CHAPTER 5

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

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Abstract

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

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

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

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

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

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

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1. Introduction

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

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

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

2. Materials and Methods

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

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

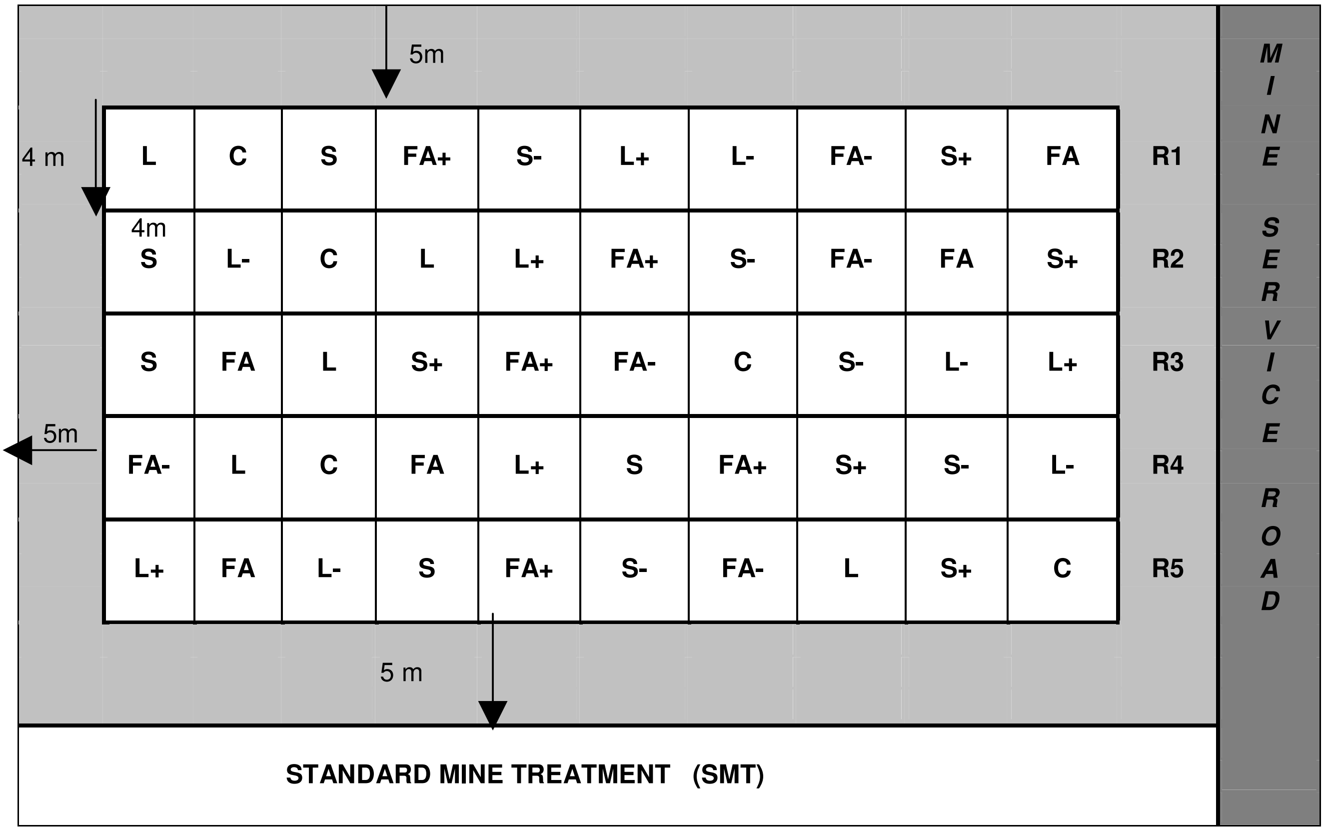

Figure 1: Experimental trial layout at Kromdraai Colliery

Figure 2: Establishment of field trial at Kromdraai colliery

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

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

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

2.1 Statistical analyses

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

3. Results and discussion

3.1 Vegetation analysis

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

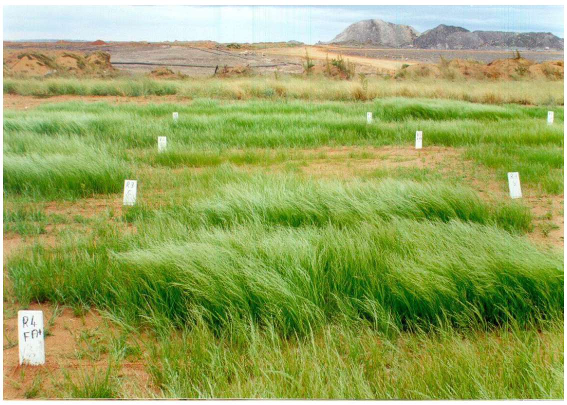

Figure 3: The vigorous growth of *Eragrostis tef* eight weeks after soil amelioration and seeding .

Figure 4: Perennial grasses predominant two seasons after establishment

3.1.1 Botanical composition

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

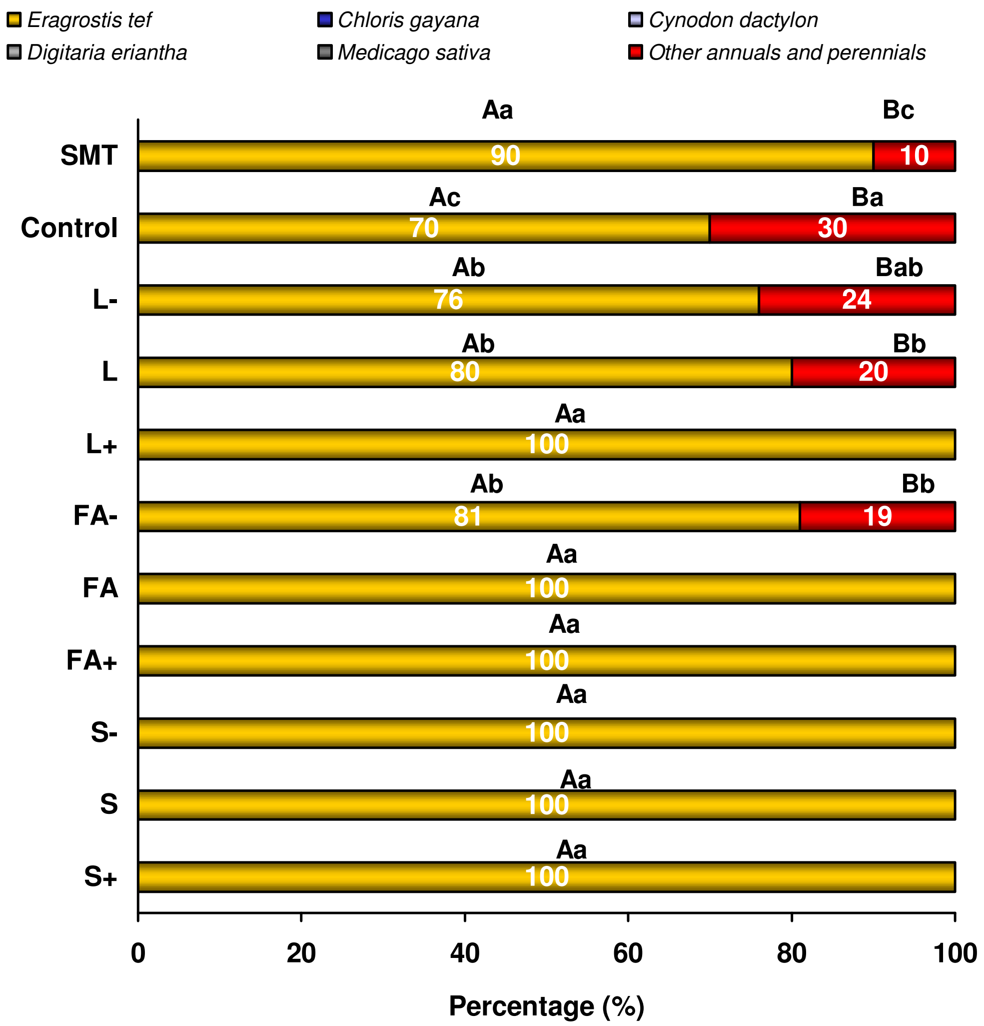

Figure 5: The influence of treatments on the botanical composition of the re-vegetated mine land in the 1999/2000 growing season.

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

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

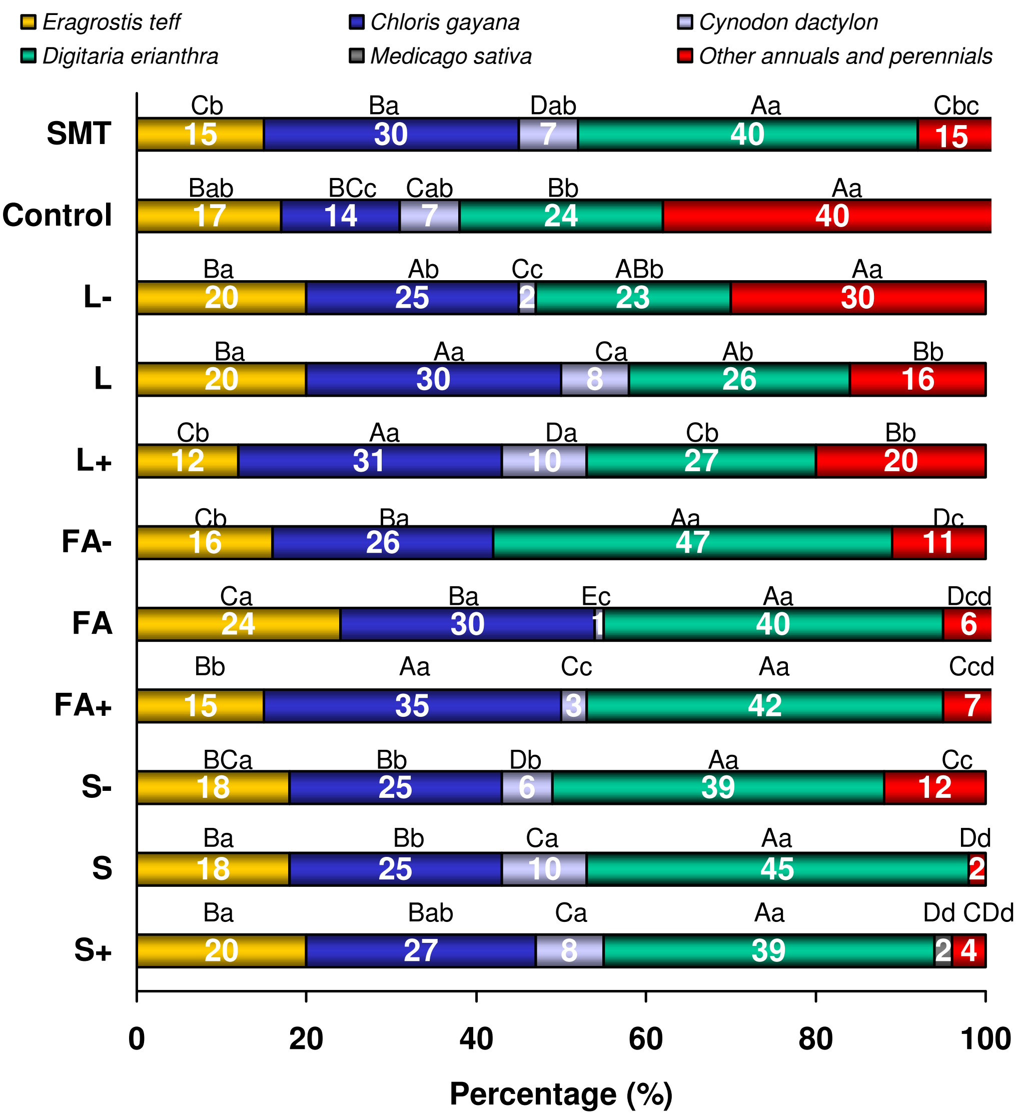

Figure 6: The influence of treatments on the botanical composition of the re-vegetated mine land in the 2000/2001 growing season.

