including the control. The B concentration differed from what was found in the leaf material, this demonstrates that B is not concentrated more in the grain than in the leaf material, and is still well below the limits set by law. To support the fact that the heavy metal content of sewage sludge varies, depending on the source, the sludge's Ni and Cd content was similar to that of the SLASH treatments and the control. However, Ni was more concentrated in the grain than in the leaves of the plant. It was, nevertheless, still well below the safety limits.

Table 3

The mean elemental concentration and (±MSE) in maize grain (mg kg^{-1}) grown on SLASH (T2-T5), sewage sludge (T6), fly ash (T7) and lime (T8) treated soils

Treatments	B	Cd	Ni
	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})
T1 – Control	26.28^{a} (±3.42)	9.89^{a} (±0.32)	106.99^{a} (±3.33)
T3 - 5% SLASH	27.27^{a} (±5.76)	9.36^{b} (±0.53)	102.79^{b} (±4.43)
T5 – 10% SLASH	29.26^{a} (±5.24)	9.81^{a} (±0.38)	104.45^{b} (±2.17)
T6 – Sewage sludge	25.61^{a} (±5.64)	8.81^{c} (±0.29)	99.13^{c} (±3.59)
Safety limit	80	15.7	400

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

4. Conclusion

Maize can be produced on acidic or nutrient depleted soils, by using an alternative method rather than the conventional liming and inorganic fertilization of soils. At the same time the environmental problem of waste disposal can be alleviated.

With the exception of sewage sludge, SLASH offered greater benefits than any individual ingredients. Plant growth responded exceptionally well to sewage sludge. It cannot, however, be recommended due to the pathogenicity of the sludge and the possible heavy metal content, depending on the source of sewage sludge, and the fact that heavy metals are not immobilized in the sludge, as they are in the SLASH. This ameliorant SLASH has promising liming qualities and is a good source of nutrients, which improves soil condition making it more suitable for plant growth.

Although SLASH is seen as a good source of nutrients required for plant growth, it does not necessarily contain a full range of nutrients. The batch of SLASH that was used in this study was devoid of K, for example, and the need will exist to supplement it with an inorganic fertilizer or possibly another organic material, which has high concentrations of K, such as animal manures.

Since waste material composition, nutrient balance and nutrient bioavailability is extremely variable, it is important to characterize the waste materials before mixing them and using them to the benefits of plant growth. Various problems can be experienced with the application of such wastes, such as possible phytotoxicity from trace element excesses or possible a fixation of other nutrients such as P. Most of these problems can be overcome by combining two or more waste materials together, thereby utilizing the combined complementary qualities of each waste for crop production.

The rationale behind such mixed wastes is that the mixture itself is a superior soil amendment to either component alone. The use of an organic waste addresses the deficiency of macronutrients in fly ash, while fly ash can act as a bulking agent for the organic wastes, substantially reduces odor, and can offset soil acidity problems that may arise through continued land application of organic wastes.

It is concluded that the 7.5-10% SLASH application rates ultimately deliver the best results compared to the other SLASH treatments. Regarding the uptake of potentially toxic elements, no significant uptake was noted or even translocated to the grain under regulated experimental conditions. The two potential problem heavy metals, Ni and Cd, and the micronutrient B, which can be toxic at very high levels, were within the current safety specifications, but these may be open for review.

For economic reasons, in South Africa the use of SLASH at high levels is limited due to high transport costs, and the ameliorant's use will be restricted to sites in relative close proximity to the waste raw materials used in it's manufacture. Nevertheless, the ameliorant SLASH has definite agricultural potential!!

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CHAPTER 5

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Forage production from cereal and grain crops on fly ash-biosolid amended soils

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Abstract

The non-agricultural activities of man compete with agriculture for land. The demands on land made by increasing urban, industrial, mining, recreation and other developments, and the attendant infrastructure – largely the result of a fast growing population – leave an ever-shrinking area for producing food and fibre. Utilization of natural resources is of importance for the survival of people as long as it is not at the expense of environmental degradation i.e. it must be sustainable.

Many waste materials, which are the end products of processes that ensure life on earth, have to be used beneficially. The combination of waste materials such as sewage sludge and fly ash is not unknown to the scientific world as a beneficial technology to stabilize sewage sludge by adding an alkaline material. The use of such a mixture of waste products for agricultural purposes, still, however, needs to be refined.

Previous research, both internationally and in South Africa, has developed effective waste product mixtures, which can be used for agricultural purposes. SLASH (60% class F fly ash, 30% sewage sludge and 10% reactive lime (CaO)) is such a waste product mixture, which can be used as a soil ameliorant to address the problems of soil acidity and infertility.

The utilization of SLASH as such in crop production has already been researched but what is relevant in this study is how the SLASH compares to its individual components in terms of forage production and long-term residual effects. It was evident from this study that the effect of 5-10% SLASH treatments still persisted and gave up to 30% better yields

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36 months after the initial application of treatments. Sewage sludge on the other hand, although giving the best forage production for almost the entire study, can not be recommended because of its pathogenicity and possible heavy metal translocation. Furthermore, the sewage sludge treatment showed signs of becoming depleted by the end of the study, indicating that it did not compare favourably with the "slow release" capability (slow release of essential nutrients required for plant growth) of SLASH.

Keywords: Acid and infertile soils, fly ash, sewage sludge, SLASH, soil ameliorant, waste materials.

1. Introduction

South Africa is characterized by a poor resource base [1,2]. Socio-economic problems in this resource poor sub-continent have been compounded by a large population, a rapid population growth rate of 2.5% per annum, growing urbanization and a high rate of unemployment. There is, therefore, a desperate need for strategies, which will improve both national and household food security, and at the same time create more job opportunities. In a country where natural resources have already been seriously impacted by agricultural, industrial and mining industries, and where the disposal of waste products is often a problem, the possibility of using waste products to improve the natural resources (especially soil) deserves more intensive investigation. [2].

Previous work conducted to determine the feasibility of converting waste disposal problems in South Africa into a soil beneficiation strategy has been positive [3]. Two problems experienced in the past were, firstly, that sewage sludge often contains heavy metals and pathogens. As a result its use is restricted for agricultural land application. Secondly, fly ash production in countries, which rely on coal for energy, such as South Africa, presents a major problem to those responsible for the consequences and implications of disposing of such "waste" products [4].

The co-utilization of fly ash and sewage sludge with added lime delivered a product termed SLASH (containing 60 % class F fly ash, 30 % sewage sludge and 10% unslaked lime on a dry matter basis), which has beneficial soil ameliorant effects [3]. The use of fly ash (FA) as a soil amendment is hindered by a lack of macronutrients in the ash and concerns about trace element availability. Mixing FA with an organic waste can increase macronutrients while reducing odor and improving material handling, but the trace element solubility requires investigation. [5]

As with fly ash, only a fraction of total nutrients (especially N and P) supplied by organic wastes are available to crops in a particular season, since they must first be mineralized from organic to inorganic forms. Despite these limitations, sewage sludge and animal manures may be the most cost effective supplement for co-utilization with fly ash in crop fertilization. Mixtures of fly ash with organic wastes already have a proven track record [5,6,7,8,9,10,11,12,13], but the preparation of mixtures has usually proceeded by trial and error.

Prediction of plant nutrient supply from fly ash and bio-solids (sewage sludge and poultry manure) may enhance their agricultural use as a crop fertilizer. The resin method was useful for major nutrient (N, P, K, Ca, Mg, S) extraction from fly ashes and organic materials, particularly where mineralizable fractions of N and P under aerobic conditions are required [13]. Extraction of fly ash using a dilute-buffered nutrient solution was more successful because micronutrient recovery was improved; macronutrients were correlated to the resin method. The overall nutrient supply from extremely variable fly ashes was: Cu = Fe, B, Mo > Ca > S > Zn >Mn > N > Mg > P > K (high micronutrient, low macro nutrient supply). For bio-solids, the macronutrients ranked: P > N, Ca > S > Mg > K (sewage sludges), and N > Ca, K > P > Mg > S (poultry manures). In mixtures of fly ash with 26% sewage sludge the order was: Ca > S > N > Mg > P > K, while in mixtures of fly ash and 13% poultry manure, the nutrients ranked: Ca > K, N, S > Mg > P. Optimal plant nutrition (especially N-P-K balancing) should be possible by mixing these three waste materials [13].

The initial cropping cycle of this programme was to determine how sewage sludge, fly ash and lime both in combination (SLASH) and individually, would affect the growth of various flower and vegetable crops [14]. Subsequently, another study, prior to the one being reported on, had also been undertaken which represented the 2nd cropping cycle of the programme [15]. It focused on the production of maize (*Zea mays*) on the soils, which were used in this study. The objective of that study was to determine if two specific heavy metals (Ni, Cd) and micronutrient B would be translocated to the leaves and grain of maize. Translocation would possibly take place from soils treated with SLASH and it was compared to the individual components of which SLASH is made of. In addition to this, dry matter (DM) and grain production were also recorded. This investigation followed on that work.

The objective of this study was to further evaluate the long-term residual effect, which different levels of SLASH might have (in terms of forage production), in comparison to the individual components of SLASH. It is hypothesized that while the individual components each have their own beneficial characteristics, these do not compare with the complementary effect of the mixture in sustaining optimal plant growth. The soils treated with different amendments were utilized intensively after the 2nd cropping cycle of maize, with consecutive crops such as Triticale (*Triticale sp.*), sorghum (*Sorghum sp.*) and rye (*Secale sp.*) as successive 3rd, 4th and 5th cropping cycles over a period of 24 months.

2. Material and Methods

When using SLASH for flower and crop production, the best performance was achieved with the 5% and 10% SLASH levels [16,17]. It was because of this conclusion that this raised bed study was undertaken to compare SLASH treatments to the individual components of SLASH. Constructed raised beds (net plot: 1.2m x 0.50m = 0.6m^2) as illustrated in (Fig.1) were used at the Hatfield Experimental Farm, Pretoria, South Africa (25°45'S 28°16'E), 1327m above sea level.