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

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

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

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

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

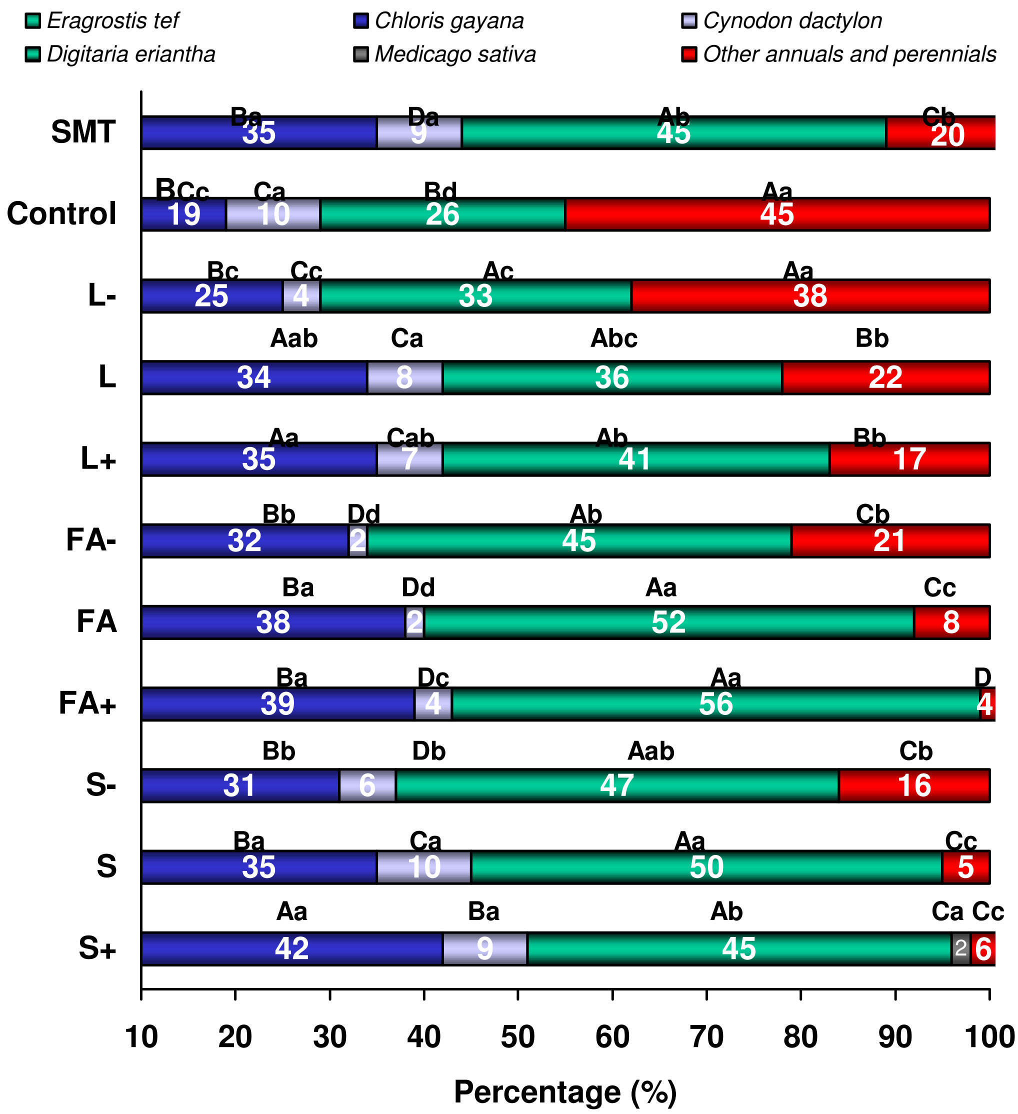

Figure 7: The influence of treatments on the botanical composition of the re-vegetated mine land in the 2001/2002 growing season

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

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

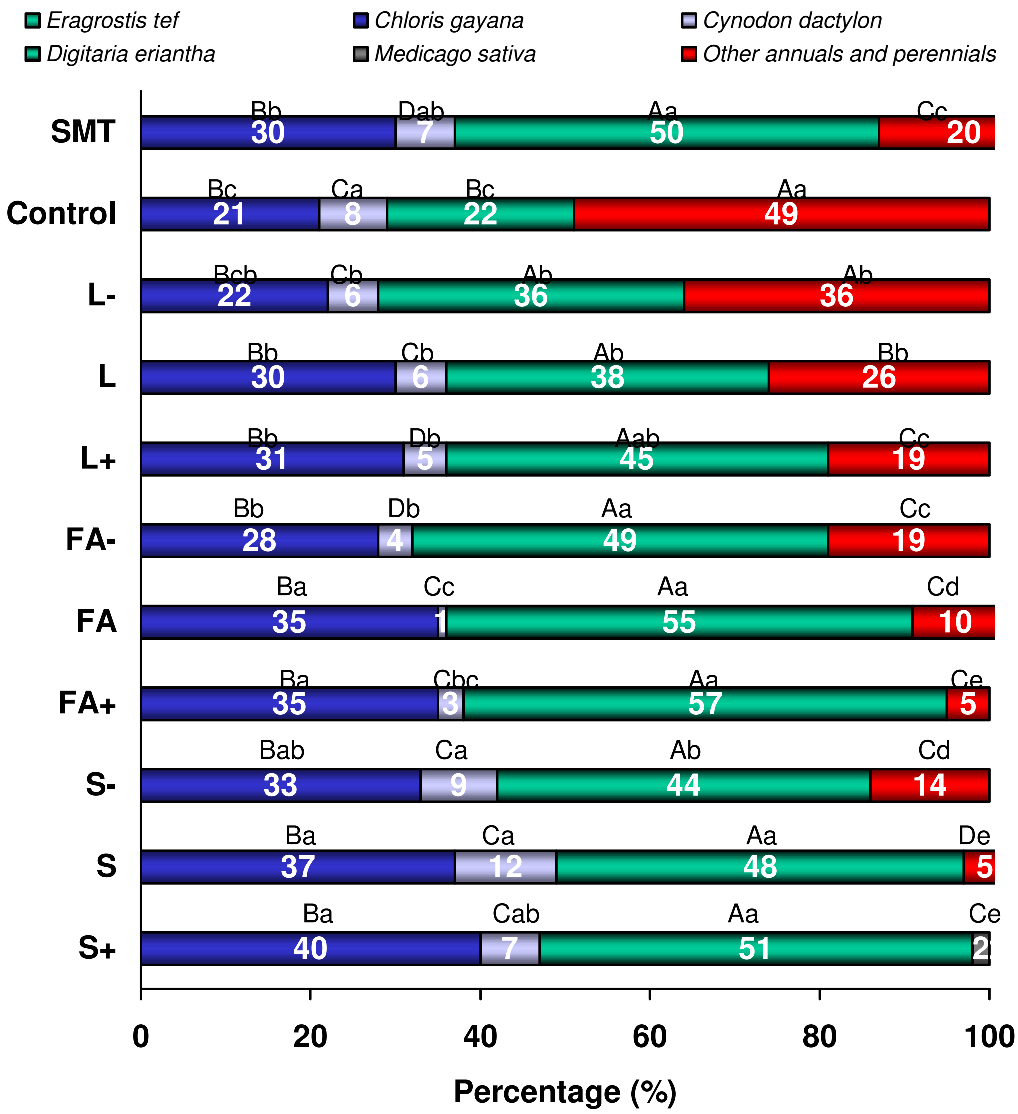

Figure 8: The influence of treatments on the botanical composition of the re-vegetated mine land in the 2002/2003 growing season

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

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

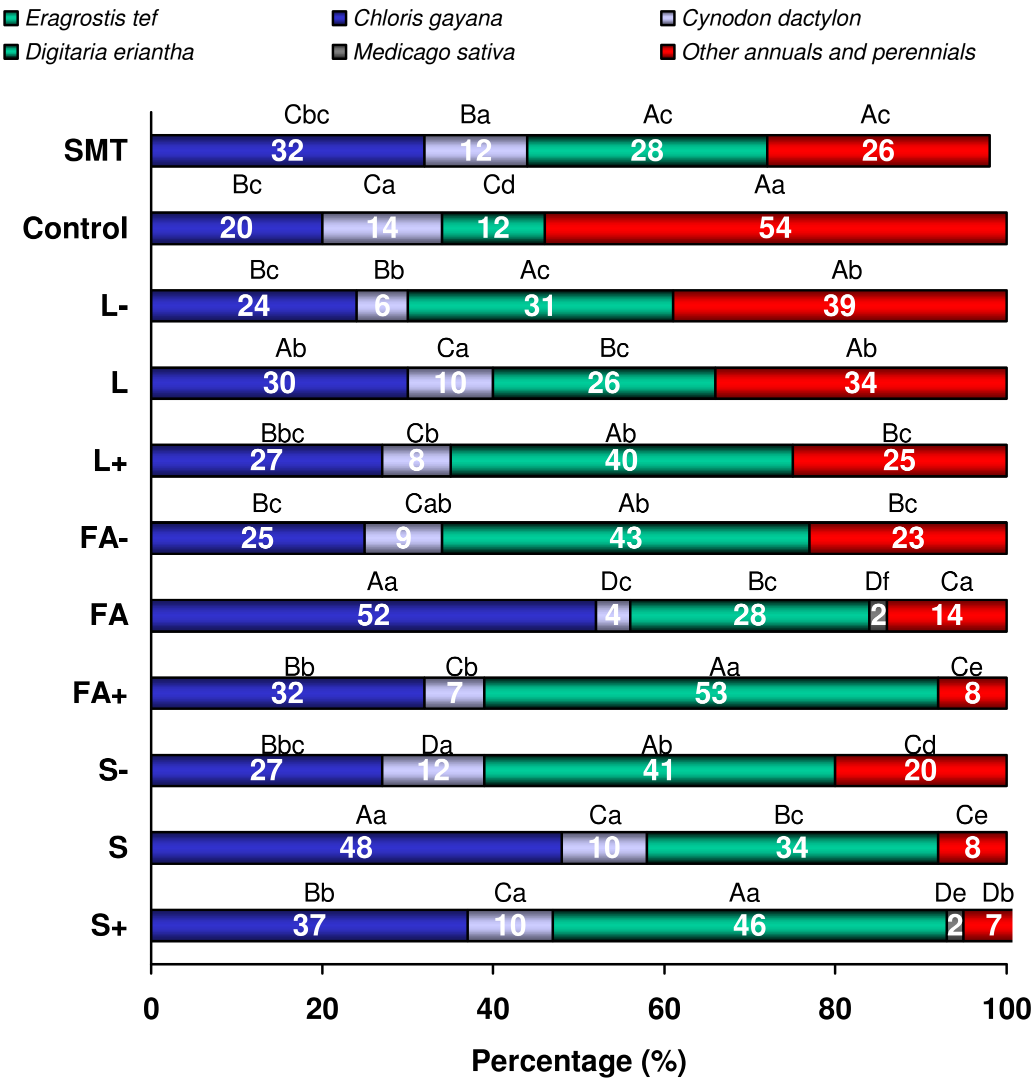

Figure 9: The influence of treatments on the botanical composition of the re-vegetated mine land in the 2003/2004 growing season.