Fig. 1. Raised bed illustration

A uniform sandy loam soil was ameliorated with sewage sludge, fly ash and reactive lime (CaO) in combination (SLASH) at four different levels and individually. The treatments were: T1 (Control - 0% SLASH), T2 – [2.5% SLASH (8kg)], T3 – [5.0% SLASH (16kg)], T4 – [7.5% SLASH (24kg)], T5 – [10% SLASH (32kg)], T6 – Sewage Sludge (4.32kg), T7 – Fly ash (10.24 kg) and T8 – Lime (1.44kg) and were replicated five times.

After these raised beds were used to evaluate the relative effects of SLASH, sewage sludge, lime and fly ash in soil on the production of flowers and vegetables [14] maize (*Zea mays*) [15, 19], Triticale (*Triticale hexaploide*), sorghum (*Sorghum sp.)* and rye *(Secale sp.*) were cropped intensively for 24 months.

After the 2nd cropping cycle of maize (*Zea mays*) the soils were planted to Triticale (*Triticale hexaploid)*, sorghum (*Sorghum sp.*) and rye *(Secale sp.*) as successive 3rd, 4th, and 5th cropping cycles. Triticale (*Triticale hexaploid)* and rye (*Secale sp.) are* winter growing cereal crops, and *Sorghum sp.* is a summer growing grain crop. These crops are generally used for animal forage. These crops were sown at a rate of 150kg/ha in three evenly spaced rows of 12.5cm for each treatment in the raised beds (Fig 1). Forage production was assessed by regular harvests within each growing season. Once the best treatment had reached flowering stage, the harvest was taken. Three harvests were recorded for *Triticale hexaploid* and *Sorghum sp.* and two harvests for *Secale cereala* .All treatments received regular watering to eliminate moisture as a limiting growth factor. No additional fertilizer had been applied to the soil during the period of this study, since the cropping with maize.

2.1 Statistical analyses

All dry matter production and root study data was statistically analyzed using PROC GLM (1996/1997 and 1997/1998). Statistical analysis was performed using SAS software [20]. LSD's were taken at $P \leq 0.05$.

3. Results and Discussion

The response of Triticale (*Triticale hexaploide*), a hybrid between wheat (*Triticum*) and Rye (*Secale*), in the third cropping cycle on these raised beds to (a) different levels of SLASH and (b) the different components which make up SLASH, was assessed in the winter and spring of 2000. The relative mass (g) of the uniform sample taken from each treatment for consecutive harvests is shown in Table 1.

Despite this being the 3rd cropping cycle on these raised beds, the response pattern of the Triticale (in terms of forage production) was still essentially the same as that of maize in the second cropping cycle [15]. The growth response of Triticale to the SLASH and sewage sludge treatments was markedly better than the control, fly ash and lime treatments. Nevertheless, fly ash and lime treatments had a marginal beneficial effect on plant yield above the control, (12 and 11% respectively). SLASH, in contrast, improved plant yields by 240%. However, sludge on its own improved plant yields by 368% over the control.

Table 1

Influence of sewage sludge, lime and fly ash individually and in combination (SLASH) on the mean dry matter production (g/net plot) and the ±MSE of the cereal crop (*Triticale hexaploid)* ~ 350 days after the treatment application and preceded by two cropping cycles.

Treatments	**1st Harvest Dry Mass**	**2nd Harvest Dry Mass**	**3rd Harvest Dry Mass**
	Relative mass (g)	**Relative mass (g)**	**Relative mass (g)**
T1-Control	15.84^{a}_{a} (±2.46)	15.58^{a}_{a} (±2.56)	28.60^{a}_{a} (±3.56)
T2- 2.5% SLASH	25.06^{a}_{b} (±7.70)	22.28^{a}_{a} (±3.10)	35.00^{a}_{a} (±3.47)
T3- 5% SLASH	30.76^{a}_{b} (±3.85)	27.70^{a}_{a} (±5.12)	45.16^{a}_{a} (±7.11)
T4- 7.5% SLASH	32.54^{a}_{b} (±4.81)	31.08^{a}_{a} (±3.58)	46.46^{b}_{a} (±5.48)
T5- 10% SLASH	45.76^{a}_{b} (±16.27)	44.92^{a}_{b} (±9.84)	53.10^{a}_{a} (±8.03)
T6- Sewage sludge	80.72^{a}_{c} (±20.17)	63.54^{b}_{c} (±14.57)	76.66^{ac}_{b} (±8.33)
T7- Fly ash	21.24^{a}_{a} (±5.84)	21.58^{a}_{a} (±3.68)	31.00^{a}_{a} (±3.28)
T8- Lime	19.86^{a}_{a} (±7.98)	18.08^{a}_{a} (±3.99)	29.88^{a}_{a} (±3.15)

***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)

Due to sludge's limitations it is not, however, safe and practical to use. It should be noted, that the higher the SLASH application, 0-10%, the higher the growth response was in terms of yield. This substantiates the results obtained from other studies [16,17], that the best results were obtained from the 5-10% SLASH levels. It is evident from Table 1 that the third harvest gave a much higher yield that the other two harvests. This can be ascribed to the longer interval between harvests because seasons were changing and Triticale was becoming reproductive. The total dry matter production (all three harvests) of all three harvests Triticale *(Triticale hexaploid)* for the growing season is illustrated in (Fig 2).

It is shown that the total dry matter production of Triticale (*Triticale hexaploide*) as illustrated in the histogram (Fig 2) for the entire growing season, was most definitely the highest on the sewage sludge treatment (T6). Sewage sludge improved the yield of Triticale by 268%. Due to the limitations on the use of sewage sludge, as previously mentioned, the next best treatment to sewage sludge, which was the 10% (T5) SLASH treatment, is recommended. This treatment gave a 140% better yield than the control. The rest of the SLASH treatments, together with the fly ash and lime treatments, also gave better yields than the control.

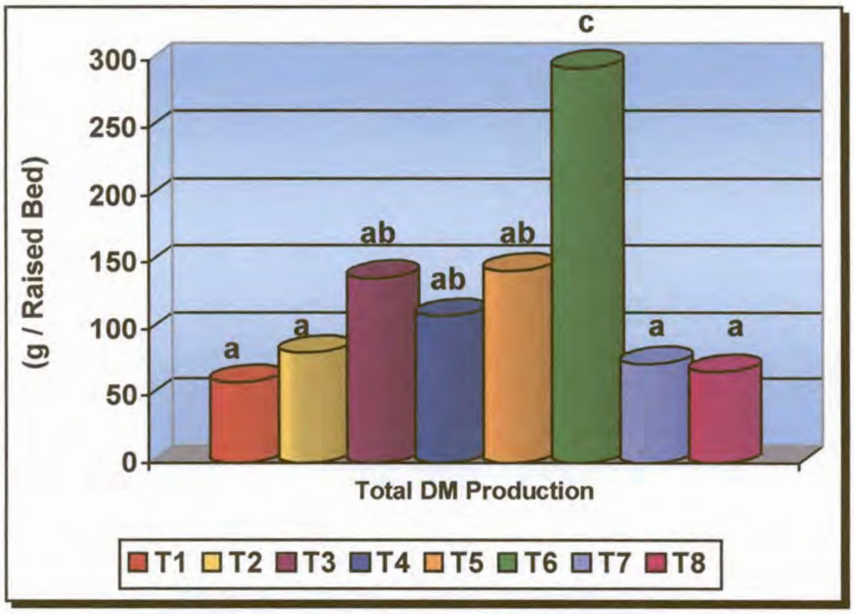

Fig. 2. The total dry matter production [g/ net plot] in the winter growing season of Triticale (*Triticale hexaploid*) in response to SLASH and its individual components. * Means with the same letter are not significantly different (P>0.05) (Tukey's Studentized Test).

Following the Triticale, sorghum was planted and similar trends were noted (Table 2). This summer crop represented the 4th cropping cycle. The soils had still not been treated with any additional fertilizer since the maize crop in the 2nd cycle.

What was particularly relevant in this phase was that the sewage sludge treatment (T6) was showing signs of depletion. From Table 2 it can be seen that the mean DM production of the T6 treatment was lower than that of the 10% SLASH. It can be assumed that the SLASH treatments have a much slower release of nutrients than the sewage sludge. This substantiates why the sewage sludge treatment previously gave markedly higher yields than the other treatments.

Table 2

Influence of sewage sludge, lime and fly ash individually and in combination (SLASH) on the mean dry matter production (g/net plot) and (±MSE) of sorghum (*Sorghum sp.*cv. Hypergraze) ~ 470days after the treatment application and preceded by three cropping cycles

Treatments	**1st Harvest Dry Mass**	**2nd Harvest Dry Mass**	**3rd Harvest Dry mass**
	Relative mass (g)	**Relative mass (g)**	**Relative mass (g)**
T1- Control	48.72^{a}_{a} (±7.45)	45.26^{a}_{a} (±2.50)	46.80^{a}_{a} (±8.68)
T2- 2.5% SLASH	87.24^{a}_{a} (±14.36)	65.44^{a}_{ab} (±10.38)	60.20^{a}_{a} (±15.02)
T3- 5% SLASH	90.42^{a}_{b} (±16.61)	69.78^{a}_{ab} (±7.35)	65.72^{a}_{a} (±9.12)
T4- 7.5% SLASH	102.48^{a}_{b} (±15.11)	82.34^{a}_{abc} (±8.85)	78.18^{a}_{a} (±9.74)
T5- 10% SLASH	130.40^{a}_{b} (±72.97)	91.26^{a}_{bc} (±19.24)	82.26^{a}_{a} (±15.73)
T6- Sewage sludge	71.24^{a}_{a} (±16.86)	81.82^{a}_{abc} (±38.68)	89.32^{a}_{b} (±11.74)
T7- Fly ash	73.08^{a}_{a} (±17.30)	56.40^{a}_{a} (±5.43)	52.56^{a}_{a} (±6.37)
T8- Lime	47.46^{a}_{a} (±15.49)	45.64^{a}_{a} (±7.87)	46.74^{a}_{a} (±5.34)

***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)

Fig. 3 clearly shows that, on average, the 10% SLASH treatment gave the best forage production. The T5 treatment gave approximately 120% better yield than the control, 80% better yield than the sewage sludge treatment (T6) and 60% better yield than the fly ash treatment (T7). Reasons for this sudden change in production on the sewage sludge treatment may be ascribed to the depletion of the organic and nutrient source.

In other studies it is noted that after 36 months of multiple cropping, the soils treated with sewage sludge had markedly high phosphate levels [19]. These nutrient inbalances could impact negatively on plant growth, which may explain the reduction in plant growth response to the sewage sludge treatment. On the other hand SLASH treatments maintained a relatively good performance.

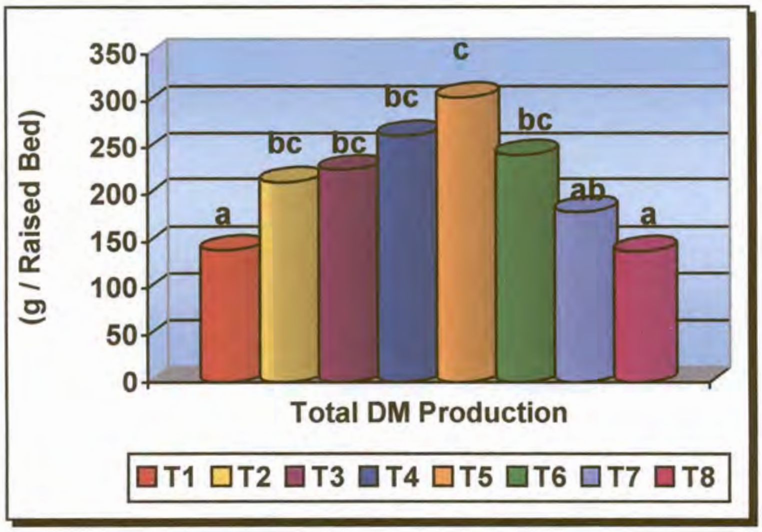

Fig. 3. The total dry matter production [g/ net plot] in the summer growing season of sorghum (*Sorghum sp.*cv. Hypergraze) in response to SLASH and it's individual components. * Means with the same letter are not significantly different (P>0.05) (Tukey's Studentized Test).

Once the Sorghum growing cycle was completed, and the stubble and roots removed, the raised beds were planted to a second winter cereal crop, namely rye (*Secale sp.* cv SSR 729). Forage production of the rye followed similar trends to that of the sorghum (Table 3).

Table 3

Influence of sewage sludge, lime and fly ash individually and in combination (SLASH) on the mean dry matter production (g/net plot) and (±MSE) of winter rye *(Secale sp.* cv. *SSR729)*

Treatments	1st Harvest Dry Mass	2nd Harvest Dry Mass
	Relative mass (g)	Relative mass (g)
T1	31.38^a_a (±12.94)	56.62^b_a (±10.83)
T2	37.02^a_a (±15.23)	52.34^a_a (±5.63)
T3	34.46^a_a (±7.60)	62.88^b_a (±5.74)
T4	39.68^a_a (±18.39)	67.88^b_a (±10.57)
T5	44.14^a_a (±19.18)	74.76^b_a (±15.37)
T6	35.58^a_a (±15.13)	76.28^b_a (±10.76)
T7	29.08^a_a (±5.74)	57.34^b_a (±6.95)
T8	33.86^a_a (±16.72)	49.00^a_a (±9.87)

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

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

Looking at Table 3 and Fig. 4 the T6 treatment was marginally poorer than T5, comparable with T4 but better than T1, T2, T3, T7 and T8. On average it appeared that all the SLASH and sewage sludge treatments were showing signs of depletion, although, yields were still 20 –30% higher than the control, fly ash and lime treatments. As a matter of fact, the control was even tending to produce better yields than the fly ash and lime treatments. These results could, however, be expected after 36 months of intensive cultivation with no additional fertilizer or lime applications.

Figure 4 illustrates the leveling out of the better performing treatments and their effects on the total forage production of winter rye (*Secale sp*. cv SSR 729) 36 months after initial treatment application. The 5-10% SLASH treatments and sewage sludge treatments were still, however, yielding up to 35% more than the other treatments. The results of this study emphasize that SLASH has long-term residual effects on crop production.

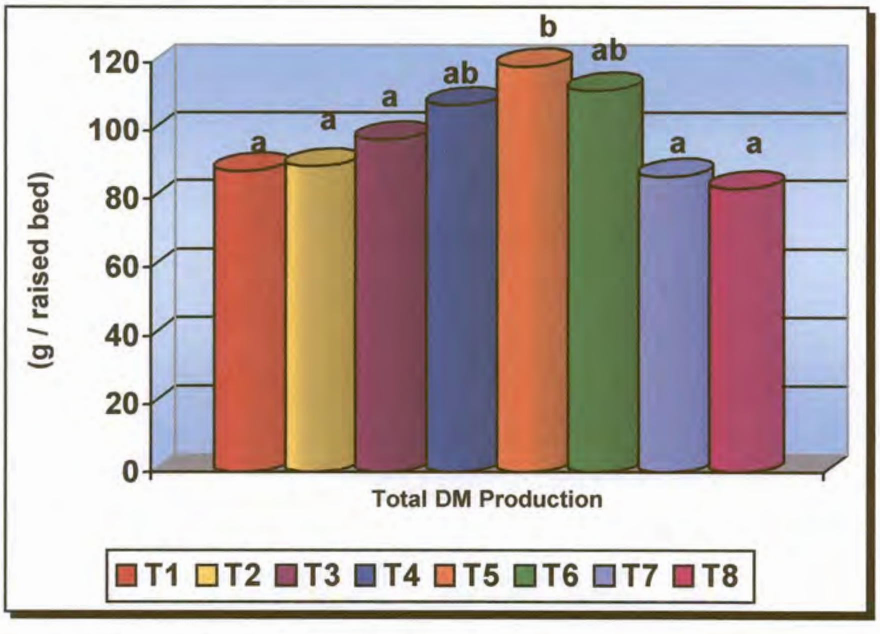

Fig. 4. The total dry matter production [g/net plot] in the winter growing season of rye (*Secale cereala cv.* SSR 729) in response to SLASH and its individual components. * Means with the same letter are not significantly different (P>0.05) (Tukey's Studentized Test).

4. Conclusion

The addition of SLASH to infertile or acidic soils as a soil ameliorant holds definite agricultural potential. 7.5%-10% SLASH delivers the best results compared to the rest of the SLASH treatments. Although SLASH is seen as a good source of nutrients required for plant growth, it does not contain a full range of nutrients. Depending on the source of sewage sludge used, it may lack, for example, adequate K, thereby creating the need for supplementary fertilization. Quality control of waste products used in such mixtures, is therefore, essential to be able to calculate the required levels for specific soils and crops.

Focusing on the performance of the individual waste products (sewage sludge and fly ash), it is clear from the results that sewage sludge (T6) gave the best overall yields. Although sewage sludge is a good source of organic material with high amounts of essential macronutrients, it must be taken into consideration that the use of sludge is limited because of its potential disease risk and possible heavy metal pollution. The fly ash treatment (T7) did not give significantly higher yields than the control. This supports the importance of organic material for optimum plant growth. Fly ash is a good source of micronutrients, which may be beneficial to certain plant growth processes, but on its own it does not necessarily contribute to the enhancement of plant growth. Fly ash characteristically has a larger influence on the soil properties and hence indirectly enhances plant growth, by ensuring a good medium for plant growth, especially in acidic soils.

Sustainable crop productivity depends on the use of non-acidic soils and ameliorated acid soils. From this study the conclusion can be drawn that SLASH has marked beneficial effects on plant productivity. This is ascribed to the ameliorating effects, which this product has on soil pH and soil nutrient status. These effects, unlike many inorganic fertilization programmes, have long-term residual effects.

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CHAPTER 6

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The influence of a fly ash-biosolid mixture on soil chemical properties

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Abstract

Agricultural and industrial activities have greatly accelerated the pace of soil acidification. Soil acidification and nutrient depletion is, therefore, a serious socio-economic concern. Very few countries can afford the decline in food production, which often accompany the changes, which are taking place in our soils. Nutrient management practices affect the viability of agricultural ecosystems. 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.

Many countries experience waste product disposal problems. Many of these waste materials are excellent sources of plant nutrients and also have potential soil ameliorating qualities, which can be utilized for crop production if rendered innocuous. One of the more recent methods of sewage sludge treatments, which are being more widely used, is the alkaline stabilization of biosolids. This process involves the mixing of partially dewatered sewage sludge with an alkaline material such as fly ash or a blend of materials. This advanced technology, which has also been used in South Africa, has provided a product termed SLASH. Not only has SLASH become a possible solution to various problems experienced in South Africa such as ash and sewage sludge disposal, but is also an alternative measure for ameliorating our acid and nutrient depleted soils.

Where fertility was limiting, SLASH had a beneficial effect. 5-10% SLASH levels improved the soil pH and have thereby made essential plant growth elements more readily available over a longer period. SLASH does have beneficial soil ameliorating qualities, and can be used as an

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alternative amendment. SLASH's effectiveness has been recorded over at least 36 months, maintaining an improved pH of one pH unit on average relative to the control, even during intensive cropping of soils. Long-term residual effects of sewage sludge are also prolonged by combining it with fly ash. SLASH and similar products definitely have agricultural potential.