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

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

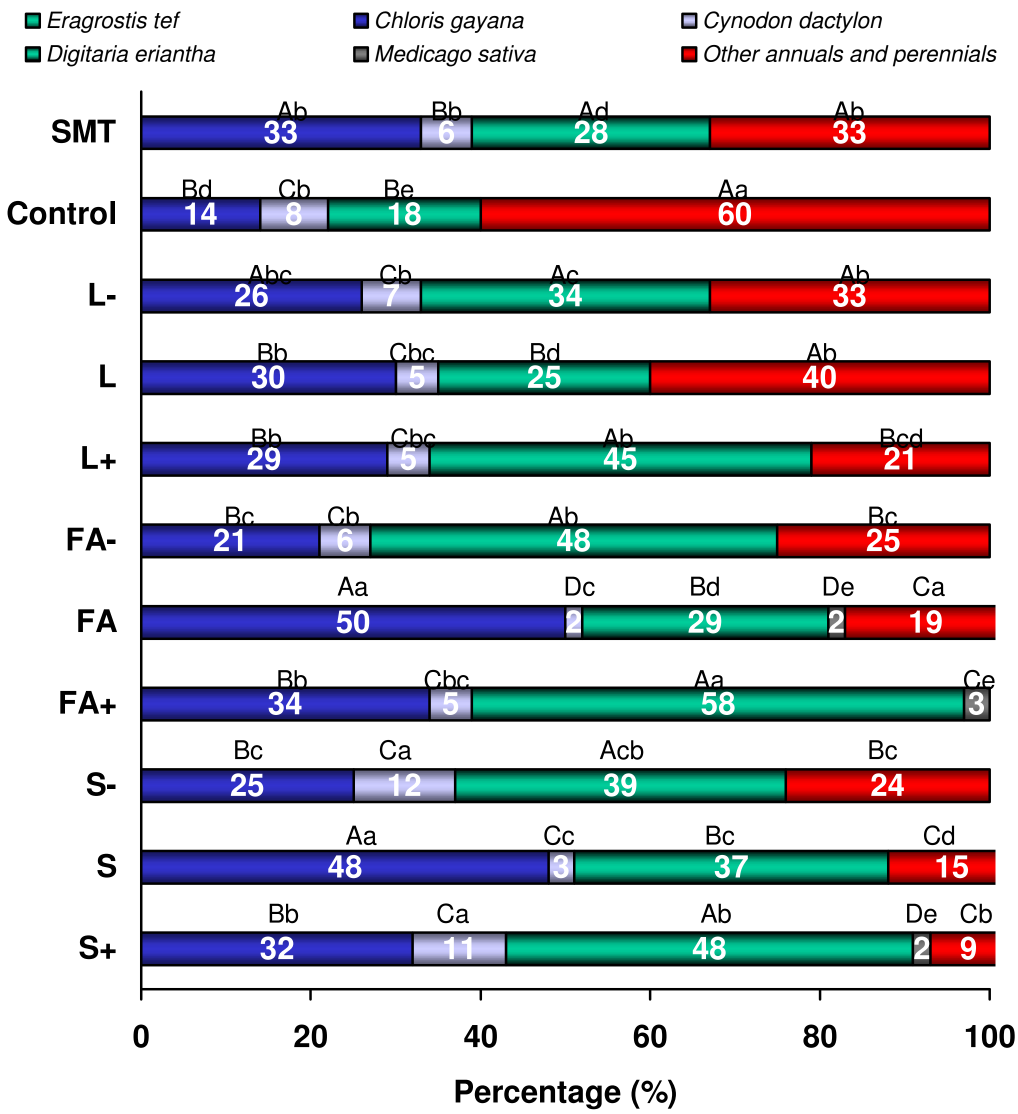

Figure 10: The influence of treatments on the botanical composition of the re-vegetated mine land in the 2004/2005 growing season.

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

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

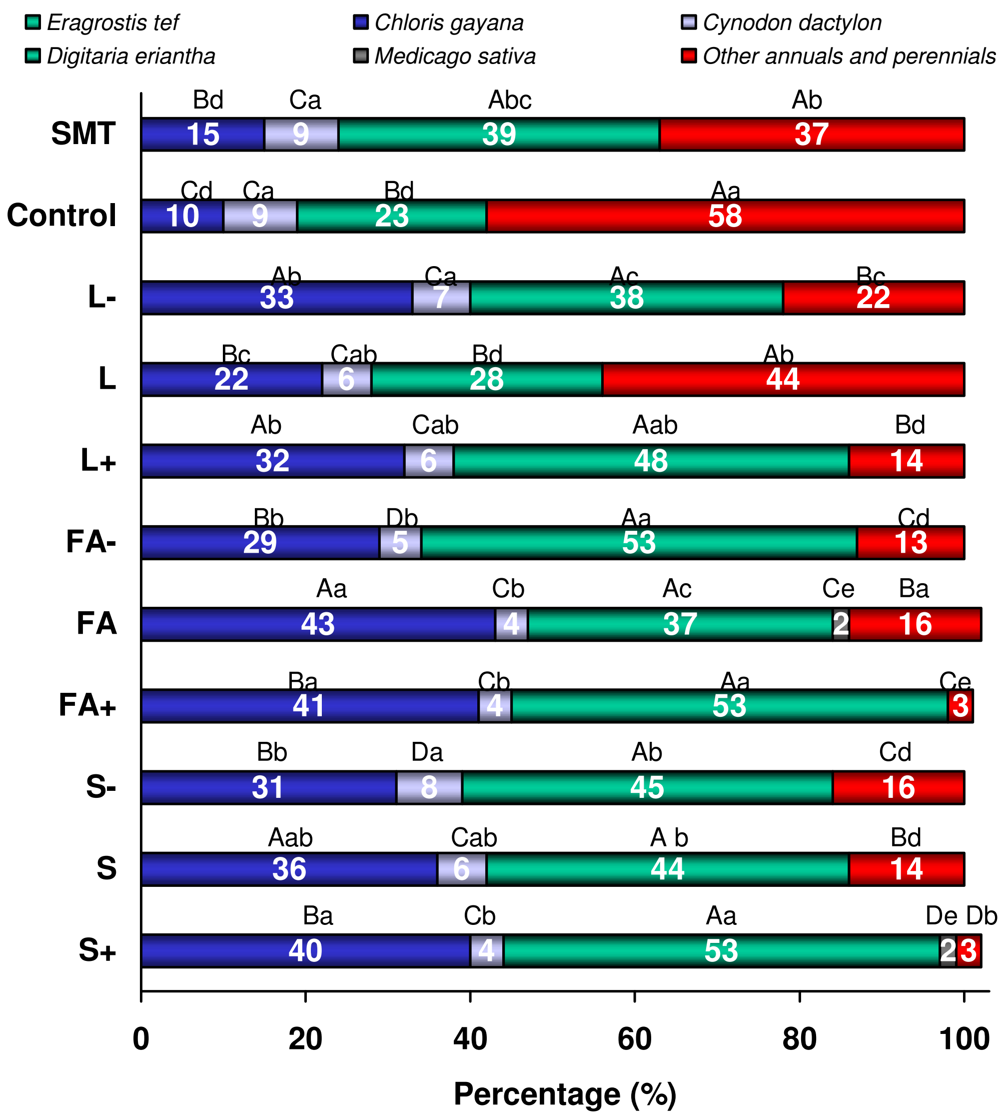

Figure 11: The influence of treatments on the botanical composition of the re-vegetated mine land in the 2005/2006 growing season.

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

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

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

3.1.2 Basal cover

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.1.3 Dry matter production

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

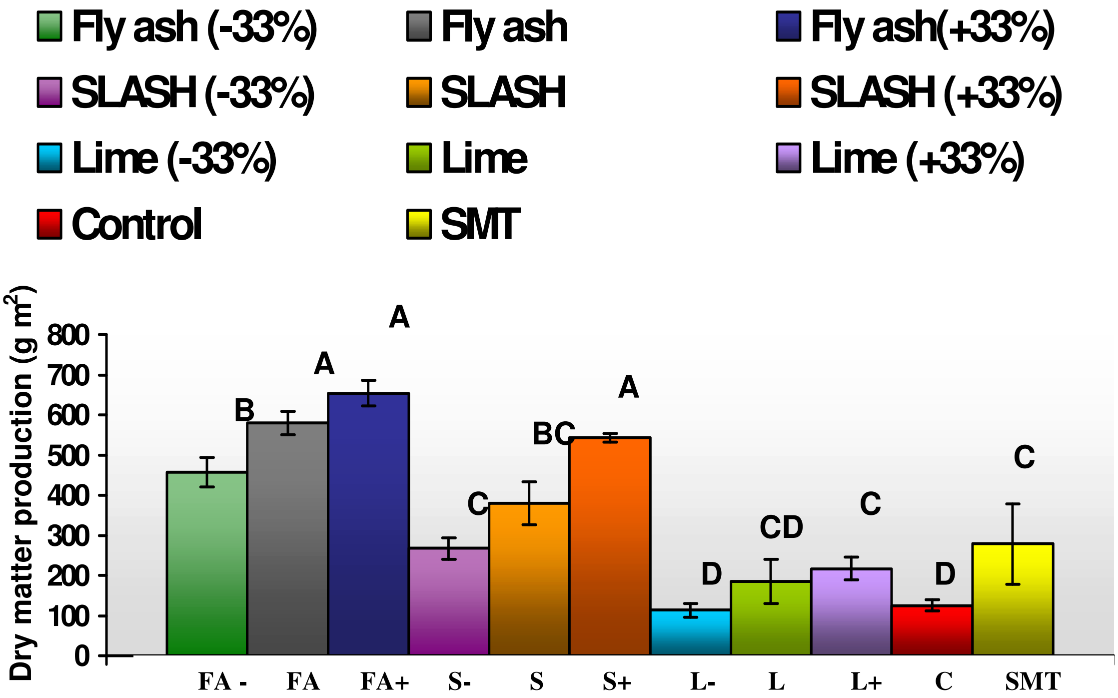

Figure 12: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 1999/2000 growing season.

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

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

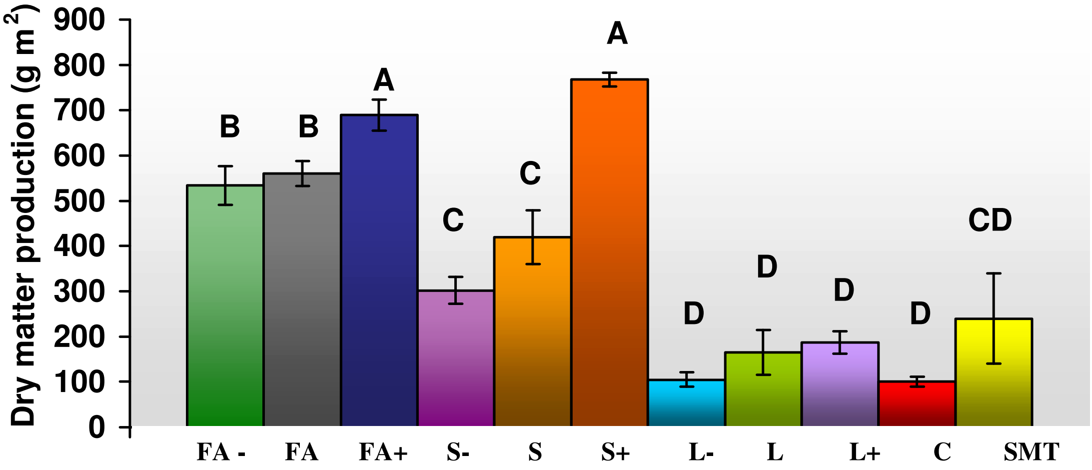

Figure 13: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 2000/2001 growing season

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

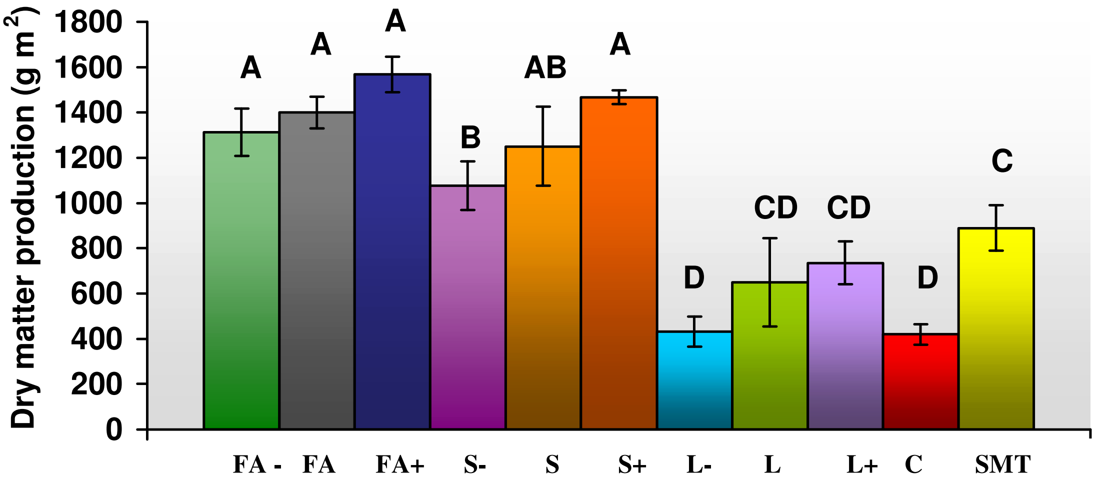

Figure 14: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 2001/2002 growing season.