Keywords: Alkaline stabilization, biosolids, fly ash, nutrient depletion, SLASH, soil acidification

1. Introduction

Nutrient poor and acidic soils in South Africa are becoming more prevalent and many farmers require alternatives to the high priced conventional methods of soil amelioration currently in use [1].

Previous work has indicated that the application of limestone and CCB's (coal combustion by-products) increases P availability efficiency (the amount of plant yield produced per unit of extractable P and P utilization (amount of plant yield produced per unit of P in the plant) [2,3,4,5]. Either limestone or CCB application increased the availability of soil P to plants, probably due to a better developed root system resulting from the alleviation of Al toxicity and increased availability of Ca [6, 9]. It can, therefore, be said that the application of CCB's and limestone to acidic soils results in healthier plants with a better developed root system due to higher soil pH and increased Ca and Mg supply. The better developed root systems result in an enhanced P availability and P utilization efficiency and thus improved plant-soil relationship of P in acid soils [5].

Coal combustion by products (CCB's) have been widely used as cost effective amendments for acid soils. It holds true that ashes have several advantages, and their application is often recommended [6]. Although information is needed on the proper combination of CCB's with chemical fertilizers or other organic and inorganic amendments to improve the productivity of acid soils. [7]

1.1 Fly ash

In South Africa approximately 28 million tons of ash is produced annually, by the energy generation industry to meet the energy requirements of a population of

45 million people and growing. This largely untapped resource, together with the power utilities, is generally situated in areas with high agricultural potential, which are being acidified because of the effect of "acid rain" and agronomic practices. Only a small percentage of this untapped resource of fly ash is currently used in the cement, plastics, rubber and paint industries [8].

The alkaline nature of fly ash has led to an examination of its use as a liming agent to replace reagent grade $CaCO_3$ on acidic agricultural soils and coal mine spoils [9,10,11]. Furthermore, the enriched macro- and micronutrients which fly ash contains, may enhance plant growth in nutrient-deficient soils [12,13,11].

Because fly ash is relatively rich in trace elements, it has also been successfully used to alleviate micronutrient deficiencies [14,15]. Fly ash amendments have been used to correct deficiencies of B [9,16,17], Mg [18,17], Mo [17,19,20,], S [17,18,20,21], and Zn [9, 17,22,].

Fly ash alone, as previously mentioned, is usually a poor source of the macronutrients such as N and P [15]. Nitrogen is volatilized during the process of coal combustion, while most fly ash P is relatively unavailable [15,23]. Notwithstanding these facts, land application of fly ash is still viewed as an attractive alternative means of disposal [15].

Coal fly ash has physical and chemical characteristics that make it useful as a soil amendment. One of the more important of these being the potential to permanently improve the soil water relations of sandy, drought-prone soils. Changes in the infiltration rate and water holding capacity of a sandy soil after application of high rates (up to 950 tons ha^{-1}) of a Class F fly ash were examined. Fly ash amendment not only increased water-holding capacity but also increased plant available water. [24].

1.2 Biosolids

Sewage sludge is classified as a toxic waste and is produced at a rate of 800 tons/day dry mass in South Africa [25]. This problem, in addition to the large volumes of fly ash produced, emphasizes the need for co-utilization of wastes and thereby identifies possible strategies for the safe disposal (use) of such waste products.

Regarding amendment of infertile soils, many studies have demonstrated the ability of sewage sludge to restore degraded lands [26]. Sewage sludge can be a valuable source of plant nutrients such as N, P, and S, and the organic matter contained in the sludge can also help improve soil physical conditions thereby reducing runoff and increasing infiltration, which in turn results in increased biomass growth and quality. Of the major environmental problems associated with the land use of sewage sludge is the addition of potentially toxic heavy metals in soils and possible pathogenicity. Repeated applications of heavy metal-contaminated sewage sludge can result in an accumulation of such toxic metals in the soil. Once accumulated, heavy metals are highly persistent in the topsoil, and can cause potential problems such as phytotoxicity, injury to soil microorganisms and elevated transfer to food chain [27] especially under acidic conditions.

Local authorities, both overseas and in South Africa, are continually searching for environmentally acceptable, as well as beneficial and economical, means of disposal of sewage sludge [28]. Land application of biosolids is still not completely accepted in the scientific community as a beneficial disposal option, with concern persisting over the fate and phyto-availability of biosolids-applied trace metals over time [29,30].

1.3 Biosolid-fly ash mixtures

The addition of organic wastes such as sewage sludge, chicken manure or compost will increase the organic carbon content in soil receiving ash amendment. This will initiate soil microbial activities for the cycling of nutrients [31, 32]. The high N and P contents in these wastes may also reduce the need for inorganic fertilizer. Fly ash mixed with other organic waste will be an attractive and economical option that should be considered [32].

If the pathogen reduction process in sewage sludge treatment involves the addition of hydrated lime and/or an alkaline substance, resulting in a pH of 12, a built in source of alkalinity is realized [33], and can be regarded as a possible amendment for acidic and infertile soils.

The extreme variability measured in fly ash and organic wastes in terms of total nutrient concentrations, extractable nutrients, and relative nutrient balance is common in many studies, reinforcing the urgent need to characterize waste materials before mixing and use in crop fertilization. The potential pitfalls of indiscriminate waste application to soil include (I) potential phytotoxicity from micronutrient excesses (especially B); (ii) shortages of essential macro nutrients such as N, P, and K due to low supply; (iii) nutrient deficiencies caused by unfavorable fly ash pH, slow nutrient release, and fixation of other nutrients such as P already present in the soil solution; and (iv) induced nutrient deficiencies from the supply of elements in incorrect proportions. Most of these problems can be overcome by exploiting the complementary nature of fly ash, sewage sludge, and poultry manure, and additional nutritional benefits (especially N-P-K balancing) should be possible by mixing these three waste materials together [17].

Previous work by Reynolds *et al* [34] to determine the feasibility of converting waste disposal problems in South Africa into a soil beneficiation strategy has proven viable. The co-utilization of fly ash and sewage sludge with added lime delivered a product termed SLASH (that contains 60 % fly ash, 30 % sewage sludge and 10% unslaked lime on a dry matter basis), which has beneficial soil ameliorant effects.

Reynolds *et al.*, [34], Rethman *et al.*, [35,36] have reported on the use of SLASH for a variety of crops- including corn, beans, potatoes, spinach and a flower crop such as asters. These reports highlighted the use of SLASH to eliminate the potential problems with disease organisms or heavy metal pollutants, while improving soil pH, Ca, Mg and P. The growth and productivity of such test crops was improved markedly under conditions of low fertility [37].

Soil type, rate of SLASH application and plant species were identified as being important in this regard. It was concluded that wherever fertility was limiting, SLASH had a beneficial effect [1,35]. At the low application rates used in these pot trials, it was found that no heavy metals had been translocated. Subsequent trials with higher application rates (up to 30 % of soil volume) were conducted and it was concluded that rates at 30 % were too high, compared to the 5-10 % treatments [1,38, 39].

The rationale behind such mixed wastes, are that the mixtures are superior soil amendments to either fly ash or sewage sludge. The use of an organic waste addresses the deficiency of macronutrients in fly ash, while fly ash can act as a bulking agent for the organic wastes, substantially reduces odor, and can offset soil acidity problems that may arise through continued land application of organic wastes. [40,15].

Based on the conclusions made by Rethman *et al*, [35, 36, 39,] and Truter, [1] this study concentrated on the effects SLASH had on soils at levels that did not exceeded 10%. The SLASH treatments were compared to sewage sludge, fly ash and lime in this study.

2. Experimental procedures

A randomized trial was conducted in constructed raised beds (net plot: 1.2m x 0.50m = 0.6m^2) on the Hatfield Experimental Farm, Pretoria, South Africa (25°45'S 28°16'E), 1327m above sea level, to determine whether a mixture of waste materials could improve infertile acidic soils, thereby creating better soil conditions for crop production.

A uniform sandy loam soil was ameliorated with sewage sludge, fly ash and reactive lime (CaO), in combination (SLASH) at four different levels and separately. These treated soils were placed into these constructed raised beds. The treatments [T1 (Control - 0% SLASH), T2 – [2.5% SLASH (8kg)], T3 – [5.0% SLASH (16kg)], T4 – [7.5% SLASH (24kg)], T5 – [10% SLASH (32kg)], T6 – Sewage Sludge (4.32kg), T7 – Fly ash (10.24 kg) and T8 – Lime (1.44kg)] were replicated five times.

These raised beds were used to evaluate the relative effects of SLASH, sewage sludge, lime and fly ash in soil on the dry matter production of various crops and soil chemical properties. Initially these raised beds were planted to cabbages, carrots, stocks, sweet peas and statice. These vegetable and flower crops represented the 1st cropping cycle of the raised bed trial [42]. Maize (*Zea mays*) [38], Triticale (*Triticale hexaploide*), sorghum (*Sorghum sp.)* and rye *(Secale cereala)* represented the 2nd, 3rd, 4th and 5th cropping cycles [43]. The treatments were applied to the soil in the raised beds at the start of the trial and were monitored over a period of 36 months. The initial analyses for this work was after the 1st cropping cycle done by Ramagadza [42].

The study also aimed to evaluate the residual effect treatments on crop production and the soils condition. The soils were sampled and analyzed once each cropping cycle had been completed. The chemical properties that were analyzed by the Soil Science Department, University of Pretoria, were the pH (H_2O) and the content of macronutrients (Bray 1 P), K, Ca and Mg. The %C was also occasionally determined.

The soils received regular watering to eliminate moisture as a limiting growth factor. Due to the variability of the raw materials used in these waste material mixtures, a relatively low concentration of a macronutrient was expected. Plants in the 1st cropping cycle showed symptoms of K deficiency and to determine if this was true for the batch of SLASH used for that study, K was applied to the 2nd cropping cycle (maize) only. This was necessary to eliminate K from being a possible growth-limiting factor for the 2nd cropping cycle. Thereafter, no additional inorganic fertilizer or additional applications of SLASH or other components were applied.

When using SLASH for flower and crop production, the best performances were achieved with the 5% and 10% SLASH levels [35,36,43]. It was because of this conclusion that this raised bed study was undertaken to compare SLASH treatments to the individual components of SLASH to notice the benefits of combining the waste materials.

Forage production for the various test crops was assessed by regular harvests within each growing season. These soils had been intensively cropped to get maximum production.

3. Results and discussion

The soils were sampled after the completion of each cropping cycle. By cropping these soils regularly the nutrients supplied by the different treatments were utilized and the long-term residual effects of the different treatments could be compared.

3.1 pH (H_2O)

After the first cropping cycle of vegetables and flower crops [42] the soil pH (H_2O) was determined. The results shown in Fig. 2 are the increase/decrease in pH units 180 days after the initial application of SLASH.

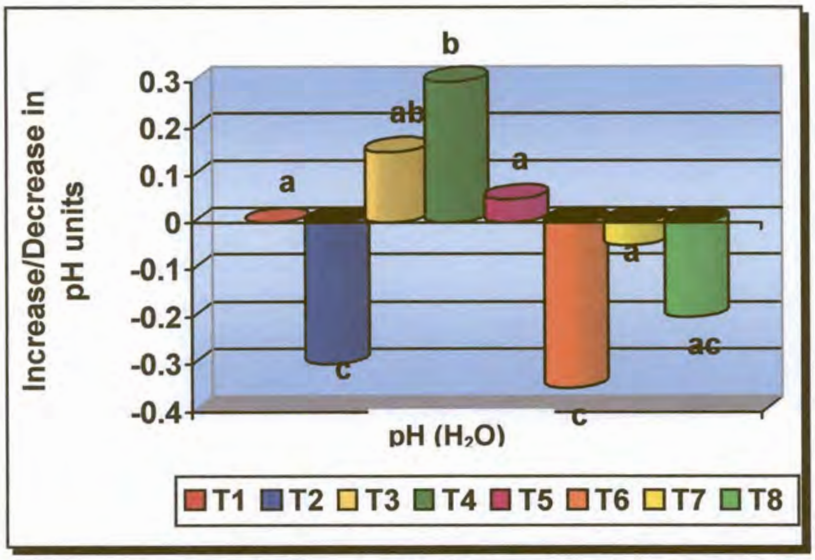

Fig. 1. Increase/decrease of pH (H_2O) units of soils treated with a mixture of sewage sludge, fly ash and lime in combination (SLASH) and separately, relative to the control, 180 days after treatment application. * Means with the same letter are not significantly different (P>0.05) (Bonferroni Test).

Fig. 1 indicates that the 5-10% levels of SLASH were the only treatments, which had a positive effect on the soils pH. The rest of the treatments had a negative effect relative to the control. These differences were not significant enough to draw any conclusions regarding the ameliorating effect of the treatments on soil pH.

Alkaline biosolids can, however, increase the soil pH (Fig.2) and precipitate toxic Al^{3+} as nontoxic $Al(OH)_3$ or other Al minerals [44,45,46,47,48]. As shown in Fig. 2. the treatments showed signs of stabilization 360 days after the initial application of SLASH. Like any liming material, the reactivity of the material depends on the fineness of the material, and usually requires some time before the ameliorant becomes effective.

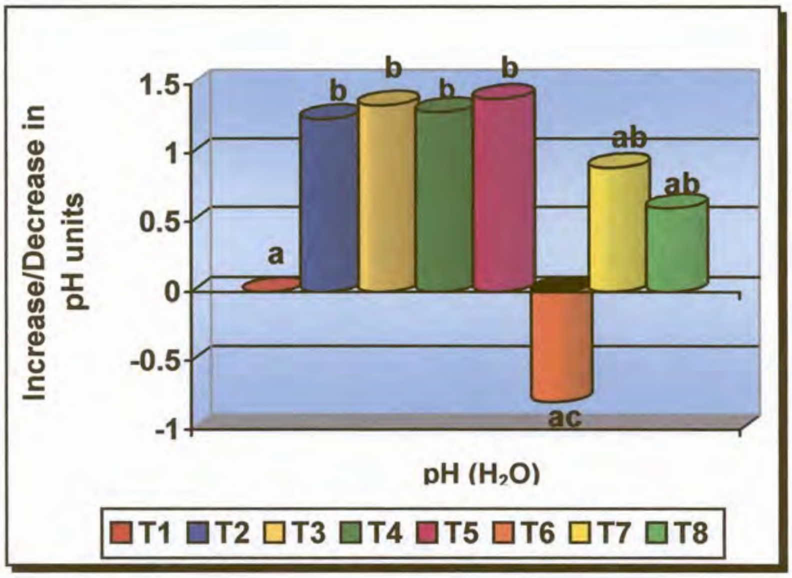

Fig. 2. Increase/decrease of pH (H_2O) units of soils treated with a mixture of sewage sludge, fly ash and lime in combination (SLASH) and separately, relative to the control, 360 days after treatment application. * Means with the same letter are not significantly different (P>0.05) (Bonferroni Test).

Similar trends were noted 540 days after treatment (Fig. 3). SLASH treatments where gradually increasing the pH. Between 1- 1.5 pH units increase was observed for all the SLASH treatments. When comparing these results to the conventional soil amendment lime (T8), it is evident that the SLASH (T2-T4) and fly ash (T8) treatments were having an effect on soil pH relative to the control.

Although the sewage sludge treatment gave the best yields for various cropping cycles [38, 43], as time passed the sewage sludge continuously acidified the soil (Fig. 1,2 & 3). This was to be expected, for it is well documented in the literature.

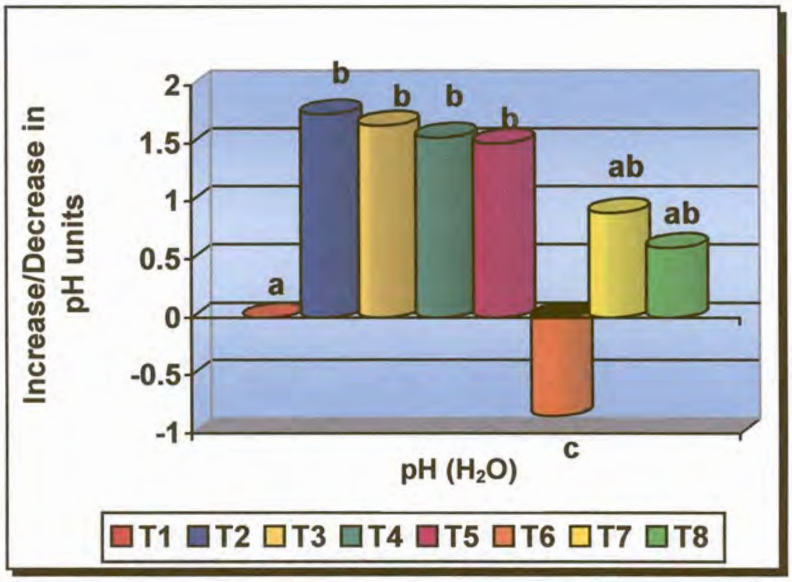

Fig. 3. Increase/Decrease of pH (H2O) units of soils treated with a mixture of sewage sludge, fly ash and lime in combination (SLASH) and separately, relative to the control, 540 days since treatment application. * Means with the same letter are not significantly different (P>0.05) (Bonferroni Test).

A change in the effect of the sewage sludge treatment was evident after 750 days (Fig. 4) and 930 days (Fig. 5) when it no longer had a significant acidifying effect. This substantiates results obtained in other studies [43], where the forage production of the 4^{th} and 5^{th} cropping cycles on the sewage sludge treatment showed signs of depletion relative to the SLASH treatments. From these results the conclusion may be drawn that alkaline stabilization of sewage sludge can prolong the growth enhancement effects of sewage sludge. The SLASH treatments in contrast maintained an improved pH for a longer period.

After 930 days of intensive cropping there was a better balance between SLASH, fly ash and lime treatments (Fig.5). The SLASH treatments, nevertheless, maintained between 25-30% better pH than the lime (T8) and between 70-80% better than the control.

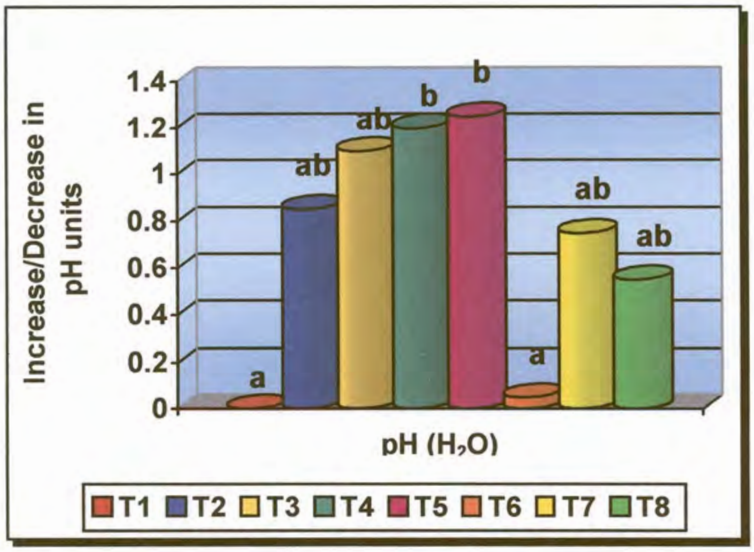

Fig. 4. Increase/decrease of pH (H_2O) units of soils treated with a mixture of sewage sludge, fly ash and lime in combination (SLASH) and separately, relative to the control, 750 days after treatment application. * Means with the same letter are not significantly different (P>0.05) (Bonferroni Test).