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

(Tukey's Studentized Range Test)

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

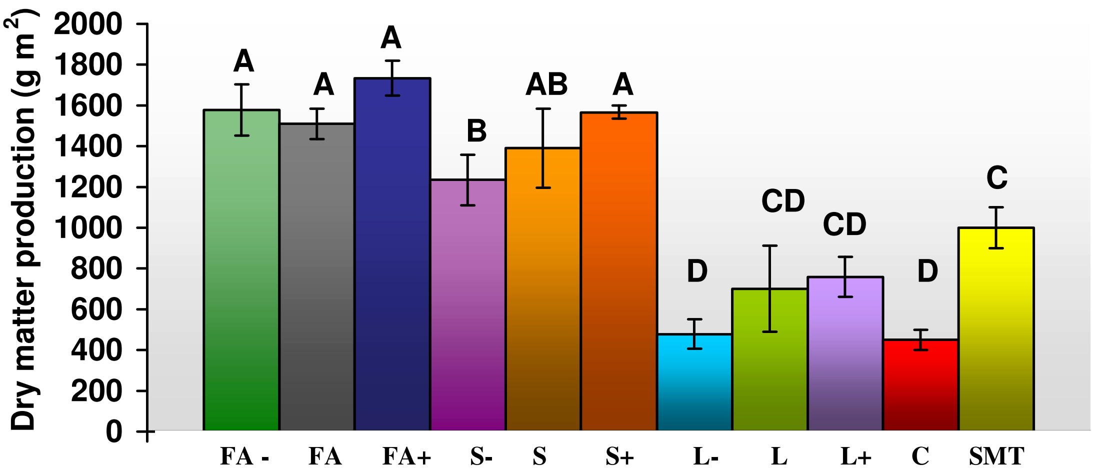

Figure 15: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 2002/2003 growing season.

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

(Tukey's Studentized Range Test)

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

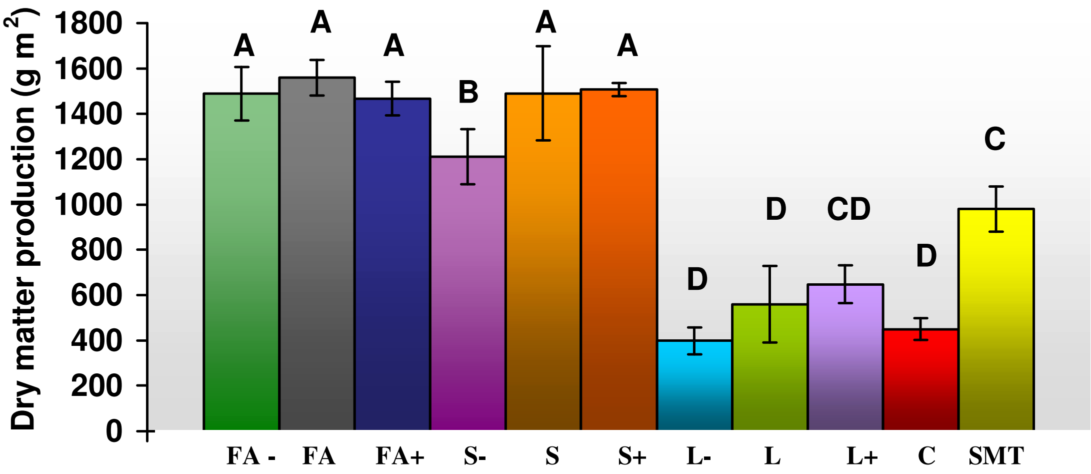

Figure 16: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 2003/2004 growing season.

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

(Tukey's Studentized Range Test)

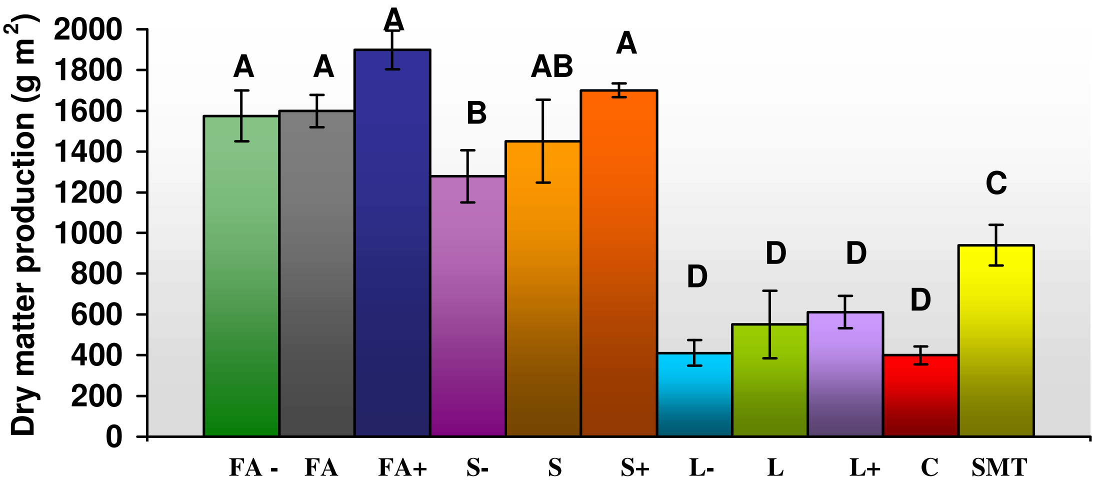

Figure 17: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 2004/2005 growing season.

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

(Tukey's Studentized Range Test)

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

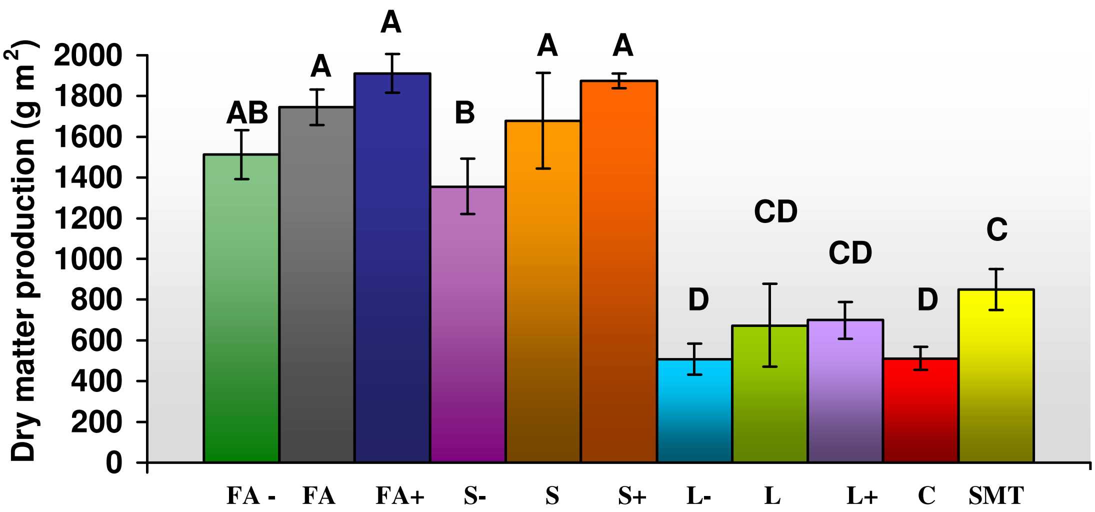

Figure 18: The dry matter production on re-vegetated soils, treated with different ameliorants, in the 2005/2006 growing season.

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

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

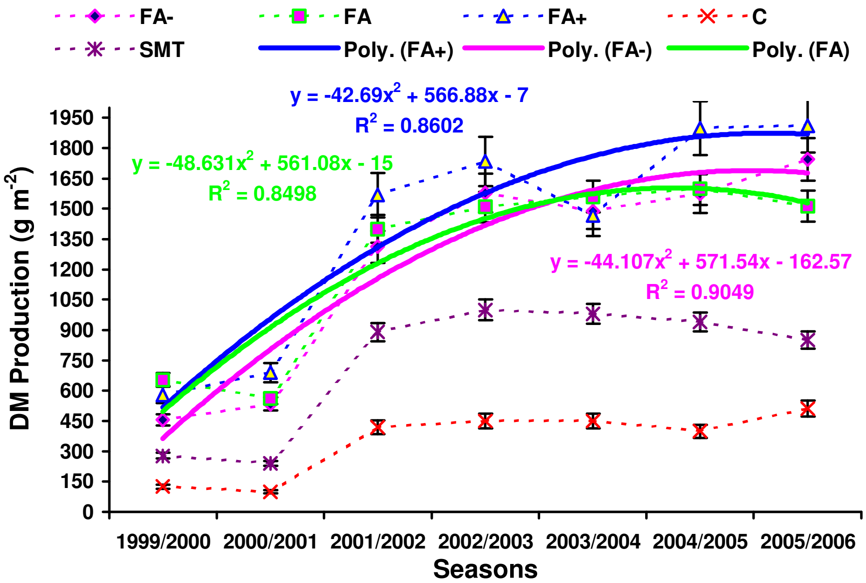

Figure 19: The dry matter production on re-vegetated soils, treated with FA ameliorants, relative to the C and SMT treatments over a 72-month period.

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

3.2 Soil Analyses

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

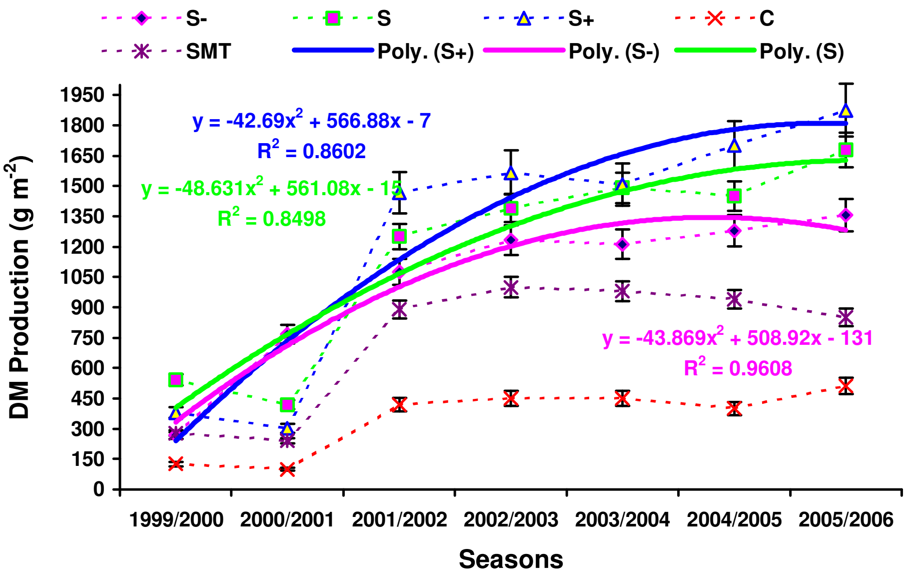

Figure 20: The dry matter production on re-vegetated soils, treated with S ameliorants, relative to the C and SMT treatments over a 72-month period.