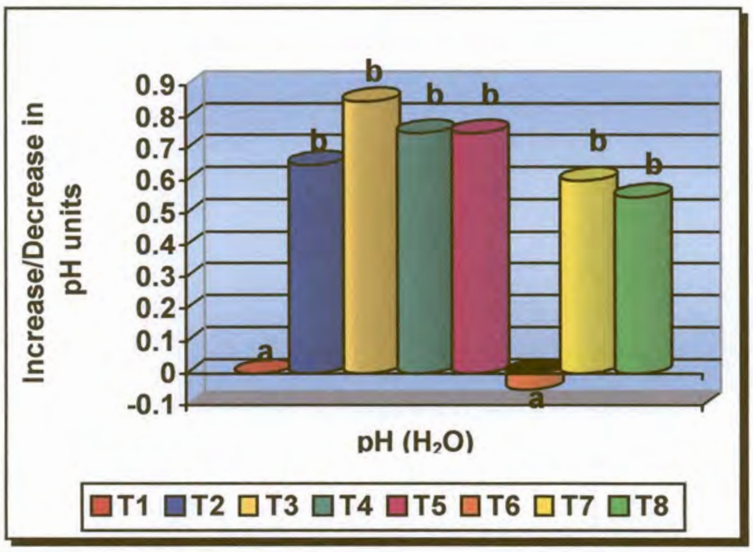

Fig. 5. Increase/decrease of pH (H_2O) units of soils treated with a mixture of sewage sludge, fly ash and lime in combination (SLASH) and separately, relative to the control, 930 days after treatment application. * Means with the same letter are not significantly different (P>0.05) (Bonferroni Test).

Alkaline biosolids can have relatively high $CaCO_3$ equivalencies (CCE) [47,48] and may serve as potential liming amendments to alleviate Al toxicity in acid soils.

The results obtained in this study suggest that SLASH had definite beneficial ameliorating effects in terms of soil pH. It can, therefore, be concluded that SLASH can maintain an improved pH for a minimum of 930 days.

3.2 Phosphorus (P)

Phosphorus is an essential macronutrient for plant growth. Because the N content of fly ash is usually nil and the P content is quite insoluble, these nutrients should be added to sustain good growth when fly ash only is applied [49].

Sewage sludge collected from waste –water treatment plants supplies N and P, provides long-term fertility [50,51], and shortens the time period for development of biological cycles critical for sustained plant growth [52].

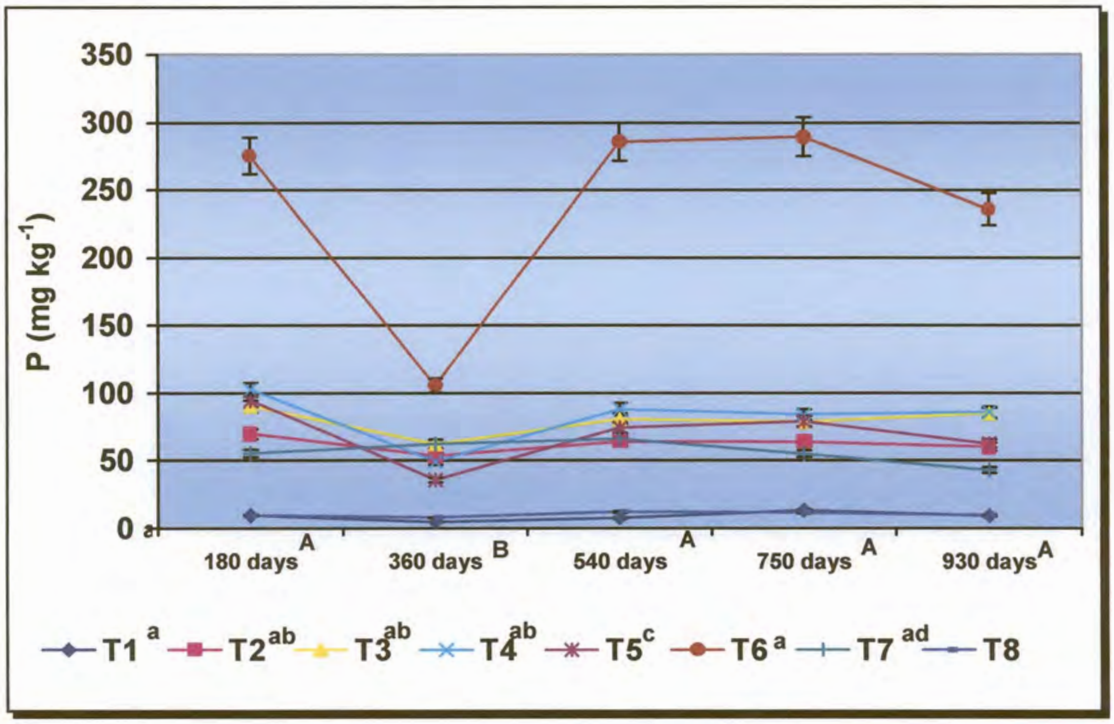

Fig. 6. Influence of SLASH, sewage sludge, fly ash and lime on the P content (mgkg^{-1}) of soils relative to the control, over time. * Means with the same letter are not significantly *different (P>0.05) (Bonferroni Test).*

The high P levels for the sewage sludge treatment (T6), as shown in Fig. 6, can cause P fixation, which could then become unavailable and even be detrimental to plant growth. However, when combining the sewage sludge with the fly ash, which is relatively low in P, it can reduce the availability of P in sewage sludge and make it slowly available over time (Fig. 6).

These effects can be attributed to an increase in soil pH by the ash and the formation of insoluble complexes [53, 54]. The lower soil P levels seen on the SLASH treatments, can be related to the conclusion made by Schumann and Sumner, [54] that the soil P deficiencies were exacerbated by fly ash applications, due to precipitation of P and cation imbalances caused from excess Ca compounds.

The P level obtained in the analysis at 360 days is not valid. This may be ascribed to a non-representative sample, which did not contain significant sewage sludge, which influenced the mean value for that period. This observation emphasizes the difficulty of handling, applying and incorporating a waste material such as sewage sludge. SLASH and similar waste product mixtures, based on the same principles, deliver a more granular soil like texture facilitating it's even incorporation into the soils.

3.3 Calcium (Ca)

Calcium is absorbed by plants in relatively large amounts and is, therefore, regarded as a macronutrient. The function of Ca in the plant is the formation of Ca pectates in the middel lamella of the cell wall and the stabilization of membranes [55,56,57]. Thus, damage of the root could result from a disturbance of cell wall formation in the root meristem or through disturbance of the integrity and function of membrane, especially the plasmalemma. [57]

The chemical barrier to root development existing in the sub-soils of acid soils is a subject of increasing interest. In order to better understand the factors involved in the amelioration of subsoil acidity, the effects of calcium sulphate, phosphogypsum and calcium carbonate on the properties of solid and liquid phases of subsoil samples and on the growth and nutrient uptake by maize (*Zea mays* L.) were evaluated [58]. Calcium carbonate reduced activity of Al^{3+} because of the increase in pH. The subsoil samples presented severe restrictions for maize root growth and all three treatments were equally effective in increasing root development, which could be attributed to the supply of calcium and a combined effect of the amendment in reducing the activity of Al and increasing the activity of Ca in the soil solution in the other soils [58].

It is possible that the Ca present in the fly ash and the SLASH occur in many different forms, but, as previously mentioned and as can be seen in Fig. 7, SLASH and other alkaline biosolids can have relatively high $CaCO_3$ equivalencies (CCE) [47,48], and may serve as potential liming amendments to alleviate Al toxicity in acid soils.

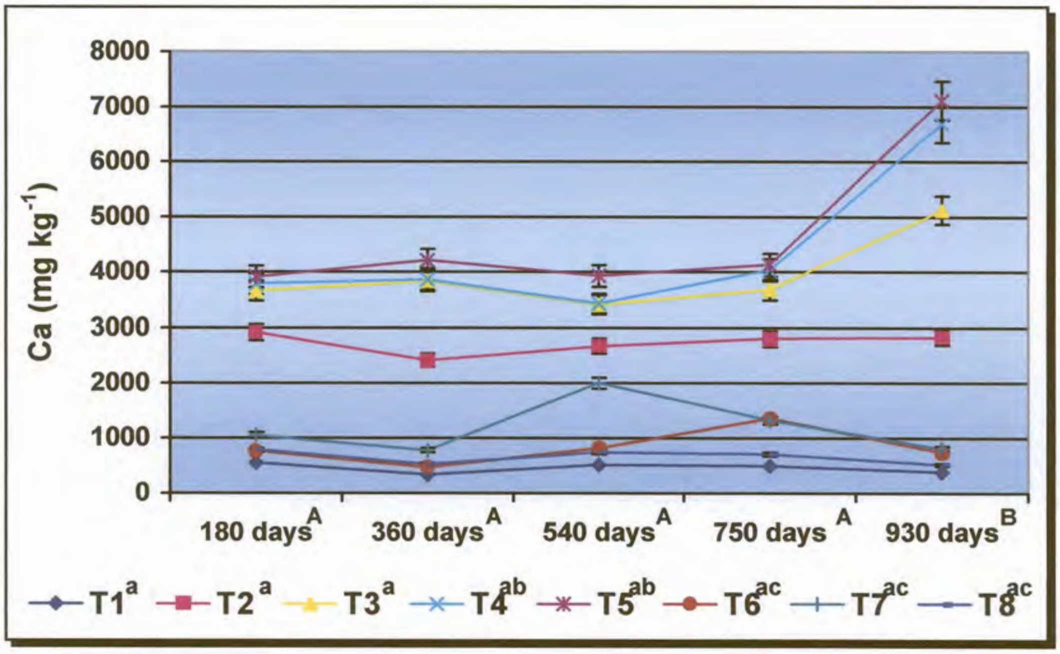

Fig. 7. Influence of SLASH, sewage sludge, fly ash and lime on the Ca content ($mgkg^{-1}$) of soils relative to the control. * Means with the same letter are not significantly different (P>0.05) (Bonferroni Test).