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

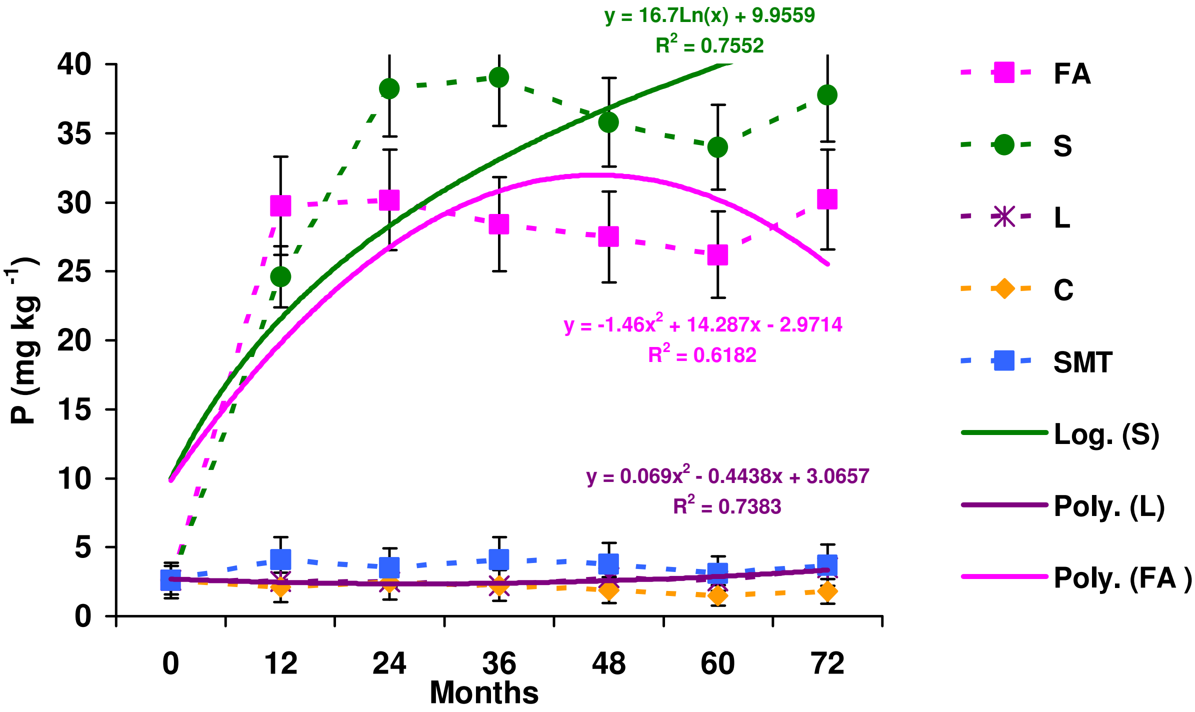

Figure 21: The influence of treatments, relative to C and SMT treatments, on the soil P status over a 72-month period

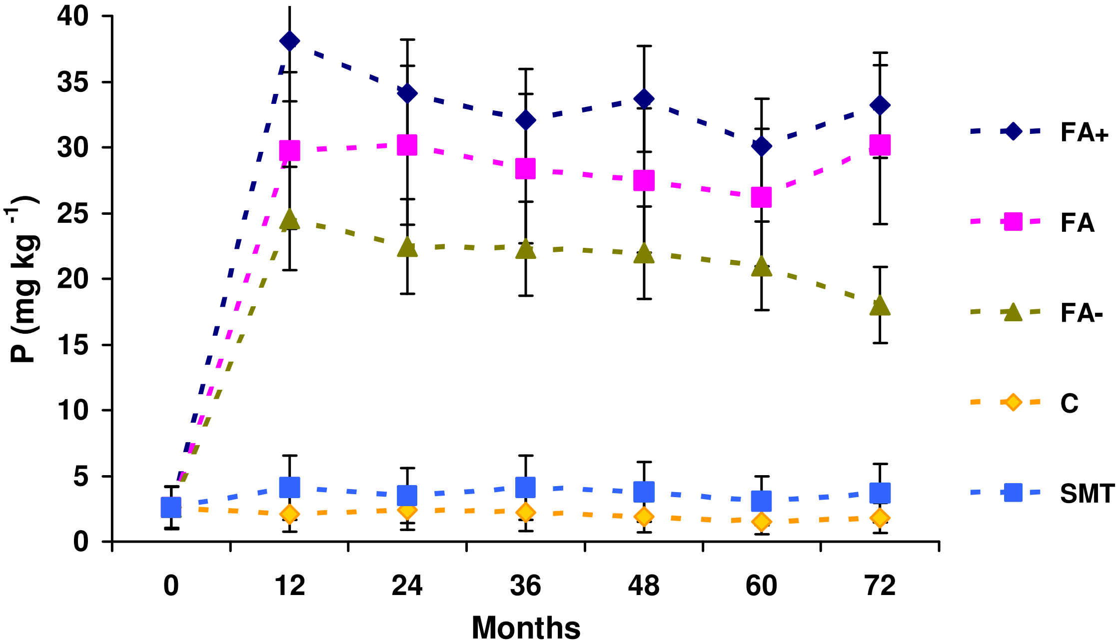

Figure 22: The influence of FA treatments, relative to C and SMT treatments, on the soil P status over a 72-month period

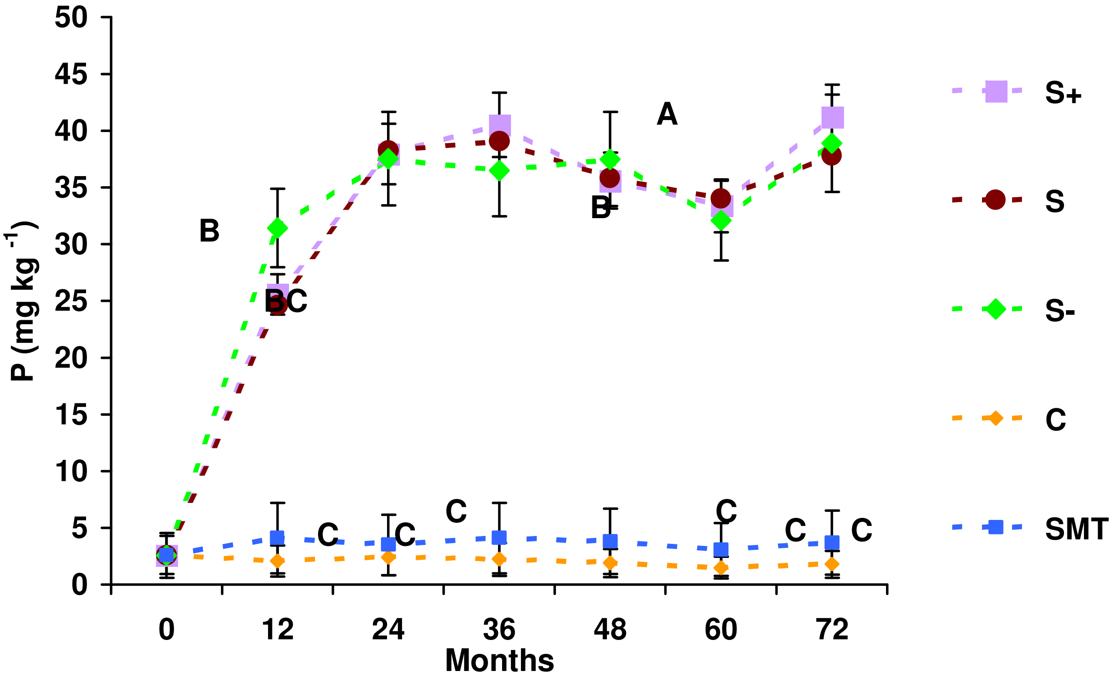

Figure 23: The influence of S treatments, relative to C and SMT treatments, on the soil P status over a 72-month period

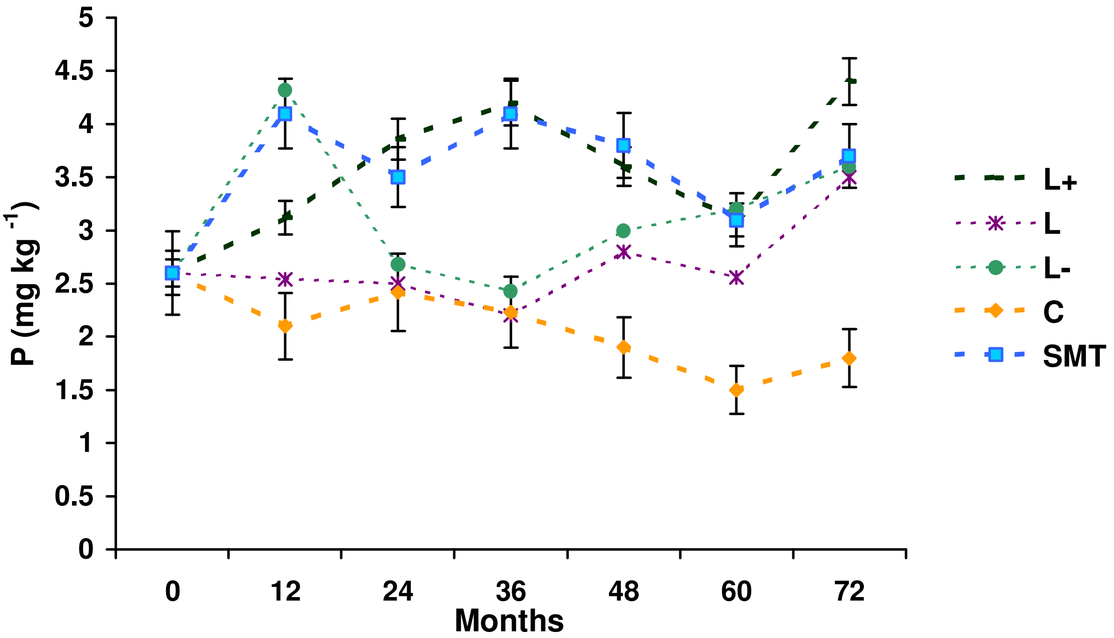

Figure 24: The influence of L treatments, relative to C and SMT treatments, on the soil P status over a 72-month period

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

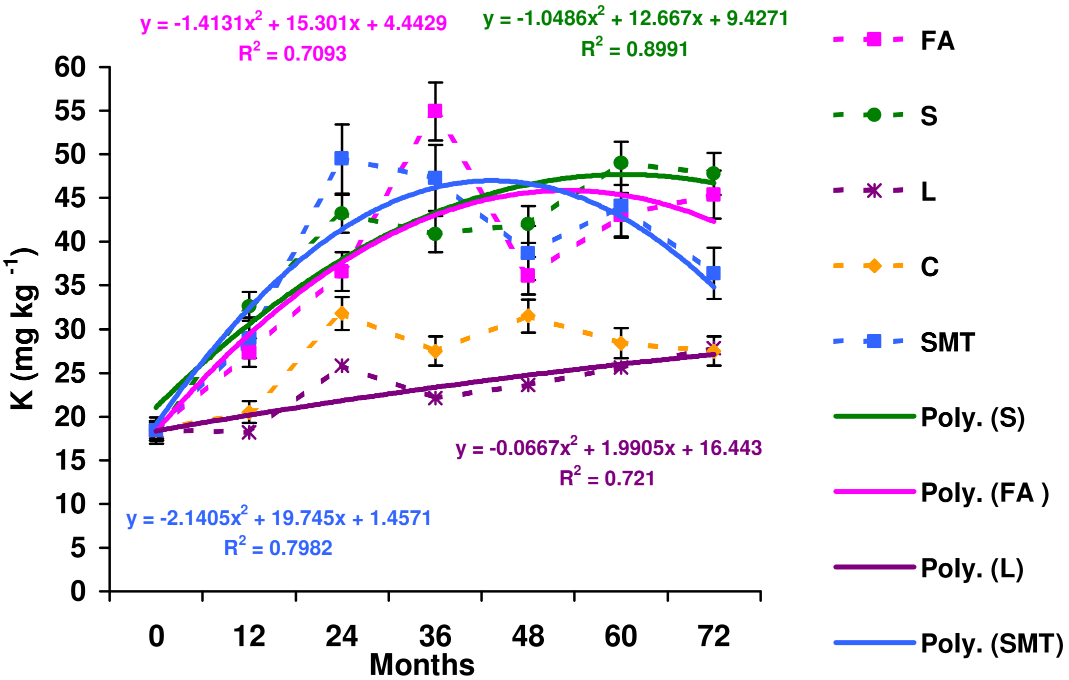

Figure 25: The influence of treatments, relative to C and SMT treatments, on the soil K status over a 72-month period

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

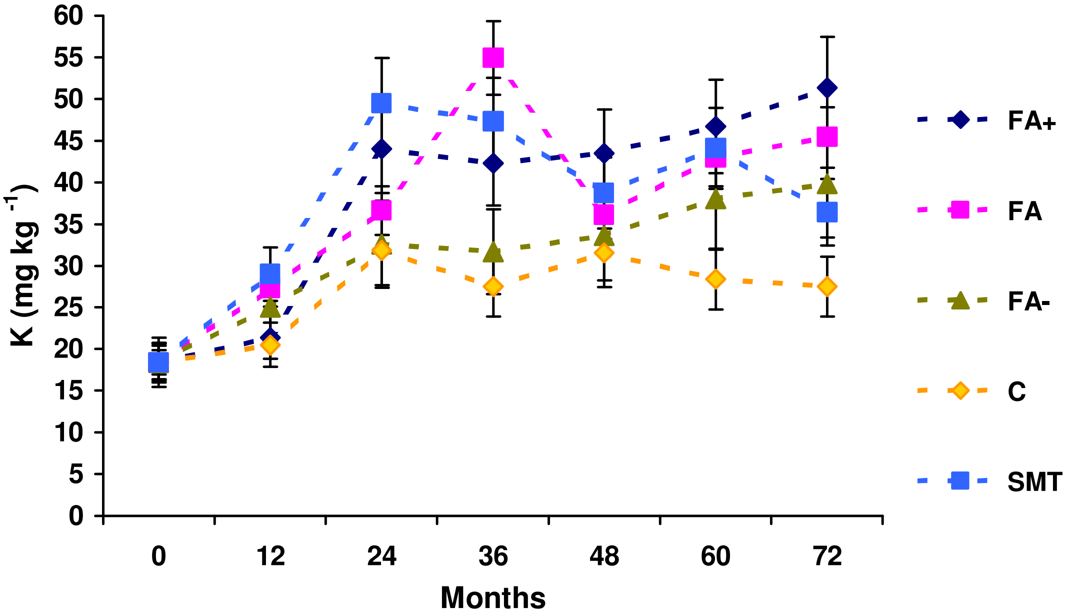

Figure 26: The influence of FA treatments, relative to C and SMT treatments, on the soil K status over a 72-month period

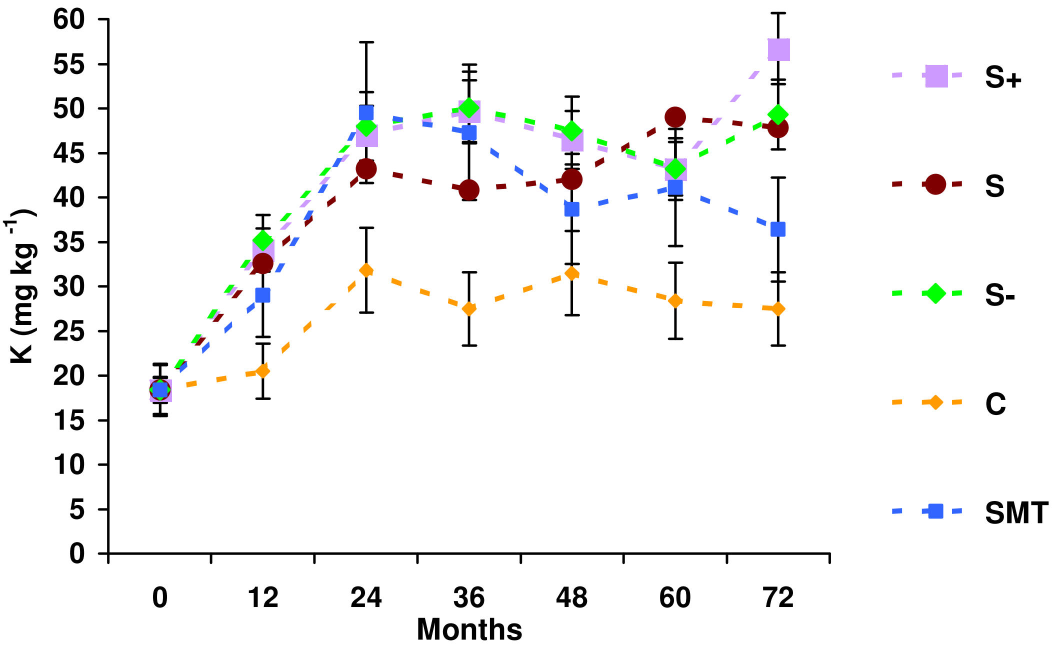

Figure 27: The influence of S treatments, relative to C and SMT treatments, on the soil K status over a 72-month period

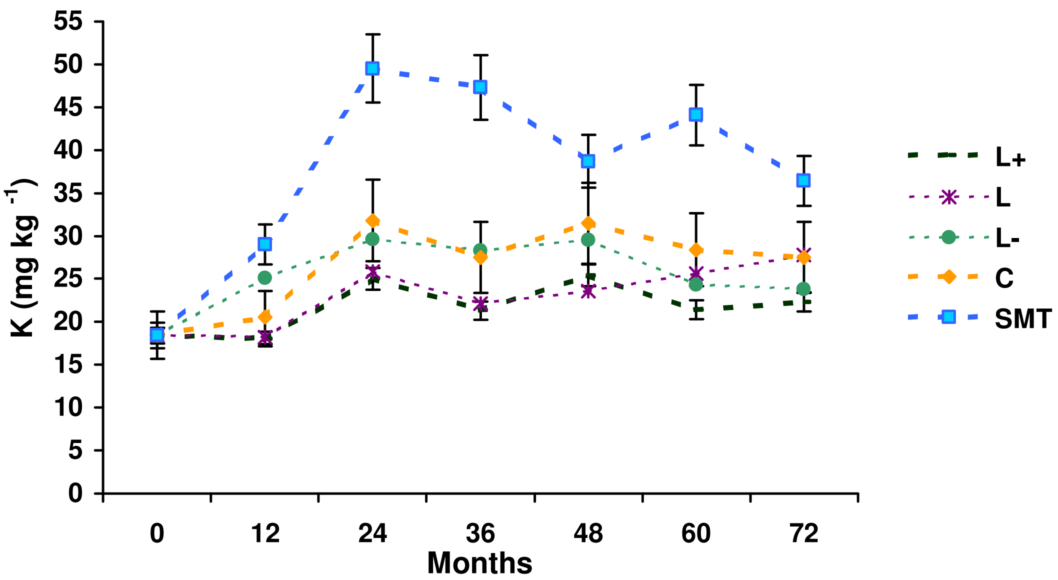

Figure 28: The influence of L treatments, relative to C and SMT treatments, on the soil K status over a 72-month period

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

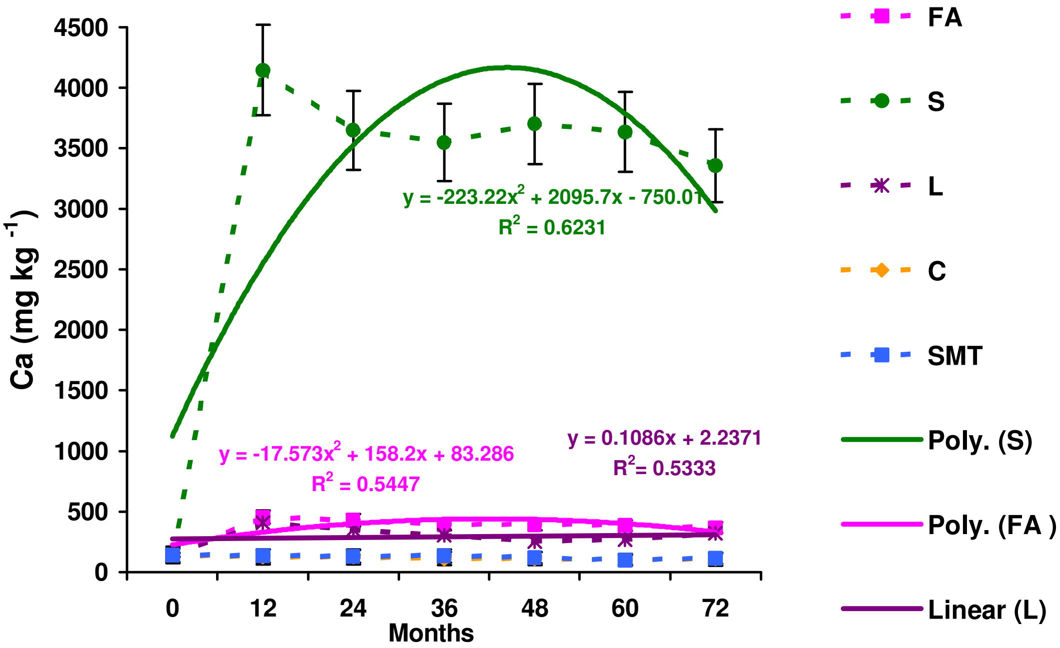

Figure 29: The influence of treatments, relative to C and SMT treatments, on the soil Ca status over a 72-month period

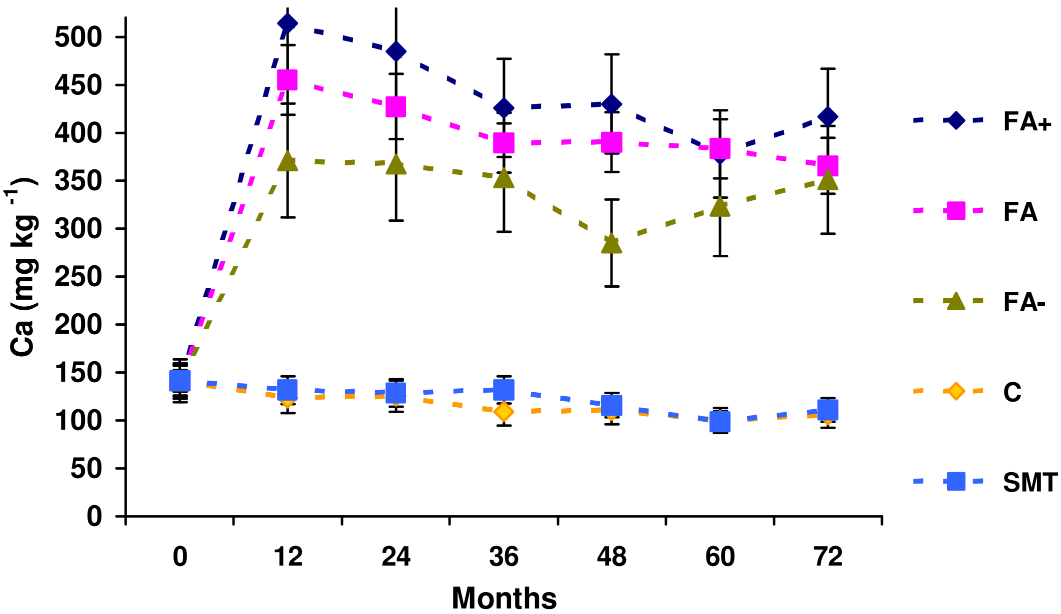

Figure 30: The influence of FA treatments, relative to C and SMT treatments, on the soil Ca status over a 72-month period