3.4 Potassium (K)

Plants require relatively high amounts of K in comparison to other minerals. K plays an important role in the transport of N in the plant, in the translocation of carbohydrates and it promotes photosynthesis.

In variable charge soils, increasing acidity results in decreasing CEC, which could reduce the ability of the soil to retain K. Thus, the more acid a soil becomes, the less K is likely to remain on exchange sites and in addition, increased levels of soluble Al would stunt the roots further exacerbating the reduced K supply to the plant. [59].

Dewatered sewage biosolids are particularly K-deficient, while animal manures are a good source of this macronutrient. [54]. What was particularly relevant from Fig. 8, was the immediate response to the K fertilizer applied to the second crop, maize. This K was applied due to the deficiency symptoms observed in the 1st cropping cycle. It was thus necessary to apply K so that it would not be the limiting growth factor. The importance and the level of K required for a crop can clearly be seen from Fig. 8. Although K was applied, it is evident that less K is available in the SLASH treated soils than the control. This can be ascribed to the fact that excessive quantities of Ca and Mg can create imbalances with respect to K leading to problems of availability and uptake. [59]

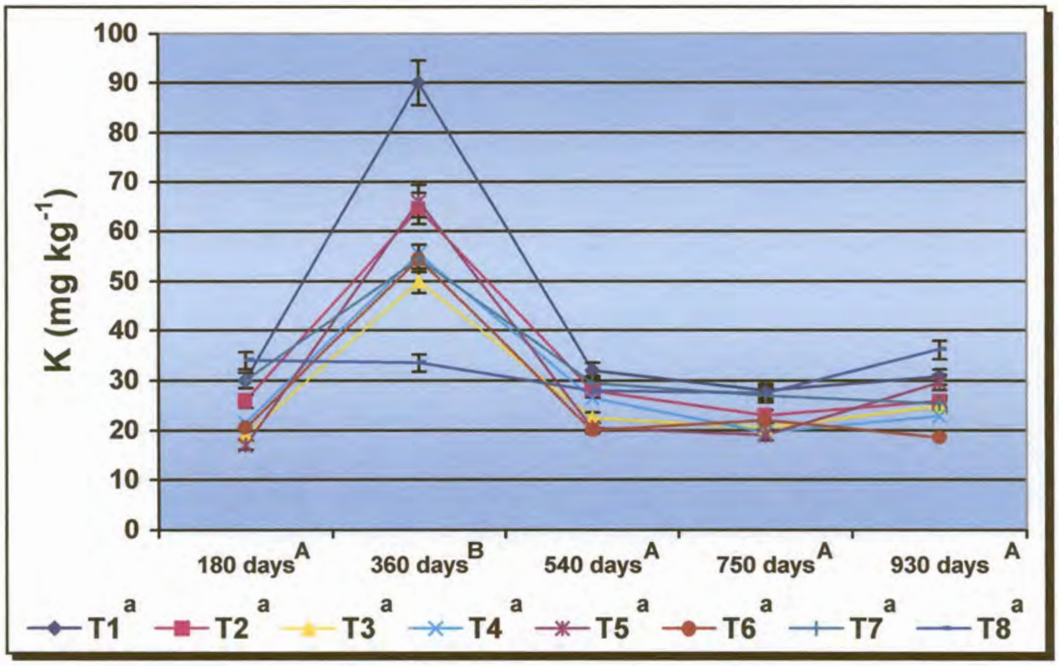

Fig. 8. Influence of SLASH, sewage sludge, fly ash and lime on the K content (mgkg^{-1}) of soils relative to the control over time. * Means with the same letter are not significantly different (P>0.05) (Bonferroni Test).

360 days since the KCL application, the K levels had returned to the original level after being depleted by the two crops that utilized this K. The remaining K levels as seen from 540 days onwards, are not sufficient for optimum crop production and quality plant material. The need, therefore, exists for supplemental inorganic fertilization, or the addition of an organic material, which is relatively high in K as are animal manures.

3.5 Magnesium (Mg)

Magnesium forms the core of the complex chlorophyll molecule, which is important in the photosynthetic process. Shortages can occur in acid, low CEC soils or sandy soils. Mg is also present in seeds and is involved in the translocation of P. Once an adequate amount of exchangeable Mg^{2+} is present, it has been shown that the ratio of Ca/Mg can be anywhere in the range of 1:1 to 49:1 without affecting crop yields [60].

Sewage sludge can supply Mg and other essential nutrients, but it depends greatly on the source from where the sewage sludge comes from. Fly ash, produced from South African coals, can be relatively low in Mg.

Nevertheless, 180 days after the application of treatments the Mg levels weren't significantly different to each other. In the following months, it is obvious from Fig. 9 that the lime, the lowest SLASH treatment, sewage sludge, fly ash and control's Mg levels dropped. While the other SLASH treatments maintained relatively constant Mg levels for at least 570 days longer than the other treatments.

These results reflect the interactions between the elements themselves, but variation in the results can also be ascribed to the different nutrient requirements of the various test crop species. Overall, the 5-10% SLASH treatments gave the best results, which can thus emphasize the benefits of combining two waste products that have unique characteristics in terms of improving specific soil conditions or enhancing plant growth processes.

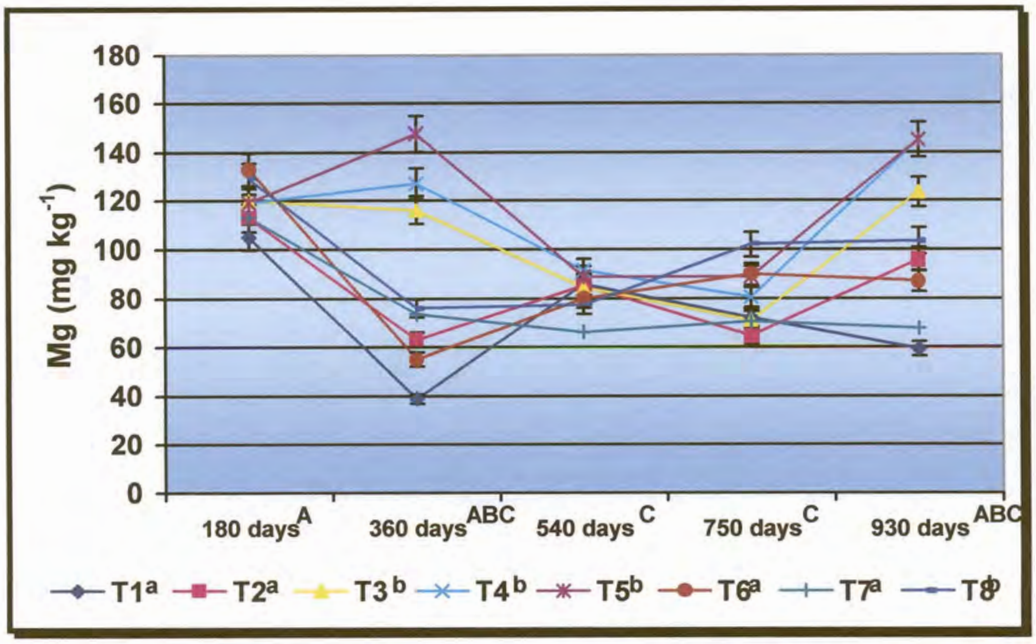

Fig. 9. Influence of SLASH, sewage sludge, fly ash and lime on the Mg content (mgkg^{-1}) of soils relative to the control over time. * Means with the same letter are not significantly different (P>0.05) (Bonferroni Test).

3.6 % C and CEC

The percentage soil organic carbon (%C) and cation exchange capacity (CEC) were only monitored occasionally. This was done to determine if there had been any significant changes over time. The results obtained, indicated that the sewage sludge and SLASH treatments had improved %C by at least 150% relative to the control, fly ash and lime. This can be ascribed to the high organic content of the sewage sludge and SLASH treatments. No significant CEC differences were noted and have been excluded.

4. Conclusion

The results obtained from the raised bed trials, have confirmed that SLASH has marked beneficial effects on plant productivity [1,8,38,43]. This may be ascribed to the ameliorating effects, which this product has on soil pH and soil nutrient status. These ameliorating effects, unlike many in-organic fertilization programmes, have long-term residual effects. Differences between the 5-10%

(T3-T5) levels were not considerable. Therefore, the optimum level of SLASH can range between 5-10% of the soil volume depending on the specific soil condition.

Sewage sludge is an excellent source of N and P. Unfortunately; P fixation can result because of these excessively high levels of P supplied by sewage sludge. By mixing sewage sludge with fly ash (SLASH) the P levels were lowered to more acceptable levels, and made available over time.

Potassium is a very essential nutrient for plant growth. Very low levels of K are found in both sewage sludge and fly ash. It is, therefore, critical that K is supplemented by adding K in an inorganic form, or possibly combining with an additional organic material, which is high in K, such as animal manures.

The improvement of physical soil properties were observed but not measured. This requires further investigation to substantiate the hypothesis that SLASH does improve physical soil properties.

Combining waste materials produces mixtures, which are superior soil amendments than the individual components. The use of organic wastes used in these mixtures can resolve the deficiency of macronutrients in the fly ash, as can the fly ash address the deficiency of micronutrients in the organic wastes. In addition to this, the fly ash acts as a bulking agent for organic wastes, reducing odour, and can offsetting soil acidity problems as well.