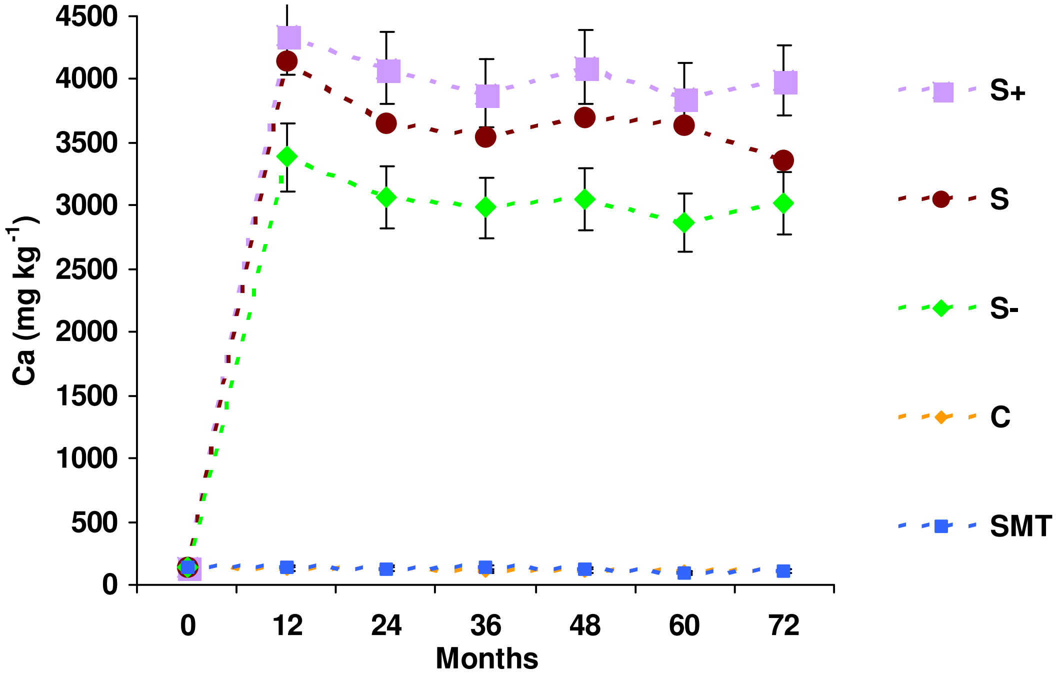

Figure 31: The influence of S treatments, relative to C and SMT treatments, on the soil Ca status over a 72-month period

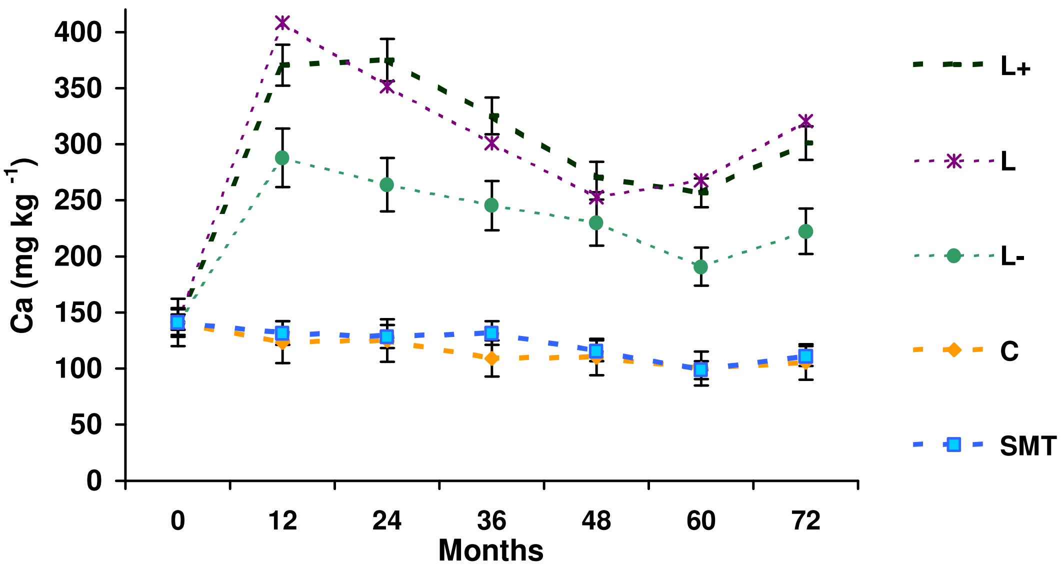

Figure 32: The influence of L treatments, relative to C and SMT treatments, on the soil Ca status over a 72-month period

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

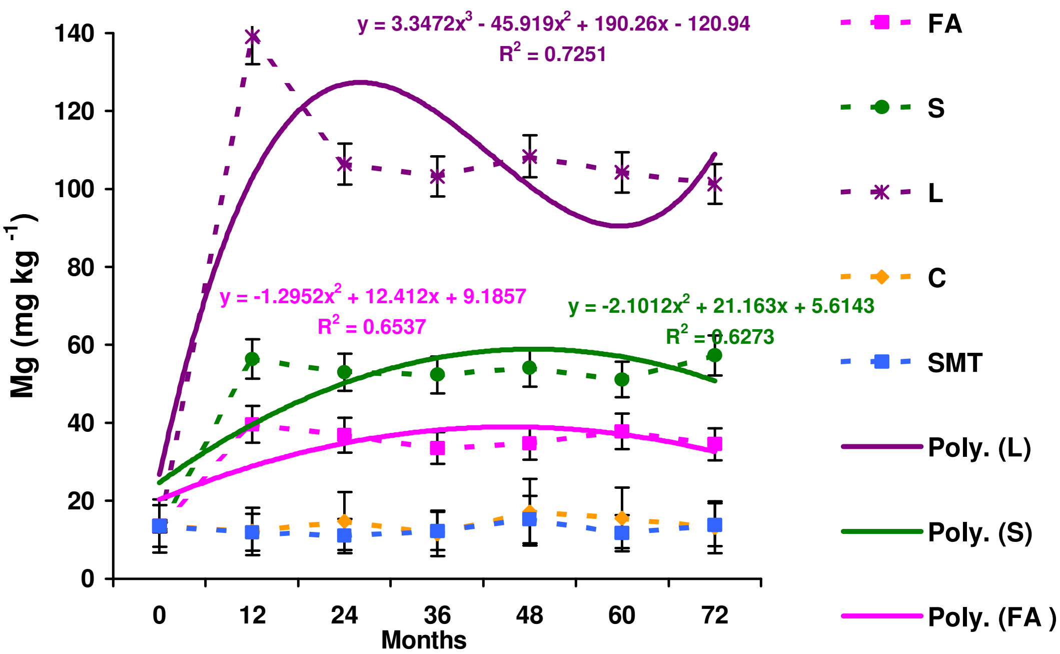

Figure 33: The influence of treatments, relative to C and SMT treatments, on the soil Mg status over a 72-month period

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

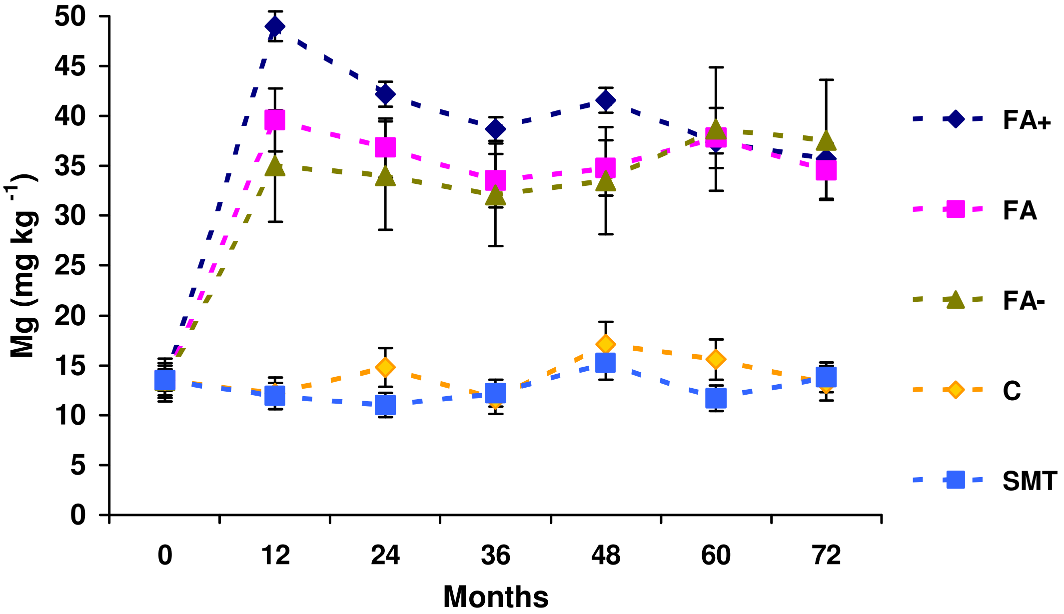

Figure 34: The influence of FA treatments, relative to C and SMT treatments, on the soil Mg status over a 72-month period

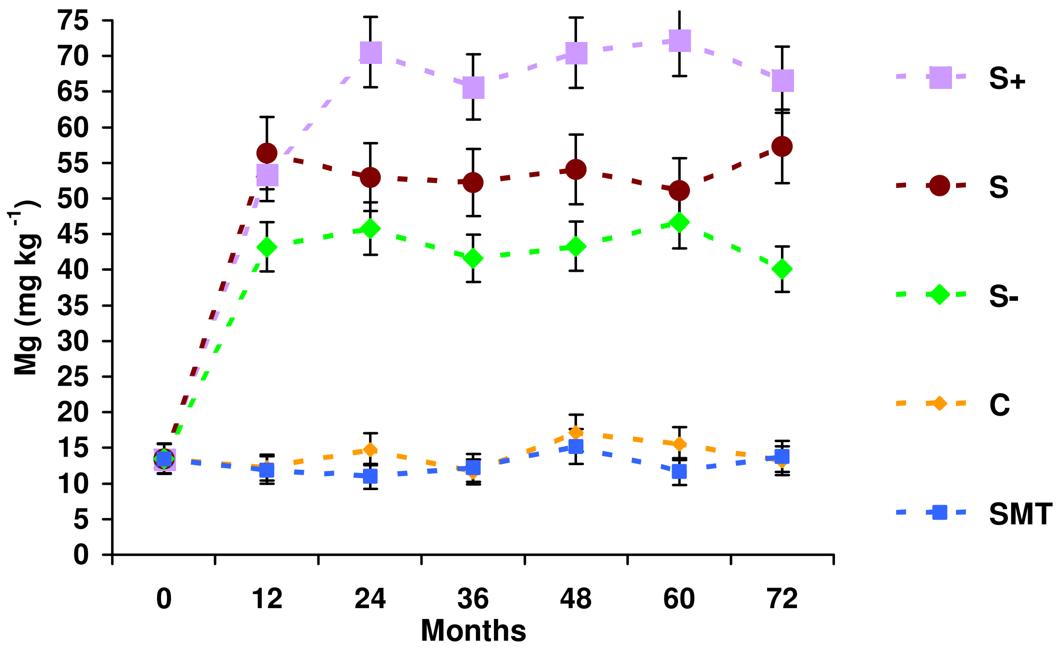

Figure 35: The influence of S treatments, relative to C and SMT treatments, on the soil Mg status over a 72-month period