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CHAPTER 7

General conclusions and recommendations

The land application of by-products from municipal, industrial or agricultural sources is certainly not a new phenomena. In many cases, a coal combustion by-product (CCB) or an organic waste may not be ideal by itself for land application as a soil amendment.

The coal combustion by-product fly ash, has shown potential as a soil amendment and is a source of trace elements beneficial to plants. However, agricultural utilization of fly ash has been restricted because it is a poor source of macronutrients such as N and P, which is evident from the results obtained in the raised bed trials. Another assumption that can be made, but needs to be researched properly, is that P can become more available, because of the Si present in the fly ash, which can physically compete with the P on the clay minerals, thus making P more available for uptake by plants. The alkaline nature of fly ash, however, has made some significant contributions to the neutralization of acid soils. It can also be hypothesized that fly ash is more mobile in the soil than lime, which is not. This is important in neutralizing subsoil acidity, and this can possibly be ascribed to the presence of Ca silicates in the fly ash, but this requires further investigation. Another conclusion drawn from these studies, is that initially the fly ash application rates were calculated on a neutralizing value of 20% of agricultural lime, but from these studies, it can be concluded that fly ash has a higher neutralizing capacity than 20%. This, however, needs to be researched in more detail. Significantly high B levels in fly ash, which can be detrimental to crop production, were of no concern in these studies, and this may be due to the source, quality and age of the fly ash used in this programme.

The application of sewage sludge, more recently known as biosolids, is not very common in many countries because very little research has been carried out under local conditions, because of the high variability of biosolid compositions. It is clear from the high yields obtained in this study that sewage sludge is a good source of organic material with high amounts of essential macronutrients (especially N and P). Unfortunately, P fixation can result because of these excessively high levels of P present in sewage sludge.

Sewage sludge also has the ability to improve physical soil properties. Improvements in water holding capacity were noted during the cultivation of the soils treated with sewage sludge. Despite the statistically different yields obtained with the sewage sludge, environmental legislation has placed restrictions on the use of this by-product because of associated problems, such as the high levels of pathogenic micro-organisms, which can become a health risk, the possible soil contamination aspects, as a result of excessive heavy metal contents, the associated odour problems and the acidifying effect it has on agricultural soils. In addition to sewage sludge's limitations, practical restrictions such as transport, handling and application of the sludge makes sewage sludge a difficult by-product to use for agricultural purposes.

It was, therefore, very important to develop technologies that can be used to produce soil ameliorants from these waste products with unique properties that can be beneficially used to address problems associated with conventional sludge and fly ash disposal practices, while simultaneously creating a beneficial use for waste products to the benefit of interested parties.

Co-utilization is simply the production of new products by combining two or more by-products. The combination of two or more waste materials results in a value added product. South Africa has successfully joined other countries in developing a technology to convert waste disposal problems into a soil beneficiation strategy. By combining sewage sludge, fly ash and CaO, a soil ameliorant SLASH is produced locally. SLASH is a superior soil amendment, which combines the amending qualities of two waste materials, which can overcome soil acidity and infertility problems by exploiting the complementary nature of fly ash and sewage sludge.

The SLASH programme has been concentrated on the agricultural use of SLASH. To extrapolate conclusions, biomass production of a wide range of species, long term residual effects, heavy metal availability and change in soil chemical properties were examined. During these studies, suprising results were observed, which emphasizes the need to investigate further possible benefits.

Concerning the rate of SLASH application, it is clear from the results obtained in these studies that the optimal level of SLASH is between 5% and 10% of the sandy loam soil volume. One may require different application rates, depending on the acidity level and type of soil that is being dealt with and benefit from the long term residual effects of SLASH. The reason one would apply lower more frequent applications would be to have a slow response over a longer period of time. Levels exceeding 10% will still deliver substantial increases in yields but may be limiting in terms of inhibiting germination of seeds or suppressing growth of seedlings in the initial growth stages. The visual observations made on the rate of seed germination indicate that the 30% SLASH treatment for example had an inhibiting and suppressing effect on seed germination and subsequently seedling establishment. However, once seedlings had established themselves, exponential growth rates were observed. These were, however, not necessarily better than the 5-10% SLASH treatments. It is, therefore, concluded that the difference between the 5-10% SLASH level and the 30% SLASH level in terms of yield increases, did not justify the higher level of SLASH.

Crop production responses of all the different species in these trials were consistently good. SLASH prolonged growth enhancement over a minimum period of 36 months before the SLASH and other treatments showed signs of depletion. Nevertheless, the 5-10% SLASH treatment still maintained the better yields. These SLASH treatments contributed significantly to the immediate growth enhancement after establishment, and produced high yields from the germination stage.

SLASH has also improved the production of leguminous plants. For a healthy and high yielding legume to establish itself, a legume needs to develop healthy nodules (usually by inoculating with Rhizobia) on it's roots to be able to fix N. This aspect is important in reducing inputs of inorganic nitrogen in any crop production system, which is reliant on nitrogen for production. Legumes produced on SLASH treated soils had dramatic yield improvements and consistently high production. This may be ascribed to three reasons, firstly, the organic contribution from

SLASH with the essential macronutrients and microorganisms supplied by the sewage sludge component and the supply of micronutrients from the fly ash component of SLASH. Secondly, the amendment of soil pH creating a better medium for root development and thirdly the development and presence of a vast amount of nodules, which were observed visually. This was an interesting observation, but would need to be researched more intensively to obtain clarity on this aspect, although the literature has indicated that fly ash encourages or stimulates microbial populations.

From these studies conducted in the SLASH programme, many answers have been provided. Nevertheless, gaps in our knowledge exist and the results obtained lead to many other questions. The response to, and the effect of, high applications of SLASH varies from crop to crop and often depends especially on whether the test crop was planted with fine seed, vegetative material or seedlings. These findings should find application in strategies using SLASH other than purely agricultural.

These ameliorating effects, unlike many inorganic fertilization programmes, have long residual effects, which is clear from the studies conducted. The exact length of these effects is approximately 36 months depending on the type and condition of the soil involved and the intensity of cropping (irrigation, multiple crops etc.). This finding, has important implications for the level and frequency of application of SLASH. In this context the following questions should also be addressed: Should heavy applications of SLASH be applied infrequently or lighter applications each year for annual crops? Although, the lifespan of SLASH has been 36 months with one heavy application (30% of soil volume), compared to lighter applications (5-10% of the soil volume), no significant differences in yields were noted. Should applications be incorporated or may top dressings also be used? Consistently good results have been obtained when the SLASH applications were incorporated, so that the treatments were able to react with the medium. The use of SLASH as a top-dressing, however, remains to be investigated.

SLASH creates favourable conditions for improved root development, which is essential to ensure enhanced aboveground plant growth. SLASH can provide a good balance of essential nutrients, which are slowly released. Although SLASH is a good source of a wide range of nutrients, it often has low levels of K, because sewage sludge and fly ash are often K deficient. This aspect emphasizes the need to supplement SLASH with a potassium source. This limitation has lead to the need for further research, incorporating other waste material, such as animal manures, which are a good source of K.

SLASH also has definite potential to improve soil physical properties, but research must be conducted to be able to substantiate the visual observations made during this study.

An important consideration, which should be kept in mind, is that eliminating water as a limiting growth factor plays an important role in the rate at which soil chemical reactions take place. Mine rehabilitation studies, using the ameliorant SLASH to improve degraded mine soils (soils impacted by acid mine drainage and acidic cover soil used in the rehabilitation process) after open cast mining operations can be important for future application. Results from dry-land crop production studies and mine rehabilitation studies using SLASH as an amendment, to improve poor agricultural soils and degraded mine soils (soils impacted by acid mine drainage and acidic cover soil used in the rehabilitation process), should also provide valuable information in terms of recommendations for large scale application.

Sewage sludge, which comes from a source which contains high levels of heavy metals, raises the concern of translocation to plant material. If sewage sludge with a high heavy metal content is used in the manufacturing process of SLASH, authorities express concern about possible heavy metal contamination. During the process of SLASH manufacture, heavy metals have been immobilized, and this programme has substantiated this. No significant translocation of two hazardous heavy metals (Ni and Cd) or the micronutrient B was measured in maize plant material. The levels measured were within current safety specifications but these may be open for review. Uptake by different crop species is another important factor to consider. It is recommended that heavy metal and other toxic element analyses be continued on other crop species.

Despite the good results obtained with SLASH, guidelines for the effective use of SLASH need to be compiled, for specific situations or conditions. Nevertheless, as a result of the high amounts of SLASH required for ameliorating soils in an extremely poor condition, such a product should only be used in close proximity to the source of individual waste products.

Many by-products have low intrinsic value, but co-utilization strategies are aimed at producing value added products. Any activity performed on a by-product, e.g. loading on trucks, transporting etc. adds an additional cost. The economics of utilizing these by products are further complicated by the fact that for many industrial, agricultural or municipal wastes, the money spent on dealing with the wastes generated is relatively low. However, the fact remains that this money is used to dispose of, or manage the waste, not necessarily utilize the waste. Co-utilization products can change the natural resource base, provide value-added products, create new industries and associated employment, and assist in handling the wastes produced by sectors of the population, and being both economically and sociably viable. Thus, production of waste product mixtures can be one of the many tools for achieving sustainability.

Future research needs to include: the evaluation of by-products mixtures ensuring an optimal nutrient balance for large scale land application; development of accurate, calibrated analyses of organic and nutrient content; environmental impact of land spreading; economic value of by-products and improved storage and handling of by-products to reduce nutrient loss. Most importantly, logistical difficulties, such as transportation and application issues, and social acceptance issues (which require education of the public, government officials, and the agricultural community) need to be addressed. If the agronomic community can realize the full benefits of co-utilization of high quality by-products, these may be viewed as the great resources they can be, rather than the difficult disposal problems they are.