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

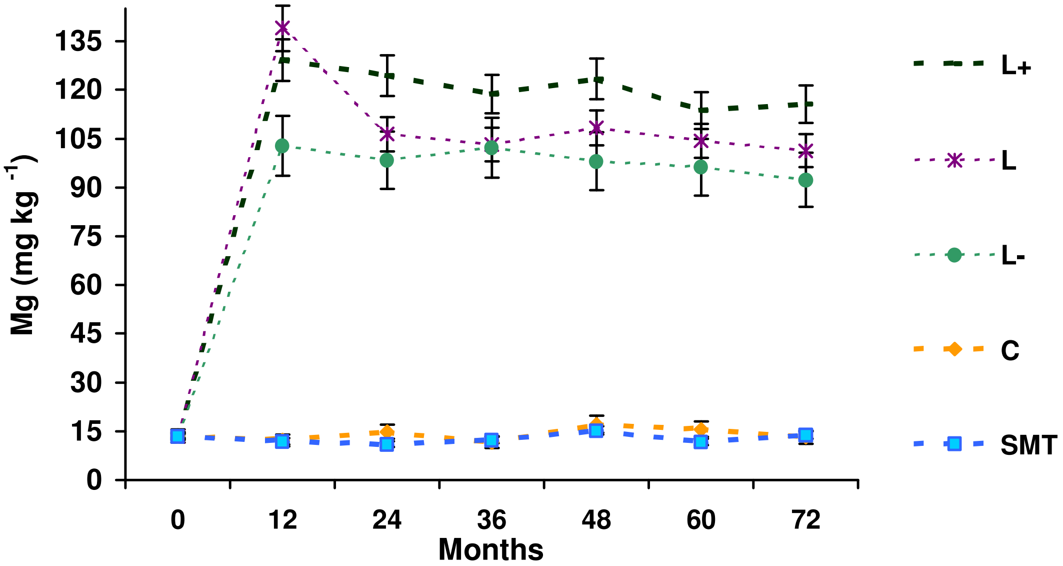

Figure 36: The influence of L treatments, relative to C and SMT treatments, on the soil Mg status over a 72-month period

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

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

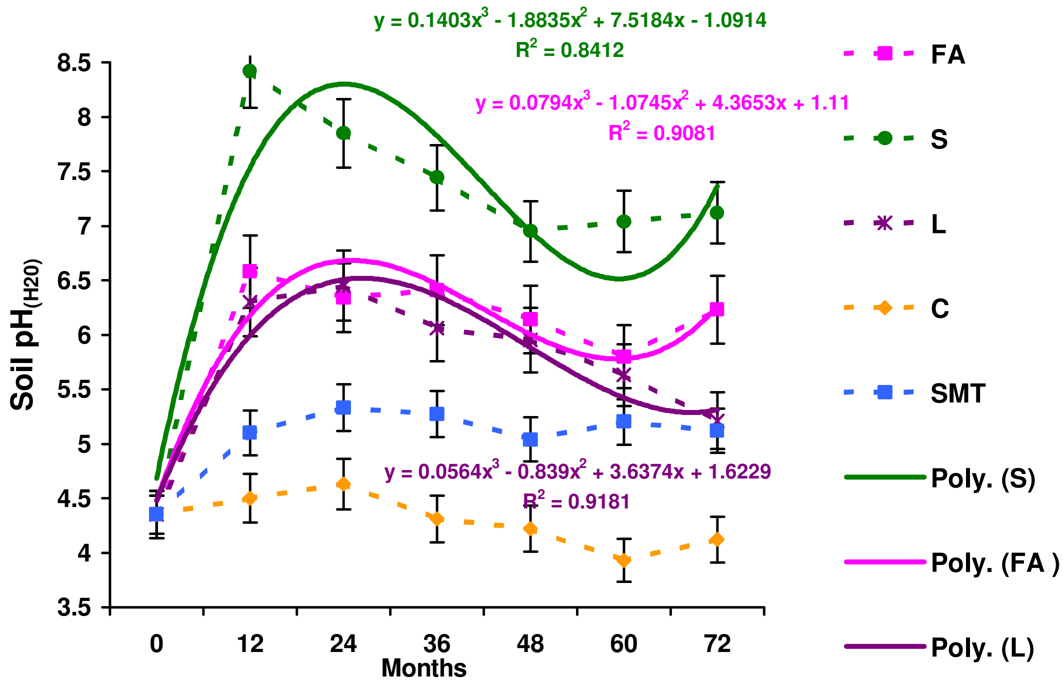

Figure 37: The influence of treatments, relative to C and SMT treatments, on the soil soil $pH_{(H20)}$ over a 72-month period

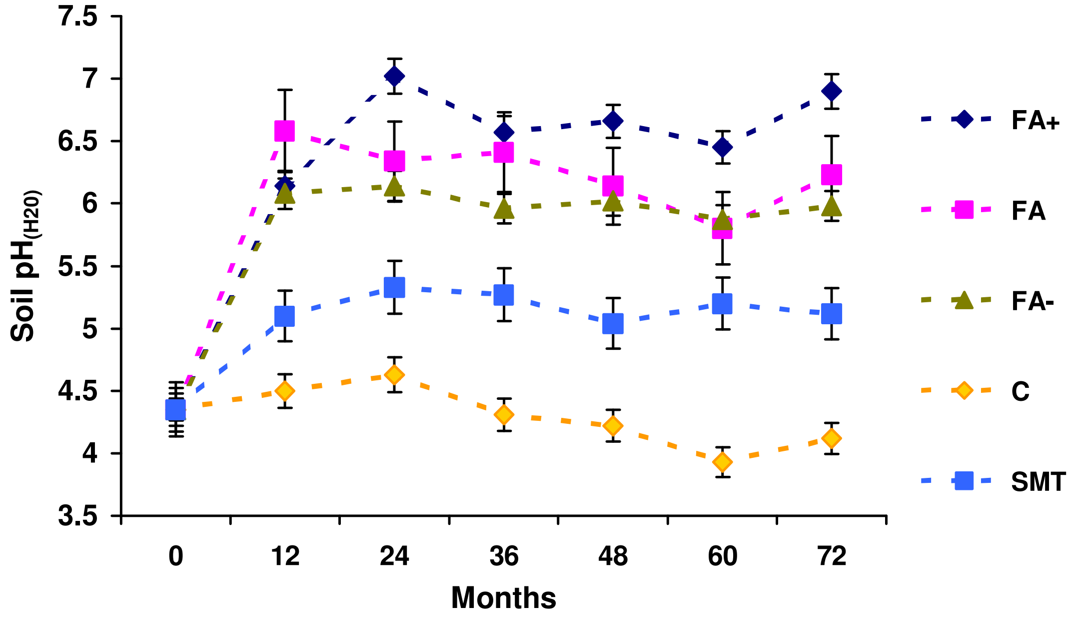

Figure 38: The influence of FA treatments, relative to C and SMT treatments, on the soil soil $pH_{(H20)}$ over a 72-month period

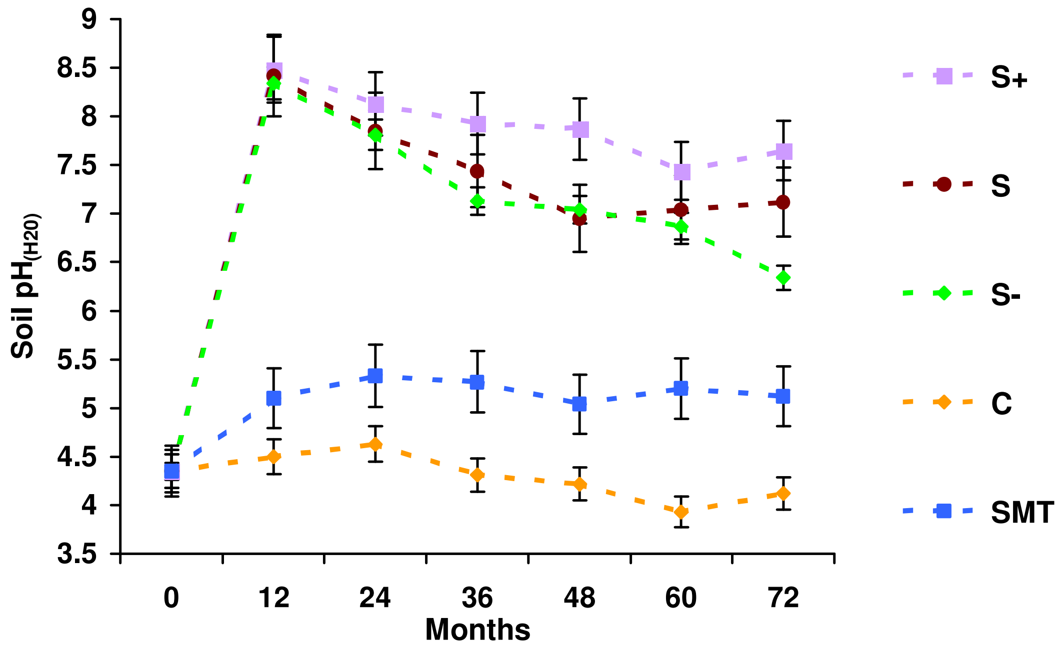

Figure 39: The influence of S treatments, relative to C and SMT treatments, on the soil soil $pH_{(H20)}$ over a 72-month period

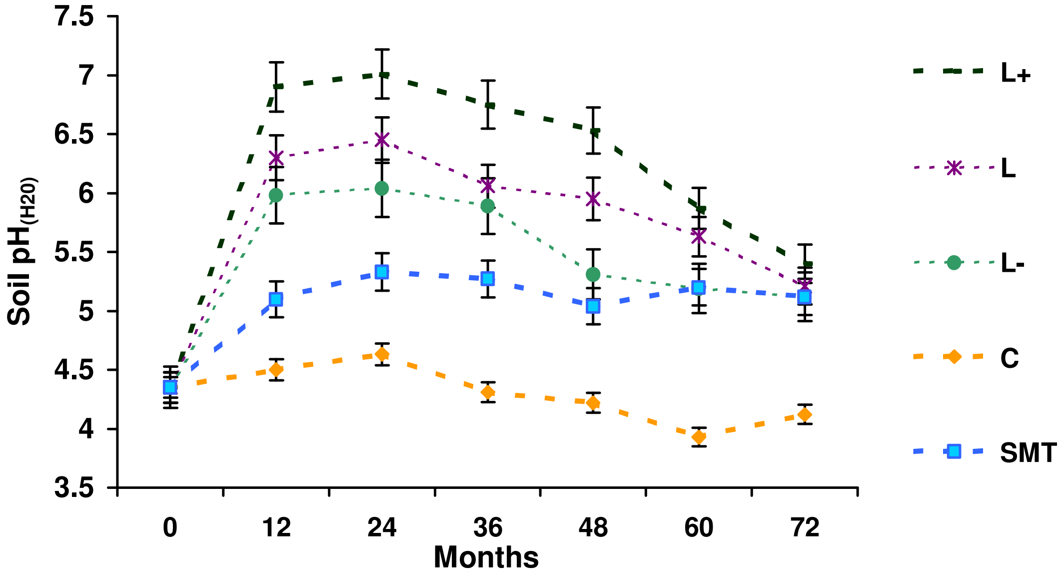

Figure 40: The influence of L treatments, relative to C and SMT treatments, on the soil soil $pH_{(H20)}$ over a 72-month period

4. Conclusions

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

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

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